Toppersnotes
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ENGINEERS ACADEMY

RRB - JE

Railway Recruitment Board

Volume - 2

Electronic Devices and Circuits

SIERRA INNOVATIONS

SEMI CONDUCTOR PHYSICS

THEORY

1.1 INTRODUCTION

As a matter of fact, solids are the most important materials handled by man for the designs, development and in day to day life.

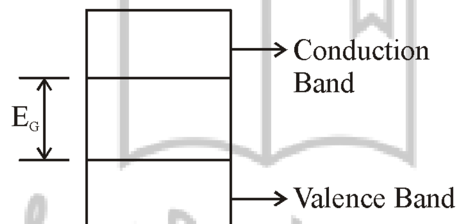
Solids may be classified into three categories with respect to energy band gap.

(1) Insulators

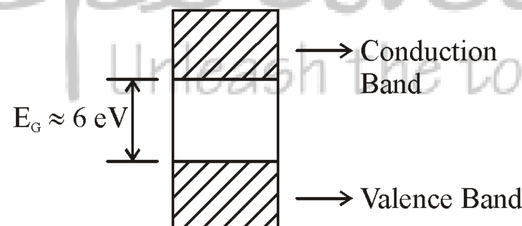
(2) Semiconductors

(3) Conductors

Note : Energy Gap (E_G) or Band Gap : The minimum energy required to detach an electron from valance band to conductor band is equal to it's Energy Gap (E_G).



(1) Insulators : E_G is very large ≈ 6 eV

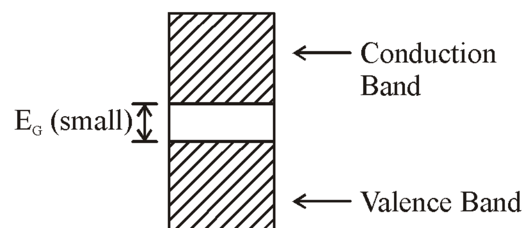


Due to large energy gap between valence and conduction band at room temperature, none of the e^- is in conduction band. Hence no conduction of electricity.

Example : Diamond, Glass.

(2) Semiconductors :

- E_G is small.
- It has the conductivity between metal and insulators.



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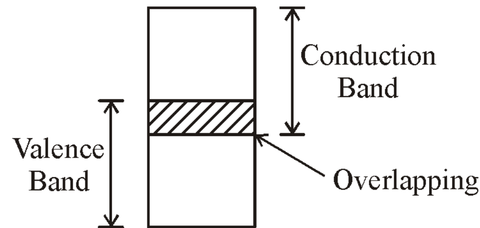
At 0 K the valence band is completely filled and the conduction band is empty. As temperature increases the electrons in valence band acquire enough energy to cross the small energy gap and move to conduction band. Hence the conductivity of semiconductors increases with temperature.

Example : For Ge $E_G \approx 0.7$ eV and for Si $E_G \approx 1.1$ eV.

(3) Conductors or Metals : Valence band and conduction band are overlapped.



Example : Sodium, lithium, Beryllium.

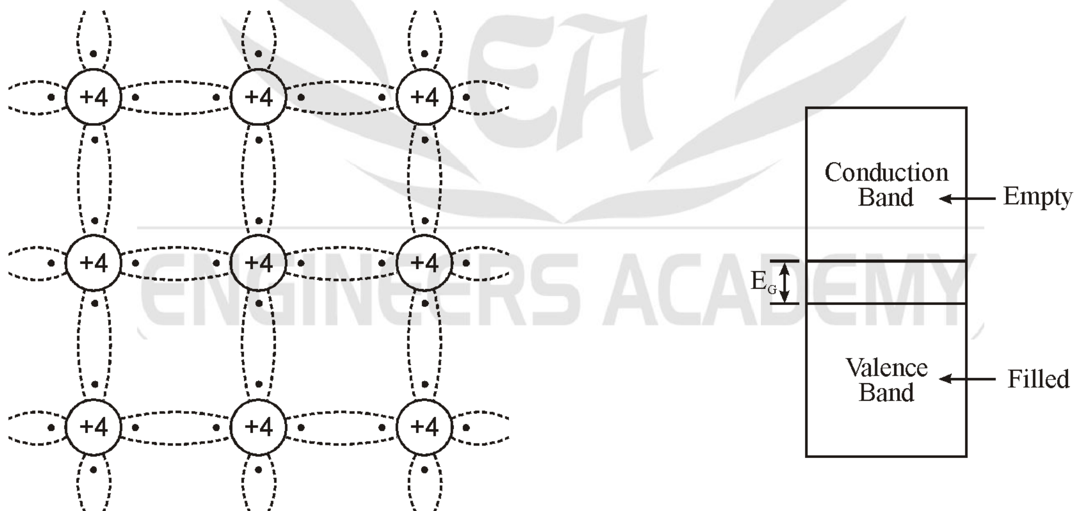
1.2 INTRINSIC AND EXTRINSIC SEMICONDUCTORS

The semiconductors may be classified into two categories :

1. Intrinsic semiconductor
2. Extrinsic semiconductor

1.2.1 Intrinsic semiconductors

- Also called pure semiconductor (or) non-degenerative semiconductor (as basic properties are not changed). Degenerate means change of basic properties by adding impurity. Hence extrinsic semiconductor is known as degenerate semiconductor.
- Valence band can accommodate a maximum of 8 electrons. When intrinsic semiconductor at 0 K is placed under electron microscope, it shows crystalline (regular 3D arrangement) structure.



Instrinsic SC at T = 0 K

Energy band diagram of intrinsic SC at 0 K

- Intrinsic semiconductor behaves as a perfect insulator at 0 K.
- The sharing of electrons with neighbouring atom is called covalent bonding.
- At 0 K all valence electrons are in perfect covalent bonding.
- Intrinsic semiconductor at 0 K is a perfect insulator.

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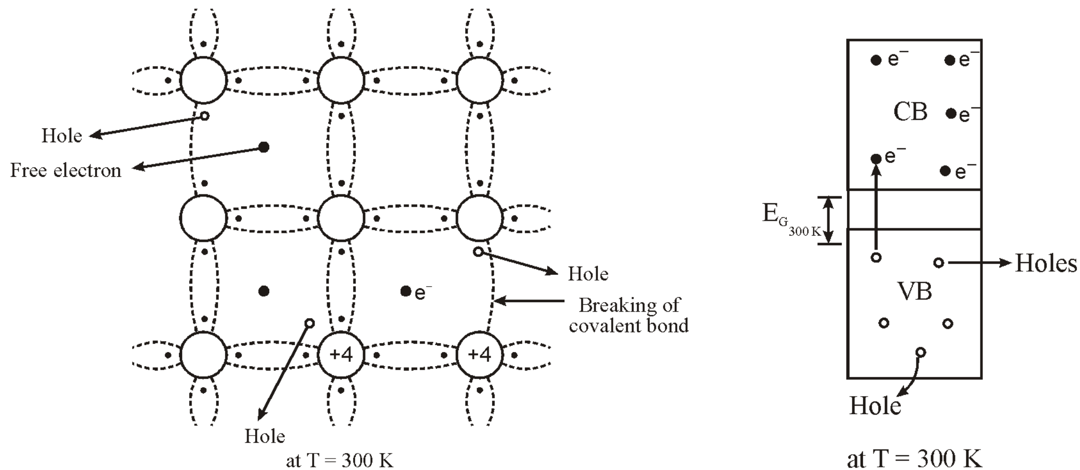

- When a covalent bond is broken, it will create one e^- and one hole.
- The electron will jump from VB to CB and become a free electron and hole will remain in VB.
- Hole is defined as deficiency of electron in the broken covalent bond.
- Hole is a carrier of current with a +ve charge of $+1.6 \times 10^{-19}$C.
- The process of breaking of covalent bond and creating electrons and holes is called "generation of electron-hole pair" or ionization.

Condition for intrinsic semiconductor is

$$n = p = n_i$$

Conductivity of intrinsic semiconductors is $\sigma_i = nq\mu_n + pq\mu_p$ ℧/cm

But $n = p = n_i$

$$\sigma_i = n_i q(\mu_n + \mu_p) \text{℧/cm}$$

$$\sigma_i \propto n_i$$

But $n_i \propto T^{3/2}$

$$\sigma_i \uparrow \text{ with } T$$

In intrinsic semiconductor, conductivity increases with temperature.

Resistivity of intrinsic semi-conductor

$$\rho_i = \frac{1}{\sigma_i}$$

$$\rho_i = \frac{1}{n_i q(\mu_n + \mu_p)}$$

Disadvantage of intrinsic semiconductor

- Conductivity is very less (As conductivity is very less, intrinsic semiconductor never used in fabrication i.e. no practical application).
- Only one device in which intrinsic semiconductor used is PIN DIODE (a micro wave diode).

1.2.2 Extrinsic Semiconductors

It is also called impurity semiconductor (or) doped semiconductors (or) artificial semiconductors (or) degenerate semiconductor or compensated semiconductor.

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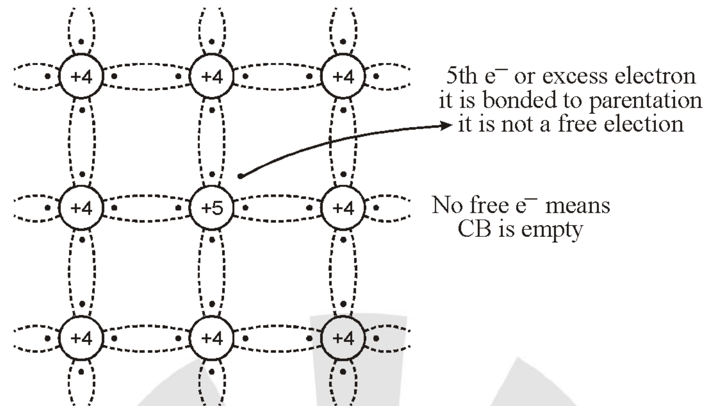
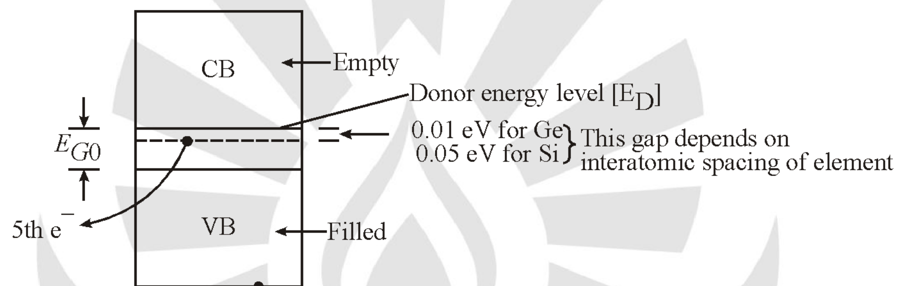
Types of extrinsic semiconductor

1. N-type semiconductor or Donors

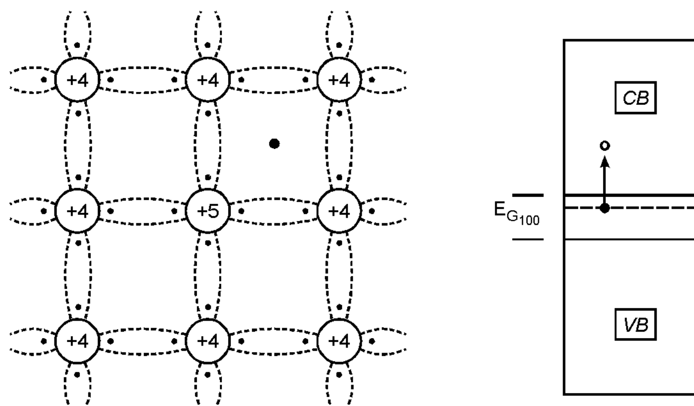
- Pentavalent impurities are added.





