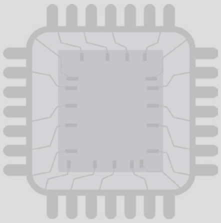
ESE 2025

UPSC ENGINEERING SERVICES EXAMINATION

Main Examination



Electronics & Telecommunication Engineering

Topicwise Conventional Solved Papers

Paper-I

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B. Singh (Ex. IES)

Director's Message

In past few years ESE Main exam has evolved as an examination designed to evaluate a candidate's subject knowledge. Studying engineering is one aspect but studying to crack prestigious ESE exam requires altogether different strategy, crystal clear concepts and rigorous practice of previous years' questions. ESE mains being conventional exam has subjective nature of questions, where an aspirant has to write elaborately - step by step with proper and well labeled diagrams and figures. This characteristic of the main exam gave me the aim and purpose to write this book. This book is an effort to cater all the difficulties being faced by students during their preparation right from conceptual clarity to answer writing approach.

MADE EASY Team has put sincere efforts in solving and preparing accurate and detailed explanation for all the previous years' questions in a coherent manner. Due emphasis is made to illustrate the ideal method and procedure of writing subjective answers. All the previous years' questions are segregated subject wise and further they have been categorised topic-wise for easy learning and helping aspirants to solve all previous years' questions of particular area at one place. This feature of the book will also help aspirants to develop understanding of important and frequently asked areas in the exam.

I would like to acknowledge the efforts of entire MADE EASY team who worked hard to solve previous years' questions with accuracy. I hope this book will stand upto the expectations of aspirants and my desire to serve the student community by providing best study material will get accomplished.

B. Singh (Ex. IES)
CMD, MADE EASY Group

ESE 2025
Main Examination

E&T Engineering
Conventional **Solved Questions**

Paper-I

Contents

■■■■

1

Basic Electronics Engineering (EDC)

Revised Syllabus of ESE: *Basics of semiconductors; Diode/Transistor basics and characteristics; Diodes for different uses; Junction and Field Effect Transistors (BJTs, JFETs, MOSFETs); Optical sources/detectors; Basics of Opto electronics and its applications.*

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1. Semiconductor Physics

1.1 Discuss “Hall Effect” in materials. [10 marks : 2000]

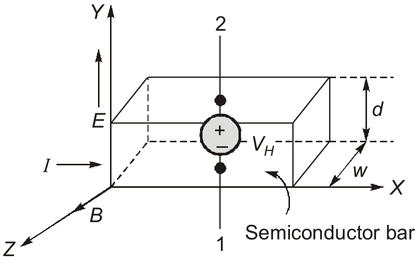
Solution:

■ Hall Effect:

- If a specimen (metal or semiconductor) carrying a current I is placed in a transverse magnetic field B, an electric field E is induced in the direction perpendicular to both I and B. This phenomenon, known as the Hall effect, is used to determine whether a semiconductor is n-type or p-type and to find the carrier concentration.

⇒ Hall effect is used in many applications as following:

(a) measurement of magnetic flux density
(b) measurement of displacement
(c) measurement of current
(d) measurement of power in Electromagnetic waves
(e) determination of carrier concentration
(f) determination of mobility of semiconductor material.

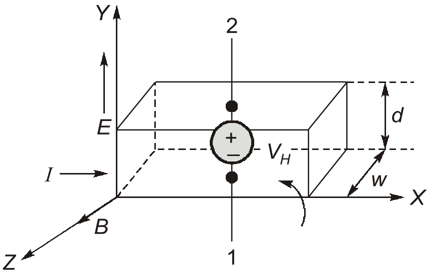


1.2 Explain how the phenomenon of Hall effect can be used to determine whether a semiconductor is ‘*n*’ type or ‘*p*’ type.

[10 marks : 2000]

Solution:

Consider the figure shown here:



- **Statements of Hall effect** “If a specimen (metal or semiconductor) carrying a current I is placed in a transverse magnetic field B, an electric field E is induced in the direction perpendicular to both I and B. This phenomenon, known as the Hall effect, is used to determine whether a semiconductor is n-type or p-type and to find the carrier concentration”.

⇒ If the semiconductor is n-type material, so that the current is carried by electrons, these electrons will accumulate on side 1 and this surface becomes negatively charged with respect to side 2. Hence, a potential, called the Hall voltage (V_H), appears between surfaces 1 and 2. If the polarity of V_H is positive at terminal 2, then as explained above, the carriers must be electrons.

⇒ If on the other hand, terminal 1 becomes charged positively with respect to terminal 2, the semiconductor must be p-type.

1.3 Define Hall Coefficient R_H. Obtain an expression for R_H in terms of Hall Voltage V_H.
[20 marks : 2000]

Solution:

Hall Coefficient R_H is defined as

$$R_H \equiv 1/\rho$$

where ρ = charge density

In the equilibrium state the electric field intensity E due to the Hall effect must exert a force on the carrier which just balances the magnetic force, or

$$qE = B\,q\,v \qquad \text{where } v \text{ is the drift speed}$$

But $E = V_H/d$

where V_H = Hall voltage

and d = distance between surfaces 1 and 2

$$\therefore \quad V_H = Ed = B\,v\,d = \frac{BJd}{\rho} \qquad [\because J = \rho v]$$

where J = current density in Amp/m^2

ρ = charge density

$$\because \quad J = \frac{I}{A} = \frac{I}{wd}$$

(where w is the width of specimen in the direction of B).

