SEMICONDUCTOR PHYSICS

Introduction:

A semiconductor is a material that has a resistivity value in between that of a conductor and an insulator. The conductivity of a semiconductor material can be varied under an external electric field. Devices made from semiconductor materials are the foundation of modern electronics, including ratio, computers , telephones, and may other devices. Semiconductor devices include the transistor, many kinds of diodes including the light emitting diode, the silicon controlled rectifier, and digital and analog integrated circuits. Solar photovoltaic panels are large semiconductor devices that directly convert light energy into electrical energy.

In a metallic conductor, current is carried by the flow of electrons. In semiconductors, current can be carried either by the flow of electrons or by the flow of positively charged holes in the electron structure of the material. Silicon is used to create most semiconductors commercially. So many other materials are used, including germanium, gallium arsenide. A pure semiconductor is often called an intrinsic material and then allowing the melt to solidify into a new and different crystal. This process is called doping.

Question: Explain the preparation of semi conducting materials?

Answer:

Preparation of semiconductor materials:

Semiconductors with predeictable, reliable electronic properties are necessary for mass production. The level of chemical purity needed is extremely high because the presence of impurities even in very small proportions can have large effects on the properties of material. High degree of crystalline perfection is also required, since faults in crystal structure (such as dislocations, twins and stacking faults) interfere with the semi- conducting properties of the material. Crystalline faults are a major cause of defective semiconductor devices. The larger the crystal, the more difficult it is to achieve the necessary perfection. Convert mass production processes use crystal ingots between 100 nm and 300 nm (4-12 inches) in a diameter which are grown as cylinders and sliced into wafers.

Because of the required level of chemical purity and the perfection of the crystal structure which are needed to make semiconductor devices, special methods have been developed to produce the initial semiconductor material. A technique for achieving high purity includes growing the crystal using the Czocharalski process. As additional step that can be used to further increase purity is known as zone refining. In zone refining , apart of a solid crystal is melted. The impurities tend to concentrate in the melted region, while the desired materials, recrystallizes leaving the solid material more pure and with fewer crystalline faults. In manufacturing semiconductor devices involving hetero-junctions between different semiconductor materials, the lattice constant, which is the length of the repeating elements of the crystal structure, is important for determining the compatibility of material.

Question : Define conduction band and valence band ?

Answer:

Conduction band:

The conduction band in the range of electron energy, higher than that of the valence band, sufficient to make the electrons free to accelerate under the influence of an applied electric field and thus constitutes an electric current. Semiconductors may cross this conduction band when they are excited.

Valence band:

The valence band is the highest range of electron energies where electrons are normally present absolute zero. In semiconductors and insulators, there is a band gap above the valence band, followed by conduction band above that. In metals, the conduction band has no energy gap separating it from the valence band.

Semiconductors and insulators owe their high conductivity to the properties of the balance band in those materials. It just so happens that the number of electrons is precisely equal to the number of states available up to the top of the valence band. There are no available states in the band gap. This means that when an electric field is applied, the electrons can not increase their energy because there are no states available to the electrons where they would be moving faster than they are already going. There is some conductivity in insulators, however this is due to thermal excitation of some of the electrons get enough energy to jump the band gap in one go. Once they are in the conduction band, they can conduct electricity, as the hole they left behind in the valence band. The hole is an empty state that allows electrons in the valence band some degree of freedom.

Question : What is intrinsic semiconductor and explain with the help of energy band diagram as a function of temperature?

Answer:

Intrinsic semiconductors:

Intrinsic semiconductors are those in which impurities are not present and therefore called pure semiconductors. In these semiconductors few crystal defects may be present. Fermi level exists exactly at mid way of the energy gap. When a semiconductor is taken at) K then it behaves as an insulator and conduction occurs at higher temperature due to thermal excitation f electrons from the valence band to the conduction band. Examples: Germanium and Silicon. Figure 1 shows the intrinsic semiconductors at T = 0 K and T >0 K
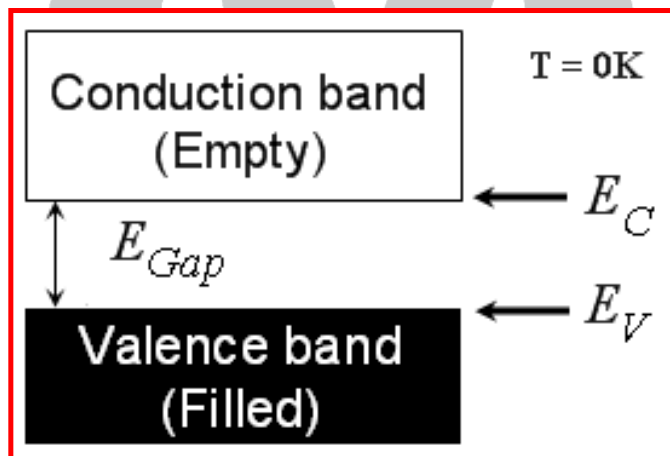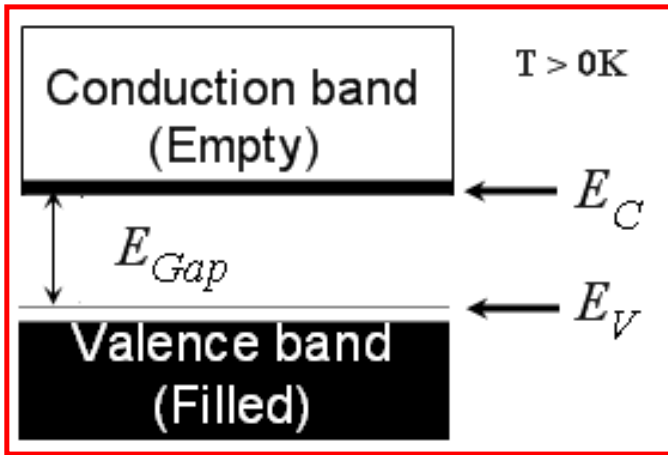
In order to get insight view of an intrinsic semiconductor, let us consider silicon, which has four valence electrons. In order to gain stability it has to make four covalend bonds. In this regard each silicon atom makes four covalent bonds with for other silicon atoms as shown in Fig.2.The electrons which are participating in the covalent bonds are known as valence electrons. If some energy is supplied then covalent bonds break, electrons will come ot and move freely, resulting in the formation of vacant sites in the covalent bonds. These are known as positive charge carriers named as holes. The electrons which came out from the valence bands move freely without any constraints and have more energy than the electron in the covalent bonds or valence bond. The number of conduction electrons will be equal to the number of vacant sites in the valence band.
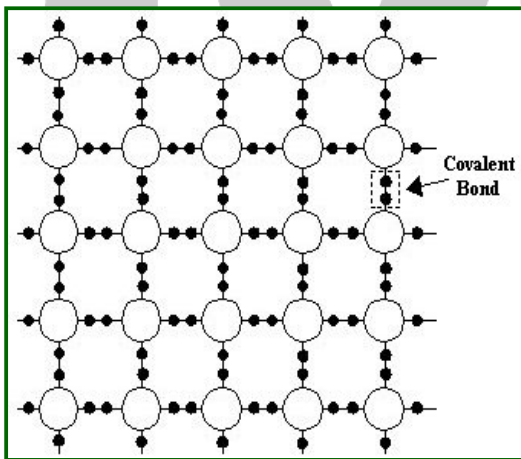

