



# POSTAL BOOK PACKAGE 2024

## ELECTRONICS ENGINEERING

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### CONVENTIONAL Practice Sets

#### CONTENTS

#### ELECTRONIC DEVICES AND CIRCUITS

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1. Basic Semiconductor Physics .....	2 - 15
2. PN Junction and Circuits .....	16 - 36
3. Bipolar Junction Transistor .....	37 - 57
4. Field Effect Transistor .....	58 - 71
5. Power Switching Devices and Circuits .....	72 - 77
6. Introduction to IC Fabrication .....	78 - 80

# Basic Semiconductor Physics

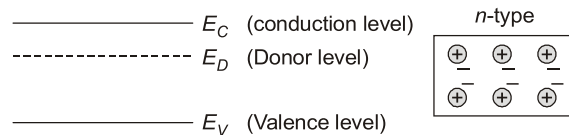
**Q1** What is doping? Give the advantage of doping.

**Solution:**

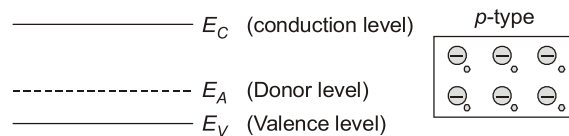
Addition of impurities to the pure semiconductor and making it impure is called doping.

Adding pentavalent impurity can cause 4 covalent bonds with the semiconductor and 1 electron is left free.

Adding this donor causes a new energy level, below the conduction band.



Adding trivalent impurity causes 3 covalent bonds and there is absence of 1 electron which will get occupied in acceptor level just above valence band.



Doping increases the conductance of semiconductor.

**Q2** Two scattering i.e. impurity and lattice are existing in a semiconductor and if only one mechanism is present, the mobility will be 250 cm<sup>2</sup>/V-sec and if other scattering mechanism only present then the mobility is 500 cm<sup>2</sup>/V-sec. Find the resultant mobility.

**Solution:**

$$\frac{1}{\mu} = \frac{1}{\mu_1} + \frac{1}{\mu_2} = \frac{1}{250} + \frac{1}{500}$$

$$\mu = 166.67 \text{ cm}^2/\text{V-sec}$$

**Q3** Distinguish between direct and indirect bandgap materials with suitable  $r$ - $k$  diagrams.

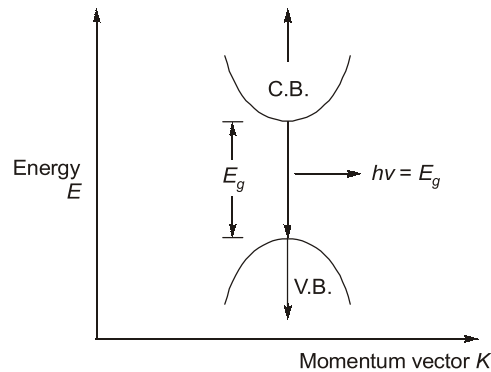
How would you make an intrinsic GaAs sample  $n$ -type or  $p$ -type? What happens when GaAs is doped with Si? What is the nature of bonding in GaAs?

**Solution:**

**Direct Band Gap Material:**

In a direct band gap semiconductor such as GaAs, an electron in the conduction band can fall to an empty state in the valence band, giving off the energy difference  $E_g$  as a photon of light.

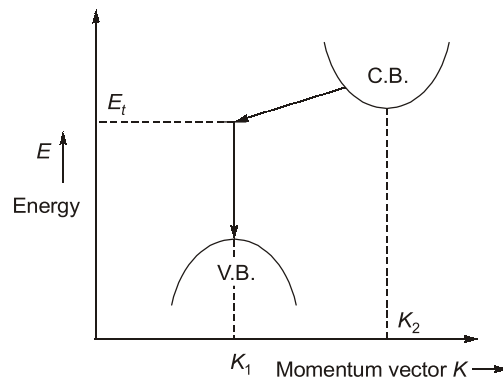
- This property of direct band gap material can be used in designing devices requiring light output.  $r$ - $k$  diagram for direct band gap material is as.