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

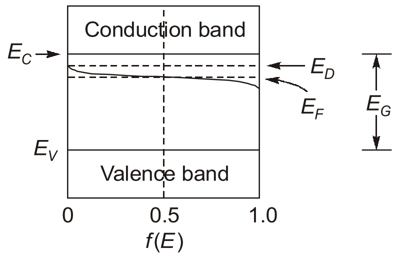
$$\because \quad R_H = 1/\rho$$

$$\therefore \quad R_H = \frac{V_H\,w}{BI} \qquad \text{i.e. } V_H \propto R_H$$

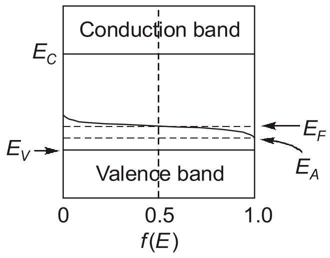
1.4 **In intrinsic silicon, the Fermi level lies near the middle of the bandgap. How does the fermi level move when it is doped with (i) phosphorus, and (ii) boron atoms? Can the Fermi level be pushed up into the conduction band? If yes, explain how. If not, explain, why.** [15 marks : 2001]

Solution:

(i) **Phosphorous is a donor-type impurity.** If a donor-type impurity is added to the crystal, then at a given temperature and assuming all donor atoms are ionized, the first N_D states in the conduction band will be filled. Hence it will be more difficult for the electrons from the valence band to bridge the energy gap by thermal agitation. Consequently, the number of electron-hole pairs thermally generated for that temperature will be reduced. Since the Fermi level is a measure of the probability of occupancy of the allowed energy states, it is clear that E_F must move closer to the conduction band to indicate that many of the energy states in that band are filled by the donor electrons, and fewer holes exist in the valence band.



Position of Fermi Level in n-type semiconductor



Position of Fermi Level in p-type semiconductor

(ii) **Boron is a p-type impurity.** The same kind of argument as above leads to the conclusion that E_F must move from the centre of forbidden gap closer to the valence band for a p-type material.

⇒ An expression of Fermi level is given by,

$$E_F = E_V + kT\ln\left(\frac{N_V}{N_A}\right) \quad \text{for } p\text{-type}$$

$$E_F = E_C - kT\ln\left(\frac{N_C}{N_D}\right) \quad \text{for } n\text{-type}$$

where N_C = effective density of states located in conduction band

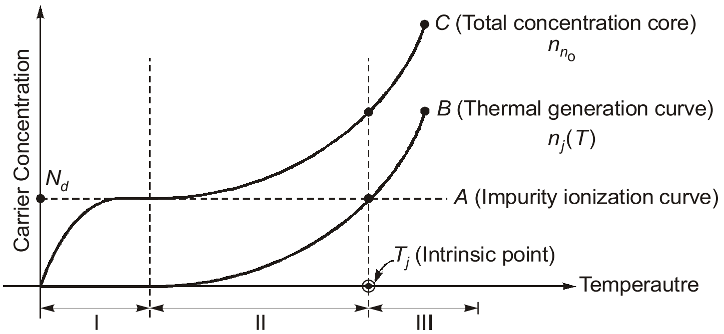
N_D = donor ion concentration

⇒ If the semiconductor is heavily doped, then $N_D > N_C$. (Corresponding to a doping in excess of 1 part in 10^3). So $\ln(N_C/N_D)$ is negative. Hence $E_F > E_C$, and the Fermi level in the *n*-type material lies in the conduction band.

1.5 **Explain why a doped semiconductor that is extrinsic at normal temperatures, behaves as an intrinsic material above a certain temperature. Upon which parameters will this temperature depend?**

[15 marks : 2001]

Solution:



Total carrier concentration (shown by curve-*C* in the above diagram) has 2 types of carrier.

(a) Carrier due to ionized dopant atom (impurity atom).

(b) $n_i(T)$, thermally generated carrier (intrinsic carriers).

The difference between energy of dopant level and that of conduction band in *N*-type, valance band in *p*-type semiconductor is typically very low as compared to band gap energy $E_g(T)$, *T* stands for temperature variation of E_g.

⇒ $(E_d - E_c)$, $(E_a - E_v) << E_g(T)$ [in extrinsic range of temperature]

Where, E_d = Donor level, E_a, acceptor level E_g is also the amount of energy to generate an electron hole pair intrinsic carrier. Due to small energy requirement of impurity ionization, $(E_c - E_d)$ or $(E_a - E_v)$, the temperature required to ionize dopant atoms is very small and typically between 100-150 Kelvin.

The above diagram shows variation of carrier concentration due to increase in temperature rate for an n-type semiconductor.

(i) Impurity ionization carrier (Curve-A).

(ii) Thermally generated carrier (Curve-B) and curve-C is just the sum of two carrier concentration. Show in the above diagram are 3 region, I, II, III. Depending on temperature range.