Figure 2

Question: Derive and expression for intrinsic carrier concentration at given temperature ?

Answer:

Intrinsic carrier concentrations:

In intrinsic semidonductors, as the temperature is increased electron-hole pairs will be generated. Hence the electron concentration, ni, in the conduction band will be equal t the hole concentration, pi in the valence band.

Let Ei be the Fermi level of the intrinsic semiconductor in equilibrium, then the number of electrons per unit volume in the conduction band,

$$n_i = 2\left(\frac{2m_e\pi K_B T}{h^2}\right)^2 \exp\left(\frac{E_i - E_c}{K_B T}\right) \quad \text{--------------------(1)}$$

and the number of holes per unit volume in the valence band,

$$p_i = 2\left(\frac{2m_h\pi K_B T}{h^2}\right)^{3/2} \exp\left(\frac{E_v - E_i}{K_B T}\right) \quad \text{----------------(2)}$$

But, in intrinsic semiconductors ni = pi hence,

$$2\left(\frac{2m_e\pi K_B T}{h^2}\right)^{3/2} \exp\left(\frac{E_i - E_c}{K_B T}\right) = 2\left(\frac{2m_h\pi K_B T}{h^2}\right)^{3/2} \exp\left(\frac{E_v - E_i}{K_B T}\right)$$

$$m_e^{3/2} \exp\left(\frac{E_i - E_c}{K_B T}\right) = m_h^{3/2} \exp\left(\frac{E_v - E_i}{K_B T}\right)$$

$$2E_i - E_c - E_y = K_B T \ln\left[\frac{m_h}{m_e}\right]^{3/2}$$

$$E_i = \frac{1}{2}(E_c - E_v) + \frac{3}{4}\ln\left[\frac{m_h}{m_e}\right]$$

If the effective masses $m_e = m_h$, then

$$E_i = \frac{E_c + E_v}{2} \quad \text{(since ln1=0)} \quad \text{---------------------(3)}$$

E_i lies midway between E_c and E_v, which happens to be the centre of the band gap any temperature.

If $m_h > m_e$, Ei linearly increases towards E_c. The material properties E_c, E_v, m_h and m_e determine the value of E_i, which for most semiconductors like Si and Ge lie at the centre of the band gap.

Combining ni and pi, values

$$n_i \cdot p_i = 4\left[\frac{2m_e KT}{h^2}\right]^{3/2}\left[\frac{2m_e KT}{h^2}\right]^{3/2}\exp\left(\frac{E_i - E_c}{KT}\right)\exp\left(\frac{E_v - E_i}{KT}\right)$$

$$n_i^2 = 4\left(\frac{2\pi K}{h}\right)^3 (m_e m_h)^{3/2} T^3 \exp\left(\frac{E_v - E_i}{KT}\right) \quad (Since\, n_i = p_i)$$

$$n^2 = AT^3 \exp\left(\frac{-Eg}{KT}\right) \quad \text{--------------- (4)}$$

where

$$. \qquad A = 4\left(\frac{2\pi K}{h}\right)^3 (m_h m_e)^{3/2}$$

and $E_g = E_c - E_v$ is the energy gap of the semiconductor.
Where A and E_g are constants for a given semiconductor and ni is called the intrinsic concentration which indicates thermally generated electrons and holes. It is a strong function of temperature T.

Question:

Define Extrinsic semiconductor and how many types of extrinsic semiconductors are available with examples?

Answer:

Extrinsic semiconductors:

In intrinsic or pure semiconductors, the carrier concentration of both electrons and holes at normal temperatures very low, hence to get appreciable current density through the semiconductor, a large electric field should be applied. This problem can overcome by adding suitable impurities into the intrinsic semiconductors.

The extrinsic semiconductors are those in which impurities of large quantity are present. In general, the impurities can be either III group elements or V group elements. Based on the impurities present in the extrinsic semiconductors, they are classifies into two categories.

