Sudan University of Science and Technology

College of Graduate Studies

Charge Carriers (Electrons and Holes) in Semiconductors

حاملات الشحنة (الإلكترونات والفجوات) في أشباه الموصلات

A thesis submitted for partial fulfillments of the requirement of the degree of science master in physics

Submitted by

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الآيــــــة

قال تعالى:(وَأَمَّا بِنِعْمَةِ رَبِّكَ فَحَدِّثْ)(11)

صدق الله العظيم

{سورة الضحى}

Acknowledgement

Thank god, the lord of the worlds, and blessings and peace be upon the prophet Mohammed and his family and companions and after:

I cannot thank almighty Allah after completing this research because I give thanks to the virtuous worker Dr. rawia abdelgani .for advice and ongoing guidance value for the success of this research, I call her health .finally, I thank everyone who has helped me.

DEDICATION

The source of my power and

inspiration....my husband

To ask of Allah because of their

satisfaction ....my parents.

The flower of life, Mohammed and

yousuf

To my brothers and sisters

To both lows for second

Both told me if the word

ABSTRACT

Had been calculate the charge carriers concentration(n_i) and energy gap (E_g), by indication of change temperature(T) ,know resistance(R_0),unknow resistance(R_t)and lengths(L_1,L_2),where it was found that whenever increase temperature decreased concentration and energy gap.

المستخلص

تم حساب تركيز حاملات الشحنة (n_i)وطاقة الحاجز (Eg) وذلك بدلالة التغيير في درجات الحرارة (T) المقاومة المعلومة(R_0) ،المقاومة المجهولة(R_T) و الأطوال(L_1,L_2)،حيث وجد أن كلما زادت درجة الحرارة ينخفض التركيز وطاقة الحاجز.

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Chapter One

1-1 Introduction:

In physics,a charge carrier is particle free to move, carrying on electric charge, especially the particles that carry electric charges in electrical conductors. Examples are electrons ,ions and holes .In conducting medium, an electric field can exert force on these free particles ,causing a net motion of the particles through the medium; this is what constitutes an electric current .In different conducting media, different particles serve to carry charge :

In metal, the charge carriers are electron one or two of the valence electrons from each atom is able to move about freely with in the crystal structure of the metal. The free electrons are referred to as conduction electrons and the cloud of free electron is called a Fermi gas.

Inelectrolyte, such as salt water, the charge carriers are ions, atoms or molecules that have gained or lost electrons so they are electrically charged. Atoms that have gained electrons so they are negatively charged are called anions;atoms that have lost electronsso they are positively charged are called cations. cations and anions of dissociated liquid also serve as charge carriers in melted ionic solid. Proton conductors are electrolytic conductors employing positive hydrogen ions carriers.

In plasma, an electrically charged gas which is found in electric arcs through air, neon signs, and the sun and stars, the electrons and Cation's of ionized gas act as charge carriers.

In a vacuum, free electron can act as charge carriers. These are sometimes called cathode rays. Invacuum tube, the mobile electron cloud is generated by a heated metal cathode, by a process called thermo ionic emission.

In semiconductors : the material used to make electronic components like transistors and integrated circuits , in addition to electrons ,the travelling

vacancies in the valence –band electron population called (holes) , act as mobile positive charges and are treated as charge carriers.

Electrons and holes are charge carriers in semiconductors.

It can be seen that in some conductors such as ionic solution and plasmas, they are both positive and negative charge carriers, so and electric current in them consist of the two polarities of carrier moving in opposite direction .in other conductors, such as metals, there are only charge carriers of one polarity, so an electric current in them just consists of charge carriers moving in one direction.[4]

1.2 Objective

This study aims to examine semiconductors and setting charge carriers(electrons, holes).

1.3 Problem:

After making this study it was found that problem lies in the following :

-Charge carriers have not only taught references.

- There's a special semiconductors laboratory only.

1.4 Previous studies:

Sami hanafi mohmud allam perform message titled nonlinear optical properties of semiconductor bullet holes. focuses on the study of movement and charge carriers state within quantitative wells raster in the for ground are introduced the concept of semiconductor quantum wells manufacturing method ,and also , as in the 2nd chapter as solved schrodinger equation in the three direction for each the electron and hole inside the wells and then get ground energy level .and the first two excited states to study influence of the dimensions and concentration of (Al) in the article (AlGaAs) on the energy level within the wells .and in the chapter three schrodinger is resolved

llaxiton trapped inside the wells , allaxiton binding energy were calculated .and in the 4th chapter study of nonlinear optical properties has been allaxiton inside the well was optical susceptibility manufactor and effect dimension of wells.

1.5 Thesis Lay out

Research consists of four chapters the first chapter an introduction, Chapter two semiconductor, the third chapter talks about the charge carriers in semiconductors, Chapter four the practical.

Chapter Two
Semiconductors

2.1 Introduction:

A semiconductor is defined as a solid crystalline material whose electrical conductivity is intermediate between that of a metal and an insulator. Semiconductors have been studied for a long time, since 1920, but were recognized as wonder materials only after the transistor was invented by Schokkttey ,Bardeen and Brattain in 1940.

The bonding between atoms in the solids accounts for the wide range of electrical conductivity. Metallic bonding produces delocalized electrons which are able to move in response to an electric field. Therefore, such materials form electrical conductors. In other types of bonding such as covalent bonding, the valence electrons are bound to a pair of atoms. Such materials should therefore form insulators. The electrical conductivity of solids ranges from $10^4 - 10^{-11} \text{ohm}^{-1}\text{m}^{-1}$ in case of semiconductors while its optimum value for a good conductor is 10^7 and minimum value for a good insulator is $10^{-19} \text{ohm}^{-1}\text{m}^{-1}$. Figure 1.1 presents the conductivity of a few selected solids on a logarithmic scale at room temperature$(\sim 293\ K)$**.**

We find from this figure that the conductivity of the best conductors, such as copper and silver, is almost 10 times higher than the best insulator (say sulphur). It is due to this vast difference between the good conductors and insulators that we are able to safely use electricity. Some interesting, although puzzling features of the bonding model raise the following questions.

Such questions are addressed adequately by the energy band theory as described partially in some preceeding chapters[1].
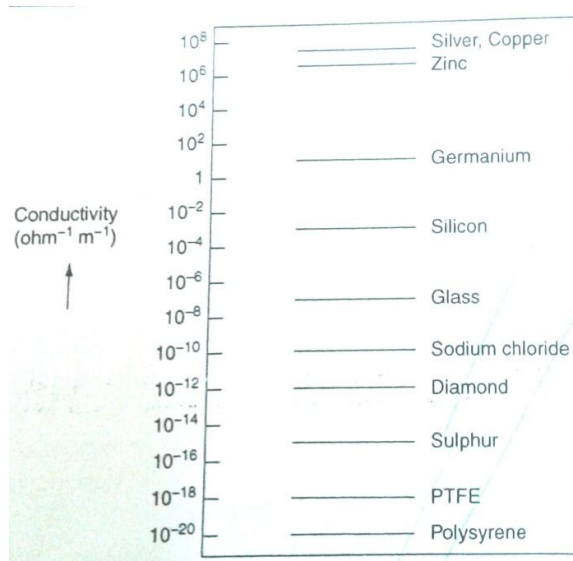
Figure 2.1 the conductivity of a few selected solids at room temperature.

2.2 Conduction in Semiconductors:

Electric current is caused due to the motion of electrons, although under some conditions, such as high temperatures, the motion of ions may be important as well. The basic distinction between conduction in metals and semiconductors arises from the energy bands occupied by the conduction electrons. This can be explained better if we take into account the case of an isolated carbon atom which contains six electrons (two each in the *Is,* 2s and 2p levels) as shown in Fig. 2.2.

If we plot the energies of the *2s* and *2p* energy levels for a group of (say *n)* carbon atoms as a function of atomic separation (r_o) we Find interaction between two sets of energy levels as shown in Fig. 1.3.
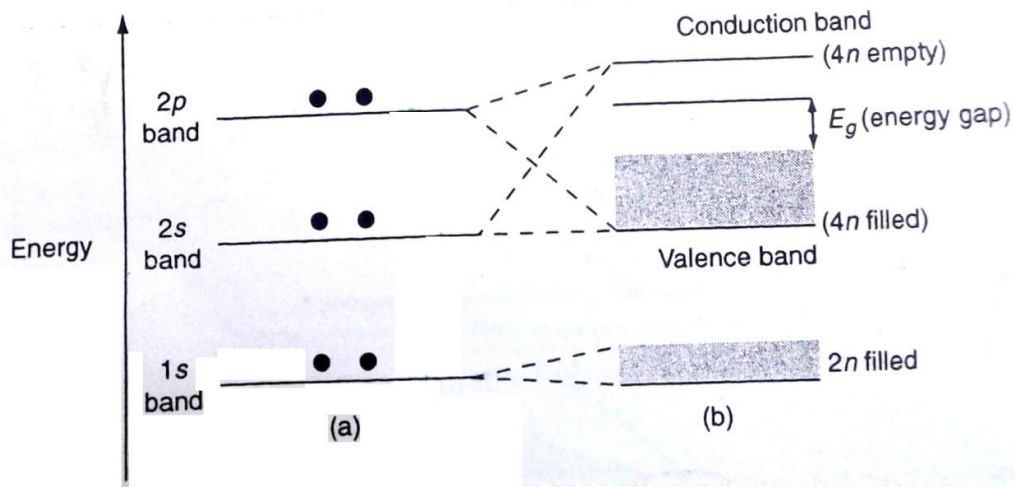
Figure 2.2 (a) Energy level occupation in case of an isolated carbon atom. (b) The energy bands in a diamond crystal.
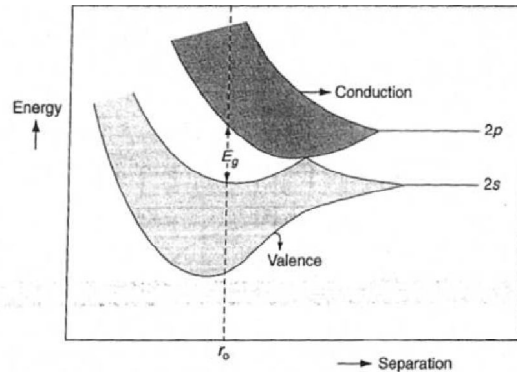
Figure 2.3 Energy levels-separation plot for a group of n carbon atoms.