- These are the materials for which lowest energy state of conduction band and higher energy state of valance band occurs for **“same value of momentum”**.
- In these type of materials the recombination occurs without the help of an external agent.  
No second particle is emitted.

#### Indirect Band Gap Material:

An electron in lowest energy conduction band of an indirect semiconductor can not fall directly to the valance band of maximum energy but also **“undergo a momentum change”** as well as **changing its energy**.  
*r-k* diagram for indirect band gap material is



- These are the materials in which higher most energy state of valance band and lower most energy state of conduction band occurs for different values of momentum.
- The probability of recombination is very less.
- So an external agent (Au) is required.
- In these materials recombination occurs in following steps:
  1. Gold create trap levels (energy state which has momentum value  $K_1$ ).
  2. As soon as any electron jumps from C.B. to trap level it's momentum value becomes  $K_1$ .
  3. Now it falls and recombine with hole having same value of momentum  $K_1$  in opposite direction.
- Energy is released mainly in the form of heat.
- A second particle phonon is emitted when electron falls from C.B. to trap energy state  $E_t$  and this phonon collides with lattice crystal and loss it's energy in the form of heat.
- In GaAs  $\rightarrow$  Ga is from III group and As is from V group.
- So in order to make GaAs *n*-type we will increase the concentration As(V group) in GaAs compare to Ga.
- In order to make GaAs *p*-type, we will increase the concentration (doping) of Ga compare to As in GaAs.
- In GaAs  $\rightarrow$  bonding is mixed bonding covalent as well as ionic character.
- Ionic bonding is due to difference in placement of Ga and As atoms in the periodic table.

- Q4** A semiconductor has a bandgap of 0.62 eV. Find the maximum wavelength for resistance change in the material by photon absorption. (Note: 1 eV =  $1.6 \times 10^{-19}$  Joules)

**Solution:**

We know that

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

Where,  $E$  = Energy bandgap = 0.62 eV (given)

$h$  = Planck constant =  $6.626 \times 10^{-34}$  Joule-sec

$c$  = Velocity of light in free space =  $3 \times 10^8$  m/sec

$\lambda$  = Wavelength

So,

$$\lambda = \frac{hc}{E} = \frac{6.626 \times 10^{-34} \times 3 \times 10^8}{0.62 \times 1.6 \times 10^{-19}}$$

$$\lambda = 2.004 \times 10^{-6} = 2.004 \mu\text{m}$$

- Q5** (a) Explain "The Mass-Action Law"?

(b) What is the Law of electrical neutrality of a semiconductor?

(c) A small number of readily ionized donors  $N_D$  are added to an intrinsic semiconductor, such that  $N_D \ll n_i$ , where  $n_i$  is the intrinsic carrier concentration. Then by using the concept involved in part (a) and (b); find the free electron and hole concentration in the semiconductor. What is the type of material?

**Solution:**

(a) **Mass-Action Law:**

In an extrinsic semiconductor, under thermal equilibrium, the product of the free negative and positive concentrations is a constant and is independent of the amount of donor and acceptor impurity doping. This relationship is called "**Mass-Action Law**" and is given by:

$$np = n_i^2 \quad \dots(i)$$

where,  $n_i$  is the intrinsic concentration and is a function of temperature.

$\Rightarrow$  This law is used to determine the concentration of minority carriers in a semiconductor.

(b) Since, the semiconductor is electrically neutral, so according to the Law of electrical neutrality – "the magnitude of the positive charge density i.e. ( $N_D + p$ ) must equal that of the negative charge concentration i.e. ( $N_A + n$ ). So,

$$N_D + p = N_A + n \quad \dots(ii)$$

where,

$N_D$  = Positive charges/ $\text{m}^3$  and is contributed by donor ions.

$N_A$  = Negative charges/ $\text{m}^3$  and is contributed by acceptor ions.