1. n-type semiconductors and
2. p-type semiconductors

n-type semiconductors:

In order for silicon crystal to conduct electricity, we need to introduce an impurity atom such as Arsenic, Antimony or phosphorus into the crystalline structure. These atoms have five outer electrons in their outermost co-valent bond to share with other atoms and are commonly called pentavalent impurities. This allows four of the five electrons tobond with its neighboring silicon atoms leaving one free electron to move about when electrical voltage is applied. As each impurity atom donates one electron, pentavalent atoms are generally known as donors. Antimoney (Sb) is frequently used as pentavalent additive as it has 51 electrons arranged in 5 shells around the nucleus. The resulting semiconductor material has an excess of current carrying electrons, each with a negative charge, and is therefore referred to as n-type material with the

electrons called majority carriers and the resultant holes minority carriers. The block diagram of n-type impurity doping and corresponding band diagram is shown in figure 1.
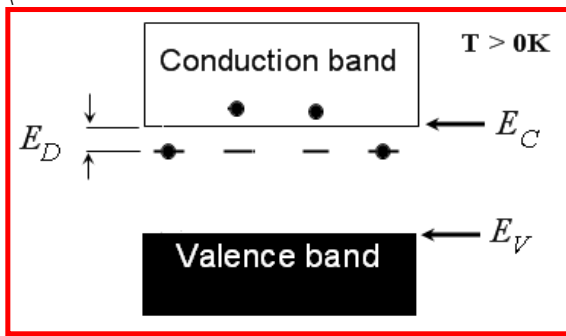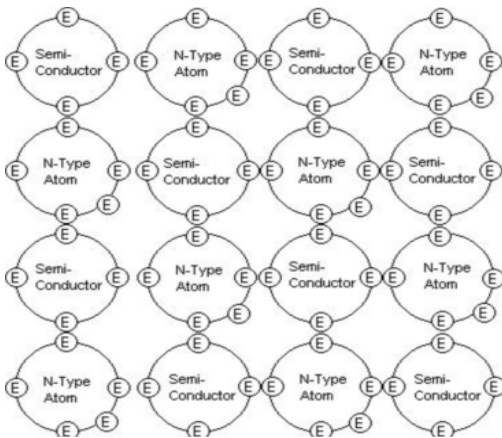
p-type semiconductors:

In contrast to n-type of semiconductor, if we introduce a trivalent (3 electron) impurity into the crystal structure, such as aluminum, Boron or indium , only three valence electrons are available in the outermost covalent bond meaning that the fourth bond cannot be formed. Therefore, a complete connection is not possible, giving the semiconductor material an abundance of positively charged carriers known as holes in the structure of the crystal. As there is a hole an adjoining free electron is attracted to it and will try move into the hole to fill it. However, the electron filling the hole leaves another hole behind, and is forth giving the appearance that the holes are moving as a positive charge through the crystal structure (conventional current flow). As each impurity atom generates a hole, trivalent impurities are generally known as acceptors as they are continually accepting extra electrons. Boron (B) is frequently used as trivalent additive as it has only 5 electrons arranged in 3 shells around the nucleus. Addition Boron causes conduction to consists mainly of positive charge carriers results in a p-type material and the positive holes are called majority carriers while the free electrons are called minority carriers.

Conduction band T > 0K

$\leftarrow E_C$

E_A

$\leftarrow E_V$

Valence band
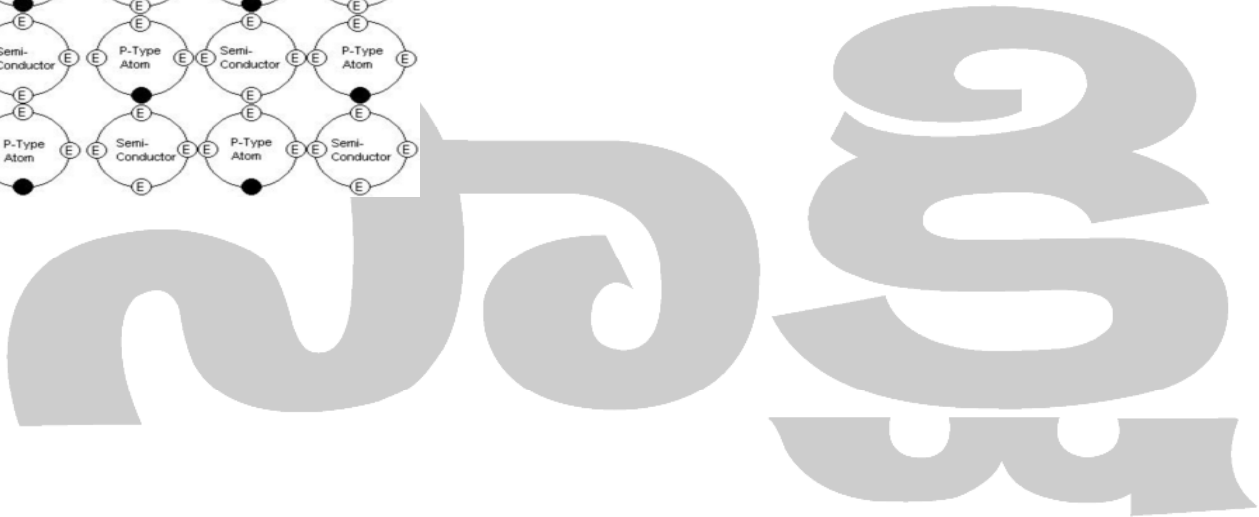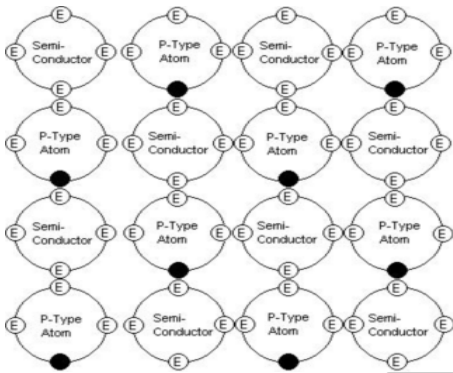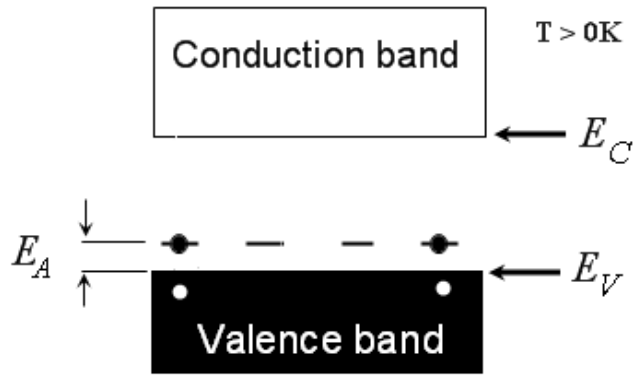
Question: Estimate electron and hole densities?