Region-I (temperature range of partial impurity ionization): It typically stretches upto 150 K. During such small temperature $n_i(T) \approx 0$ and $n_{n_o} \approx N_d^+$ is carrier concentration due to ionized dopant atoms. If N_d be concentration of dopant atom then

$$N_d^+ = N_d\left[1 + \frac{1}{2}\exp\left(\frac{E_d - E_F}{kT}\right)\right]^{-1} \quad \text{...(i)}$$

$$\left[\frac{1}{2} \text{ term accounts for degenerating of spin.}\right]$$

$$E_F = \text{Fermi level of the n-type specimen.}$$

Region-II (Extrinsic range of temperature): In this range temperature is sufficiently high to ionize impurity (dopant) atoms. So

$$N_d^+ \approx N_d \text{(all impurity atom ionized)}$$

$n_j(T)$ starts to rise but still several orders of magnitude smaller than N_d.
The Region-II ends at that temperature when $n_j(T) = N_d$ at $T = T_j$ (intrinsic temperature)
This particular temperature is called intrinsic point. At this temperature extrinsic behaviour starts to vanish intrinsic carrier concentration takes over the impurity carrier concentration.

$$n_{n_o} = n_j(T) + N_d$$

Region-III (Intrinsic range of temperatures): It start at intrinsic temperature point (T_j) $n_j(T)$ at $T_j = N_d$ (by definition given above).

$$\Rightarrow \quad n_j(T_j) = N_d$$

In this region $n_{n_o} \approx n_j(T)$ for temperature slightly above T_j and hence called intrinsic range.

Part-2: T_j by definition is the temperature at which $n_j(T_j) = N_d$ (ii)

$$\Rightarrow \because \quad n_j(T) = \sqrt{N_c N_v} \exp\left[-\left(\frac{E_g(T)}{2kT}\right)\right] \quad \text{...(iii)}$$

Where N_c, N_v, $E_g(T)$, K have usual meanings. Now we put $n_j(T_j)$ in equation.
(ii) and we get

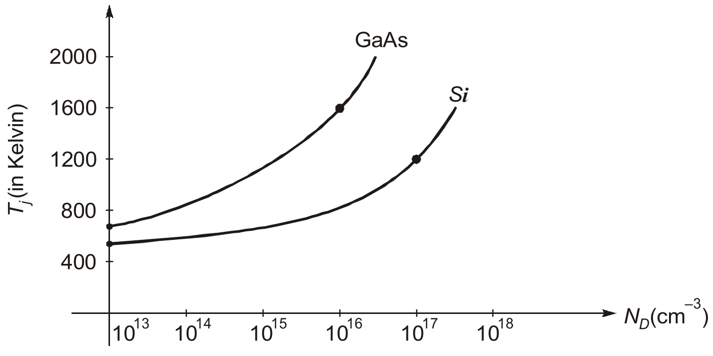
$$\sqrt{N_c N_v} \exp\left[-\frac{E_g(T_j)}{2kT_j}\right] = N_d$$

$$\Rightarrow \quad \exp\left[-\left(\frac{E_g(T_j)}{2kT_j}\right)\right] = \frac{N_d}{\sqrt{N_c N_v}}$$

$$\Rightarrow \quad \frac{-E_g(T_j)}{2kT_j} = ln\frac{N_d}{\sqrt{N_c N_v}}$$

$$\Rightarrow \quad T_j = \frac{E_g(T_j)}{2k ln\left[\frac{\sqrt{N_c N_v}}{N_d}\right]}$$

From here, we observe that for a given semiconductor T_j depends on N_d (doping concentration) and $E_g(T_j)$ or band-gap energy at intrinsic temperature point.



Intrinsic temperature Vs Doping

1.6 **"An *n*-type semiconductor has more number of electrons than holes, hence it has a net negative charge". Justify or nullify the above statement.** **[10 marks : 2001]**

Solution:

- Since the intrinsic semiconductor itself is electrostatically neutral and the doping atoms we add are also neutral, the resulting extrinsic semiconductor must be neutral.
- The neutrality of extrinsic semiconductor can be checked in another way. In an n-type semiconductor, the electrons in the conduction band are as given below:
  (i) some electrons are due to electron-hole pair generation which have their corresponding hole in the valence band.
  (ii) rest of the electrons are due to the donor impurities which have their corresponding positively ionized donor atoms in the donor energy level.

  Thus, we see that every negative charge has its corresponding positive charge (either hole or ionized donor atom). Therefore, the extrinsic semiconductor is neutral.

1.7 **Pure silicon has an electrical resistivity of 3000 Ωm. If the free carrier density in it is 1.1×10^6 m^{-3} and the electron mobility is three times that of hole mobility, calculate the mobility values of electrons and holes.**

[15 marks : 2003]

Solution:

$$\text{Conductivity, } (\sigma) = \frac{1}{\text{resistivity}}$$

$$\text{For a pure silicon, } \sigma = (\mu_n + \mu_p) n_i\, e$$

Where,

μ_n = electron mobility

μ_p = hole mobility

n_i = carrier concentration

e = electron charge $\approx 1.6 \times 10^{-19}$C

Given that: $\mu_n = 3\mu_p$

So, $$\frac{1}{3000} = (3\mu_p + \mu_p) \times 1.1 \times 10^6 \times 1.6 \times 10^{-19}$$

or $$\mu_p = 4.7348 \times 10^8 \text{ m}^2/\text{V-sec}$$

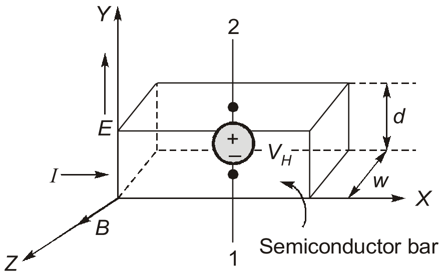
and $$\mu_n = 3\mu_p = 3 \times 4.7348 \times 10^8 = 1.42 \times 10^9 \text{ m}^2/\text{V-sec}$$

1.8 Explain Hall effect.

An *n*-type germanium sample is 2 mm wide and 0.2 mm thick. A current of 10 mA is passed through the sample (*x*-direction) and a field of 0.1 Weber/m^2 is directed perpendicular to the current flow (*z*-direction). The developed Hall voltage is – 1.0 mV. Calculate the Hall constant and the number of electrons/m^3. **[15 marks : 2004]**

Solution:

- ■ Hall effect:
- If a specimen (metal or semiconductor) carrying a current *I* is placed in a transverse) magnetic field *B*, an electric field *E* is induced in the direction perpendicular to both *I* and *B*. This phenomenon, known as the Hall effect is used to determine whether a semiconductor is *n*-type or *p*-type and to find the carrier concentration.