At equilibrium separation, the states are split into two bands (each being a mixture of *2s-* and *2p-* like states), which are known as valence (the lower one) and conduction band (the upper one). These bands are separated by an energy range in which there are no allowed energy levels. This is called *band gap* (E_g) which is quite crucial to our understanding of the electrical properties of semiconductors and insulators.

We have also learnt from the band theory of solids that only a partially filled electronic band contributes to electric current. Completely filled bands and completely empty bands do not contribute to electrical conductivity and a material which has only completely full and completely empty bands is

therefore an insulator. If $E_g \sim 1$ eV, then the finite width of the region over which Fermi distribution changes rapidly, has observable consequences at moderate and high temperatures. A very small fraction of the states in the upper edge of the valence band is unoccupied and the corresponding electrons are found in the conduction band. The simplest band structure of a semiconductor is shown in Fig. 2.4.

The energy of the conduction band (E_{cb})is characterized by the equation

$$E_{cb}(k) = E_g + \frac{\hbar^2 \mathfrak{R}^2}{2m_e} \tag{2.1}$$

Here k is the wave vector and m_e is the effective mass of the electron. The expression for energy of the valence band (E_{vb}) shall have the form

$$E_{vb}(k) = \frac{-\hbar^2 \mathfrak{R}^2}{2m_b} \tag{2.2}$$

Here m_b is the effective mass of the hole. The negative sign is due to the inverted valence band where the mass at the top is negative.
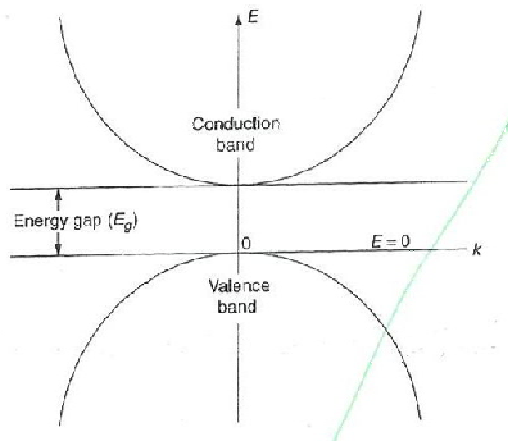
Figure 2.4Band structure of a semiconductor

The most significant property of semiconductor materials, which is not found in metals, is that their electrical conductivity can be changed by a large magnitude by simply adding small quantities of other substances. The entire field of solid state electronics relies on this unique property. Also, it is this

property that makes semiconductors scientifically useful and technologically viable[1] .

2.3 Intrinsic Semiconductors:

We understand that conduction in a semiconductor is entirely due to the motion of charge carriers, i.e., electrons and holes, which are generated by thermal excitations from the valence band to the conduction band. This process arises from the thermal disruption of the covalent bonds. The materials which exhibit this phenomenon are known as intrinsic semiconductors. The essential properties of an intrinsic semiconductor are:

1. The number of free carriers (electrons and holes) should be equal.

2. The impurity content should be less than 1 part in 100 million parts of the semiconductor.

In order to explain the concept of intrinsic semiconductors, let us take the example of a crystal of Si which has no impurities and no defects. A two-dimensional depiction of such an intrinsic semiconductor (silicon) is shown in Fig. 2.5.

Such a crystal at 0 K will have all the electrons tightly bound in the bonds; thus turning the material into an insulator. Figure 2.5 illustrates the creation of a free electron by breaking a covalent bond at position X. The vacancy thus created by the broken bond leaves a net positive charge on the atomic core. This vacancy behaves like a particle of positive charge having mass equal to that of an electron. When an electric field is applied, the conduction electrons drift opposite to the field and holes drift along the field. This is why the holes are supposed to have positive charge and they are equally capable of moving, through the crystal. The movement of this positively charged particle (hole) under the influence of thermal motion is depicted in Fig. 2.6.
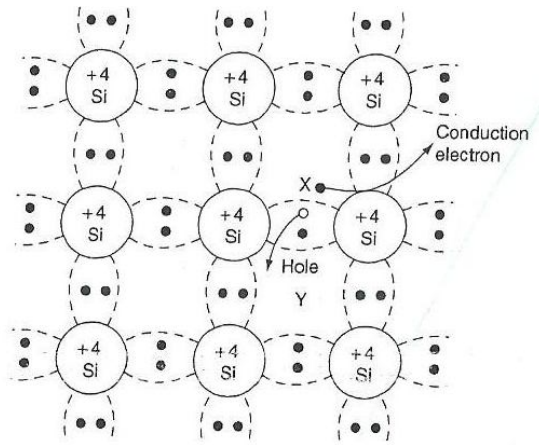
Figure 2.5A silicon crystal (two-dimensional representation) depicting the atom cores and valence electrons ,thermal generation of an electron-hole pair.
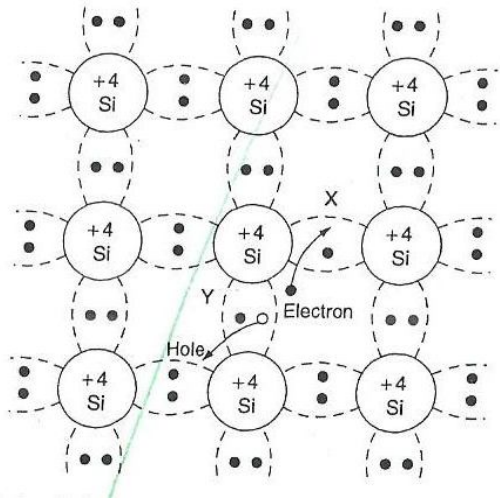
Figure 2.6Motion of an electron-hole pair (from location X to Y) in a two-dimensional schematic representation of a silicon crystal

In this figure it is demonstrated how an electron from a covalent bond at the adjacent site Y makes a transition (jump) and fills the vacancy created at A". This process results in the creation of a hole at Y. This indicates that the electron and hole have independent movement in the crystal.

Note that the electron-hole pair formation due to the thermal vibration of lattice atoms is known as the thermal generation process. This process is reversible, in the sense that a freely moving electron loses Its ionization energy by entering the broken covalent bond. This is known as the

recombination process. Hence, we conclude that when conduction in materials takes place due to the same number of electrons and holes, such materials are known as intrinsic semiconductors.
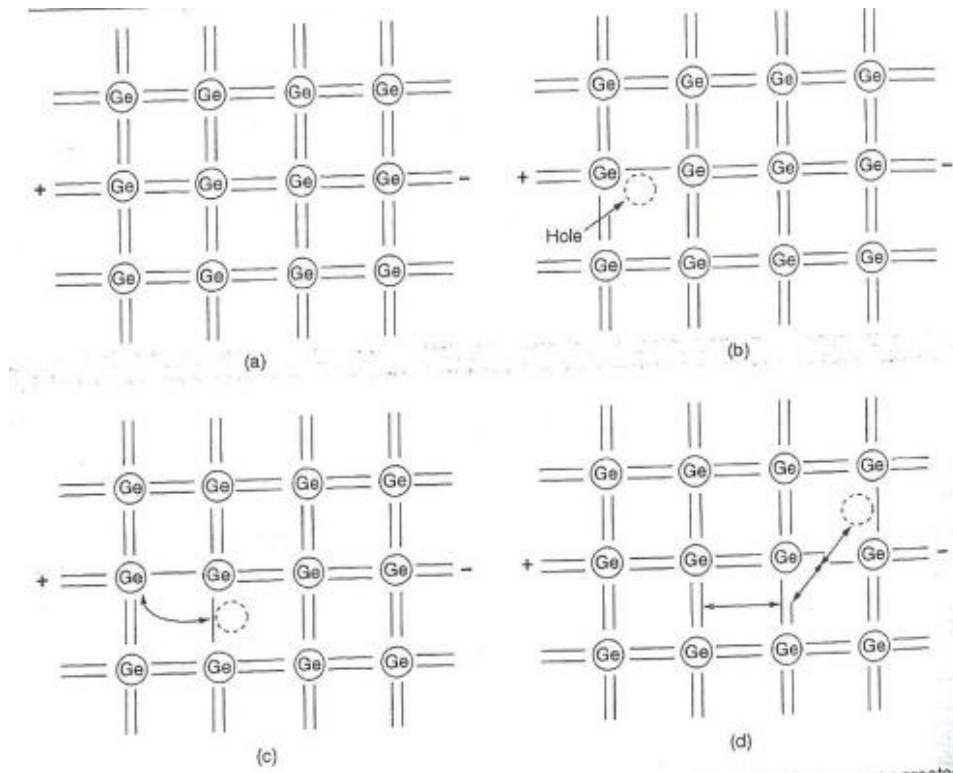
Figure 2.7 (a) A two-dimensional representation of germanium crystal at $T = 0\,K$; (b) a vacancy created-corresponds to an incomplete bond; (c) an electron moving to fill the vacant site when an electric field is applied; and (d) the hole moving towards the negative end of the germanium crystal.

We can also describe intrinsic semiconductors based on a two-dimensional representation of a germanium crystal at $T=0$ K (Fig. 2.7a). At room temperature the energy required to break a covalent bond is not very large. For example, energy required to break a bond in silicon and germanium is $1,1,$and $0.72\ eV$.

If we apply energy to the lattice of a germanium crystal, a vacancy in the covalent bond is created by a free electron which is depicted in Fig. 2.7b. Upon the application of electric field to the crystal, t e vacant site offers an opportunity to one of the electrons to move closer to the positive end of the

crystal(Fig. 2.7c). This creates a new vacant site and if this process is allowed to continue (Fig. 2.7d), we shall have a situation in which the electron moves towards the positive end of the crystal (or that the vacant state moves towards the negative end of the crystal). This vacant state is what we call a hole which carries the same amount of charge as that of an electron (but has the opposite sign)[1] .