(c) Here, let us assume that free electron and free hole concentration is ' $n_0$ ' and ' $p_0$ ' respectively. So, from equation (i) and (ii) as in part (a) and (b) we have,

$$n_0 p_0 = n_i^2 \quad \dots(iii)$$

and

$$n_0 + N_A = p_0 + N_D \quad \dots(iv)$$

Substituting the value of ' $p_0$ ' from equation (iii) into equation (iv) yields,

$$n_0 + N_A = \frac{n_i^2}{n_0} + N_D$$

$$\Rightarrow n_0^2 - (N_D - N_A)n_0 - n_i^2 = 0 \quad \dots(v)$$

$$\therefore n_0 = \left( \frac{N_D - N_A}{2} \right) + \frac{1}{2} \sqrt{(N_D - N_A)^2 + 4n_i^2} \quad \dots(vi)$$

Neglecting the negative terms of  $n_0$  as ' $n_0$ ' has the positive value.

Similarly, ' $p_0$ ' is obtained by putting the value of ' $n_0$ ' from equation (iii) into equation (iv) and thus we get ' $p_0$ ' as:

$$p_0 = -\left(\frac{N_D - N_A}{2}\right) + \frac{1}{2}\sqrt{(N_D - N_A)^2 + 4n_i^2} \quad \dots(\text{vii})$$

Neglecting the negative term of ' $p_0$ ' as ' $p_0$ ' has +ve values.

Also given that,

$$N_D \ll n_i$$

and since donors are added so,

$$N_D > N_A$$

So, we have,  $N_A < N_D \ll n_i$

...(viii)

By using expression (viii) in the equation (vi) and (vii) then we may get,

$$n_0 = n_i + \left(\frac{N_D - N_A}{2}\right)$$

and

$$p_0 = n_i - \left(\frac{N_D - N_A}{2}\right)$$

This type is called Intrinsic compensated material. This state can also occur at high temperature when,  $n_i \gg (N_D - N_A)$ .

**Q6 (a) Describe the 'Einstein Relationship'?**

**(b) Find the probability of finding an electron 0.2 eV above the Fermi level at 300°K?**

**Solution:**

**(a)** Since both diffusion and mobility are statistical thermodynamic phenomena so diffusion constant ( $D$ ) and mobility ( $\mu$ ) are not independent. The relationship between the  $D$  and  $\mu$  is given by the '**Einstein Relationship**', which is mathematically given as,

$$\frac{D_p}{\mu_p} = \frac{D_n}{\mu_n} = V_T \quad \dots(\text{i})$$

where,  $V_T$  is the 'Volt-equivalent of temperature' and is defined by,

$$V_T = \frac{\bar{k} T}{q} = \frac{T}{11600} \quad \dots(\text{ii})$$

where,  $\bar{k}$  is the Boltzmann constant in J/°K

At room temperature i.e.  $T = 300^\circ\text{K}$ ,

$$V_T = 0.026 \text{ V} = 26 \text{ mV}$$

and

$$\mu = 39 D$$

∴

$$D_n \text{ for Ge} = \mu_n V_T = 99 \text{ cm}^2/\text{sec}$$

and

$$D_p = \mu_p V_T = 13 \text{ cm}^2/\text{sec}$$

**(b)** Given that,

$$T = 300^\circ\text{K}$$

and

$$E - E_F = 0.2 \text{ eV}$$

i.e.

$$E = E_F + 0.2 \text{ eV}$$

also,

$$V_T = K \cdot T = 0.026 \text{ V}$$

∴ Probability of finding an electron 0.2 eV above the Fermi level is given by,

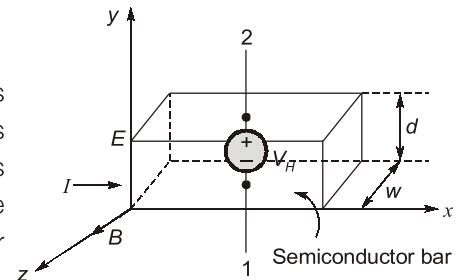
$$\begin{aligned} f(E = E_F + 0.2 \text{ eV}) &= \frac{1}{1 + \exp\left(\frac{0.2}{0.026}\right)} = \frac{1}{1 + \exp(7.692)} = 4.561 \times 10^{-4} \\ &\approx 0.0004561 \end{aligned}$$

**Q7** 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<sup>2</sup> 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<sup>3</sup>.