Energy band diagram of N-type semiconductor at T = 0 K

- Energy band diagram of N-type of semiconductor at T = 0 K (Because of addition of impurity there is disturbance in energy level. So a new discrete energy level is created below the conduction band known as donor energy level [E_D]).
- Donor energy level is a discrete energy level created just below conduction band.
- Donor energy level denotes energy level of all pentavalent atom added to the pure semiconductor.
- At 0 K the 5th electron of the impurity atoms will be existing in the donor energy level.
- The additional energy required to detach 5th electron from its orbit is equal 0.01 V for Ge and 0.050 V for Si.
- The minimum energy required to conduction in N-type Ge is 0.01 eV.
- The minimum energy required for conduction in N-type Si is 0.05 eV.
- N-type semiconductor at 0 K is a perfect insulator.

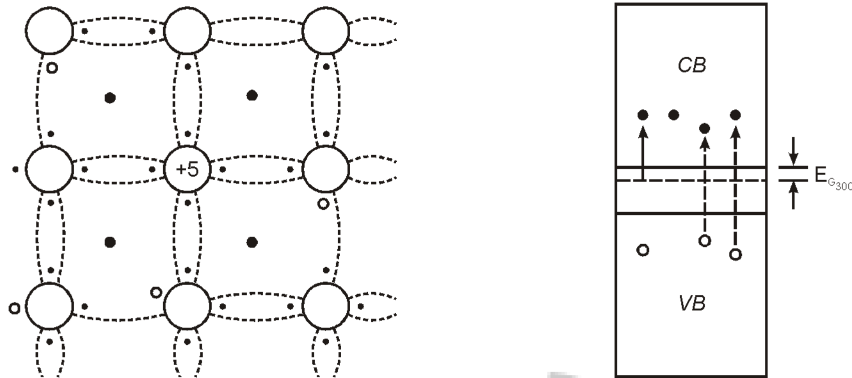


At $T = 100$ K

$$\text{No. of atoms} = 5 \times 10^{22} \times \frac{1}{10^7}$$

Impurity added = 5×10^{15} atoms/cm^3

- As temperature increases from 100 K to 300 K, covalent bond breaks creating electron hole pair.
- If 1 covalent bond breaks 1 e^- and 1 hole will be created and there is extra 1 e^- due to impurity means electrons are more as compared to hole i.e., e^- are majority charge carrier.



at T = 300 K

Silicon (Si) → 1 : 10^7 pentavalent impurity 5×10^{15} atoms/cm^3

Because of temperature → 10^4 covalent bond break

→ 10^4 e^- created

→ 10^4 holes created

→ e^- goes to CB holes remain in VB.

Total no. of e^- → $5 \times 10^{15} + 10^4 \simeq 5 \times 10^{15}$

- Donor level ionization means exciting the electrons from donor energy level into conduction band.
- Every impurity atom will be donating one electron into the conduction band. (hence N-type is called donor).
- Donor level ionization increases with temperature.
- At 300 K, donor level ionization is completed i.e., the 5th e^- of all the impurity atoms will be moving from donor energy level into the conduction band.
- Above 300 K, there is no donor level ionization.
- Majority carriers are electrons.
- Minority carriers are holes.
- The condition for N-type semiconductor $n > n_i$, $p < n_i$.
- As temperature increases because of thermal energy, a large number of covalent bonds will be broken creating equal number of electrons and holes and these electrons will be moving, into the conduction band and due to donor level ionization a large number of electrons are entering into the conduction band such that electron concentration in the conduction band is far greater than hole concentration in valance band.
- Hence electrons are majority charge carrier and holes are minority carrier.

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According to the law of electrical neutrality

$$N_D + p = N_A + n$$

In N-type semiconductor

$$N_A = 0$$

$$n = N_D + p$$

Since $n >> p$

$$n \simeq N_D$$

In N-type semiconductor, the free electron concentration is almost equal to donor concentration.

N_D is the donor concentration and it denotes no. of pentavalent atom added to pure semiconductor.

$$N_D = \frac{\text{Total no. of atoms}}{\text{Volume}} \times \text{Impurity ratio}$$

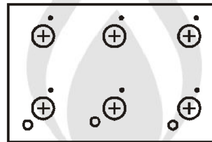
The conductivity of N-type semiconductor is

$$\sigma_N = nq\mu_n + pq\mu_p \ \mho/\text{cm}\ ; \ \simeq nq\mu_n \ \mho/\text{cm} \simeq N_D q\mu_n \ \mho/\text{cm}$$

i.e., $\sigma_N \propto N_D$

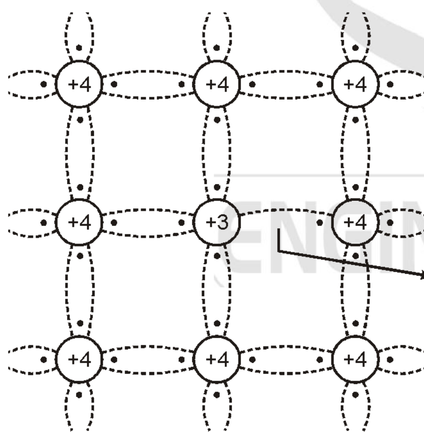
$\Rightarrow$ $\sigma_N \uparrow$ with doping

- **Representation for N-type semiconductor :** The one impurity atom will donate one electron and after donating, it will become positive ion.

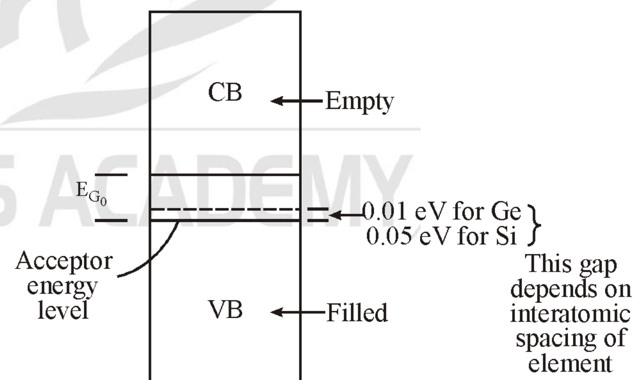


2. P-type semiconductor or Acceptors

- The impurity is trivalent.

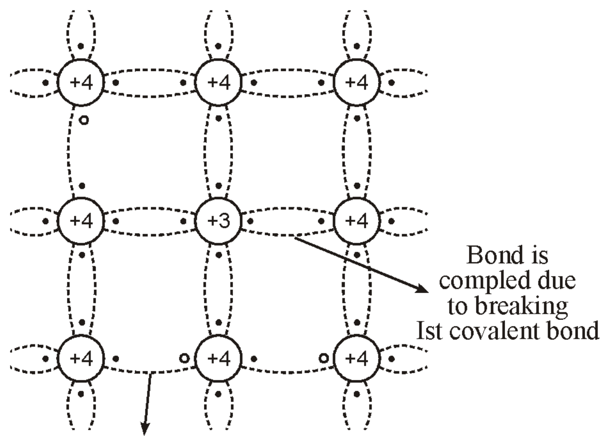


Crystalline structure at 0 K

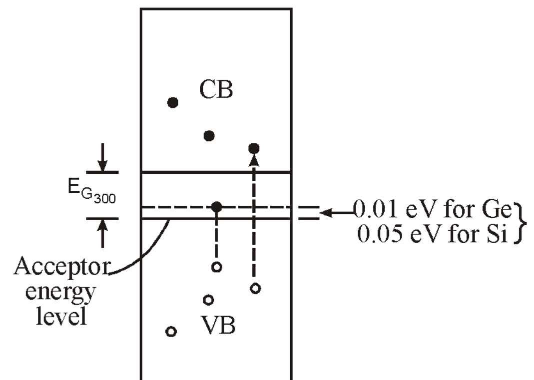


Energy level diagram at 0 K

- P-type semiconductor at 0 K behave like insulator (as 7 valence e^-)
- N-type semiconductor at 0 K behave perfect insulator (as 8 valence e^-)
- Acceptor energy level is a discrete energy level created just above the valence band.
- Acceptor energy level denotes energy level of trivalent atoms added to the pure semiconductor.
- P-type semiconductor at 0 K is an insulator.



Breaking of covalent bond at T = 300 K



at T = 300 K

- In P-type semiconductor every impurity atom will be receiving one e^- to complete its covalent bonding.
- As temperature increases a large number of covalent bond will be broken creating equal no. of e^-s and equal no. of holes and majority of these electrons will be going into acceptor energy level for bonding and very few electrons will be reaching the conduction band. Hence electron concentration in the conduction band is very less when compared to hole concentration in VB.
- Hence, holes are majority carrier and e^-s are minority carrier.

  Condition for P-type semiconductor is $p > n_i$, $n < n_i$.
- In P-type semiconductor as hole concentration increases above n_i, the electron concentration falls below n_i and this is due to large number of bondings.

According to law of electrical neutrality.

$$N_D + p = N_A + n$$

In P-type semiconductor $\quad N_D = 0$

$$p = N_A + n$$

Since $\quad p >> N_A$

$$p \simeq N_A$$

N_A is called acceptor concentration and it denotes the number of trivalent atoms added to the pure semiconductor.

$$N_A = \frac{\text{Total no. of atoms}}{\text{volume}} \times \text{Impurity ratio}$$

In P-type semiconductor current is dominated by holes. The conductivity of P-type semiconductor is

$$\sigma_P = nq\mu_n + Pq\mu_p \ \mho/\text{cm}$$

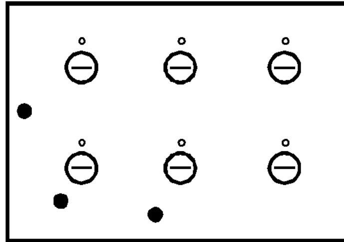
$$\sigma_P \simeq pq\mu_p \ \mho/\text{cm}$$

$$\sigma_P \simeq N_A q\mu_0 \ \mho/\text{cm}$$

$$\sigma_p \propto N_A$$

$\Rightarrow \quad \sigma_p \uparrow$ with doping

- **Representation for P-type semiconductor :** The impurity atom after receiving the e^- will become an negative ion.