Answer:

Electron and hole Densities:

The computation of the elecgtron and hole densities in semi-conductor is the most important application of Fermi-Dirac statists.

Carrier density at a given level in n-type semiconductor:

Consider an extrinsic semiconductor doped with donor atoms give rise to donor levels E_d close to the conduction band edge Ec as shown in Fig. Let N_d be the number of impurity of atoms, gives rise to a single electron state at Ed. Then the number of electrons in the energy level E_d would be

$N_d = g_e(E_d)P_e(E_d)$ --------------------(1)

But, $g_e(E_d) = N_D$ represents the density of states and

$$P_e(E_d) = \frac{1}{1 + \exp\left(\dfrac{E_d - E_F}{K_B T}\right)}$$

Where E_F is the Fermi level at a temperature T.
Substituting the above values in equation (1)

$$n_d = N_D \frac{1}{1 + \exp\left(\dfrac{E_d - E_F}{K_B T}\right)} \qquad \text{---------------- (2)}$$

Total number of energy states per unit volume at E_d is N_D
The total number of filled energy states per unit volume at E_d is n_d
The total number of vacant energy states per unit volume at E_d, $N_{D+} = N_D - n_d$
i.e N_D is the number of states per unit volume can be assumed to be singly ionized donors.

Hence,

$$N_D^+ = N_D - N_D \frac{1}{1 + \exp\left(\dfrac{E_d - E_F}{K_B T}\right)} \qquad \text{----------------(3)}$$

$$N_D^+ = \frac{N_D}{1 + \exp\left(\dfrac{E_F - E_d}{K_B T}\right)} \qquad \text{---------------- (4)}$$

The donor levels thus have two possible states:

1. nd is the number states that are filled with electrons. These correspond to unionized donor atoms and are neutral.
2. The remainig ND number of states are empty. These corresponding to thr absence of electrons

Carrier density at a given level in p-type semiconductor:

Now consider the case of a semiconductor doped with NA number of acceptor atoms per unit volume. The acceptor atoms give rise to acceptor levels Ea slightly above the valence band edge Ev as shown in Fig. IF some of the atoms, let na get ionized by accepting electrons, then those atoms are becoming negatively charged. The number os such electrons na occupying energy level Ea would be

$$n_a = g_a(E_a) P_e(E_a) = N_A^- \qquad \text{------------------ (1)}$$

But, ge(Ea) = NA, represents the density of states and

$$P_e(E) = \cfrac{1}{1 + \exp\left(\cfrac{E_a - E_F}{K_B T}\right)} \qquad \text{----------------- (2)}$$

Where E_F is Fermi level at a temperature T, substituting the above values in equation (1)

$$.\qquad n_a = N_A^- \cfrac{1}{1 + \exp\left(\cfrac{E_a - E_F}{K_B T}\right)} \qquad \text{-------------------- (3)}$$

The total number of acceptor atoms per unit volume at Ea is NA
The total number of ionized acceptor per unit volume at Ea is NA
The number of unionized acceptor atoms per unit volume at Ea, NA = NA- NA-

$$N_A^o = N^- - \cfrac{N_A}{1 + \exp\left(\cfrac{E_a - E_F}{K_B T}\right)}$$

$$N_A^o = \cfrac{N_A}{1 + \exp\left(\cfrac{E_F - E_a}{K_B T}\right)}$$

Acceptor levels this can also have two possible states

1. When filled with electrons, they are charged negatively and their concentration is given by Na
2. When empty, they are neutral and their concentration is given by NA0.

Question: Estimate both electron and hole densities in bands?

Answer:

Carrier densities in Bands:

At temperatures above) K, two types of gree charge carriers exist in a semiconductor, electrons in the conduction band and holes in the valence band, In general, it is taken that conduction is extended from E_C to + and the valence band is extended from -- to E_F.

Computation of electron density: Let n be the number of electrons per unit volume of a homogenously doped semiconductor crystal in equilibrium. If the conduction band extends from Ec to then the electron density can be written as

$$n_o = \int_{E_e}^{x} g_e(E) P_e(E) dE \qquad \text{--------------- (1)}$$

but, $\quad g_e(E) = \dfrac{1}{2\pi}\left(\dfrac{2m_e}{2}\right)^{3/2}(E - E_c)^{1/2}$

$$p_e(E) = \dfrac{1}{1 + \exp\left(\dfrac{E - E_F}{K_B T}\right)}$$

hence, $\qquad n_o = \int_{E_e}^{x} \dfrac{1}{2\pi^2}\left(\dfrac{2m_e}{\hbar^2}\right)\dfrac{(E - E_c)^{1/2}}{1 + \exp\left(\dfrac{E - E_F}{K_B T}\right)} dE$

In this integral, the energy being considered always greater than E_C. If temperature T is such that (E_C – E_F)/KT then the expression for n_O reduces to

$$n_o = \int_{E_e}^{x} \dfrac{1}{2\pi^2}\left(\dfrac{2m_e}{\hbar^2}\right)^{3/2}\dfrac{(E - E_c)^{1/2}}{1 + \exp\left(\dfrac{E - E_F}{K_B T}\right)} dE \qquad \text{------------------------(2)}$$

substituting $x = \dfrac{E - E_c}{K_B T}, dx = \dfrac{1}{K_B T} dE, dE = K_B T \ dx$

limits transform from (Ec,) to (0 ,) and (E-Ec) = (KBT)x

$$\exp\left(\dfrac{E - E_F}{K_B T}\right) = \exp\left(\dfrac{E - E_C}{K_B T}\right) = \exp\left(\dfrac{E_C - E_F}{K_B T}\right) = e^x \exp\left(\dfrac{E_C - E_F}{K_B T}\right)$$

substituting the above values and changing the limits in eq (2)

$$n_o = \dfrac{i}{2\pi^2}\left(\dfrac{2m_e}{\hbar^2}\right)^{3/2} \int_{0} \dfrac{(K_B T)^{3/2} x^{3/2}(K_B T) dx}{e^x \exp\left[\dfrac{E_C - E_F}{K_B T}\right]}$$

$$n_o = \dfrac{i}{2\pi^2}\left(\dfrac{2m_e}{\hbar^2}\right)^{3/2} \exp\left[\dfrac{-(E_c - E_F)}{K_B T}\right]\int_{0}^{\infty} x^{1/2} e^{-x} dx \qquad \text{--------------(3)}$$