2-4 Conductivity of charge carriers:

The number of electrons and holes in a semiconductor is not very important but the density of charge carriers (the number of carriers per unit volume) is significant. If n is the number of electrons and p the number of holes, then for an intrinsic semiconductor

$$n_i = n = p \tag{2.3}$$

Here n_i is the carrier concentration in an intrinsic *(pure)* semiconductor which varies with temperature and is different for different semiconductors.

Let us compute the specific *conductance* of an intrinsic semiconductor. If σ_n is the conductivity due to free electrons and σ_p due to holes, then specific conductance σ_i) is given by the expression

$$\sigma_i = \sigma_n + \sigma_p \tag{2.4}$$

Since n and p are the number of electrons and holes having charge e, their corresponding mobility's are μ_n and μ_p, respectively. Therefore, Eq. 1.4 becomes

$$\sigma_i = ne\mu_n + pe\mu_p \tag{2.5}$$

Since $n = p = n_i$, Eq. 1.5 can be rewritten as

$$\sigma_i = n_i e \left(\mu_n + \mu_p \right) \tag{2.6}$$

Since it has already been stated that the mobility of charge carriers depends on temperature, the power law $(\mu \alpha 1/T^{3/2})$ in case of the mobility of electrons and holes plays a role, i.e.,

$$\mu_n = \alpha T^{-3/2} \text{ and } \mu_p = \beta T^{-3/2}$$

So, $(\mu_n + \mu_p) = (\alpha + \beta)T^{-3/2}$

or

$$(\mu_n + \mu_p) = \gamma T^{-\frac{3}{2}} \tag{2.7}$$

where α and β are constant of proportionality and γ is equal to $(\alpha + \beta)$. Substituting this equation in Eq. 1.6, we get

$$\sigma_i = \gamma(n_i e)T^{-\frac{3}{2}} \tag{2.8}$$

On using certain equations for deriving the intrinsic (semiconductor) carrier concentration, we get

$$n_i = 4.83 \times 10^{21} T^{3/2} \exp\left(\frac{-E_g}{2k_B T}\right) \tag{2.9}$$

Using this expression in Eq. 1.8 we find

$$\sigma_i = \gamma e \times 4.83 \times 10^{21} \exp\left(\frac{-E_g}{2k_B T}\right)$$

Therefore,

$$\sigma_i = A \exp\left(\frac{-E_g}{2k_B T}\right) \tag{2.10}$$

where A is equal to $4.83 \times 10^{21} \gamma e$. This becomes an expression for the conductivity of an intrinsic semiconductor. The reciprocal of conductivity gives us resistivity which is expressed as

$$\rho_i = \frac{\exp\ (E_g/2k_B T)}{A} \tag{2-11}$$
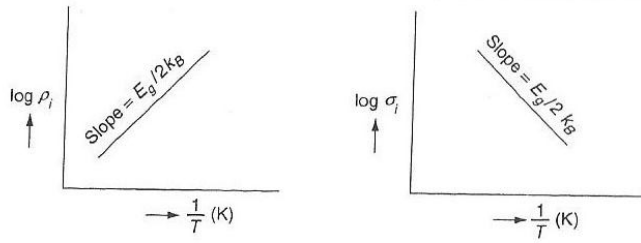
Figure 2.8(a) A plot of resistivity versus temperature $[1/T(K)]$ on a logarithmic scale, (b) Conductivity versus $1/T(K)$.

$$= B \exp\left(\frac{E_g}{2k_B T}\right) \tag{2.12}$$

Where B is reciprocal of A. Taking logarithm of Eq. 2.12, we get

$$\log \rho_i = \frac{E_g}{2k_B T} + \log B \tag{2.13}$$

Here E_g is energy gap of an intrinsic semiconductor. Equation 2.13 shows that the conductivity of intrinsic semiconductor varies exponentially with increase in temperature. Figure 2.8 presents a plot of intrinsic resistivity (Fig. 2.8a) and conductivity (Fig. 2.8b) at different temperatures. The slope of the; curve shown in Fig. 2.8 is given as

$$\frac{E_g}{2k_B T} \tag{2.14}$$

From this equation we can determine the energy gap for an intrinsic semiconductor.

The above discussion leads us to the following conclusions about intrinsic semiconductors:

1. The resistivity (or conductivity) of an intrinsic semiconductor is dependent on the concentration of charge carriers (electrons and holes).

2. The conductivity of charge carriers is a function of their mobilitys.

3. The mobility of electrons and holes is influenced by the presence of impurity atoms *(detects)*.

4. The conductivity also depends upon the number of charge carriers which are in thermal equilibrium[1] .

2.5 Carrier Concentration in Intrinsic Semiconductors:

We know now that the particles responsible for carrying the electric current in semiconductors are electrons and holes which are also called as free carriers. The electrical conductivity of a semi-conducting material depends only upon the number of free carriers it contains. In order to understand the basics of carrier concentration in intrinsic semiconductors, let us study carrier concentration in thermal equilibrium.

The charge carriers in semiconductors are regarded as free carriers which are actually electrons and holes. The carrier concentration in thermal equilibrium condition is the steady-state condition at a given temperature without any external conditions (such as light, pressure or electric field). Thermal agitation at a given temperature increases the excitation potential of electrons. This results in the excitation of electrons from the valence band to the conduction band and subsequent creation of an equal number of holes in the valence band. An intrinsic semiconductor is one that contains relatively small amounts of impurities as compared to the thermally generated electrons and holes.

In order to determine the number of free carriers, we need to make use of some basic results of statistical physics. The probability that an electron occupies an electronic state with energy E is given by the Fermi-Dirac distribution function given in Eq. 2.15.

$$F(E) = \frac{1}{1 + \frac{\exp(E - E_F)}{k_B T}} \qquad (2.15)$$

This is also known as the Fermi distribution function which gives the probability that an energy level E. is occupied by an electron when the system is at temperature T. In this expression E_F is the energy of the Fermi level, k_B is the Boltzmann constant, T is the absolute temperature (in Kelvin). The Fermi energy is the energy at which the probability of occupation by an electron is exactly one-half. The Fermi distribution for different temperatures is illustrated in Fig. 2.9.

The Fermi distribution function which is symmetrical around the Fermi energy can thus be approximated by the following simpler expressions:

$$F(E) = \exp\frac{(E - E_F)}{k_B T} \text{ for}(E - E_F) > k_B T \tag{2.16}$$

and

$$F(E) = \exp\frac{(E - E_F)}{k_B T} \text{ for}(E - E_F) < k_B T \tag{2.17}$$

Equation 2.16 can be regarded as the probability that a hole occupies a state located at energy E.

To determine the electron density in an intrinsic semiconductor, it is important to evaluate first the electron density in an incremental energy range dE. This density $n(E)$ is defined as the product of the density of allowed energy states $[N(E)]$ per
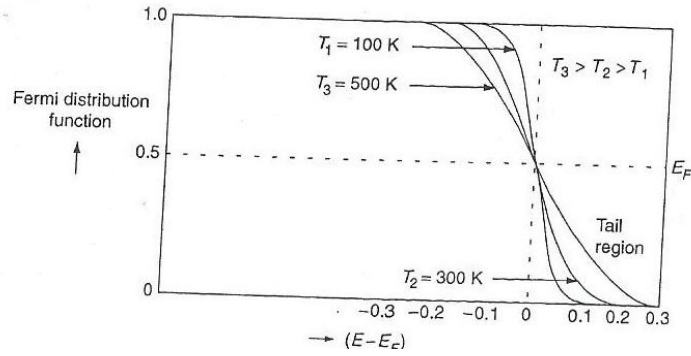
Figure 2.9 The Fermi distribution function $F(E)$ versus $(E - E_F)$ at various temperatures

energy range per unit volume, and by, the probability of occupying that energy range $F(E)$ [as given by Eq. 2.14]. Thus the electron density in the conduction band is expressed by integrating $N(E)\ F(E)\ dE$ from bottom to top of the conduction band:

$$n = \int_{E_{c_1}}^{E_{c_2}} N(E)\ F(E)dE \tag{2.18}$$

Here n is in cm^{-3} and $N(E)$ is in $(cm^3 eV)^{-1}$ and E_{c_1} and E_{c_2} are the bottom and top of the conduction band.

Figure 1.10 illustrates the band diagram, the density of states $N(E)$, the Fermi distribution function $F(E)$, and the carrier concentration for an intrinsic semiconductor.

By using Eq. 2.17, a graphical representation of the carrier concentration in terms of the product of $N(E)$ (Fig. 2.10b) and $F(E)$ (Fig. 2.10c) results in an $n(E)$ and $p(E)$ versus E curve (Fig. 2.10d) in which the shaded area corresponds to the electron density. Using Eq. 2.15 in Eq. 2.17 and also some expressions used in the band theory, the electron density equation becomes

$$n = \frac{1}{2\pi^2}\left(\frac{2m_e}{\hbar^2}\right)^{3/2} \exp\frac{E_F}{k_B T} \int_{E_g}^{\infty} (E - E_g)^{1/2} \exp-\frac{E}{k_B T} dE \tag{2.19}$$

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In order to understand the term E_g, please go through the text given in italics.