⇒ As shown in the figure above, if I is in the positive X direction and B is in the positive Z direction, a force will be exerted in the negative Y direction on the current carriers. The current I may be due to holes moving from left to right or to free electrons travelling from right to left in the semiconductor specimen. Hence, independently of whether the carriers are holes or electrons, they will be forced downward toward side 1 in the figure. Hence a potential, called the Hall voltage, V_H appears between surface 1 and 2. If the polarity of V_H is positive at terminal 2 with respect to terminal 1, then the carriers must be electrons. If terminal 1 becomes charged positively with respect to terminal 2, the semiconductor must be *p*-type.

Give that,

$$w = 0.2\text{ cm}; \qquad d = 0.02\text{ cm}$$
$$I = 10 \times 10^{-3}\text{A} \qquad B = 0.1\text{ Wb/m}^2$$
$$V_H = 10^{-3}\text{ V}$$

We know that
$$V_H = \frac{BI}{\rho w} = \frac{BI R_H}{w} \qquad \left(\frac{1}{\rho} = R_H\right)$$

$$R_H = \frac{V_H w}{BI} = \frac{10^{-3} \times 0.2 \times 10^{-2}}{0.1 \times 10^{-2}} = 2 \times 10^{-3}\text{ m}^3\text{/Coulomb} = \frac{1}{nq}$$

$$2 \times 10^{-3} = \frac{1}{n \times 1.6 \times 10^{-19}}$$

$$n = 3.125 \times 10^{21}\text{/m}^3$$

1.9 **A Si wafer is doped with 10^{15} phosphorus atoms cm^{-3}. Find the carrier concentration and Fermi level at room temperature (300° K), assume $N_C = 2.8 \times 10^{19}$/cm^3 at 300 K. Explain the concept of Fermi level.**

[10 Marks : 2005]

Solution:

Since Si-wafer is doped with phosphorus atom, so it is a n-type extrinsic semiconductor.

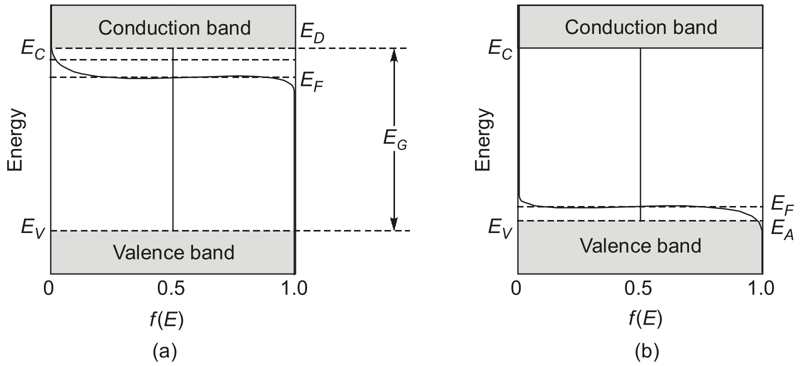
So,
$$N_D = 10^{15}\text{ atoms/cm}^3 \approx n$$
$$N_C = 2.8 \times 10^{19}\text{ atoms/cm}^3$$

According to Mass-action Law, $np = n_i^2$ ($n_i = 1.5 \times 10^{10}$/cm^3 for Si at room temp.)

⇒ carrier concentration $(n_i) = \sqrt{np}$

$$p = \frac{n_i^2}{n} = \frac{2.25 \times 10^{20}}{10^{15}} = 2.25 \times 10^5\text{/cm}^3$$

- Concept of Fermi Level (E_F) in extrinsic semiconductor:
  - ⇒ Fermi-level is a measure of probability of occupancy of the allowed energy states.
  - ⇒ In extrinsic semiconductor Fermi level moves closer to the conduction band indicating that many of the energy states in that band are now filled by donor electrons and the number of holes in the valence band are few. This concept is in respect of *n*-type material. While for *p*-type material the Fermi level is nearer to the valence band.
  - ⇒ So, the *CB* and *VB* positions will shift relatively to each other in *n*-type an d *p*-type material as shown in figure below:



Positions of Fermi level in (a) *n*-type and (b) *p*-type semiconductors

⇒ As temperature increases the density of electron increases and hence conductivity increases.

⇒ A calculation of exact position of the Fermi level in an n-type semiconductor is,

$$E_F = E_C - kT\,ln\left(\frac{N_C}{N_D}\right)$$

$$\Rightarrow \quad E_C - E_F = kT ln\left(\frac{N_C}{N_D}\right) \quad \text{...(i)}$$

For p-type material,

$$\therefore \quad E_F = E_V + kT ln\left(\frac{N_V}{N_A}\right)$$

$$\Rightarrow \quad E_F - E_V = kT ln\left(\frac{N_V}{N_A}\right) \quad \text{...(ii)}$$

Now, we have to find the Fermi level at 300° K for n-type material.
From equation (i) we have,

$$E_C - E_F = 0.03 ln\left(\frac{2.8\times10^{19}}{10^{15}}\right) \qquad \text{(At room temp. } KT \approx 0.03 \text{ eV)}$$

$$\therefore \quad (E_C - E_F) = 0.307 \text{ eV}$$

Thus E_F will be 0.307 *eV* below the bottom of the conduction band, for a donor density 10^{15} atoms/cm^3.