From standard mathematical tables

$$\int_{0}^{x} x^{1/2} e^{-x} dx = \dfrac{\sqrt{\pi}}{2} \qquad \text{--------------------(4)}$$

Substituting equation (4) in (3) . $\qquad n_o = \dfrac{1}{2\pi^2}\left(\dfrac{2m_e k_B T}{\hbar^2}\right)^{3/2} \exp\left[\dfrac{-(E_c - E_F)}{K_B T}\right]\dfrac{\sqrt{\pi}}{2}$

$$n_o = \frac{1}{4\pi^2}\left(\frac{2m_e k_B T}{\hbar^2}\right)^{3/2} \sqrt{\pi} \exp\left[\frac{-(E_c - E_F)}{K_B T}\right]$$

i.e $\quad n_o = \frac{1}{4}\left(\frac{2m_e k_B T}{\hbar^2 \pi}\right)^{3/2} \exp\left[\frac{-(E_c - E_F)}{K_B T}\right]$

$$= \frac{8}{4}\left(\frac{2\pi m_e k_B T}{h^2}\right)^{3/2} \exp\left[\frac{-(E_c - E_F)}{K_B T}\right]$$

$$n_o = 2\left(\frac{2m_e k_B T}{h^2}\right)^{3/2} \exp\left[\frac{-(E_c - E_F)}{K_B T}\right]$$

$$n_o = N_o \exp\left[\frac{-(E_c - E_F)}{K_B T}\right] \qquad \text{--------------(5)}$$

where $\quad N_c = 2\left(\frac{2\pi m_e KT}{h^2}\right)^{3/2} \qquad \text{-------------(6)}$

Which is called the effective electron density in the conduction band.

Computation of hole density:

Let p be the number of holes per unit volume of a homogenously doped semiconductor crystal in equilibrium. If the valence band extends from - to EV, the hole density, P0 in a homogenous doped semiconductors can be written as

. $\quad p_o = \int\limits_{-x}^{E} g_h(E) p_h(E) dE \qquad \text{------------------- (1)}$

But, $\quad g_h(E) = \frac{1}{2\pi^2}\left(\frac{2m_h}{\hbar^2}\right)^{3/2}(E_v - E)^{1/2}, P_h(E) = \frac{1}{1 + \exp\left(\dfrac{E_F - E}{K_B T}\right)}$

Hence, . $\quad p_o = \int\limits_{-x}^{E_v} \frac{1}{2\pi^2}\left(\frac{2m_h}{\hbar^2}\right)^{3/2} \cdot \left[\frac{(E_v - E)^{1/2}}{1 + \exp\left(\dfrac{E_F - E}{K_B T}\right)}\right] dE$

In this integral, the energy E being considered always lesser than EV. If the temperature is such that $E_F - E_V 5 K_B T$

$$p_o = \int\limits_{-x}^{E_v} \frac{1}{2\pi^2}\left(\frac{2m_h}{\hbar^2}\right)^{3/2} \exp\left[\frac{E - E_F}{K_B T}\right](E_v - E)^{1/2} dE \qquad \text{------------------- (2)}$$

Substituting,

$$\frac{E_v - E}{K_B T} = x, dx = \frac{-dE}{K_B T} \quad dE = -K_B T dx$$

limits transform from [EF-]

$$\exp\left(\frac{(E-E_F)}{K_BT}\right) = \exp\left(\frac{(-E_v-E_F)}{K_BT}\right)\exp\left(\frac{(E_v-E_F)}{K_BT}\right)$$

Substituting the above values and changing the limits in equation (2)

$$p_o = \int_{-x}^{E_v}\frac{1}{2\pi^2}\left(\frac{2m_h}{\hbar^2}\right)^{3/2}\int_0^x -(-x)^{1/2}\left(K_BT\right)^{3/2}e^{-x}dx\exp\left(\frac{E_v-E_F}{K_BT}\right)dE$$

$$p_o = \frac{1}{2\pi^2}\left(\frac{2m_hK_BT}{\hbar^2}\right)\exp\left(\frac{E_v-E_F}{K_BT}\right)\int_0^x x^{1/2}e^{-x}dx \quad \text{------------- (3)}$$

from standard integrals

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

Substituting equation eq (3) in eq(2)

$$p_o = 2\left(\frac{2\pi m_hK_BT}{h^2}\right)\exp\left(\frac{E_v-E_F}{K_BT}\right)$$

$$p_o = N_v\exp\left(\frac{E_v-E_F}{K_BT}\right) \quad \text{------------- (4)}$$

Where $\quad N_v = 2\left(\frac{2\pi m_hK_BT}{h^2}\right)^{3/2} \quad \text{------------- (5)}$

Question: Define drift current and obtain an expression for conductivity?

Answer: Drift current and conductivity:

In the presence of electric field, the drift velocity V_{de} & V_{dh} of carriers superpose on the thermal velocities V_{te} & V_{th} . But the flow of charge carriers result in an electric currents in the semiconductor crystal known as the drift currents. Let an electric field E be applied in the positive X-direction creating drift currents J_{nd} & J_{pd} of electrons and holes respectively.