1.3 MASS-ACTION LAW

In a semiconductor (intrinsic and extrinsic) under thermal equilibrium the product of e^- holes is always a constant and is equal to the square of intrinsic concentration.

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

where n = concentration of e^-

p = concentration of holes

n_i = intrinsic concentration

1.3.1 For N-type semiconductor

Mass-action law is given by

$$n_n p_n = n_i^2$$

where n_n = concentration of e^-

p_n = concentration of holes

For n-type materials concentration of e^- is almost equal to the donor concentration.

$$\therefore \quad n_n \simeq N_D$$

$$N_D p_n = n_i^2$$

$$p_n = \frac{n_{i^2}}{N_D}$$

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1.3.2 For p-type semiconductor

Mass action law is given by

$$n_p n_p = n_i^2$$

where n_n = concentration of e^-

p_n = concentration of holes

For n-type materials concentration of e^- is almost equal to the acceptor concentration

$$p_p \simeq n_A$$

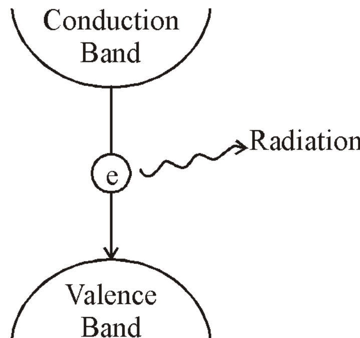
$$N_p \cdot N_A = n_i^2$$

$$N_p = \frac{n_i^2}{N_A}$$

1.4 DIRECT AND INDIRECT BAND GAP SEMICONDUCTORS

1.4.1 Direct Band-Gap semiconductor

In this type of semiconductor electrons from excited state in conduction band jump directly to valence band.



While jumping from conduction band to valence band the electron loose an energy, equal to the band gap in the form of radiation.

$$h\nu = E_G$$

where h = plank constant = 6.626×10^{-34} JS

ν = frequency of radiation

$$\nu = \frac{c}{\lambda}$$

where c = velocity of light = 3×10^8 m/s

λ = wave length

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

$$\lambda = \frac{hc}{E_G} \Rightarrow \lambda = \frac{1.24}{E_G}\ \mu m$$

where λ in μm and E_G in eV.

Example : GaAs

Note : In this most of the falling e^- from conduction band to valence band will be directly releasing energy in form of light (99%) and very few e^- while falling from conduction band to valence band will collide with the crystal of atoms and these crystal will be absorbing the energy from the falling electrons and gets heated up and they will release energy in form of heat (1%).

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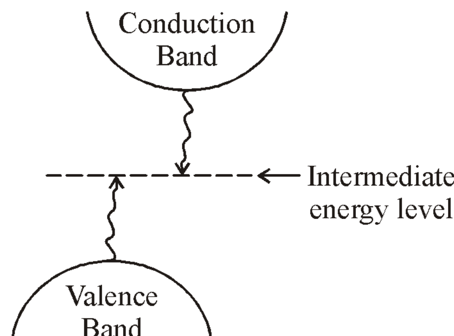
1.4.2 Indirect Band-Gap

The semiconductor in which electrons from conduction band do not jump directly to valence band rather first jump from conduction band to some intermediate energy level called defect level and then from intermediate energy level to valence band are called indirect band gap.



Example : Ge and Si

Note : In Indirect Band Gap semiconductor most of the falling electrons from conduction band to valence band will collide with the crystal of the atom and these crystal will be absorbing the energy from the falling electron and gets heated up and they will release energy in the form of heat (99%) and very few electrons falling on conduction band to valence band will directly falling and they will release energy in form of light (1%).

1.5 BAND GAP OF Si AND Ge

E_G depends on Temperature,

(i) For Si : $E_G(T) = 1.21 - 3.60 \times 10^{-4}\ T$

at T = 0 K, $E_G(T) = 1.21$ eV

at room temperature of 300 K

$$E_G(T) = 1.12 \text{ eV}$$

(ii) For Ge : $E_G(T) = 0.785 - 2.23 \times 10^{-4}\ T$

at T = 0 °C, $E_G(T) = 0.785$ eV

at room temperature of 300 K

$$E_G(T) = 0.72 \text{ eV}$$

1.6 ELECTRICAL PROPERTIES OF SEMICONDUCTORS

(1) Resistivity (ρ)

- Unit (ohm-m)
- Semiconductors are having negative temperature co-efficient (NTC) of resistance. Means ρ ↓ with Temperature

  Note : In metal : ρ ↑ with Temperature having positive temperature coefficient (PTC).

(2) Conductivity (σ)

- It is the reciprocal of resistivity.
- Unit ℧-m
- Conductivity for semiconductor is given by

$$\sigma = nq\mu_n + pq\mu_p$$

(i) For intrinsic semiconductor

$$n = p = n_i$$

$$\sigma = n_i q(\mu_n + \mu_p)$$

(ii) For n-type semiconductor

$$n >> p \text{ and } n_n \approx N_D$$

$$\sigma \approx N_D q\mu_n$$

(iii) For p-type semiconductor

$$p >> n,\ p_p \approx N_A$$

$$\sigma \approx N_A q\mu_p$$

In semiconductor ρ ↑ with temperature

Temperature ↑ ρ ↓ σ ↑

∵ $\sigma = nq\mu_n + pq\mu_p$

when Temperature ↑ = n ↑, p ↑ [covalent bond will be broken]

but $= \mu_n$ ↓, μ_p ↓ [slightly]

Means conductivity (σ) increases with temperature.

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(3) Current Density (J) : Current passing per unit area.

$$J = I/A \text{ Amp/m}^2$$

$$J = \sigma E \text{ Amp/m}^2$$

In semiconductor $J = (nq\mu_n + pq\mu_p)E \text{ A/m}^2$

(4) Drift velocity : The motion of charge carriers under the influence of electric field is called "Drifting". The drift velocity of charge curriers is given by

$$V_d = \mu E$$

(5) Mobility : Mobility means how fast the charge carrier moves from one place to another place.

$$\mu = \frac{\text{Drift velocity}}{\text{Field intensity}} = \frac{V_d}{E}, \frac{m^2}{V.sec} \text{ or } \frac{cm^2}{V.sec}$$

Mobility of e^- and holes is given by :

$$\mu_n = \frac{e\tau_n}{2m_n}$$

$$\mu_p = \frac{e\tau_p}{2m_p}$$

where, τ_n = average collision time of electrons

τ_p = average collision time of holes

m_n = effective mass of e^-

m_p = effective mass of holes

Mobility of semiconductor as a function of temperature

$$\mu \propto T^{-m}$$

where m is a constant and is given by :

For Ge	For Si
m = 1.66 for e^-	m = 2.5 for e^-
= 2.33 for hole	= 2.7 for hole

Mobility of semiconductors as a function of electric field

m = constant for $E < 10^3$ V/cm

$\mu \propto E^{-1/2}$ for $10^3 \text{ V/cm} < E < 10^4$ V/cm

$\mu \propto E^{-1}$ for $E > 10^4$ V/cm

Electron mobility is always greater than hole mobility

$$\mu_n > \mu_p$$

For Si $\mu_n = 1300 \text{ cm}^2/\text{V-s}$

$\mu_p = 500 \text{ cm}^2/\text{V-s}$

For Ge $\mu_n = 3800 \text{ cm}^2/\text{V-s}$

$\mu_p = 1800 \text{ cm}^2/\text{V-s}$

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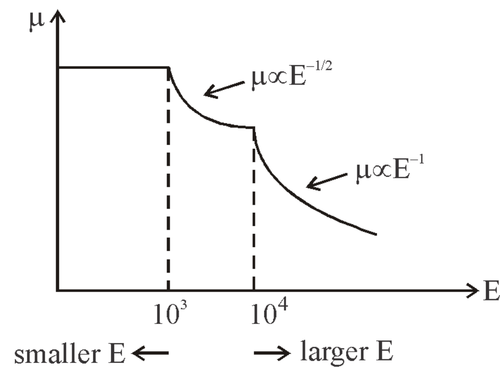
Mobility V/s electric field intensity curve :



1.7 EINSTEIN'S EQUATION

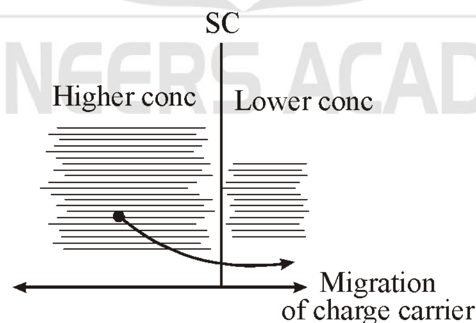
It gives the relation between diffusion constant, mobility and thermal voltage.

$$\frac{D_n}{\mu_n} = \frac{D_p}{\mu_p} = \frac{KT}{q} = V_T = \frac{T}{11600}$$

Thermal voltage $V_T = \frac{KT}{q}$

1.8 DIFFUSION AND DIFFUSION CURRENT

- The migration of charge carrier from higher concentration to lower concentration (or) from higher density to lower density is called as diffusion.
- Diffusion is mainly due to concentration gradient.
- Diffusion current flows only in semiconductor.
- In semiconductor diffusion is due to unequal distribution of charge carrier. (in metal charge carriers are density packed. So no unequal distribution no diffusion. In insulators charge carrier are negligible so no question of diffusion).



$\frac{dn}{dx}$ = electron concentration gradient

$\frac{dp}{dx}$ = hole concentration gradient

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L is the length of diffusion $L = \sqrt{D\tau}$ cm

But $D = \mu \times V_T$

$$L = \sqrt{\mu V_T \tau} \text{ cm}$$

Length of diffusion depends on : (i) diffusion constant (ii) mobility, (iii) temperature, (iv) carrier life time.