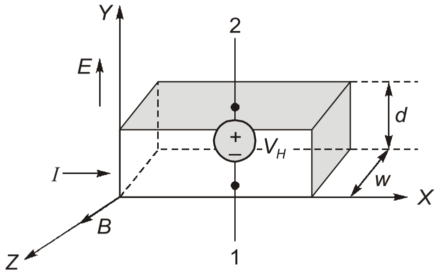
1.10 When a current is passed through a semiconductor and a magnetic field is applied at right angles to the direction of the current flow, it is observed that an electric field is induced in a direction mutually perpendicular to the magnetic field and the flow of current. Name this phenomenon and calculate the voltage developed.

[15 Marks : 2005]

Solution:

The given phenomenon is Hall Effect.

According to this effect the statements are:



- If a specimen (metal or semiconductor) carrying a current I is placed in a transverse magnetic field B, an electric field E is induced in the direction perpendicular to both I and B. This phenomenon, known as the Hall effect, is used to determine whether a semiconductor is n-type or p-type and to find the carrier concentration.
- Consider a semiconductor specimen bar having volume charge density ρ_v (in C/m^3), width '*w*', thickness '*d*', cross-sectional area '*A*' and developed Hall voltage is "V_H".

Since, $E = \frac{F}{e}$

$\therefore$ $F = eE$ ...(i)

also, $\vec{F} = q(\vec{v} \times \vec{B})$ ...(ii)

In the equilibrium state,

Force on specimen due to electric field (E) = Force on specimen due to magnetic field (H)

$\Rightarrow$ $eE = e\,v_d B$ [where v_d = drift velocity]

$\Rightarrow$ $E = v_d B$ ...(iii)

Also, $E = \frac{V_H}{d}$ ...(iv)

$\therefore$ $V_H = Bv_d d$ ...(v)

Drift velocity of charge carrier $= v_d = \frac{E}{B} = \frac{J}{\rho_v}$

Now from equation (v),

$$V_H = \frac{BdJ}{\rho_v} = \frac{BId}{A\rho_v} = \frac{BId}{w \times d \times \rho_v}$$

$\Rightarrow$ $V_H = \frac{BI}{\rho_v w}$ ...(vi)

This equation (vi) represents the Hall voltage (V_H) developed in a semiconductor bar.

1.11 The intrinsic resistivity of Germanium at room temperature is 0.47 Ω-cm. The electron and hole mobilities at room temperature are 0.39 and 0.19 m^2/V-s respectively. Calculate the density of electrons in the intrinsic semiconductor. Also calculate the drift velocities of these charge carriers for a field of 10 kV/m.

[10 marks: 2005]

Solution:

Given that

Resistivity $\rho_i = 0.47\ \Omega\ \text{cm}$

$\mu_n = 0.39\ m^2/\text{V-sec}$

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

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

$$0.47 \times 10^{-2} = \frac{1}{n_i \times 1.6 \times 10^{-19}(0.39 + 0.19)}$$

$n_i = 2.29 \times 10^{21}/m^3$

Drift velocity $v_d = \mu E$

For electron $v_d = \mu_n E = 0.39 \times 10$ km/sec

$v_d = 3.9$ km/sec

For hole $v_d = \mu_p E = 0.19 \times 10 = 1.9$ km/sec

1.12 In intrinsic GaAs, the electron and hole mobilities are 0.85 and 0.04 m^2/V-S respectively and corresponding effective masses are 0.068 m_0 and 0.5 m_0 respectively, where m_0 is the rest mass of an electron. If the energy gap of GaAs at 300° K is 1.43 *eV*, calculate the intrinsic carrier concentration and conductivity. ($m_0 = 9.11 \times 10^{-28}$ gm).

[15 Marks : 2006]

Solution:

Given that, $\mu_n = 0.85\ \text{m}^2/\text{V-sec}$; $\mu_p = 0.04\ \text{m}^2/\text{V-sec}$; $m_n = 0.068\ \text{m}_0$; $m_p = 0.5\ \text{m}_0$

$$E_g(300) = 1.43\ \text{eV}$$

$$m_0 = 9.11 \times 10^{-28}\text{gm}$$

Now

$$N_c = 2\left(\frac{2\pi\ \text{m}_n\text{kT}}{\text{h}^2}\right)^{3/2}$$

$$N_c = 2\left[\frac{2\times\pi\times 0.068\times 9.11\times 10^{-31}\times 1.38\times 10^{-23}\times 300}{\left(6.626\times 10^{-34}\right)^2}\right]^{3/2}$$

$$N_c = 2 \times 2.2236 \times 10^{23} = 4.447 \times 10^{23}\ /\text{m}^3$$

$$N_v = 2\left(\frac{2\pi m_p kT}{h^2}\right)^{3/2} = 2\left[\frac{2\times\pi\times 0.5\times 9.11\times 10^{-31}\times 1.38\times 10^{-23}\times 300}{\left(6.626\times 10^{-34}\right)^2}\right]^{3/2}$$