When electric field is removed , the carriers moving with a uniform velocity in the negative X-direction due to the application of electric field E in the positive X-direction. Suppose AB, a small rectangular box element of length   and unit sides of the square end faces a and B in the semiconductor as shown in Fig.1

$$\left\{\begin{matrix}\text{Total charge in}\\ \text{the box AB}\end{matrix}\right\}Q = \{\text{Density of Particles}\}\times\{\text{Density of Particles}\}\times\left\{\begin{matrix}\text{Charge on}\\ \text{each Particles}\end{matrix}\right\}$$

$$Q = \left(v_{de} \times 1 \times 1\right) \times n \times -q$$

Thus, $$Q = -q \; n \; v_{de} \qquad \text{------------------(1)}$$

Where n is the number of electrons per unit volume. The entering charge into the box through the face A will cross the face B in unit time. Thus, the drift current density J due to the free electrons at the face B will be

$$J = \frac{ch\arg e}{time \times Area} \qquad \text{----------------------(2)}$$

From eq (1) and (2), the current density of electrons,

$$J_{nd} = -q \; n \; v_{de}$$

similarly the current density of holes,
$$J_{pd} = q \; p \; v_{dh} \qquad \text{------------------ (3)}$$
But, the drift velocities in terms of mobilities are
$$v_{de} = - \; \mu_n \; E \; \text{------------(4)}$$
$$v_{dh} = \; \mu_p \; E \; \text{------------(5)}$$

Hence, substituting equations eq (4) and (5) in equation (2)

$$J_{nd} = n \; q \; m_n \; E$$
And
$$J_{pd} = pq \; \mu_p \; E$$

Even though electrons and holes move in opposite direction, the effective charge flow is same for both and hence they get added up. Hence the total current density die to both electrons and holes will be

$$J_d = J_{nd} + J_{pd}$$
$$J_d = \left(nq \, \mu_n + pq \; \mu_p\right)E \qquad \text{----------------------(6)}$$

But, according to Ohm's law, the current density,

$$J_d = \sigma \; E \quad \text{----------------------(7)}$$
On comparing the equations (5) and (6), the conductivity

$$\sigma = n \; q \; \mu_n + p \, q \; \mu_p$$
$$\sigma = \sigma_n + \sigma_p$$

Where $\sigma_n = n \; q \; \mu_n$ and $\sigma_p = p \, q \; \mu_p$, the electrical conductivities due to electrons and holes respectively,

In a strong n-type semiconductor $n_0 \gg p_0$, Hence $\sigma_n \gg \sigma_p$ and $\sigma \sim \sigma_n$

But, the electric field at a point is, the negative potential gradient, and thus, gradient of any of the energy levels E_C, E_V or E_F, Thus,

$$E = -\frac{\partial V}{\partial x}$$

$$E = \frac{1}{q}\frac{\partial E_c}{\partial x} = \frac{1}{q}\frac{\partial E_v}{\partial x}$$

$$E = \frac{1}{q}\frac{\partial E_i}{\partial x}$$

Therefore,

$$J_{nd} = E = \frac{\sigma_n}{q}\frac{\partial E_i}{\partial x} = \frac{\sigma_n}{q}\frac{\partial E_c}{\partial x} = \frac{\sigma_n}{q}\frac{\partial E_v}{\partial x}$$

Question: Give short notes on diffusion currents?

Answer:

Diffusion currents: A directed movement of charge carriers constitute an electric current. Diffusion takes place die to the existence of a non-uniform concentration of carriers. In fact, Fick's first law states that the diffusion flux F i.e, the particle current is proportional to and in a direction opposite to the concentration gradient of the particles. Mathematically it can be written as

Diffusion Currents

$$F \propto -\frac{\partial N}{\partial x}$$

$$F = -D\frac{\partial N}{\partial x} \quad \text{--------------}(1)$$

Where D is the diffusion constant.

If n and p are the electron and hole concentrations, then the flux densities of electrons and holes J_e and J_n can be written as

$$J_e = -D_n\frac{\partial N}{\partial x} \quad \text{------------------}(2)$$

$$J_h = -D_p\frac{\partial p}{\partial x} \quad \text{-----------------}(3)$$

Where Dn and Dp are diffusion constants of the electrons and holes respectively,

Then diffusion current densities become,

$$J_{n\ \text{diff}} = +qD_n\frac{\partial n}{\partial x}$$

$$J_{p\ \text{diff}} = +qD_n\frac{\partial n}{\partial x}$$

Question: Give an account of continuity equation?

Answer: The continuity equation:

Consider unit value of a semiconductor crystal having free carriers n and p per unit volume. If the equilibrium is upset by the creation of electrons at a point and the flow of electrons away from the point will be

$$\frac{\partial n}{dt} = \frac{dn}{dt} - div.J \quad \text{-----------------(1)}$$

This equation is known as the continuity equation for free electron. At any point with in the crystal, the net rate of increase of carriers is equal to the difference between the number of carriers created there and the number of carriers flowing out.

Here (dn/dt) represents the rate of increase of electrons, (dn/dt) represents the number of electrons created and divJe reprents the net out flow of electrons.

If the flow of electrons assumed only in the x-direction, the equation of continuity deduces to

$$\frac{\partial n}{dt} = \frac{dn}{dt} - \frac{\partial j_e}{\partial x} \quad \text{-----------------(2)}$$

Similarly, for holes the continuity equation,

$$\frac{\partial p}{dt} = \frac{dp}{dt} - \frac{\partial j_h}{\partial x} \quad \text{---------------(3)}$$

As the net rate of recombination process of electrons and holes is given by +R and their creation rate by –R. Then the equation can be written as

$$\frac{\partial n}{dt} = -R - \frac{\partial j_e}{\partial x}$$

and

$$\frac{\partial p}{dt} = -R - \frac{\partial j_h}{\partial x}$$

But for an intrinsic semiconductor $+R = \dfrac{\partial n}{\tau_p}$, Hence,

$$\frac{\partial n}{dt} = -\frac{\partial n}{\tau_p} - \frac{\partial j_e}{\partial x} \quad \text{--------------------(4)}$$

and $\quad \dfrac{\partial p}{dt} = -\dfrac{\partial p}{\tau_p} - \dfrac{\partial j_h}{\partial x}$ --------------------(5)

The current densities due to electrons and holes,

$$J_n = -qJ_e \text{ and } J_p = qJ_h \text{ ------------(6)}$$

Since, q is electronic charge, Jp number of electrons crossing the unit area per sec, Je is the number of holes crossing the unit area per second.