Electron diffusion length $L_n = \sqrt{D_n \cdot \tau_n}$ cm

τ_n = carrier life time of e^-

Hole diffusion length $L_p = \sqrt{D_p \cdot \tau_p}$ cm

e^- diffusion current density

$$J_n(\text{diff.}) = +qD_n \cdot \frac{dn}{dx} \text{A/cm}^2$$

hole diffusion current density

$$J_p(\text{diff.}) = -qD_p \cdot \frac{dp}{dx} \text{A/cm}^2$$

Total Current Density in a Semiconductor

The total current density $J = J_n + J_p$

But $J_n = J_n(\text{drift}) + J_n(\text{diffusion})$

$$= nq\mu_n E + qD_n \frac{dn}{dx} \text{A/cm}^2$$

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

$$= pq\mu_p E - qD_p \frac{dp}{dx} \text{A/cm}^2$$

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1.9 CONTINUITY EQUATION

The continuity equation gives the rate of change of carrier concentration inside a differential section of semiconductor bar. Let J_p is holes current density inside bar. The change of concentration of minority carriers as a function of time is given by :

$$\frac{\partial P}{\partial t} = \frac{P_0 - P}{\tau_p} - \frac{1}{q}\frac{\partial J_p}{\partial x}$$

where

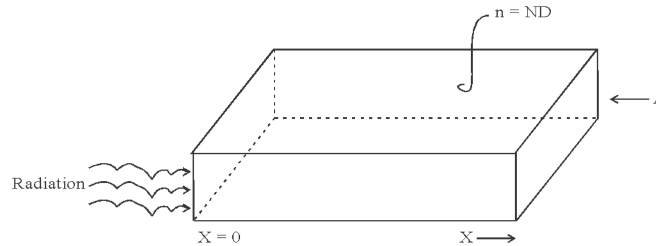
$\frac{P_0 - P}{\tau_p}$ = change in concentration due to generation and recombination.

$-\frac{1}{q}\frac{\partial J_p}{\partial x}$ = decrease in concentration due to J_p.

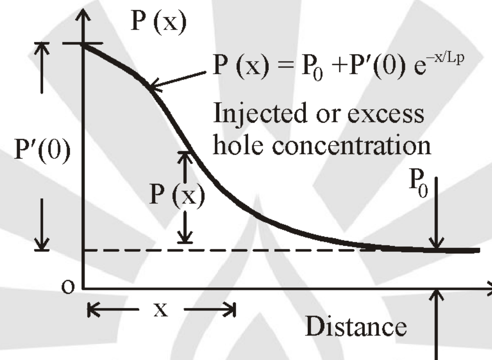
Note : Continuity equation based upon the principle of conservation of charges.

1.10 INJECTED MINORITY-CARRIER CHARGES

When radiation falls upon the end of the semiconductor by at $x = 0$, some of the photons are captured by the bound electrons in the covalent bonds near the illuminated surface. As a result of this energy transfer, these bonds are broken and holes electron pairs are generates.



Light falls upon the end of a - long semiconductor bar



Injected concentration is

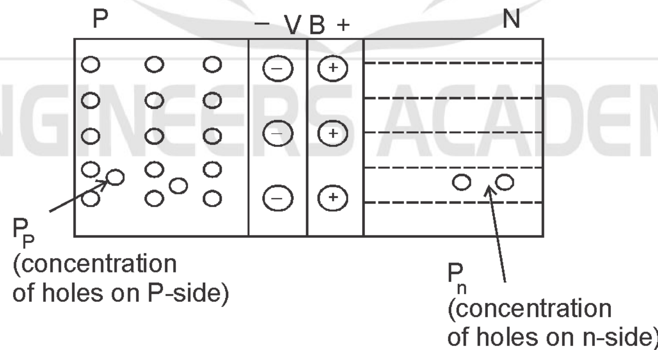
$$P'(x) = P'(0)\ e^{-x/L_p}$$

$$= P(x) - P_0$$

where L_p = diffusion length for holes

$L_p = (D_p \tau_p)^{1/2}$ m

1.11 POTENTIAL VARIATION IN GRADED SEMICONDUCTOR



Diffusion current density due to holes from P to N

$$= -q\ D_p \frac{dp}{dx}$$

Drift current density of holes from N to P

$$= \sigma_p E = pq\mu_p E$$

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So net current inside the bar is zero

$$J_{drift} + J_{diffusion} = 0$$

$$+pq\mu_p E - qD_p \frac{dp}{dx} = 0$$

$$pq\mu_p E = qD_p \frac{dp}{dx}$$

$$pE = \frac{D_p}{\mu_p}\frac{dp}{dx}$$

$\because$ $$E = -\frac{dv}{dx}$$

$$\frac{Dp}{\mu_p} = V_T \quad \text{[From Einstein relation]}$$

$$p\left(-\frac{dv}{dx}\right) = V_T \frac{dp}{dx}$$

$$\int_0^{V_B} dv = -\int_{p_p}^{p_n} V_T \frac{dp}{p}$$

$$V_B = -V_T \ln\frac{p_n}{p_p}$$

$$V_B = V_T \ln\frac{p_p}{p_n}$$

On p-side $p_p \approx N_A$

on N-side $n_n \approx N_D$

$\because$ $n_n\, p_n = n_i^2$ (mass-action law)

$$p_n = \frac{n_i^2}{n_n} = \frac{n_i^2}{N_D}$$

$$V_B = V_T\, l n \frac{N_A N_D}{n_i^2}$$

1.12 FERMI LEVEL IN SEMICONDUCTOR

1.12.1 Fermi level

- Fermi energy is expressed in eV.
- Fermi energy is defined as the maximum energy possessed by an electron at 0 K.
- Fermi energy is defined as the maximum kinetic energy possessed by an electron at 0 K.

$$\text{Max. KE} = \frac{1}{2}mV_{max}^2$$

$$E_F = \frac{1}{2}mV_{max}^2$$

$$\text{Max. velocity of } e^- = V_{max} = \sqrt{\frac{2E_F}{m}} \text{ m/sec}$$

- Fermi energy is also defined as the energy possessed by fastest moving e^- electron at 0 K.

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1.12.2 Fermi-Diarc Function f(E)

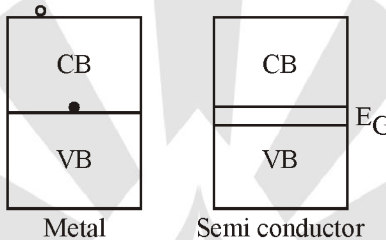
Also called fermi-Diarc probability function. In a metal or in a semiconductor $f(E) = \frac{1}{1+e^{(E-E_F)/kT}}$ fermi-diarc probability function.

Fermi diarc function is used to find the probability of e^- (s) existing as a function of energy level. E is called energy possessed by electron in eV.

At T = 0 K : We get 2 conditions :

(i) $E > E_F$ $\quad f(E) = \frac{1}{1+e^{\infty}} = \frac{1}{1+\infty} = 0$

(ii) $E < E_F$ $\quad f(E) = \frac{1}{1+e^{-\infty}} = \frac{1}{1+0} = 1$



At T ≠ 0 K :

Let $\quad E = E_F$

$$f(E) = \frac{1}{1+e^0} = \frac{1}{1+1} = \frac{1}{2} = 0.5 = 50\%$$

- Fermi level energy is the energy level with 50% probability of being filled if no forbidden band exist.
- For metals f(E) = 1 (or) 100%.
- In a semiconductor if the probability of electron existing is f(E) then probability of hole existing is 1 − f(E).

1.12.3 Fermi Level in Intrinsic Semiconductor

The condition in intrinsic semiconductor is n = p

$$\Rightarrow \quad N_C e^{-(E_C-E_F)/kT} = N_V e^{-(E_F-E_V)/kT}$$

$$\Rightarrow \quad \frac{N_C}{N_V} = e^{(-E_F+E_V+E_C-E_F)/kT}$$

$$\frac{N_C}{N_V} = e^{(E_C+E_V-2E_F)/kT}$$

$$\log_e \frac{N_C}{N_V} = \frac{E_C+E_V-2E_F}{kT}$$

$$\frac{E_C+E_V-2E_F}{kT} = \ln\frac{N_C}{N_V}$$

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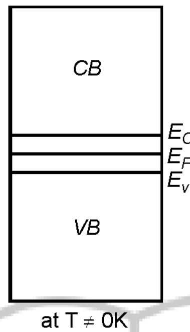
$$E_C + E_V - 2E_F = kT \ln \frac{N_C}{N_V}$$

$$E_F = \frac{E_C + E_V}{2} - \frac{kT}{2} \ln\left(\frac{N_C}{N_V}\right)$$

Case I : Let $M_n = M_p$

then $N_C = N_V;\ \ln \frac{N_C}{N_V} = 0$

$$E_F = \frac{E_C + E_V}{2}$$



at T ≠ 0K

Case II : T = 0K $E_F = \frac{E_C + E_V}{2}$

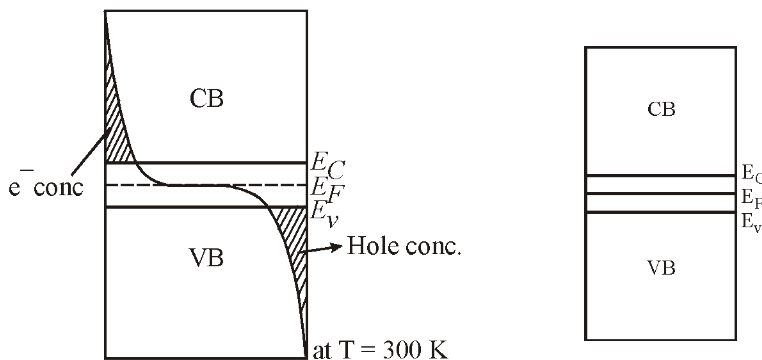
In intrinsic semiconductor at 0K, fermi level will be existing exactly at the center of energy gap.

Note : In intrinsic semiconductor fermi level will be existing at the center of energy gap when :

- $M_n = M_p$
- $N_c = N_v$
- T = 0K

Case III : T = 300 K $E_F = \frac{E_C + E_V}{2} - \frac{kT}{2} \ln \frac{N_C}{N_V}$

e^- concentration = hole concentration



Fermi level energy diagram at T = 0 K.

At 0 K electron concentration and hole concentration are zero and therefore conductivity is 0 and intrinsic semiconductor at 0 K is an insulator.

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Notes on Case III : In intrinsic semiconductor, at room temperature. Fermi level will be passing through the center of energy gap. At 300 K, e^- concentration and hole concentration are created and there will be a conductivity in the semiconductor.

Case IV :

- Position of Fermi Level at Different Temperature.
- As temperature increases carrier concentration increases and conductivity increases.