$$N_v = 2 \times 4.4335 \times 10^{24}$$

$$N_v = 8.867 \times 10^{24}\ /\text{m}^3$$

$\therefore$

$$n_i = \sqrt{N_c N_v}.\exp\left(-\frac{E_g}{2kT}\right) = \sqrt{4.447\times 8.867\times 10^{47}}\times\exp\left(\frac{-1.43}{2\times 26\times 10^{-3}}\right)$$

$$n_i = 2.26 \times 10^{12}\ /\text{m}^3$$

Conductivity

$$\sigma = n_i q(\mu_n + \mu_p) = 2.26 \times 10^{12} \times 1.6 \times 10^{-19}[0.85 + 0.04]$$

$$\sigma = 3.22 \times 10^{-7}\ \text{S}$$

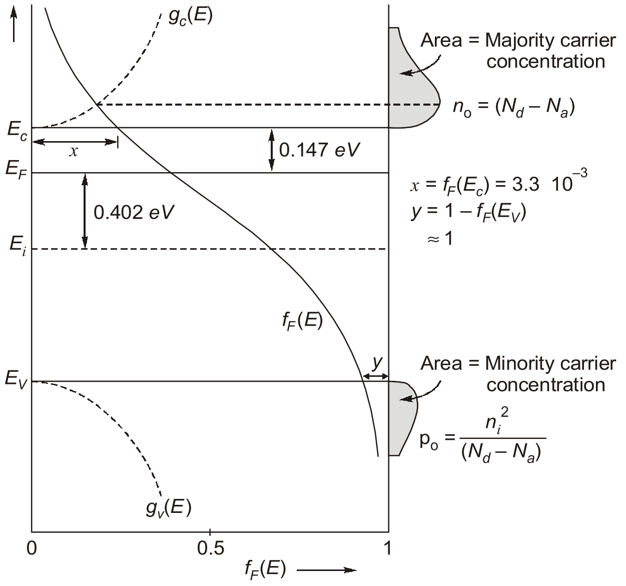
1.13 Sketch the variation of the density of states function, Fermi Dirac probability distribution function and electron and hole concentration for n-type silicon where $N_d = 10^{17}$/c.c. and $N_a = 10^{16}$/c.c. Write down the condition for charge neutrality in a compensated semiconductor at $T = 300°$ K.

In an n-type semiconductor at $T = 300°$ K, the electron concentration varies linearly from 2×10^{18} to 5×10^{17} per c.c. over a distance of 1.5 mm and the diffusion current density is 360 A/cm². Find the mobility of electrons.

[15 Marks : 2006]

Solution:

PART-1



Above diagram shows:

(a) Density of states function $g_c(E)$, $g_v(E)$ in conduction and valance band respectively.

(b) Fermi-dirac distribution function $f_F(E)$.

(c) Electron and hole concentration (n_o, p_o) for a n-type compensated semiconductor.

$\because$ $n_i(300\text{ K})$ = Intrinsic carrier concentration for Silicon = $1.5 \times 10^{10}/\text{cm}^3$

and given $N_d = 10^{17}/\text{cm}^3$, $N_a = 10^{16}/\text{cm}^3$

Where N_d, N_a are donor and acceptor concentrations

$$\Rightarrow \quad N_d - N_a = (10^{17} - 10^{16})/\text{cm}^3 = 9 \times 10^{16}/\text{cm}^3$$

$$\because \quad E_F - E_i \triangleq KT\, In\left(\frac{N_d - N_a}{n_j}\right)$$

$$= 0.0258\, In\left(\frac{9\times10^{16}}{1.5\times10^{10}}\right) = 0.0256 In(6\times10^6)$$

$$E_F - E_i = 0.0258 \times 15.607 = 0.402 \text{ eV}$$

and
$$E_c - E_F = \frac{E_g}{2} - (E_F - E_{Fi}) = (0.55 - 0.402)\text{eV} = 0.147 \text{ eV}$$

$$\Rightarrow \quad f_F(E_c) = \frac{1}{1+\exp\left(\frac{E_c - E_F}{KT}\right)} = \frac{1}{1+\exp\left(\frac{0.147}{0.0258}\right)} = \frac{1}{1+\exp(5.69)} = 3.3\times10^3$$

Condition for charge neutrality $\Rightarrow$ positive charge = negative charge

$$\Rightarrow \quad N_d^+ + p_o = N_a^- + n_o$$

N_d^+ = Donor ion concentration

N_d^- = Acceptor ion concentration

P_o, n_o equilibrium hole, electron concentration in valance band and conduction band respectively.

PART-2

Now, in an n-type semiconductor at 300°K, diffusion electron current density = $J_{n.}$

$$\Rightarrow \quad J_n = qD_n\left|\frac{dn}{dx}\right|$$

$$\Rightarrow \quad 360 \text{ A/cm}^2 = 1.6\times10^{-19}\times D_n \times\left|\frac{5\times10^{17} - 2\times10^{18}}{1.5\,mm}\right|$$

$$\Rightarrow \quad 360 = 1.6\times10^{-19}\times\frac{15\times10^{17}}{1.5\times10^{-1}}\times D_n$$

$$\Rightarrow \quad \text{Diffusion constant for electron} = D_n = \frac{360}{1.6} = 225 \text{ cm}^2/\text{sec}$$

Again by using Einstein relationship,

$$\frac{D_n}{\mu_n} = \frac{D_p}{\mu_p} = V_T$$

$$\Rightarrow \quad \mu_n = \frac{D_n}{V_T} = \frac{225\text{cm}^2/\text{sec}}{0.026 \text{ Volt}}$$

$\therefore$ mobility of electron = μ_n =8653.84 cm^2/V-sec

1.14 Define carrier mobility. Draw a graph showing the variation of carrier mobility in a semiconductor with increasing temperature. A 100-ohm resistor is to be made at room temperature in a rectangular silicon bar of 1 cm in length and 1 mm^2 in cross-sectional area by doping it appropriately with phosphorous atoms. If the electron mobility in silicon at room temperature be 1350 cm^2/V. sec, calculate the dopant density needed to achieve this. Neglect the insignificant contribution by the intrinsic carriers.