Hence substituting equation (6) in equations (4) and (5) the rate of increase if carriers become

$$\dfrac{\partial n}{\partial t} = \dfrac{\partial n}{\tau_p} + \dfrac{1}{q}\dfrac{\partial J_h}{\partial x} \text{ ------------(7)}$$

$$\dfrac{\partial p}{\partial t} = -\dfrac{\partial p}{\tau_p} - \dfrac{1}{q}\dfrac{\partial J_p}{\partial x} \text{ ----------------(8)}$$

and

Finally, let n_0, and p_0 represent equilibrium concentrations in homogeneous n-type semiconductor and ∂n and ∂p the excess carrier concentrations. The actual concentrations n and p can be written as

$$n = n_0 + dn \text{ and } p = p_0 + dp \text{ ------------(9)}$$

Since equilibrium concentrations n0 and p0 do not change with time, differentiating the equations (9)

$$\dfrac{\partial n}{\partial t} = \dfrac{\partial(\partial n)}{\partial t} \text{ ------------(10)}$$

and

$$\dfrac{\partial p}{\partial t} = \dfrac{\partial(\partial p)}{\partial t} \text{ ----------(11)}$$

Substituting the equations (10) and (11) in the equations ((7) and (8) respectively

$$\dfrac{\partial}{\partial t}(\delta n) = \dfrac{\delta n}{\tau_n} + \dfrac{\partial J_n}{\partial x} \text{ --------------(12)}$$

$$\dfrac{\partial}{\partial t}(\delta p) = \dfrac{\delta p}{\tau_p} + \dfrac{\partial J_p}{\partial x} \text{ ------------(13)}$$

These are the continuity equations for electrons and holes respectively.

Question: Define Hall effect phenomena and derive an expression for Hall voltage ?

Answer:
Hall effect:

When a magnetic field is applied perpendicular to a current carrying conductor or semiconductor, a voltage is developed across the specimen in a direction perpendicular to both the current and the magnetic field. This phenomenon is called the Hall effect and the voltage so developed is called Hall voltage.

As shown in figure 1 , consider a uniform thick metal strip placed with its length parallel to X-axis. Let a current I is passed in the conductor along X-axis and a magnetic field B is established along X-axis. Due to the magnetic field, the charge carriers experience a force F D perpendicular to X-Z plane (i.e along Y-axis) The direction of this force is given by Fleming left hand rule. IF the charge carriers are electrons then they will experience a force in the negative direction of Y. Hence, they will be accumulated on the back surface of the strip. Due to this fact the back surface will be charged negatively while the front surface will be charged positively. Thus, a transverse potential difference is created/ This emf is known as Hall emf. If the charge carriers are positively charged particles like protons of holes, the sign of emf is reversed. Thus, the nature of charge carriers can be found by determining the sign of Hall emf which can be measured by a potentiometer. Experiments showed that the charge carriers in metals are electrons while the charge carriers in p-type semiconductors are holes.
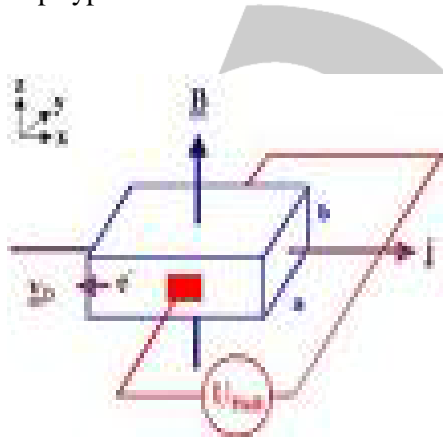
Magnetic deflecting force

$$F_p = q(v_d \times B) \text{ --------------(1)}$$

Hall electric deflecting force

$$F_n = q\ E_H \text{ --------------(2)}$$

When an equilibrium is reached, the magnetic deflecting forces on the charge carriers are balanced by the electric forces due to electric field.

Hence, the net force on the charge carriers become zero and from equation (1) and (2)

$$q(v_d \times B) + q\ E_n = 0$$

or

$$E_H = -(v_d \times B)$$

In terms of magnitude $E_H = v_d B$

Where Vd is drift velocity of electrons

The relation between current density and drift velocity is

$$v_d = \frac{J}{nq} \quad \text{-----------(3)}$$

Where n is the number of charge carriers per unit volume.

Substituting equation (3) in equation (4), the Hall emf

$$E_H = \left(\frac{j}{nq}\right) JB \quad \text{-------------(4)}$$

If V_H is the Hall voltage in equilibrium, the Hall electric field, $E_H = \left(\frac{V_H}{d}\right)$ -----(5)

Where d is width of metal strip.

Thus measuring the current I in the slab, the current density can be calculated by using the formula (i/A) where A is the area of cross section of the slab. The magnetic field can be measured by a Gauss-meter. SO on substituting the values of EH, J and B in equations (4), the value of (1/nq) can be calculated.

Hall coefficient R_H is defined as $R_H = \dfrac{E_H}{JB}$ --------(6)

From equation (4)

$$\frac{E_H}{JB} = \frac{1}{nq}$$

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

The Hall coefficient is negative when the charge carriers are electrons and poitive when the charge carriers are holes.