**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. It 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 towards 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.



Given that,

$$w = 2 \text{ mm}$$

$$d = 0.2 \text{ mm}$$

$$I = 10 \text{ mA}$$

$$B = 0.1 \text{ Weber/m}^2$$

$$V_H = -1.0 \text{ mV}$$

$$\therefore |V_H| = \frac{BI}{\rho w} = 1.0 \text{ mV}$$

where,  $\rho = \text{charge density (C/m}^3\text{)}$

$$\Rightarrow \rho = \frac{BI}{V_H w} = \frac{0.1 \times 10 \times 10^{-3}}{1 \times 10^{-3} \times 2 \times 10^{-3}} = 0.5 \times 10^3 \text{ C/m}^3$$

Hall constant  $R_H$  is defined by

$$R_H \equiv 1/\rho$$

$$\therefore R_H = 1/0.5 = 2 \times 10^3 \text{ m}^3/\text{C}$$

since  $\rho = nq$

where  $n = \text{number of electrons/m}^3$

and  $q = \text{charge of electron} = 1.6 \times 10^{-19} \text{ Coulomb}$

$$\Rightarrow n = \frac{0.5 \times 10^3}{1.6 \times 10^{-19}} = 3.125 \times 10^{21}$$

Therefore, Hall constant,  $R_H = 2 \times 10^3 \text{ m}^3/\text{C}$

and number of electrons per m<sup>3</sup>,  $n = 3.125 \times 10^{21}$ .

**Q8** A sample of Germanium is doped to the extent of  $10^{14}$  donor atoms/cm<sup>3</sup> and  $5 \times 10^{13}$  acceptor atoms/cm<sup>3</sup>. At 300°K, the resistivity of the intrinsic Germanium is 60  $\Omega$ -cm. If the applied electric field is 2 V/cm. Find the total conduction current density? (Assume  $\mu_p/\mu_n = 1/2$  and  $n_i = 2.5 \times 10^{13}/\text{cm}^3$  at 300°K)

**Solution:**

Given that,  $n_i = 2.5 \times 10^{13}/\text{cm}^3$  at 300°K and  $\mu_n = 2 \mu_p$  and  $E = 2 \text{ V/cm}$

$$N_D = 10^{14} \text{ atoms/cm}^3 \Rightarrow N_D > N_A$$

and also,

$$N_A = 5 \times 10^{13} \text{ atoms/cm}^3$$

$$\rho_i = 60 \Omega\text{-cm}$$

$\therefore$

$$\sigma_i = \frac{1}{\rho_i} = \frac{1}{60} = 0.0166 (\Omega\text{-cm})^{-1}$$

For an intrinsic "Ge" semiconductor,

$$\sigma_i = n_i q[\mu_n + \mu_p]$$

or

$$0.0166 = 2.5 \times 10^{13} \times 1.6 \times 10^{-19} \times 3\mu_p$$

or

$$\mu_p = 1388.8 \text{ cm}^2/\text{V-sec} \approx 1389 \text{ cm}^2/\text{V-sec}$$

$\therefore$

$$\mu_n \approx 2\mu_p \approx 2778 \text{ cm}^2/\text{V-sec}$$

As we know that when semiconductor is simultaneously doped with donor and acceptor impurities then the type of semiconductor it is can be determined as:

$\Rightarrow$  If  $N_D > N_A$  then this semiconductor turns into the  $n$ -type semiconductor and in this case conductivity ( $\sigma_n$ ) is equal to,

$$\sigma_n = q\mu_n[N_D - N_A] = 1.6 \times 10^{-19} \times 2778 [10^{14} - 5 \times 10^{13}]$$

$\therefore$

$$\sigma_n = 0.02215 (\Omega\text{-cm})^{-1}$$

So, the total current density (here assume only  $n$ -type semiconductor, so only electrons are majority carriers) is,

$$J = \sigma_n |E| = 0.02215 \times 2 = 0.0443 \text{ A/cm}^2$$

$\therefore$

$$J = 44.3 \text{ mA/cm}^2$$

**Q.9** 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<sup>2</sup> in cross-sectional area by doping it appropriately with phosphorous atoms. If the electron mobility in silicon at room temperature be 1350 cm<sup>2</sup>/V. sec, calculate the dopant density needed to achieve this. Neglect the insignificant contribution by the intrinsic carriers.