[15 Marks : 2007]

Solution:

If a constant electric field E is applied to the semi conductor, as a result of this electrostatic force and electron would be accelerated and velocity would increase indefinitely with time, till it will not collide with ions. At each in elastic collision with an ion, electron loss energy and steady state condition is reached, where finite value of speed called drift speed is attained.

So drift speed v_d is proportional to $\in$.

$$v_d \propto E$$

$$v_d = \mu E$$

where μ = Mobility

Mobility is defined as drift velocity per unit electric field.

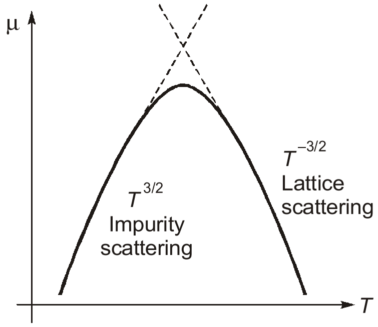
$$\mu = \frac{v_d}{E}$$

Relation between Mobility with Temperature

Two types of scattering influence electron and hole mobility are

1. Lattice scattering, and
2. Impurity scattering

In Lattice scattering a carrier moving through crystal is scattered by a vibration of lattice, resulting from Temperature. Frequency of such scattering events increases as temperature increases, since thermal agitation of lattice becomes greater. Therefore we should expect the mobility to decrease with increase in temperature.



On other hand scattering from crystal defect becomes dominant mechanism at low temperature since a slowly moving carrier is likely to be scattered move strongly by an interaction with a charged iron than is a carrier with greater momentum. So impurity scattering event cause a decrease in mobility with decrease in temperature.

$$R = 100\ \Omega$$

$$l = 1\text{ cm}$$

$$\mu_n = 1350\text{ cm}^2/\text{vsec}$$

$$A = 1\text{ mm}^2 = 10^{-2}\text{ cm}^2$$

we know that

$$R = \rho\frac{l}{A}$$

$$\rho = \frac{RA}{l} = \frac{100\times10^{-2}}{1} = 1\ \Omega\text{cm}$$

$$\sigma_N = \frac{1}{\rho} = nq\mu_n$$

$$n = \frac{1}{\rho\times q\times\mu_n} = \frac{1}{1\times1.6\times10^{-19}\times1350} = 4.6\times10^{15}/\text{cm}^3$$

For N-type

$$n \simeq N_D$$

$$N_D = 4.6\times10^{15}/\text{cm}^3$$

1.15 A silicon bar is doped with 10^{17} arsenic atoms/cm^3. What is the equilibrium hole concentration at 300 K? Where is the Fermi level (E_F) of the sample located relative to intrinsic Fermi level (E_i)? It is known that $n_i = 1.5 \times 10^{10}/\text{cm}^3$. [10 Marks : 2008]

Solution:

Since doped material is Arsenic i.e. pentavalent impurity, so it is an *n*-type material.

$$N_D = 10^{17} \text{ atoms/cm}^3$$

$$n_i = 1.5 \times 10^{10}/\text{cm}^3$$

According to the law of mass-action

$$np = n_i^2 = 2.25 \times 10^{20} \qquad \text{...(i)}$$

According to the principle of electrical neutrality

$$n + N_A = p + N_D$$

$$\Rightarrow \qquad n = p + N_D = p + 10^{17}$$

$$\therefore \qquad n \simeq 10^{17} \qquad [\text{as } N_D >> p]$$

Therefore

$$p = \frac{2.25 \times 10^{20}}{10^{17}} = 2.25 \times 10^3 \text{ atoms/cm}^3$$

Fermi level energy for *n*-type material is given by relation

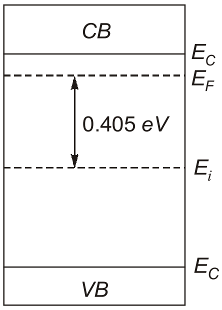
$$n = n_i e^{[E_F - E_i]}/kT$$

$$\frac{n}{n_i} = e^{[E_F - E_i]}/kT$$

$$\Rightarrow \qquad E_F - E_i = KT\, ln\left(\frac{n}{n_i}\right) = 8.62 \times 10^{-5} \times 300\; ln\left(\frac{10^{17}}{1.5 \times 10^{10}}\right)$$

$$\Rightarrow \qquad E_F - E_i = 0.0258\; ln\left(\frac{10^7}{1.5}\right)$$

$$\Rightarrow \qquad E_F - E_i = 0.405 \text{ eV}$$

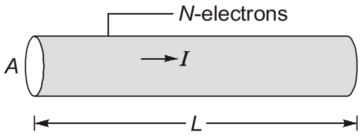


1.16 Derive an expression for current density in an n-type semiconductor in terms of drift velocity. Show that the conductivity is given by $\sigma = ne\mu_n$. [15 Marks : 2008]

Solution:

- Current density

- If *N* electrons are contained in a length *L* of a conductor as shown in figure below. If *T* is time taken to traverse distance *L*, the total number of electrons passing through any cross section of wire in *T* per unit time is *N*/*T*.