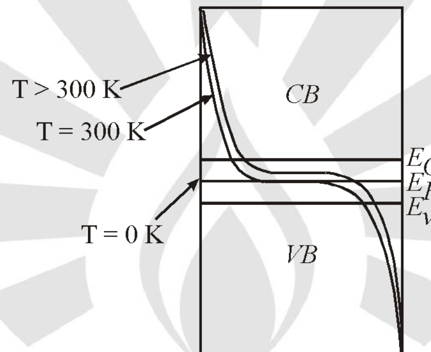
1.12.4 Fermi Level in N-Type Semiconductor

$$n \simeq N_D$$

$$N_C e^{-(E_C - E_F)/kT} = N_D$$

$$\frac{N_C}{N_D} = e^{(E_C - E_F)/kT}$$

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



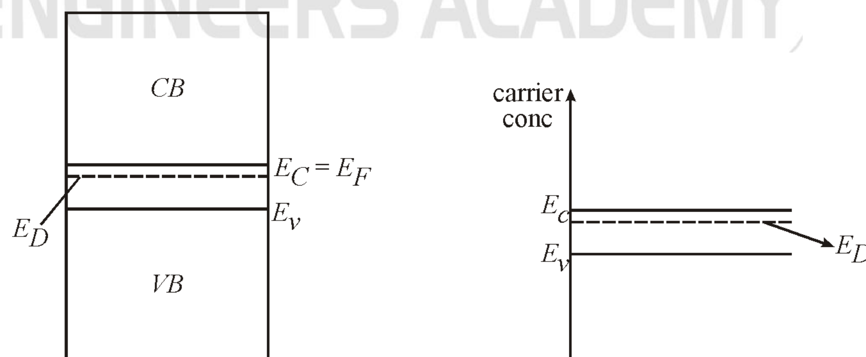
$$E_C - E_F = kT \ln \frac{N_C}{N_D}$$

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

In entire semiconductor fermi level depends on temperature and doping concentration (N_D).

Case I : T = 0K $\quad E_F = E_C$

E_F coincides with E_c.



Ferrmi level at T = 0K

At 0 K, e^- concentration and hole concentration are zero. Hence conductivity is zero. Hence entire semiconductor at 0 K is an insulator.

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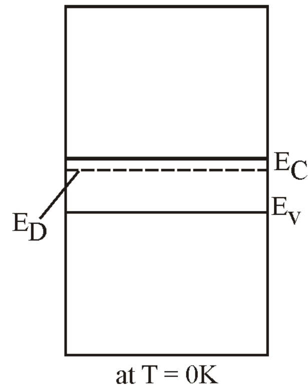
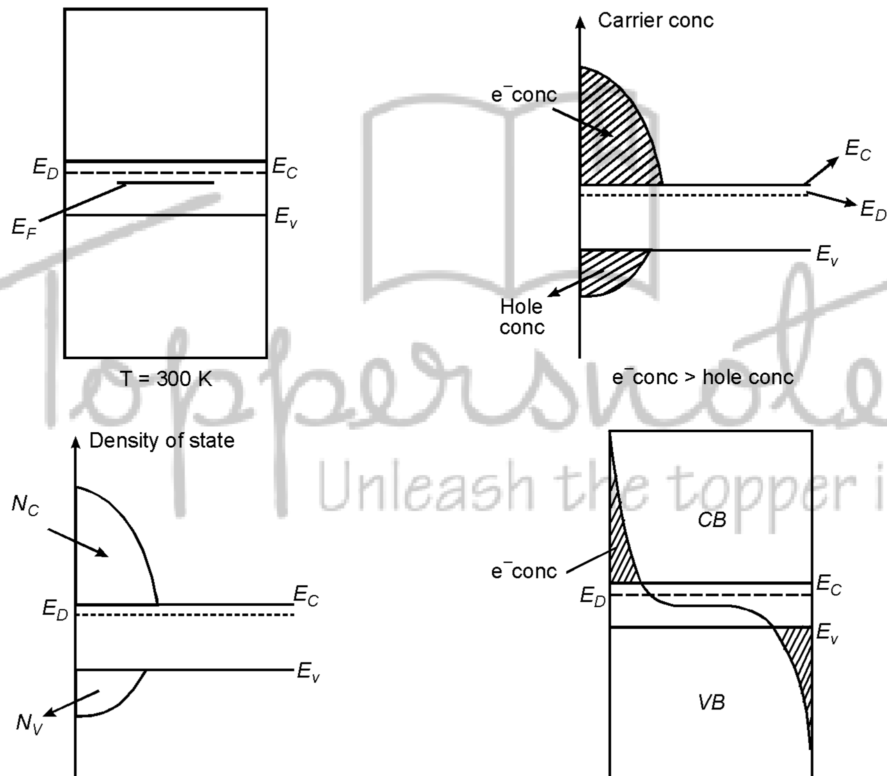
Case II : T = 300 K $E_F = E_C - kT\ln\frac{N_C}{N_D}$

In N-type semiconductor at room temperature



Fermi level will be existing just below the donor energy level.



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Case III : $E_F - E_C = kT\ln\frac{N_C}{N_D}$

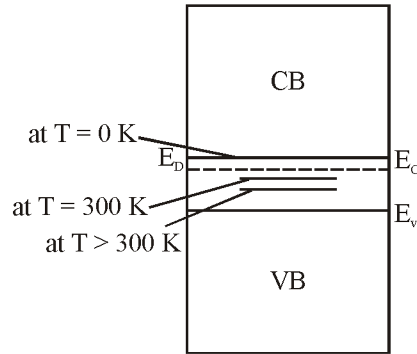
(i) When T ↑, N_C ↑ and let $N_C > N_D$

$$E_C - E_F > 0$$

or $$E_C > E_F$$

As T ↑ in N-type semiconductor, E_F moves away from CB.

or E_F moves towards the center of energy gap.



Hence σ↓ with temperature

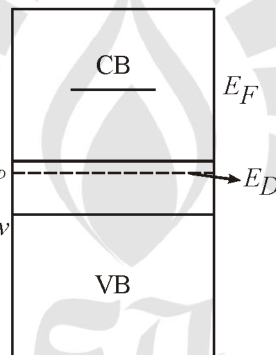
In N-type semiconductor, at curie temperature fermi level exist at the center of **energy gap**.

(ii) When dopping ↑, N_D ↑ and let $N_D > N_C$

$$E_C - E_F < 0$$

$$E_C < E_F$$

As doping ↑ in N-type semiconductor, E_F moves into the CB or E_F moves away from the centra of energy gap.



Hence σ ↑ with doping

In N-type semiconductor, as dopping increases, fermi level takes upward shift. In a highly degenerative, N-type (means N^+) the fermi level lies in the CB.

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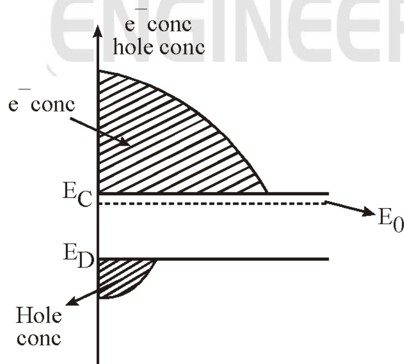
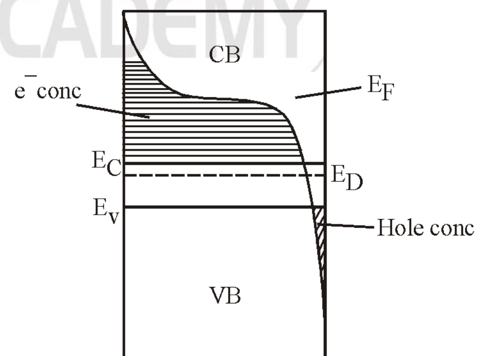


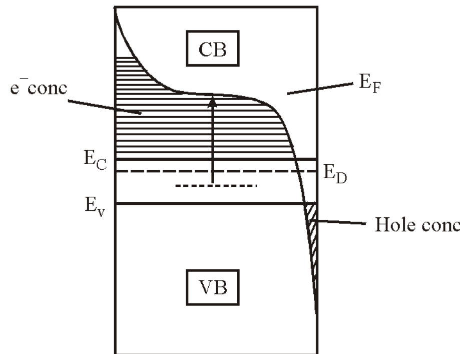


Case IV : Shift in the position of E_F due to doping (or)

Shift in the position of E_F from the center of energy gap.

Shift in Fermi Level $E_F = kT\log_e \frac{N_D}{n_i} eV$

or $\text{Shift} = kT\log_e \frac{N_D}{n_i} eV$



1.12.5 Fermi Level in P-type Semiconductor

$$P \simeq N_A$$

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

$$\frac{N_V}{N_A} = e^{(E_F - E_V)/kT}$$

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

$$E_F - E_V = kT\ln\frac{N_V}{N_A}; \qquad E_F = E_V + kT\ln\frac{N_V}{N_A}$$

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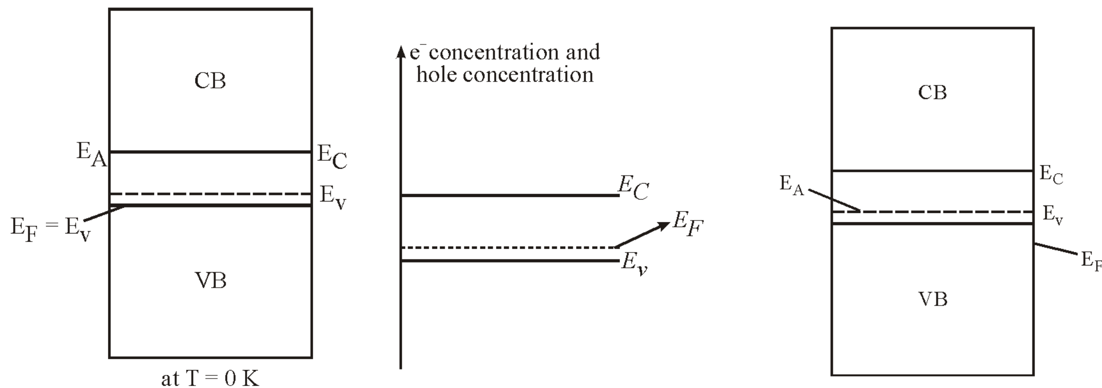
In P-type semiconductor fermi level is a function of temperature and doping concentration

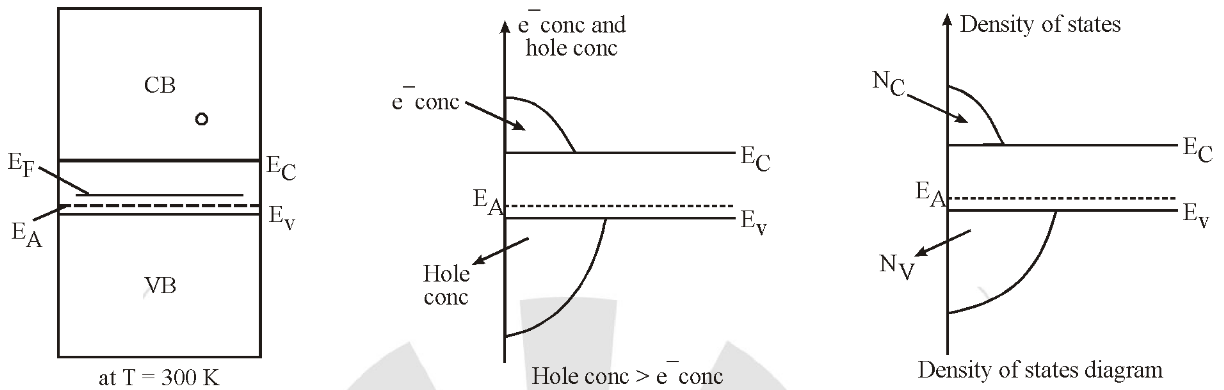
Case I : Let T = 0K $E_F = E_V$ i.e., E_F coincides with E_V.