*The simplest band structure of a semiconductor is shown in Fig. 2.11. The energy of the conduction band has the form $E_c(k) = E_g + \hbar^2 k^2 / 2m_e^*$ where **k** is the wave vector and m_e^* the effective mass of the electron. The energy E_g represents the energy gap.*

Solving Eq. 2.18 gives us the expression for carrier concentration which is

$$n = 2 \left(\frac{m_e k_B T}{2\pi \hbar^2} \right)^{3/2} \exp \frac{E_F}{k_B T} \exp - \frac{E_g}{k_B T} \tag{2.20}$$
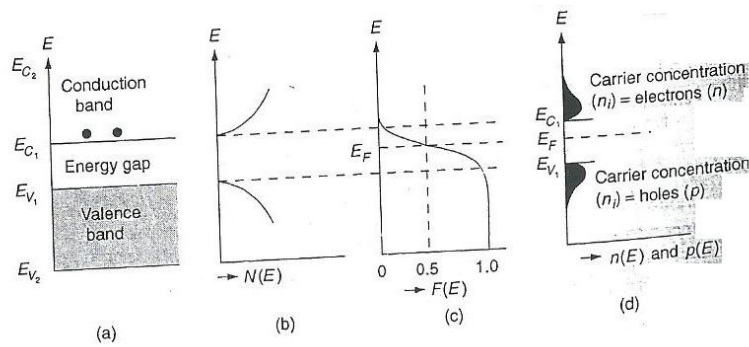
Figure 2.10 (a) Band diagram for an intrinsic semiconductor; (b) the density of states, (c) tie distribution function; and (d) the carrier concentration for an intrinsic semiconductor
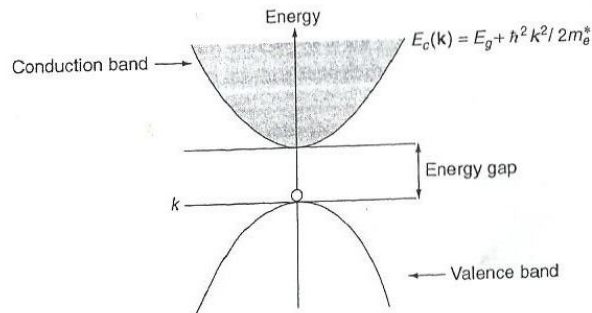
Figure 2.11Depicting conduction band energy in the band structure of a semiconductor.

Since we assume holes also to be charge carriers, we can write a similar expression for hole concentration

$$p = \left(\frac{m_b k_B T}{2\pi \hbar^2}\right)^{3/2} \exp \frac{-E_F}{k_B T} \tag{2.21}$$

Looking at Eqs . 2.19 and 2.20 it seems that holes and electrons are independent quantities. But, in fact, these two quantities are equal to each other because the electrons in the conduction band are due to excitations from

Eq. 2.22 becomes very small as compared with the first one, and the Fermi energy level gets close to the middle of the energy gap. This result is in agreement with the theory that the bottom of the conduction band and the top of the valence band are far from the Fermi level.

If we use Eq. 2.22 in Eq. 2.19, we find that the valence band across the energy gap and for each electron thus excited, a hole is created in the valence band. Hence,

$$n = P \tag{2.22}$$

If we equate Eqs. 2.19 and 2.20 with reference to Eq. 2.21, we find an expression for the unknown quantity, i.e., Fermi energy

$$E_F = \frac{1}{2} E_g + \frac{3}{4} k_B T \log \left(\frac{m_b}{m_e}\right) \tag{2.23}$$

Since $k_B T \ll E_g$ under ideal conditions, the second term on the right side of

$$n = 2 \left(\frac{k_B T}{2\pi \hbar^2}\right)^{3/2} (m_e m_b)^{3/4} \exp \frac{-E_g}{2k_B T} \tag{2.24}$$

The most important feature of this equation is that n varies rapidly (exponentially) with temperature. Hence it is concluded that a large number of electrons are excited across the energy gap when the temperature is raised. If

we substitute $E_g = 1\ eV, m_e = m_b = m_0$, and $T = 300\ K$. In Eq. 2.23, we find that

$$n \simeq 10^{15} \text{electrons cm}^{-3} \tag{2.25}$$

This number is the characteristic value of charge carrier (electron) concentration in semiconductors. This analogy holds good for holes as well. This is so because the above discussion is based on the premise of a *pure* semiconductor and whenever the concentration of electrons and holes is equal, we refer to it as an intrinsic semiconductor.

Based on the discussion we had about the carrier concentration in intrinsic semiconductors and their nature, the following conclusions can be made:

1. The number of electrons in the conduction band is equal to the number of holes in the valence band.

2. The carrier concentration, in equilibrium, is equal, i.e.,

$$n = p = n_i \tag{2-26}$$

where n_i is cailed the intrinsic carrier density.

3. The Fermi level (E_F) lies in the energy gap (E_g) between the valence and conduction band, i.e.,

$$E_F = \frac{E_g}{2} \tag{2-27}$$

4. The electron and hole can behave as a bound pair which is usually referred to as an exciton.

5. Intrinsic semiconductors are not of much practical use because their conductivity is very low, i.e., only one atom in 10^9 contributes to electrical conduction. Therefore, we look for the ways to introduce impurity energy levels[3] .

2.6 Extrinsic Semiconductors:

On finding low conductivity in intrinsic semiconductors, researchers tried to add some suitable impurity. atoms in the semiconductor to see if this process could yield appreciable conduction. It was found that the presence of impurities even to the extent of 1 in 10^9 changes significantly the conduction of Ge and Si. Thus it was accepted that adding appropriate impurities to a semiconductor leads to a change in -existing quantum states, i.e., one or more new energy levels may appear in the band structure of semiconductors. The resulting material is known as an extrinsic semiconductor. The process of adding impurity is called doping and the impurity is called dopant. The extrinsic semiconductors are also referred to as doped or impure semiconductors which sometimes contain either only electrons or holes. Almost a the semiconductor devices employ extrinsic semiconductors and these are of two types:

1. In which the impurity (dopant) contributes additional electro-ns in the conduction band.

2. In which the dopant contributes additional holes in the valence band.

To explain it further, let us assume that atoms like phosphorus or arsenic from group V of the periodic table are added to the molten silicon or germanium. Crystallization takes place when the melt is cooled into a position usually occupied by a silicon or germanium atom. It is important that the impurity occupies a substitutional position rather than an interstitial position. Essentially, this is so because after the four covalent bonds are formed (as demanded by the structure), an extra valence electron is e which may occupy one of the states in the conduction band. Escape of this electron to large distances leaves the impurity atom with a net positive charge. At finite separations, the positive charge exerts an attractive force on the electron and leads to the existence of a bound state for the electron. With such a *charged-impurity* plus *electron* system, we can estimate the strength of this binding by

adapting the standard result for the energy levels to allow for the fact that the electron is moving through a crystal rather than vacuum.

If m_e is assumed as the mass of electron and ϵ_r is the relative permittivity (dielectric constant) of the crystal, then the express-ion for energy becomes

$$E_n = -\frac{m_e e^4}{2 \, \epsilon_r^2 \, \hbar^2 n^2 (4\pi \, \epsilon_0)^2} \tag{2.28}$$

The radius of the corresponding orbits (Eq. 2.26) as given by the Bohr Theory is used for the estimation of the spatial extent of the bound state wave functions.

$$r_n = \frac{\epsilon_r \, n^2 \hbar^2}{m_e e^2} 4\pi \, \epsilon_0 \tag{2.29}$$

Using values of effective mass of Ge = 0.2 electron masses, and dielectric constant = 15.8 in Eqs. 2.25 and 2.26 we get the following values

$$E_1 = -0.01 \, eV \text{ and } r_1 \simeq 40 \text{Å} \tag{2.30}$$

Here E_1 is the ground state binding energy of an extra electron and r_1, is the radius of the corresponding orbit. A combination of small effective mass and large dielectric constant thus gives rise to the weak binding of the extra electron to the impurity, and an extended wave function for the bound state.

As the bound state wave function is extended over many atomic diameters, the approximation of using an effective mass and (macroscopic) dielectric constant should work very well If we visualize the energy level diagram for the electron (Fig. 2.12) the bound state will be referred to as a donor impurity
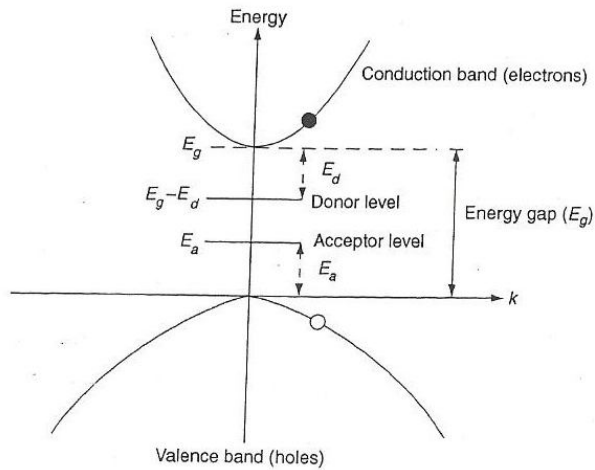
Figure 2.12 Electron energy states depicting the bound state and donor and acceptor impurities the dispersion relations for electrons near the top of the valence band and the bottom of the conduction band.
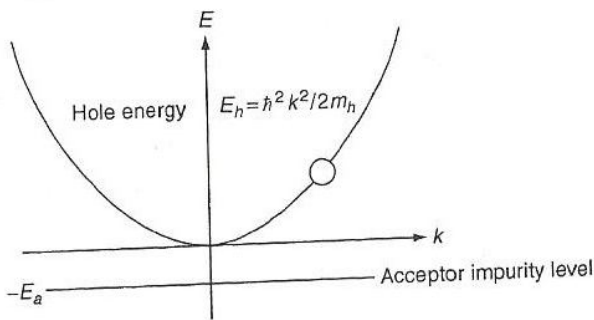
Figure 2.13 Acceptor impurity level for a hole which is (0.01 *eV*) below the bottom of the hole valence band.

level because it is capable of giving an electron to the conduction band. The donor level is represented by a dotted horizontal line in Fig. 2.12.

If we generate a similar situation (as described above for group V impurities) for group III impurities (e.g., boron or aluminum), there are fewer electrons to form the four covalent bonds as demanded by the diamond structure of silicon or germanium. Thus, the missing electron forms a hole in the valence band with a tendency to be bound to the *B* or Al ion. This results in the appearance

of an acceptor impurity *level* for a hole about 0.01 *eV* below the bottom of the hole valence band as depicted in Fig. 2.13.