**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  $E$ .

$$v_d \propto E$$

$$v_d = \mu E$$

where

$$\mu = \text{Mobility}$$

Mobility is defined as drift velocity per unit electric field.

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

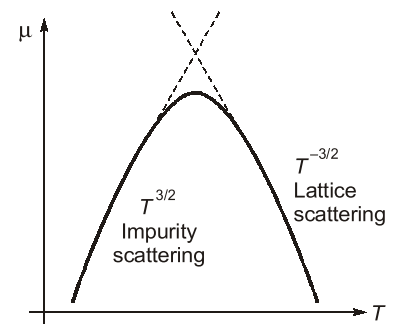
**Relation between Mobility with Temperature**

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 more strongly by an interaction with a charged ion 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

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

$$\rho = \frac{RA}{l} = \frac{100 \times 10^{-2}}{1} = 1 \, \Omega\text{cm}$$

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

$$n = \frac{1}{\rho \times q \times \mu_n} = \frac{1}{1 \times 1.6 \times 10^{-19} \times 1350} = 4.6 \times 10^{15}/\text{cm}^3$$

For N-type

$$n \simeq N_D$$

$$N_D = 4.6 \times 10^{15}/\text{cm}^3$$

**Q.10** Consider the intrinsic germanium and silicon at room temperature i.e. at 300°K. By what percentage does the conductivity increases per degree rise in temperature?

**Solution:**

The conductivity of an intrinsic semiconductor is given by the relation,

$$\sigma_{\text{int.}} = n_i(\mu_n + \mu_p)q \quad \dots(i)$$

where,

$n_i$  = intrinsic concentration

$\mu_n$  = mobility of electrons

$\mu_p$  = mobility of holes

$q$  = electronic charge in Coulomb

As we know that with increasing the temperature, the density of hole-electron pairs increases and correspondingly, the conductivity increases.

From equation (i) it is clear that ' $\sigma_{\text{int.}}$ ' depends upon ' $n_i$ ' as well as  $\mu_n$  and  $\mu_p$ . For finding the percentage change in conductivity per degree change in temperature, we take an assumption that mobility ( $\mu$ ) does not vary with temperature i.e. it is more or less constant. In this situation, the conductivity ( $\sigma_{\text{int.}}$ ) varies as ' $n_i$ '

$$\therefore n_i^2 = A_0 T^3 e^{-E_{G_0}/kT} \quad \dots(ii)$$

where,

$A_0$  = Constant independent of T

$E_{G_0}$  = Energy gap at 0°K

$k$  = Boltzmann constant

Now, from equation (ii),

$$n_i = A_0^{1/2} T^{3/2} e^{-E_{G_0}/2kT}$$

Taking ' $\ln$ ' both sides we get,

$$\ln n_i = \frac{1}{2} \ln A_0 + \frac{3}{2} \ln T - \frac{E_{G_0}}{2kT}$$

$\Rightarrow$

$$\left( \frac{dn_i}{n_i} \right) = \frac{3}{2} \cdot \frac{dT}{T} + \frac{E_{G_0}}{2kT^2} \cdot dT = \left( \frac{3}{2} + \frac{E_{G_0}}{2kT} \right) \cdot \frac{dT}{T}$$

$\therefore$

$$\frac{dn_i}{n_i} = \left( 1.5 + \frac{E_{G_0}}{2kT} \right) \cdot \frac{dT}{T} \quad \dots(iii)$$