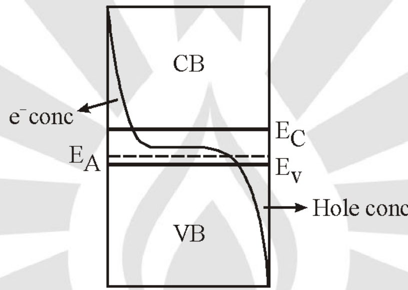
At 0K, electron concentration and hole concentrations are zero and therefore conductivity is zero and therefore P-type semiconductor at 0 K is an insulator.

Case II : T = 300 K

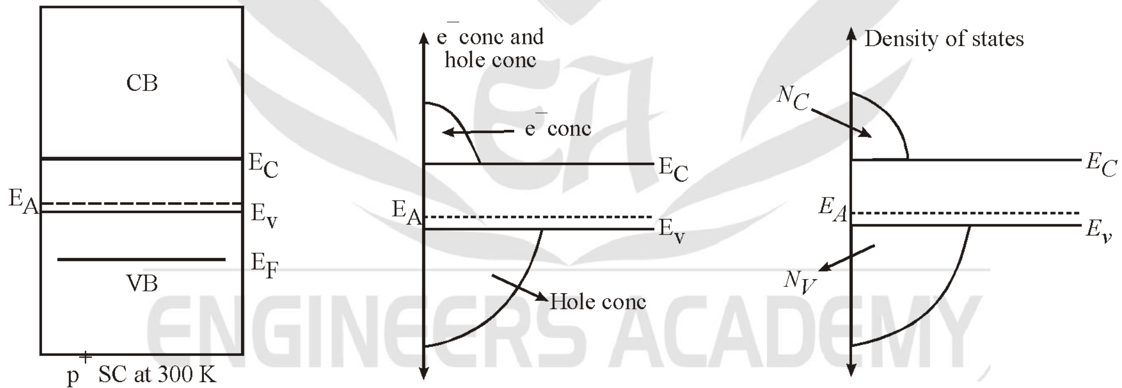
$$E_F = E_V + kT\ln\frac{N_V}{N_A}$$



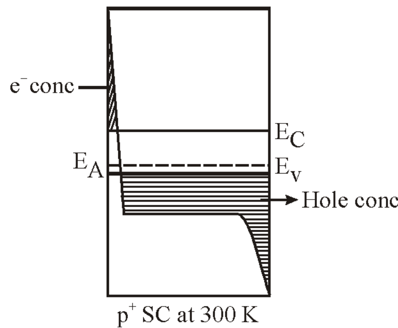
In P-type semiconductor, Fermi level lies just above the acceptor energy level at 300 K.



Holes are majority carrier and the current is dominated by the flow of holes.

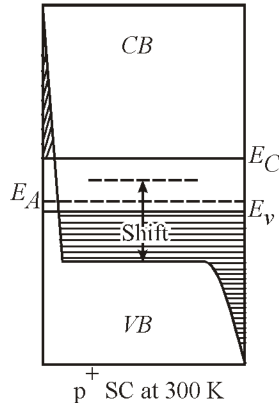


Case III : In P-type semiconductor as doping increases the fermi level takes downward shift. In a highly degenerative P-type semiconductor, the fermi level exist in the valence band.



Case IV : Shift in position of E_F due to doping.

Shift in position (or) of E_F w.r.t. position of E_F of intrinsic semiconductor.



p^+ SC at 300 K

Shift in position of E_F w.r.t. center of energy gap is given by

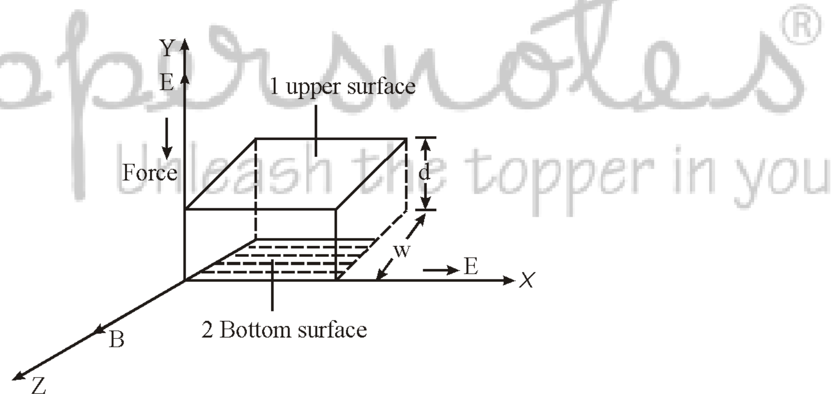
$$\text{Shift} = kT\ln\frac{N_A}{n_i}\text{eV}$$

or

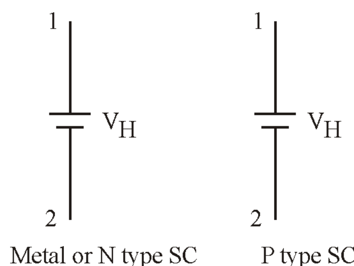
$$\text{Shift} = kT\ln\frac{P}{n_i}\text{eV}$$

1.13 HALL EFFECT

Hall effect states that : "If a specimen (metal or semiconductor) carrying the current I is placed in transverse magnetic field B, an electric field intensity E is induced in a direction perpendicular to both I and B".



- w is the width of specimen d is the height or thickness of the specimen (or) spacing between bottom surface and upper surface of specimen.
- Representation of Hall voltage



Hall effect can be used to determine :

- Whether the given specimen is a metal or semiconductor.
- The concentration of charge carrier in the specimen.
- Mobility of charge carrier.
- To measure the signal power in EM wave.
- In designing of hall effect transducer.

The polarity and magnitude of induced Hall voltage will indicate whether the given specimen is a metal or semiconductor.

Hall voltage is induced voltage (any induced voltage is very very small) in μV, mV, etc.)

Electric field intensity $E = \frac{V_H}{d}$ V/m

Hall voltage $V_H = Ed$ Volt

Hall voltage $V_H = \frac{BI}{\rho w}$ Volt

where ρ = charge density

$$\rho = \frac{1}{R_H}$$

R_H = Hall coefficient.

So $V_H = \frac{BIR_H}{w}$ Volt

i.e., $V_H \propto R_H$

According to Hall experiment mobility $\mu = \frac{8}{3\pi}\sigma R_H$

σ is the conductivity of given specimen.

$$\mu \simeq \sigma R_H \qquad \left(\because \frac{8}{3\pi} \approx 1\right)$$

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Application

- Hall effect multiplier
- Magnetofield meter

Note : (i) When one input signal is applied in the form of current and another input signal is applied in form of magnetic field the induced Hall voltage is directly proportional to the product of two input signal. Hence Hall experiment can be used for designing of Hall effect multiplier.

- In Hall effect multiplier the induced Hall voltage is related to multiplication of two input signal.
- Magnetofield meter is an instrument used to measure magnetic flux density (Wb/m^2)

Note : Mobility of charge carrier can be experimentally found by using :

- ✧ Hall experiment
- ✧ Hayness-Schockley experiment
- ✧ Hayness-Schockley experiment can be used for measurement of :
  - (1) Mobility of charge carrier
  - (2) Diffusion constant of charge carrier

$$D = \mu V_T$$

- If the polarity of Hall voltage is positive for the bottom surface of the specimen, the given specimen is P-type semiconductor.
- In Hall experiment Hall voltage is measured w.r.t. bottom surface.

For P-type semiconductor, Hall voltage is negative.

For N-type semiconductor, Hall voltage is positive.

For metal, Hall voltage is positive.

For intrinsic semiconductor Hall voltage is zero (no explanation).

Charge density $\rho = \dfrac{1}{R_H}$

Hall coefficient $R_H = \dfrac{1}{\rho} = \dfrac{1}{\text{Charge} \times \text{Carrier concentration}}$

According to Hall effect $\mu \simeq \sigma R_H;\ R_H \simeq \dfrac{\mu}{\sigma}$

Since $V_H \propto R_H$

$$V_H \propto \frac{1}{\sigma}$$

In metal : σ is large and V_H is small (μV)

In semiconductor : σ is small, V_H is large (mV)

- Hall voltage is small in metal and hall voltage is large in semiconductor.
- Hall coefficient $R_H \propto$ temperature coefficient of resistance of the given specimen.

In metal, resistance has positive temperature coefficient because

Hall coefficient (R_H) ↑ with temperature

In intrinsic semiconductor, resistance has negative temperature coefficient because

Hall coefficient (R_H) ↓ with temperature

In extrinsic semiconductor, resistance has positive temperature cofficient because

Hall coefficient (R_H) ↑ with temperature

Example 1 : Find intrisic conductivity and intrinsic resistivity of Ge at 300 K.

Solution : In intrinsic concentration Ge

$$n_i = 2.5 \times 10^{13} \text{ atoms/cm}^3$$

$$\mu_n = 3800 \text{ cm}^2\text{/V-sec}$$

$$\mu_p = 1800 \text{ cm}^2\text{/V-sec}$$

$$\sigma_i = n_i q(\mu_n + \mu_p) = 2.5 \times 10^{13} \times 1.6 \times 10^{-19} (3800 + 1800) = 0.0224 \mho\text{/cm}$$

$$\rho_i = \frac{1}{\sigma_i} = \frac{1}{0.0224} = 44.64\ \mho - \text{cm}$$

Example 2 : Calculate the conductivity and resistivity of pure Si at 300 K.