Based on the above discussion, the following observations can be made

1. Adding an impurity does not change the total number of electron energy levels. Rather, levels are detached from the conduction and valence bands to form the donor and acceptor impurity levels.

2. When small amounts of tetravalent (valence four) or pentavalent (valence five) impurity is added during crystal formation of a semiconductor, the impurity atoms lock into the crystal lattice since they are not much different in size from germanium or silicon atom, and the crystal is not unduly distorted.

Depending on the nature of the impurity (dopant), the extrinsic semiconductors can be classified into two types[3] .

2.6.1 *n*- Type semiconductors:

To explain an «-type semiconductor, let us imagine that a very small amount of phosphorus is added to a pure crystal of silicon, The impurity atom (phosphorus) occupies a lattice site which is host to a silicon atom (Fig. 2.14).

In this figure, it is shown that the impurity atom phosphorus has five electrons, of which four are **i** involved in covalent bonding while the fifth one is bound to the impurity atom by weak electrostatic forces. This electron (possessing a relatively small binding energy) requires a very small amount **of** energy to get *ionized* to become a conduction electron at a moderate temperature. The impurity is called *donor* impurity as it donates electron and the crystal is called *n- type* semiconductor.

In order to understand what exactly happens to the fifth electron, let us see the figure in which the electrons are shown at their average distance from the nucleus (Fig. 2.15).
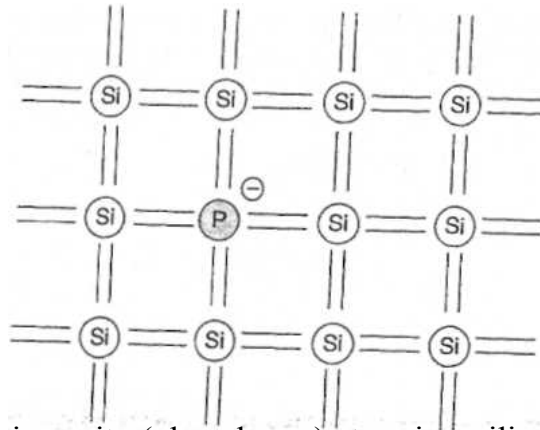
Figure 2.14A donor impurity (phosphorus) atom in a silicon crystal.
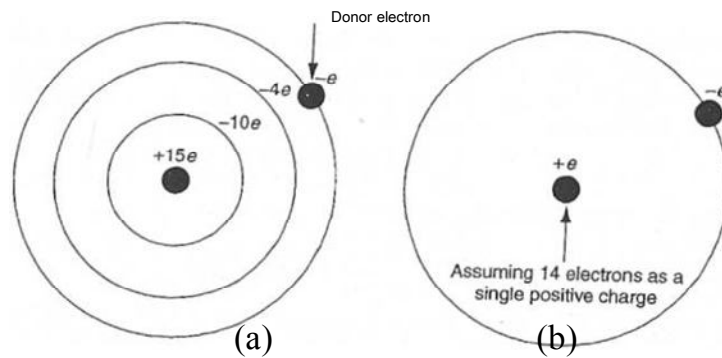
Figure 2.15(a) Electronic arrangement associated with phosphorus impurity in silicon; (b) a collection of 14 electrons as a single positive charge.

There are a total of 10 electrons in the two filled shells closest to the nucleus. Four more take part in the bonds with neighboring silicon atoms and so we place them farther from the nucleus, finally, we have the fifth valence electron, which is referred to as the donor electron. This electron is not involved in any of the bonds, so it is assumed that it is the farthest electron from the nucleus and has the smallest binding energy. Figure 2.15a holds good if we assume that the donor electron is screened from most of the nuclear charge by the presence of the other fourteen electrons. This suggests that on average the donor electron *counts the* nucleus and the collection of other 14 electrons as just a single positive charge, as shown in Fig. 2.15b. This situation resembles the system of a hydrogen atom.

In order to calculate the binding energy of the donor electron, we may use Bohr's theory for hydrogen atom. The following two modifications must be made:

1. The mass of the electron to be replaced by the effective mass, m_e^*.

2. The electron in a hydrogen atom is assumed to move in a vacuum and so we used the dielectric constant (ϵ_0) for vacuum. In this instance, the electron is in a silicon crystal and so we should use the dielectric constant for silicon, which can be written as $\epsilon\epsilon_0$, where $\epsilon = 11.7$.
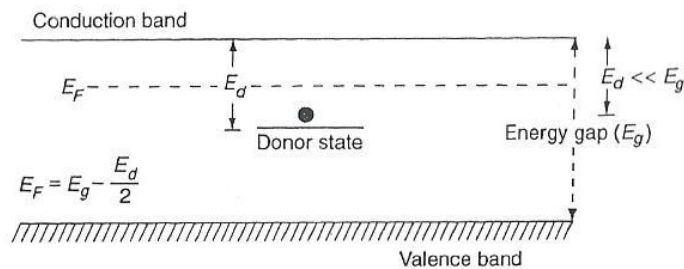
Figure 2.16A pictorial representation of the energy band implying that the donor electron is in the band gap ($E_d \ll E_g$).

Using these two modifications in the expression for binding energy for donor electron, the experimental measurements show that the binding energy of a donor electron in silicon is typically between about 40-50 meV depending on the type of donor impurity.

The next step in understanding the n-type semiconductors is to find out how the donor electron fits into the energy band picture. The electron does not take part in bonding, so there is no place for it in the valence band. It cannot belong to the conduction band either since it is weakly attached to the phosphorus atom. However, if we supply the small amount of energy to let the fifth electron liberate from the impurity atom (phosphorus), then it will be able to take part in conduction. This implies that the donor electron must occupy a state at the energy E_d below the conduction band edge, as shown in Fig. 2.16.

This representation of the energy band implies that the donor electron is in the band gap where there are no allowed states. This statement is contradictory in itself. Now, we know that there are no allowed states in the band gap of a perfect crystal. But if an impurity is present then the crystal is no longer perfect and hence it is quite reasonable for a state associated with the impurity to be located in the band gap.

While discussing the location of donor electron in the band structure, we must also try to find out as to where the Fermi energy is in this case. In n-type semiconductor, the Fermi level goes down in energy as the temperature is increased. The Fermi energy also depends on the concentration of donor impurities, i.e., it gives rise to two situations:

1. When the donor concentration is very *low,* then the Fermi energy is near the center of the band gap at moderate temperatures because the number of intrinsic carriers is comparable with the number of donor electrons.

2. When the donor concentration is quite *high,* then the intrinsic carrier concentration is negligible even at temperatures close to the melting point, and so the Fermi energy never moves far below the conduction band edge.

The variation of Fermi energy with temperature and doping concentration is shown in Fig. 2.17.

Now that we know about the Fermi energy in this case, let us find out how the presence of donor impurity affects the conductivity of a semiconductor. We also know that the number of intrinsic carrier concentration is given by Eq. 2.9 where the energy term is $-E_g/2k_BT$. Under the new circumstances, this term in the exponent is replaced by

$$n_i = C \exp - \frac{(E_g - E_F)}{k_BT} \qquad (2.31)$$
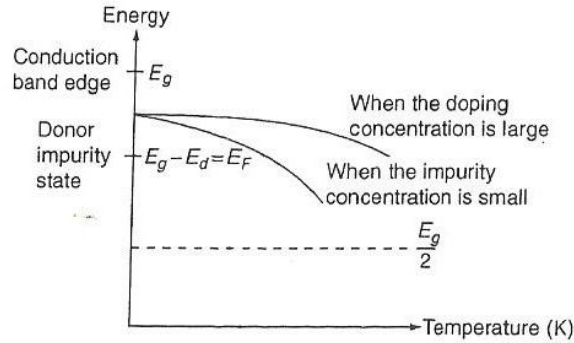
Figure 2.17 Variation of Fermi energy with temperature.

Here C is a constant. In Fig. 2.17, we can see that for an n-type semiconductor the Fermi energy is generally much closer to the conduction band edge than it is to the valence band edge, i.e.,

$$\left(E_g - E_F\right) \ll \frac{E_g}{2} \tag{2.32}$$

Hence, this results in an exponential increase in the number of carriers in the doped case[3] .

2.6.2 p-Type semiconductors:

p-type semiconductors can be described in a manner similar to the n-type semiconductors. The fundamental difference is that in p-type semiconductors, a trivalent impurity (having three electrons in the outermost orbit), such as iridium, aluminum, or boron, is added to a germanium or silicon (intrinsic) semiconductor. When the impurity atoms are injected into the material, the germanium atoms will be displaced in the crystal during its formation. This phenomenon is depicted in Fig. 2.18. In this case only three out of the four possible covalent bonds are filled while the fourth bond is vacant *(hole)*.

The presence of an incomplete bond means that we have a hole in the valence band. This, however, is not true because the hole is bound to the trivalent acceptor impurity, just like the extra electron is bound to the donor impurity. In order to create a hole which can move through the valence band, we need

to excite a valence electron into this incomplete bond and so ionize the acceptor impurity. This makes the acceptor state go above the valence band Thus, the trivalent edge. It is shown in the energy band diagram (Fig. 2.19).

impurity (also known as *acceptor* or *p*-type impurity) injects billions of holes into the crystal and the majority carriers become the holes which eventually become responsible for the conductivity of the crystal. For this reason such crystals are called *p*-type semiconductors or simply *p*-type crystals.