(A = cross-sectional area)

Therefore,

$$I = \frac{Nq}{T} = \frac{Nqv}{L} \qquad \text{...(i)}$$

$\therefore$ Current density

$$(J) = \frac{I}{A} = \frac{Nqv}{LA} \qquad \text{...(ii)}$$

(unit of J = amp/m^2)

Since, $\frac{N}{LA} = n$ (electron concentration in electrons per cubic meter)

$\therefore$ $J = nqv = nev = \rho v$ ...(iii)

where $\rho \equiv ne$ is the **charge density** in Coulombs per cubic meter and v in meters per second.

- The conductivity of a material can be related to the number of charge carriers present in the materials. Now, combining equations (i) and (iii) we get,

$$J = nqv = nq\mu E$$

$\Rightarrow$ $J = \sigma E$ ...(iv)

where, $\sigma = nq\mu$ ...(v)

where σ is conductivity in $(\text{ohm-meter})^{-1}$

1.17 Derive an expression for current density in an n-type semiconductor in terms of drift velocity. Show that the conductivity is given by $\sigma = ne\mu_n$ [15 marks: 2008]

Solution:

Let force F on the particle when an electric field E is applied is given by

$$F = qE = eE$$

We know that $F = ma$

so $ma = eE$

So Acceleration $a = \frac{eE}{m}$

Because of collision of electron during motion, electron, will not get accelerated indefinitely, if τ is the relaxation time, average velocity of electron known as drift velocity given by

$$v_d = a \times \tau = \frac{aE}{m}\tau$$

Let current I flowing through conductor on application of E with corresponding drift velocity v_d. In time dt, electron will travel $v_d dt$ and number of electron crossing cross-section A will be $Av_d dt$.

Total charge flowing through section $dq = env_d A\,dt$

So $I = \frac{dq}{dt} = env_d A$

Now current density $J = \frac{I}{A}$

By ohm's law $J = \sigma E$

and $v_d = \mu E$

$$\sigma E = env_d$$

$$\sigma E = en\mu E$$

$$\sigma = en\mu$$

1.18 Describe the Hall effect in a semiconductor bar specimen. Derive the expression for the Hall voltage. [15 marks: 2009]

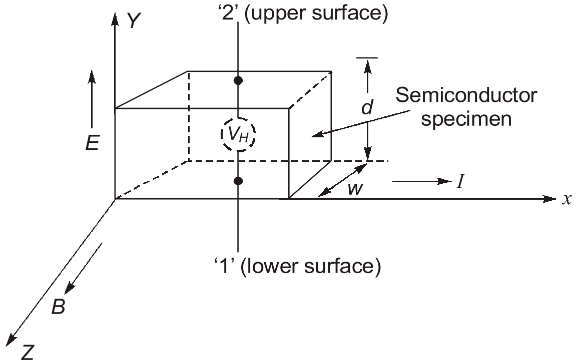
Solution:

■ Hall Effect:

- The **Hall effect** has played a decisive role in revealing the mechanism of conduction in semiconductors.
- "If a specimen (metal or semiconductor) carrying a current 'I' is placed in a **transverse magnetic field 'B'**, an electric field 'E' is induced in the direction perpendicular to both I and B. This phenomenon is known as the **"Hall effect"**.
- In figure **'I'**, is in positive X-direction and B is in positive Z-direction a force will be exerted in the negative Y-direction on the current carriers.

- The current (I) may be due to holes (if specimen is p-type) moving from left to right or to free electrons (if specimen is n-type) moving from right to left in the specimen.
- Hence independently of whether the carriers are holes or electrons, they will be forced downward **toward side '1'.**
- If the semiconductor is **n-type material**, then all free electrons will accumulate on **side '1'** and so the lower surface becomes negatively charged with respect to **side '2'**. Hence a potential, called the **Hall voltage** (V_H) appears between surfaces '1' and '2'.
- If the polarity of **"V_H"** is positive at terminal '2', then as explained above, the carrier must be electrons and so the specimen is **n-type.**

  On the other hand, if terminal '1' becomes charged positively with respect to terminal '2', the semiconductor bar must be **p-type.**



- Consider a semiconductor specimen bar having volume charge density ρ_v (in C/m^3), width 'w', thickness 'd', cross-sectional area 'A' and developed Hall voltage is "V_H".

Since, $$E = \frac{F}{e}$$

∴ $$F = eE \quad \text{...(i)}$$

also, $$\vec{F} = q(\vec{v}\times\vec{B}) \quad \text{...(ii)}$$

In the equilibrium state,

Force on specimen due to electric field (E) = Force on specimen due to magnetic field (H)

⇒ $$eE = e\,v_d\,B \quad \text{[where } v_d = \text{drift velocity]}$$

⇒ $$E = v_d B \quad \text{...(iii)}$$

Also, $$E = \frac{V_H}{d} \quad \text{...(iv)}$$

∴ $$V_H = Bv_d d \quad \text{...(v)}$$

drift velocity of charge carrier = $v_d = \dfrac{E}{B} = \dfrac{J}{\rho_v}$

Now from equation (v),

$$V_H = \frac{BdJ}{\rho_v} = \frac{BId}{A\rho_v} = \frac{BId}{w\times d\times\rho_v}$$

⇒ $$V_H = \frac{BI}{\rho_v w} \quad \text{...(vi)}$$

This equation (vi) is the required expression for the Hall voltage.