Solution : Assume for Si $n_i = 1.5 \times 10^{10}$ atoms/cm^3

$$\mu_n = 1300 \text{ cm}^2/\text{V-sec}$$

$$\mu_p = 500 \text{ cm}^2/\text{V-sec}$$

$$\sigma_i = n_i q(\mu_n + \mu_p) = 1.5 \times 10^{10} \times 1.6 \times 10^{-19} (1300 + 500)$$

$$= 4.32 \times 10^{-6} \text{ ℧/cm}$$

$$\rho_i = \frac{1}{\sigma_i} = \frac{1}{4.32 \times 10^{-6}} = 231481 \text{ ℧} - \text{cm}$$

Example 3 : A pure semiconductor (Ge) is subjected to donor impurities to the extent of 1 impurity atom for every 10^7 atom. Find :

(1) Donor concentration

(2) Concentration of electron and holes

(3) Conductivity and resistivity of doped semiconductor

(4) How many times the conductivity is increased because of doping

$$\text{Total no. of atom} = 4.421 \times 10^{22}/\text{cm}^3$$

$$n_i = 2.5 \times 10^{13} \text{ atoms/cm}^3$$

$$\mu_n = 3800 \text{ cm}^2/\text{V-sec}$$

$$\mu_p = 1800 \text{ cm}^2/\text{V-sec}$$

Solution : (1) Since, donor impurities are added, the semiconductor becomes N-type. Donor concentration

$$= \frac{\text{Total no. of atoms}}{\text{volume}} \times \text{Impurity ratio}$$

$$= 4.421 \times 10^{22} \times \frac{1}{10^7} = 4.421 \times 10^{15} \text{ atoms / cm}^3$$

(2) In N-type semiconductor $n \simeq N_D$

Electron concentration $n \simeq 4.421 \times 10^{15}/\text{cm}^3$

Holes concentration $p = \dfrac{n_i^2}{n} = \dfrac{(2.5 \times 10^{13})^2}{4.421 \times 10^{15}}$

$$p = 1.41 \times 10^{11}/\text{cm}^3$$

(3) Pure semiconductor $n = p = n_i = 2.5 \times 10^{13}$

with 1 : 10^7 doping n ↑ from 10^{13} to 10^{15}

p ↓ from 10^{13} to 10^{11}

$$\sigma_N \simeq N_D q \mu_n \simeq 4.421 \times 10^{15} \times 1.6 \times 10^{-19} \times 3800$$

$$\sigma_N \simeq 2.68 \text{ ℧ / cm}$$

$$\rho_N \simeq \frac{1}{\sigma_N} = \frac{1}{2.68}$$

$$\rho_N = 0.373 \ \Omega\text{-cm}$$

(4) If semiconductor is intrinsic its σ is

$$\sigma_i = n_i q(\mu_n + \mu_p) = 0.0224 \text{℧/cm}$$

By adding 1 : 10^7 doping σ ↑ from 0.0229 to ℧/cm to 2.68 ℧/cm.

Increase in conductivity $(\sigma) = \dfrac{2.68}{0.0224} \simeq 120$ times

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Example 4 : A pure semiconductor (Si) is doped with acceptor impurities of 1 : 10^6 : (i) Find conductivity due to majority carrier. (ii) Conductivity due to minority carrier.

$$\text{Total no. of atoms} = 5 \times 10^{22} \text{ atoms/cm}^3$$
$$n_i = 1.5 \times 10^{10} \text{ atoms/cm}^3$$
$$\mu_n = 1300 \text{ cm}^2\text{/V-sec}$$
$$\mu_p = 500 \text{ cm}^2\text{/v-sec}$$

Solution : Since acceptor impurities are adder, semiconductor becomes P-type.

$$N_A = 5 \times 10^{22} \times \frac{1}{10^6} = 5 \times 10^{16} / \text{cm}^3$$

In p-type semiconductor majority carriers are holes.

$$p \simeq N_A = 5 \times 10^{16}/\text{cm}^3 = \text{hole concentration}$$

$$n = \frac{n_i^2}{p} = \frac{(1.5 \times 10^{10})^2}{5 \times 10^{16}} = 4500 /\text{cm}^3 = \text{electron concentration}$$

(i) $\sigma_p = N_A q \mu_p = 5 \times 10^{16} \times 1.6 \times 10^{-19} \times 500 = 4\Omega/\text{cm} = \sigma_{majority}$

(ii) $\sigma_N = nq\mu_n = 4500 \times 1.6 \times 10^{-19} \times 1300 = 9.36 \times 10^{-13}\ \Omega/\text{cm} = \sigma_{minority}$

Example 5 : In a N-type semiconductor, the fermi level lies 0.3 eV below the conduction band at 300 K. If the temperature is increased to 330 K. Find the approximate new position of fermi level.

Solution : In N-type $E_C - E_F = kT \ln \frac{N_C}{N_D}$

Let variation of the N_C with T is neglected (as if T ↑ N_C ↑)

$$E_C - E_F \propto T$$

$$0.3 \text{ eV} \propto 300 \quad \ldots(1)$$

$$E_C - E_{F_2} \propto 330 \quad \ldots(2)$$

$$\frac{E_C - E_{F_2}}{0.3} = \frac{330}{300}$$

$$E_C - E_{F_2} = \frac{330}{300} \times 0.3 = 0.33 \text{ eV}$$

Example 6 : In a N-type semiconductor, the fermi level lies 0.4 eV below the conduction band. If the concentration of donor atoms is doubled. Find the new position of fermi level. Assume kT = 0.03 eV.

Solution : In N-type : $n \simeq N_D$

$$N_D \simeq N_C e^{-(E_C - E_F)/kT}$$

$$N_D \simeq N_C e^{-(0.4)/0.03} \quad \ldots(1)$$

$$2N_D \simeq N_C e^{-(E_C - E_{F_2})/0.03} \quad \ldots(2)$$

$$\frac{(1)}{(2)} = \frac{1}{2} = e^{-\left(\frac{0.4}{0.3}\right) + \frac{E_C - E_{F_2}}{0.3}}$$

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$$\Rightarrow \qquad \ln\frac{1}{2} = -\left(\frac{0.4}{0.3}\right)+\left(\frac{E_C - E_{F_2}}{0.03}\right)$$

$$\Rightarrow \qquad -0.693 = -\frac{0.4 + E_C + E_{F_2}}{0.03}$$

$$\Rightarrow \qquad E_C - E_{F_2} = (0.4) - 0.693 \times 0.03 = 0.379 \text{ eV}$$

Example 7 : In a P-type semiconductor, the fermi lies 0.4 eV above the valence band. If the concentration of acceptor atoms is tripled. Find the new position of fermi level. Assume kT = 0.03 eV.

Solution : In P-type semiconductor

$$p \simeq N_A$$

$$N_A \simeq N_V e^{-(E_F - E_V)/kT}$$

$$N_A \simeq N_V E^{-0.4/0.03Ev} \qquad \ldots(1)$$

$$3N_A \simeq N_V e^{-(E_{F_2} - E_V)/0.03} \qquad \ldots(2)$$

$$\frac{(1)}{(2)} = \frac{1}{3} = e^{-\frac{0.04}{0.03}+\frac{E_{F_2}+E_V}{0.03}}$$

$$\Rightarrow \qquad \frac{-0.4 + E_{F_2} - E_V}{0.03} = \ln\frac{1}{3} = -1.098$$

$$\Rightarrow \qquad E_{F_2} - E_V = -1.098 \times 0.03 + 0.04 = 0.367 \text{ eV}$$

$$E_{F_2} = 0.367 + E_V$$

So the new fermi level lies 0.367 eV above the valence band.

Example 8 : In a P-type semiconductor if the concentration of acceptor atoms is increased by a factor of 10 find the shift in position of fermi level. Assume kT = 0.03 eV.

Solution :

$$N_A \simeq N_V e^{-(E_F - E_V)/kT}$$

$$E_{F_2} - E_{F_1} = -0.069 \text{ eV}$$

Using shift formula, we won't get negative sign but for P-type shift is downward so put negative sign.

$$N_A \simeq N_V e^{-(E_{F_1} - E_V)/0.03} \qquad \ldots(1)$$

$$10N_A \simeq N_V e^{-(E_{F_2} - E_V)/0.03} \qquad \ldots(2)$$

$$\frac{(1)}{(2)} = \frac{1}{10} = e^{-\frac{(E_{F_1}-E_V)}{0.03}+\frac{E_{F_2}-E_V}{0.03}}$$

$$\Rightarrow \qquad \frac{-E_{F_1} + E_V + E_{F_2} - E_V}{0.03} = \ln\frac{1}{10} = -2.302$$

$$\Rightarrow \qquad E_{F_2} - E_{F_1} = -2.302 \times 0.03 = -0.069 \text{ eV}$$

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Example 9 : In a semiconductor at room temperature the intrinsic carrier concentration and resistivity are $1.5 \times 10^{16}/m^3$ and 2×10^{13} m respectively. It is converted to an extrinsic semiconductor with a doping concentration of $10^{20}/m^3$. Find the shift in the fermi level due to doping.

Solution : Given $n_i = 1.5 \times 10^{16}/m^3$

$\rho_i = 2 \times 10^{13}\Omega\text{-m}$

Doping concentration $= 10^{20}/m^3$

$$\text{Shift} = kT\ln\frac{\text{Doping conc.}}{n_i}\text{eV}$$

$$= (8.62\times10^{-5})\times300\ln\frac{10^{20}}{1.5\times10^{16}}\text{eV} = 0.227\text{ eV}$$

Example 10 : Si is doped with B to a concentration of 4×10^{17} atoms/cm^3. Assume the intrinsic carrier concentration of Si is 1.5×10^{10} atoms/cm^3 and is operated at a temperature of 300 K. Compare to undoped Si, the fermi level of doped Si is :

Solution : Semiconductor is P-type :

$$\text{Shift} = kT\ln\frac{N_A}{n_i} = 8.62\times10^{-5}\times300\ln\frac{4\times10^{17}}{1.5\times10^{10}}\text{eV}$$

$= 0.442$ eV downward shift

Example 11 : A Si semiconductor is doped with donor impurities with resultant in doping profile as $n = Gx$ and $n >> n_i$. The sample is placed isolated. Find the built in electric field as a function of x. Also calculate the field at x = 1 μm at room temperature.

Solution : Sample is placed isolated means no current $\Rightarrow \sigma = 0$

The electron current density in sample is :

$$J_n = J_{n(drift)} + J_{n(diff)} = nq\mu_n E + qD_n\frac{dn}{dx}$$

But $n = Gx$ $\quad \frac{dn}{dx} = G$

Since sample is isolated $\quad J_n = 0$

$$0 = G \times q\mu_n E + qD_n G$$

$$0 = x\mu_n E + D_n$$

$$x\mu_n E = -D_n$$

$$E = -\frac{D_n}{\mu_n}\cdot\frac{1}{x} = -\frac{\mu_n V_T}{\mu_n}\cdot\frac{1}{x} = -\frac{V_T}{x}$$

i.e., E is a function of x.