The position of Fermi energy can also be obtained using a similar argument as *n*-type semiconductors. At absolute zero the highest energy occupied state is at the top of the valence band and the lowest vacant state is the acceptor level, so the Fermi energy can be assumed to be at an energy level of $E_a/2$ above the valence band edge. At higher temperatures, the effect of the intrinsic carriers is to push the Fermi energy upwards towards the middle of the band gap, but at room temperature we can assume that the Fermi energy is much closer to the valence band than to the conduction band.
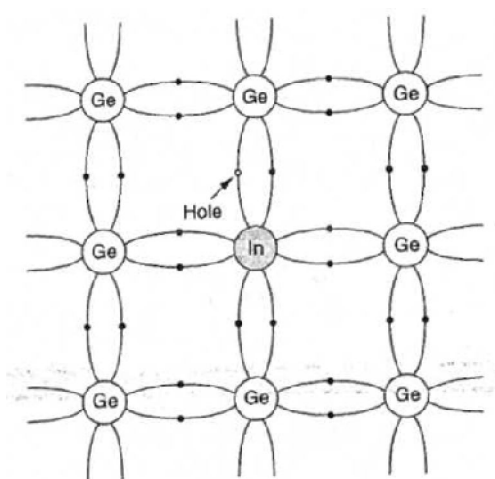
Figure 2.18 Germanium atom getting displaced due to the insertion of impurity (indium) in a *p*-type semiconductor
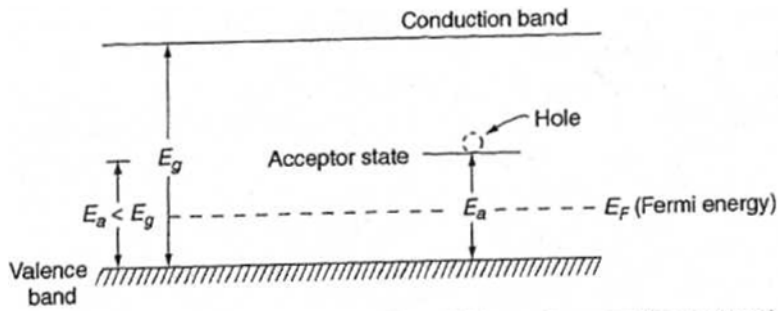
Figure 2.19 The acceptor state at energy $E_a \ll E_g$ for a p-type semiconductorat $T = 0\ K$.

The concentration of holes in a doped semiconductor (p-type) can be determined account the probability that a state with energy E is occupied at temperature T.The probability is represented by the Fermi-Dirac distribution. [

$$F(E) = \left[\left\{\exp\frac{(E - E_F)}{k_B T}\right\} + 1\right]^{-1} \tag{2.33}$$

Since we have defined the zero energy to coincide with the top of the valence band the number of electrons at the valence band edge is proportional to the Fermi-Dirac distribution (Eq. 2.30) with $E = 0$

$$F(0) = \left[\left\{\exp-\frac{E_F}{k_B T}\right\} + 1\right]^{-1} \tag{2.34}$$

Since a hole is a state which is not occupied by an election, the probability of finding a hole at the valence band edge is

$$1 - F(0) = 1 - \left[\left\{\exp-\frac{E_F}{k_B T}\right\} + 1\right]^{-1}$$

or

$$1 - F(0) = \frac{\exp - \frac{E_F}{k_B T}}{\left(\exp - \frac{E_F}{k_B T}\right) + 1} \tag{2.35}$$

Since the Fermi energy is typically much larger than the thermal energy $k_B T$ (except at very high level of p-type doping), the exponent is large and negative .

$$\exp - \frac{E_F}{k_B T} \ll 1 \tag{2.36}$$

Therefore,

or

$$F(0) = \left\{ \exp - \frac{E_F}{k_B T} \right\} + 1 \tag{2-37}$$

Hence, the concentration of holes is given by the expression

$$p = C \ \exp - \frac{E_F}{k_B T} \tag{2.38}$$

where C is a constant.

2-7 Charge carrier density in extrinsic semiconductors:

So far we have demonstrated the nature and role of charge carriers (electrons and holes) in both n- and p-type of semiconductors. We also know that the introduction of impurities in pure semiconductors increases the density of one type or another type of charge carriers. The product of holes and electrons in a semiconductor is constant depending on the width of energy gap and temperature and hence the introduction of the impurities results in an increase in the density of one type of carriers and reduction in the density of other type of carriers.

In an extrinsic semiconductor, the carriers introduced by the impurities are called *majority* carriers and *minority* carriers. Note that the low value for

minority carrier density is due to added recombination. Let n_d be the donor impurity density, n_a the acceptor impurity density, p the density of holes and n the density of electrons in an extrinsic semiconductors.

From the condition of charge neutrality, we have

$$n_d + p = n_a + n \tag{2-39}$$

or $n = (n_d - n_a) + p \tag{2.40}$

Since from Eq. 2.3 $np = n_i^2$, Eq. 2.35 can be rewritten as

$$n = (n_d - n_a) + \frac{n_i^2}{n} \tag{2-41}$$

or $n^2 - (n_d - n_a)n - n_i^2 = 0 \tag{2.42}$

Solving this quadratic in n, we get

$$n = \frac{(n_d - n_a) \pm \sqrt{(n_d - n_a)^2 + 4n_i^2}}{2} \tag{2-43}$$

or $n = (n_d - n_a)$ when $(n_d - n_a) \gg n_i$ (2.44)

Equation 2.37 implies that the electron density in the n-type semiconductor equals the difference in the donor and acceptor impurity densities when they are large compared to the intrinsic density. A similar equation

$$p = n = (n_a - n_d) \text{when} (n_a - n_d) \gg n_i \tag{2.45}$$

can be deduced for determining the density of holes in a semiconducting material[2] .

2.8 Motion of Carriers in Electric and Magnetic Fields:

The transport properties exhibited by the charge carriers can be explained if we take into account the following two aspects related to their mobilities due to electric and magnetic fields.

❖ Electrical conductivity

The Newton's law for particles of mass m_n (the subscript n represents an electron) and charge $-e$ is expressed as

$$m_n \frac{dv}{dt} = -eE - eV \times B \tag{2.46}$$

In the absence of an applied magnetic field, Eq. 2.39 predicts that a DC electric field will cause a constant acceleration of the electrons, giving a steadily increasing electrical current. This does not happen in practice because the electrons suffer collisions with thermal vibrations of the ion cores and with imperfections in the crystal such as impurity atoms. We allow for collisions by modifying Eq. 2.39 as

$$m_n \frac{dv_n}{dt} + \frac{v_n}{\tau_n} = -eE - eV_n \times B \tag{2.47}$$

The effect of the additional term (v_n/τ_n) is to cause v_n to decay exponentially to zero with a time constant τ_n on removal of the applied field; v_n is therefore interpreted as the *drift velocity* of the electrons. The drift velocity is the additional velocity associated with the departure from the thermal equilibrium state given by the Fermi-distribution function.

The corresponding equation of motion for a hole is written as

$$m_p \left(\frac{dv_p}{dt} + \frac{v_p}{\tau_b} \right) = +eE + eV_p \times B \tag{2.48}$$

When (only) a dc electric field is present, the solution for Eq , 2.40 and 2.41 becomes

$$v_n = -\frac{e\tau_n}{m_n}E = -\mu_n E \qquad (2.49)$$

$$v_p = -\frac{e\tau_p}{m_p}E = \mu_p E \qquad (2.50)$$

Here μ_n and μ_p are the electron and hole mobilities in the steady-state. The resulting current density can be obtained by summing up the electron and hole contributions .

$$J = -nev_n + pev_p = \left(\frac{ne^2\tau_n}{m_n} + \frac{pe^2\tau_p}{m_p}\right)E$$

$$= (ne\mu_n$$

$$+ pe\mu_p)E \qquad (2.51)$$

or $\quad J = \sigma E \qquad (2.52)$

This is an expression for Ohm's law with an electrical conductivity σ given by Eq. 2.5, i.e.,

$$\sigma = ne\mu_n + pe\mu_p \qquad (2\text{-}53)$$

Since the electron and hole mobilities are usually comparable, the relative carrier densities determine the relative contribution of the electrons and holes to the conductivity. Table 2.1 lists mobility for various semiconductors.[5]

Table 2.1 Mobilities for various semiconductors at room temperatures

| Crystal | $\mu\ cm^2(Vs)^{-1}$ | |
	Electron	Hole
C	1800	1600
Si	1350	475
Ge	3900	1900
GaAs	5800	400
Ga P	110	75
GaSb	4000	1400
In A_s	33000	460
In P	4600	150
In Sb	80000	750
Cds	340	18
Cd Se	600	-
Cd Te	300	65
ZnS	120	5
ZnSe	530	16
Zn Te	530	900
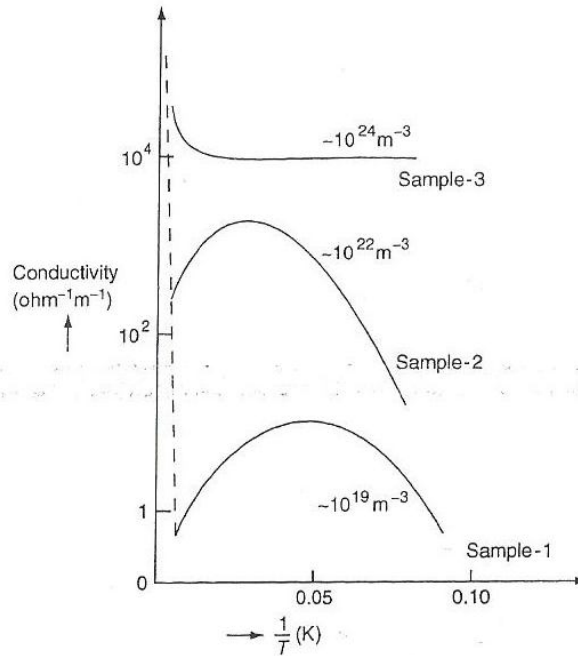
Figure 2.20 Temperature dependence of conductivity of three samples of germanium containing arsenic donor impurity.

In the intrinsic region the two contributions are usually similar but in the extrinsic region the conductivity is normally dominated by the majority carrier.

To explain it further, Fig. 2.20, which is based on the research carried out by Debye and Conwell (1954), presents a graph plotted between temperature and conductivity for three samples of germanium containing arsenic donor impurities with the approximate concentrations indicated.

The temperature dependence of the conductivity for arsenic-doped n-type germanium can be explained as follows:

1. The steep increase in σ(conductivity) at high temperatures, given by the broken line on the left, which has been observed in the purest specimen only, represents the increase in electrons and holes associated with the transition to intrinsic behavior.