Question: Write short notes on direct and indirect band gap semiconductors?
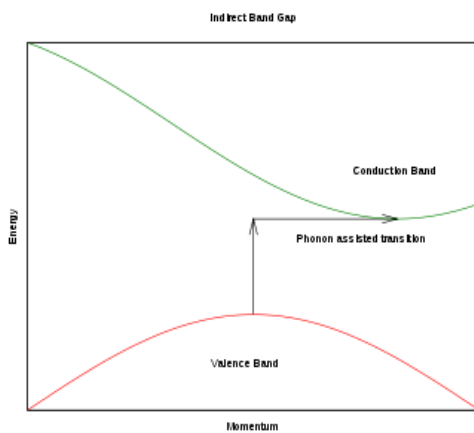
Answer:
Direct and indirect band gap in semiconductors:

      To observe electroluminescence it is necessary to select an appropriate semiconductor material. The most useful materials for this purpose are direct band gap semiconductors in which electrons and holes on either side of the forbidden energy gap have the same value of crystal momentum and thus direct recombination is possible. This process is illustrated in fig.1with an energy band diagram for a direct band gap semiconductor. It may be observed that the energy maximum of the valence band occurs at the same value of electron crystal momentum as the energy minimum of the conduction band. Hence electron-hole recombination occurs, the momentum of the electron remains virtually constant and the energy released, which corresponds to the bandgap energy Eg, may be emitted as light. This direct transition of an electron

across the energy gap provides an efficient mechanism of photon emission and the average timetime the minority carrier remains in agree state before recombination. Some of the examples of direct band gap semiconductors GaAs, Ge, InSb, GaSb etc.
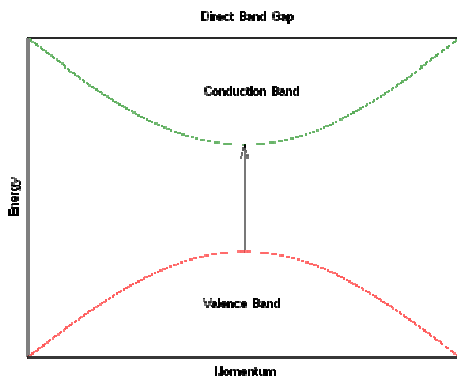
Direct Band Gap

In direct band gap semiconductors are those where the maximum and minimum energies occur at different values of crystal momentum (fig.2). For electron-hole pair recombination to take place it is essential that the electron losses momentum such that it has a value of momentum corresponding the maximum energy of valence band. The conservation of momentum requires the emission or absorption of a third particle, phonon. So, the recombination in indirect band gap semiconductors is relatively. This is reflected by much longer minority carrier life time together with a greater probability of nonradiative transitions. Some of the examples are Si.

Indirect Band Gap

Problems:

1. The following data are given for intrinsic Ge at 300 . $n_i = 2.4 \times 10^{19} \text{ m}^{-3}$; =0.39m^{2}v^{-1}s^{-1}; µp=0.19 m^2 v^{-1}s^{-1}, calculate the resistivity of the sample.

Solution:

Principle: $\sigma = n_i e\left(\mu_e + \mu_p\right)$

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

Answer: 0.448 ohm-cm

2.The electron and hole mobilities of Si sample are 0.135 and 0.048 m^2/V-s respectively. Density of Si atoms ni = 1.5 x 10^{16} m^{-3}. Determine the conductivity of Intrinsic Si at 300 K. The sample is then doped with 10^{23} phosphorous atom/m3. Determine the equilibrium hole concentration and conductivity.

Principle: $\sigma_i = n_i e(\mu_e + \mu_p)$

$$\sigma = N_D \mu_n e$$

Equilibrium hole concentration $p = \dfrac{n_i^2}{N_D}$

Answer: $\sigma_i = 0.44 x 10^{-3} s$

$$\sigma = 2.16 x 10^3 s$$
$$P = 2.25 \text{ x } 10^9 \text{ m}^{-3}$$

3.The RH of a specimen is 3.66 x 10-4 m3 c-1. Its resistivity is 8.93 x 10 -3 ohm-cm. Find μ and n.

Principle : $\mu = \sigma R_H = \dfrac{R_H}{\rho}$

$$n = \dfrac{1}{R_H e}$$

Answer: μ = 0.4116 m^2/Vs

N = 1.7 x 10^{22}/m^3

4. Calculate the intrinsic carrier density and conductivity at 300 K in germanium. Given that Ge atomic weight is 72.6; density is 5400 kg/m3. Mobility of electrons is 0.4 mr/VS, mobility of holes is 0.2 m2/Vs, and band gap is 0.7 eV,

Principle:

$$n_i = 2\left(\frac{2\pi m K_B T}{h^2}\right)^{\frac{3}{2}} \left\{\exp\frac{-E_g}{2K_B T}\right\}$$
$$\sigma = n_i e(\mu_e + \mu_p)$$

Answers: 3.5 x 1019/m^3

3.36ohm^{-1}cm^{-1}

5.The resistivity of an intrinsic semiconductor is 4.5 ohm-m at 20 °C and 2.0 ohm-m at 32 °C. What is the energy gap?

Principle: $\sigma = e n_i \mu$

$$n_i = CT^{\frac{3}{2}} \exp\left(\frac{-E_g}{2K_B T}\right)$$

Answer: E$_g$ = 0.96 eV.

Objective type questions

1. When the temperature of a semiconductor is increased, the conductivity of a semiconductor _____.

2. The conductivity of a semiconductor is due to the drifting of electron and _____.

3. When the temperature of semiconductor is nearly 0 K, it behaves as good as _____.

4. The order of energy gap of semiconductor is _____.

5. The position of Fermi level in intrinsic semiconductor lies _____.

6. The majority charge carriers are electrons in _____.

7. The minority carriers are electrons in _____.

8. In n-type of semiconductor the Fermi level lies close to _____.

9. In p-type semiconductor the Fermi level lies close to _____.

Answers:

1. increases
2. holes
3. insulator
4. 1 eV
5. lies midway between conduction and valence bands
6. n-type
7. p-type
8. conduction band
9. valence band

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