(ii) x = 1 μm. At room temperature

$$V_T = +26\text{mV}$$

$$E = -\frac{26\text{mV}}{1\mu\text{m}} = -26\text{ KV/m}$$

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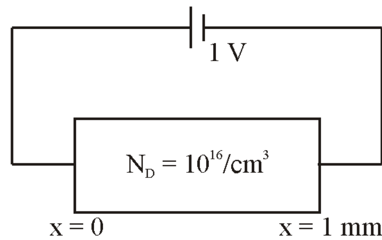
Example 12 : The Si sample with unit cross sectional area is given below is under thermal equilibrium. The following information is given T = 300 K, electronic charge = 1.6×10^{-19} C. Thermal voltage = 26 mV and electron mobility = 135 cm^2/V-sec.



(i) The magnitude of electric field at x = 0.5 μm is

(ii) The magnitude of the electron drift current density at x = 0.5 μm is

Solution : Given,

$$T = 300\text{ K}$$
$$e = 1.6 \times 10^{-19}\text{C}$$
$$V_T = 26\mu$$
$$\mu = 1350\ cm^2/\text{V-sec}$$
$$N_D = 10^{16}/cm^3$$

(i) E at x = 0.5 μmV at x = 0.5 μm = $\frac{1}{2} = 0.5\text{V}$

$$|E| = \frac{V_1}{x_1} = \frac{0.5\text{V}}{0.5\mu\text{m}} = \frac{0.5\text{V}}{0.5 \times 10^{-4}\text{ cm}} = 10^4\text{V/cm} = 10\text{kV/cm}$$

(ii) $J_n = nq\mu_n E$, $n \simeq N_D = 10^{16}$

E at 0.5 μm = 10^4

$$= 10^{16} \times 1.6 \times 10^{-19} \times 1350 \times 10^4 = 21600$$
$$= 2.16 \times 10^4\ \text{A/cm}^2$$

Example 13 : In a semiconductor at room temperature the intrinsic concentration and intrinsic resistivity are $1.5 \times 10^{16}/m^3$ and 2×10^3 Ω-m respectively. It is converted into extrinsic semiconductor with a doping concentration of $10^{20}/m^3$ for the extrinsic semiconductor calculate :

(i) minority carrier concentration

(ii) electron mobility

(iii) resistivity of doped semiconductor

(iv) minority carrier concentration

When its temperature is increased to a value at which the intrinsic carrier concentration n_i doubles. Assume the mobility of majority carriers is equal to the mobility of minority carrier.

Solution :

$$n_i = 1.5 \times 10^{16}\ /m^3$$
$$\rho_i = 2 \times 10^3 \Omega\text{-m}$$
$$\text{Doping concentration} = 10^{20}/m^3$$

(i) $\mu_n = \mu_p$

$$\text{Minority carrier concentration} = \frac{n_i^2}{\text{Doping conc.}} = \frac{(1.5 \times 10^{16})^2}{10^{20}} = 2.25 \times 10^{12} / m^3$$

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(ii)
$$\rho_i = \frac{1}{n_i q(\mu_n + \mu_p)}$$

$$\mu_n = \mu_p = \frac{1}{n_i q 2\mu}$$

$$\mu = \frac{1}{\rho_i n_i q \times 2} = \frac{1}{2\times10^3 \times 1.5\times10^{16} \times 1.6\times10^{-19} \times 2}$$

$$\mu = 0.10 \frac{\mu m^2}{V - sec} = \mu_n = \mu_p$$

(iii)
$$\rho_{doped} = \frac{1}{\sigma_{doped}} = \frac{1}{\text{Doping concentration} \times q \times \mu}$$

$$= \frac{1}{10^{20} \times 1.6\times10^{-19} \times 0.104}$$

$= 0.5996\ \Omega$-m $= 0.6\ \Omega$-m

(iv) As T ↑, n_i is doubled. Let new n_i is given by n_i'.

$$n_i' = 2 \times 1.5 \times 10^{16}\ /m^3$$

Minority carrier concentration with ↑ in temperature $= \dfrac{(n_i')^2}{\text{Doping concentration}}$

$$= \frac{(2\times1.5\times10^{16})^2}{10^{20}} = 9\times10^{12}\ /\ m^3$$

Example 14 : Find intrinsic carrier concentration of Ge it is the intrinsic resistivity at 300 K is 0.47 Ω-m and μ_n = 0.38 m^2/V-sec, μ_p = 0.19 m^2/V-sec.

Solution :

$\rho_i = 0.47\ \Omega$-m

$\mu_n = 0.38\ m^2$/V-sec

$\mu_p = 0.19\ m^2$/V-sec

$$\rho_i = \frac{1}{n_i q(\mu_n + \mu_p)}$$

$$n_i = \frac{1}{\rho_i \times q \times (\mu_n + \mu_p)} = \frac{1}{0.47\times1.6\times10^{-19}(0.38+0.19)}$$

$= 2.33 \times 10^{19}$ atoms/m^3

Example 15 : The electron and hole concentration in an intrinsic semiconductor are n_i and p_i respectively. When doped with a P-type material these values changes to n and p respectively. Then :

Solution : When intrinsic $n_i \times p_i = n_i^2$

When P-type semiconductor $np = n_i^2$

So $np = n_i p_i$

Condition for minimum Conductivity in semiconductor

In semiconductor, Conductivity

$$\sigma = nq\mu_n + pq\mu_p \qquad \ldots(1)$$

According to mass action law $n = \dfrac{n_i^2}{p}$ ...(2)

Substitute (2) in (1)

$$\sigma = \frac{n_i^2}{p} q\mu_n + pq\mu_p$$

Differentiating the above equation w.r.t. p

$$\frac{d\sigma}{dp} = \left(-\frac{1}{p^2}\right) n_i^2 q\mu_n + q\mu_p$$

Taking the second derivative

$$\frac{d^2\sigma}{dp^2} = \frac{2}{p^2} n_i^2 q\mu_n + 0$$

Since second derivative is positive we get the condition for minimum conductivity.

The condition for minimum conductivity can be obtained by equating.

$$\frac{d\sigma}{dp} = 0; \left(-\frac{1}{p^2}\right) n_i^2 q\mu_n + q\mu_p = 0$$

$$\Rightarrow \quad -\frac{n_i^2}{p^2}\mu_n = \mu_p; \; p^2 = n_i^2 \frac{\mu_n}{\mu_p}$$

$$p = n_i \sqrt{\frac{\mu_n}{\mu_p}} \qquad \ldots(3)$$

Also called p_0 = thermal equilibrium holes in semiconductor.

Substituting equation (3) in equation (2)

$$n = \frac{n_i^2}{n_i \sqrt{\frac{\mu_n}{\mu_n}}}$$

$$\Rightarrow \quad n = n_i \sqrt{\frac{\mu_p}{\mu_n}} \qquad \ldots(4)$$

where, n_0 = Thermal equilibrium electrons in semiconductor.

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Equations (3) and (4) denote the concentration of holes and electrons when the semiconductor is having minimum conductivity. Substituting equation (3) and (4) in equation :

$$\sigma = n_i\sqrt{\frac{\mu_p}{\mu_n}}q\mu_n + n_i\sqrt{\frac{\mu_p}{\mu_n}}q\mu_p$$

$$= n_i q\left[\sqrt{\mu_n\mu_p} + \sqrt{\mu_n\mu_p}\right]$$

$$= n_i q\left[2\sqrt{\mu_n\mu_p}\right]$$

$$\sigma_{min} = 2n_i q\sqrt{\mu_n\mu_p}$$

Example 16 : A semiconductor has the following parameters :

$$\mu_n = 7500\frac{cm^2}{V-sec},\ \mu_p = 300\frac{cm^2}{V-sec},\ n_i = 3.6\times10^{-12}/cm^3$$

Find :

(a) minimum conductivity (σ_{min}).

(b) hole concentration in the semiconductor when σ is min.

(c) e^- concentration in semiconductor under thermal equilibrium.

Solution : (a)

$$\mu_{min} = 2n_i q\sqrt{\mu_n\mu_p}$$

$$= 2\times3.6\times10^{12}\times1.6\times10^{-19}\sqrt{7500\times300}$$

$$= 1.728\times10^{-3}\ \mho/cm$$

(b)

$$p = n_i\sqrt{\frac{\mu_n}{\mu_p}} = 3.6\times10^{12}\sqrt{\frac{7500}{300}} = 18\times10^{12}/cm^3$$

(c)

$$n = n_i\sqrt{\frac{\mu_p}{\mu_n}} = 3.6\times10^{12}\sqrt{\frac{300}{7500}} = 7.2\times10^{11}/cm^3$$

Example 17 : A doped semiconductor specimen has hall coefficient 3.6×10^{-4} m^3/c and resistivity 9×10^{-3} Ω-m. Assuming single carrier conduction the mobility and density of carriers in the specimen approximately are given by :

Solution :

$$R_H = 3.6\times10^{-4}$$

$$\rho = 9\times10^{-3}$$

$$\mu = 0^- R_H$$

$$= \frac{1}{\rho}\times R_H = \frac{1}{9\times10^{-3}}\times3.6\times10^{-4} = 0.4\times10^{-1} \approx 0.04$$

$\Rightarrow$

$$\mu \simeq 0.04$$

$$R_H = \frac{1}{\rho} = \frac{1}{\text{Charge}\times\text{Carrier concentration}}$$

$$\text{Carrier concentration} = \frac{1}{1.6\times10^{-19}\times3.6\times10^{-4}} = 1.736 \times 10^{22}\ /m^3$$

Assume single carrier conduction i.e., metal.

$$\sigma = \text{carrier concentration} \times q \times \mu$$

$$\text{carrier concentration} = \frac{\sigma}{q\mu}$$

$$= \frac{1}{\text{Resistivity}\times q\times\mu}$$

$$= \frac{1}{9\times10^{-3}\times1.6\times10^{-19}\times0.04} = 1.736 \times 10^{22}\ /m^3$$

Example 18 : Find the magnetic field in a rectangular semiconductor specimen having 4 mm wide and 2 mm thick with a hall coefficient 10^{-3} m^3/c. When a current of 1 mA is passed through the sample a hall voltage of 2 mV is induced.

Solution :

$$V_H = \frac{BI}{\rho w}$$

$$V_H = \frac{BIR_H}{w}$$

$$2mV = \frac{B\times1mA\times10^{-3}}{4mm}$$

$$\Rightarrow \quad B = 8\frac{Wb}{m^2}$$

Example 19 : Find the magnitude of hall coefficient in a N-type Ge bar of width 3 mm and height 2 mm. Assume B = 0.9 Wb/m^2, E = 5 V/cm, I = 1.5 mA.

Solution :

$$V_H = \frac{BIR_H}{w}$$

$$E.d = \frac{BIR_H}{w} \qquad \left[\because E = \frac{V_H}{d} V/m\right]$$

$$5 \times 10^{-2} \times 2mm = \frac{0.9\times1.5\ mA\times R_H}{3mm}$$

$$R_H = 2.22\ m^3/c$$

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