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2. The fall in conductivity at low temperatures on the right of the figure for the two purest specimens is associated with the *freezing* out of electrons on the donor levels; since the slopes of these two curves differ approximately by a factor of 2, it is interesting to associate the upper curve with Eq. 2.46

$$n = \sqrt{n_c n_d} \, \exp -\frac{E_F}{2k_B T} \tag{2.54}$$

where n_c is the number of electrons in the conduction band, and n_d is the number of donor e and the lower curve with Eq. 2.47

$$n \approx n_c \exp -\frac{E_F}{k_B T} \tag{2.55}$$

3. At intermediate temperature the donors are fully ionized. The observed decrease in conductivity with rising temperature results from the decrease in electron mobility caused by increased scattering from thermally excited lattice vibrations[3] .

❖ **The Hall effect:**

We have discussed so far the motion of charge carriers in an electric field. Let us imagine a situation in which a magnetic field is applied perpendicular to the electric field. This scenario was used in an experiment by Edwin Hall in 1879. He stated that the carrier concentration in a semiconductor may be different from the impurity concentration, because the ionized impurity density depends on the temperature and the impurity energy level.

The Hall method is one of the most convincing and acceptable techniques to demonstrate the existence of holes as charge carriers. To explain this technique, let us consider a situation (as shown in Fig. 2.21) in which a p-type semiconductor having thickness t is subjected to an electric field E_x along the x-axis and a magnetic field B_z along the z-axis.

From electromagnetic theory we know that the electrons are deflected in the direction which is perpendicular to both the applied electric and magnetic fields. This leads to an accumulation of negative charge on one side of the sample, and hence produces an electric field (E_H) in the y-direction. Since there is net current flow along the y-direction in the steady state, the electric field along the y-axis exactly balances the Lorentz force (F),

$$F = e(v \times B) = ev_x B_z \qquad \text{(2-56)}$$

$$eE_H = ev_x B_z \qquad \text{(2-57)}$$

$$E_H = v_x B_z \qquad \text{(2.58)}$$

This force which is due to the magnetic field will exert an average upward force on the holes flowing the x-direction. Once the electric field (E_H) becomes equal to $v_x B_z$ no net force along the y- direction
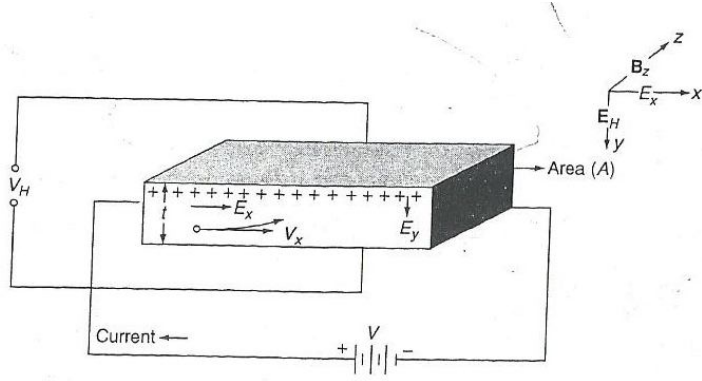
Figure 2.21an experimental setup for the Hall effect. The electric field (E_r) is applied along x-axis and magnetic field (B_z) along the z-axis of a semiconductor specimen having thickness t.

Is experienced by the holes as they drift along the x-direction, the establishment of the electric field is known as the Hall Effect.

The Hall field (E_H) is found to be proportional to the strength of the magnetic field, B_z, and the current density flowing in the x-dircction along the sample, J_p so we can write

$$E_H - R_H J_p B_z \tag{2.59}$$

Where R_H is known as the Hall coefficient and J_p is the hole current density. The Hall coefficient can also be represented as

$$R_H = \frac{1}{ep} \tag{2.60}$$

A similar result can be obtained for n-type semiconductor, except that the Hall coefficient is negative

$$R_H = -\frac{1}{en} \tag{2.61}$$

Equation 2.51 is quite useful in practice. Since R_H is inversely proportional to the electron concentration (n), we can determine n by measuring the Hall field. This makes the Hall effect the standard technique for determining electron concentration. The technique is particularly valuable because, apart from n, the only other quantity on which R_H depends is the charge on the electron, which is a fundamental physical constant whose precise value is known.

The terminal voltage associated with the Hall experiment can be computed as

$$V_H = E_H t \tag{2.62}$$

Here t is the thickness of the sample. A measurement of the Hall voltage (V_H) for a known current and magnetic field yields

$$p = \frac{1}{eR_H} = \frac{J_p B_z}{eE_H} \tag{2.63}$$

Replacing J_p by (I/A) (A is the area, I is the current) and E_H by $(V_H l_t)$, Eq. 2.53 can be rewritten as

$$p = \frac{I_t B_z}{e \, A V_H} \qquad (2.64)$$

All quantities on the right side of this equation can be measured. Hence, the carrier concentration and carrier type can be obtained directly from the Hall measurement. The above analysis shows that the Hall effect is a very interesting aspect of the transport process in the presence of a magnetic field[3].

2.9 Carrier Diffusion: Einstein Relation:

We know that when an electric field is applied, the transport of carriers takes place and it gives drift current .Let us assume a situation where spatial variation of carrier concentration in the semiconductor takes place. In that case the carriers will move from a region of high concentration to a region of low concentration. This movement or transport of the carrier will give rise to charge diffusion or diffusion current.
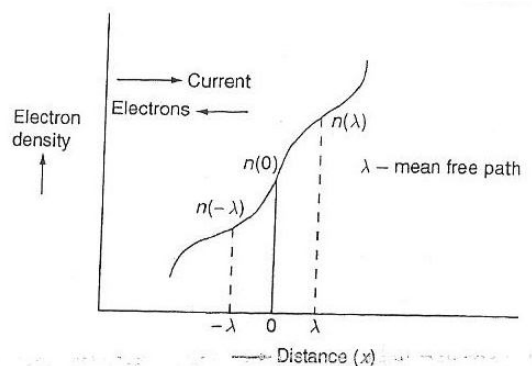
Figure 2.22 Electron concentrations versus distance.

To understand the process of diffusion current, let us assume an electron density that varies with distance (a:) (Fig. 2.22)

Since the semiconductor is held at a uniform temperature, the average thermal energy of electrons does not vary with x. It is only the density $n(x)$ which

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varies. Let us now assume the number of electrons crossing the plane at $x = 0$ per unit time per unit area. Since the temperature is taken as finite, the electrons will have random thermal motion with a thermal velocity (v_{th}) and mean free path (λ) which is expressed as

$$\lambda = \tau_e v_{th} \tag{2.65}$$

Here τ_e, is the mean free time of the electrons.

The electrons at $x = -\lambda$ (one mean free path away on the left side) will have equal chances of moving left or right; and in a mean free time τ_e, one half of them will move across the plane $x = 0$. The average rate of electron flow per unit area of electrons crossing the plane $x = 0$ from the left is given by an equation

$$f_1 = \frac{1}{2} n(-\lambda) \frac{\lambda}{\tau_e} \tag{2-66}$$

$$f_1 = \frac{1}{2} n(-\lambda) v_{th} \tag{2.67}$$

On the basis of a similar analogy, the average rate of electron flow per unit area of electrons at $x = \lambda$ crossing the plane $x = 0$ from the right can be expressed as

$$f_2 = \frac{1}{2} n(\lambda) v_{th} \tag{2.68}$$

The net rate of carrier flow from left to right is

$$f = f_1 - f_2 = \frac{1}{2} v_{th} [n(-\lambda) - n(\lambda)] \tag{2.69}$$

Approximating the densities at $x = \pm\lambda$ by the first two terms of a Taylor series expansion, we get an expression

$$f = -D_n \frac{dn}{dx} \tag{2.70}$$

Where

$$D_n = \lambda v_{th} \tag{2.71}$$

is known as the diffusion coefficient or diffusivity.

Since each electron carries a charge$-e,$ the carrier flow gives rise to a current

$$J_n = -ef = eD_n \frac{dn}{dx} \tag{2.72}$$

Equation 2.61 suggests that the diffusion current is proportional to the spatial derivative of the electron density.

If we use the theorem for equipartition of energy, Eq. 2.61 for a one-dimensional case can be written as

$$\frac{1}{2}m_n(v_{th})^2 = \frac{1}{2}kT \tag{2.73}$$

Making use of the equation for mobility(μ_n), Eqs, 2.59 and 2.62, and the relation$\lambda = v_{th}\tau_e,$ we get an expression for the diffusion coefficient

$$D_n = \left(\frac{kT}{e}\right)\mu_n \tag{2.74}$$

Equation 2.63 is known as the *Einstein relation*, which relates diffusivity and mobility. This is how the carrier transport by diffusion and drift is characterized in a semiconductor. The Einstein relation is true only for non-degenerate semiconductors and is found to be extremely useful in current flow problems in a number of semiconductor devices[3] .

2.10 Semiconductor Devices:

A semiconductor device is a unit which consists, partially or wholly, of semiconducting materials and which can perform useful functions in electronics and solid state research. A complete understanding of this topic can be made on the basis of an illustration as presented in Fig. 2.23.

Let us assume that two dissimilar metals X and Y have work functions ϕ_x and ϕ_y respectively, and that

$$\phi_x < \phi_y \qquad\qquad (2.75)$$
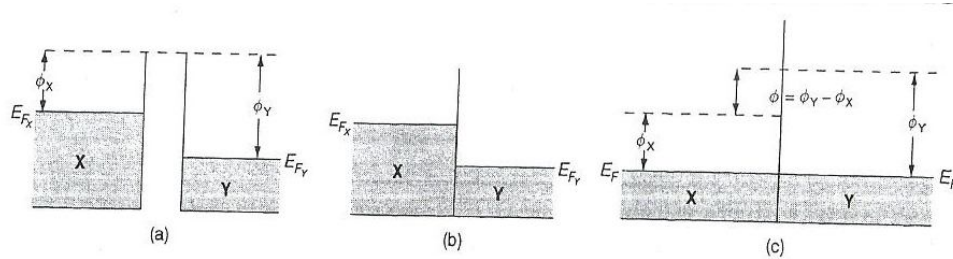
Figure 2.23 (a) Two isolated metals, X and Y, with work functions ϕ_x and ϕ_y; (b) electrons flow from X to Y when both metals are in contact; and (c) for the lower energy states in metal Y, the electron flow continues till the Fermi energies attain a state of equilibrium on both sides of the metallic junction.

The electrons in metal X have higher energy states as compared to that in metal Y. When we bring these two metals in contact with each other, the movement of electrons from higher energy states to lower energy states takes place till a state of (near) equilibrium is achieved, i.e., the Fermi energy levels become the same. This gives rise to a contact between two metals whose contact potential depends upon the difference between their work functions.

$$\phi = \phi_y - \phi_x \qquad\qquad (2.76)$$

The idea of placing two metals in contact is useful because it enables us to see how the equilibrium stage is achieved. This can be explained better by way of making a junction between two types of extrinsic semiconductors[2] .

2-11 The _p-n_ junction:

The above illustration can be extended to the _p-_ and _n_-type of semiconductors. If these two types of semiconductors are brought in contact with each other, then, initially it is presumed that electrons and holes will stay in their respective compartments. This situation is unlikely to last for long

because the conduction electrons move about at random, and some of them find their way into the *p*-type material. This happens due to the process of diffusion as already discussed in Section 2.7. Similarly, some of the holes diffuse into the *n*-type region. However, this process is complicated by the fact that the electrons and holes can recombine with one another (Fig. 2.24).

Let us imagine a situation where a single conduction electron diffuses across the junction from the *n*-type layer to the *p*-type region. As it crosses the junction the electron sees a large concentration of holes. This gives quite high probability of electron recombining with a hole before it travels deep in the *p*-region. Now when the number of electrons crossing the junction increases, its recombination with holes also increases. Hence, the number of carriers in the junction region is reduced. This gives rise to a layer on either side of the junction which has a relatively lower carrier concentration as compared to the rest of the crystal. This is known as the *depletion layer*(Fig. 2.25).
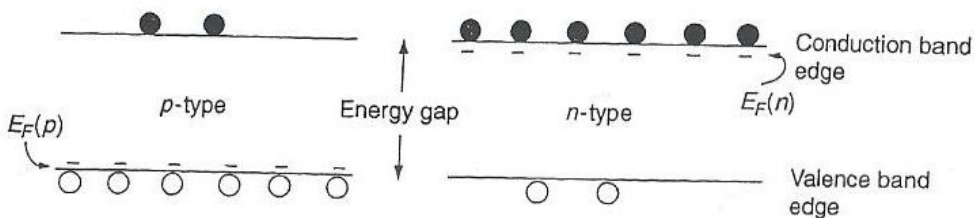
Figure 2.24A *p*- and n-type semiconductors exhibiting Fermi energy near valence band and conduction band edges, respectively
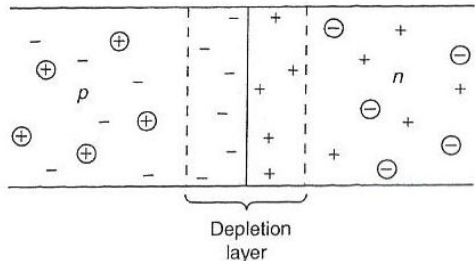
Figure **2.25** Depletion layer caused by the diffusion of the carries when the p- and n-type regions are brought in contact.
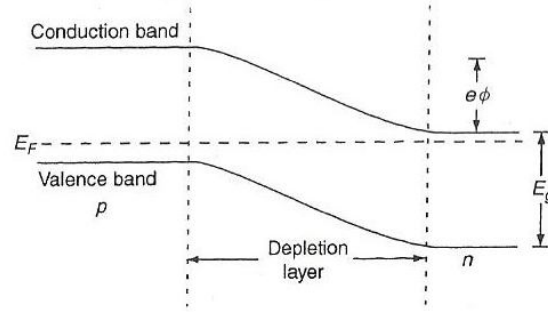
Figure 2.26 the distribution of charge at p-$n$junction produces a contact potential ϕacross the junction. The conduction band edge on the p-side of the junction is at an energy $e\phi$ greater than that on the n-side.

In this figure the negative charge is shown to have accumulated on the n-type side and positive charge on the p-type side. The build-up of this charge on an energy band diagram is shown in Fig. 2.26. This figure indicates that the energy of the conduction band edge is more on the p-type side than on the n-type side. The energy required to excite an electron across the contact potential $\phi$is written as

$$E_{cp} = e\phi \tag{2.77}$$

The contact potential energy $(E_{cp})$is equal to the difference between the Fermi energies in two materials (n- and p-type), i.e.,

$$E_{cp} = E_{Fn} - E_{Fp} \tag{2.78}$$

It is at this energy (or equilibrium state) that the Fermi energy alignment is achieved which acts as a key to the formation of a p-$n$junction.

The answer to these questions is not easy as it involves the Poisson's equation. Therefore, the following direct expressions are given for determining various parameters:

The magnitude of contact potential $\phi$is given by the expression

$$\phi = \frac{e}{e \, \epsilon\epsilon_0} \left(d_n L_n^2 + a_n L_p^2 \right) \tag{2.79}$$

44

Here $\in$ is the dielectric constant of the material, d_n is the number of donors, a_n is the number of acceptors, and L_n and L_p represent the depletion layer whose extent lies between

$$x = -L_p \text{ to } + L_n \tag{2.80}$$

The expression for depletion layer width on the p-side is given as

$$L_p = \left[\frac{2\phi d_n \in \in_0}{e a_n (a_n + d_n)} \right] \tag{2.81}$$

If we replace d_n by a_n in Eq. 1.70, we get a similar expression for depletion layer width on the n-side.

The expression for the determination of contact potential is written as

$$\phi = \frac{k_B T}{e} \ln \left[\frac{a_n d_n}{n_i} \right] \tag{2.82}$$

This expression relates the contact potential to the concentration of acceptors (a_n), donors (d_n), and intrinsic carriers (n_i). It is also independent of the width of the depletion layer.

By making use of typical values of the parameters in microelectronic devices, it has been reported that for a silicon p-n junction the contact potential[3] .

$$\phi \sim 0.7 \ eV$$

And the depletion layer widths are

$$L_p, L_n \sim 0.1 - 1.0 \ \mu m$$

2-12 Current-voltage characteristics of p-n junction:

A symbolic representation of the p-n junction in the form of an arrow is shown in Fig. 2.27. The arrowhead defines the p-region of the material. It also shows the direction of flow of holes (or conventional current). If we apply some potential to the junction, its plotted projection (V versus I) will give rise

to a situation in which the current increases *linearly* as the *bias* voltage is increased (Fig. 2.28).
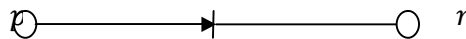
Figure 2.27 Representation of *p-n* junction.
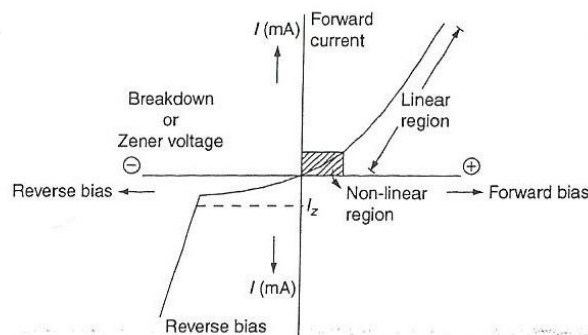
Figure 2.28Current-voltage characteristics of a *p-n*junction diode.

This makes the junction a linear device over a large portion of its operating voltage. The shaded area near the origin of the graph shows a non-linear behavior because the overall current comprises of majority and minority carrier. Since the majority carriers are low energy carriers, majority current starts first, and then as the voltage is raised, minority current adds in giving rise to non-linear rise in current. Further increase in voltage gives rise to a linear curve as the minority carriers whose number is small get saturated.

When reverse bias is applied, a slight reverse current flows. As the bias voltage increases, the increase in reverse current is quite negligible. But a sudden rise in current is observed which takes place due to the covalent bonds of the material breaking down in substantial numbers. This breakdown potential is termed *Zener voltage* which is very useful in some special voltage-regulating circuits.

On the basis of the observations from the forward and reverse bias, we can see that the characteristics of the junction vary enormously, depending upon the polarity of the applied voltage. In the former case - also known as forward

bias - the current increases exponentially with the voltage, whereas in the latter case-known as reverse bias, the current remains very small regardless of the magnitude of the voltage. We can safely assume that a *p-n*junction only allows current to flow one way, and so one use of a *p-n*junction is as a rectifier to change alternating current into direct current. However, the properties *of p-n* junctions are exploited in a wide range of other electronic devices[3] .

2.13 The Transistor:

A transistor is a solid state device which is capable of performing the following primary functions:

1. It can amplify an electrical signal (i.e., as an amplifier).

2. It serves as a switching device ('ON' or 'OFF') which allows computers to process and store the information.

Both types of transistors can be used in amplifying and switching modes .We shall concentrate on the bimodal(bipolar) and field effect transistors (FETs)[3] .

2-14Bimodal (bipolar) junction transistor (BJT):

A bimodal transistor consists of two *p-n*junctions configured back to back in either *n-p-n*or*p-n-p*mode. The charge carrier in it has negative as well as positive polarity and so the nomenclature bimodal (or bipolar) junction transistor (BJT) is used.
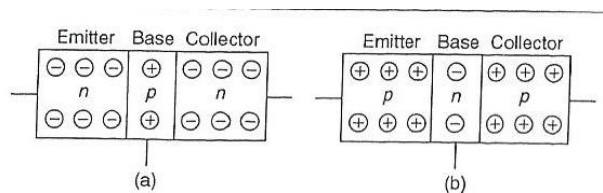
Figure 2.29 A bimodal (bipolar) junction transistor: (a) *n-p-n*and (b) *p-n-p*transistor.
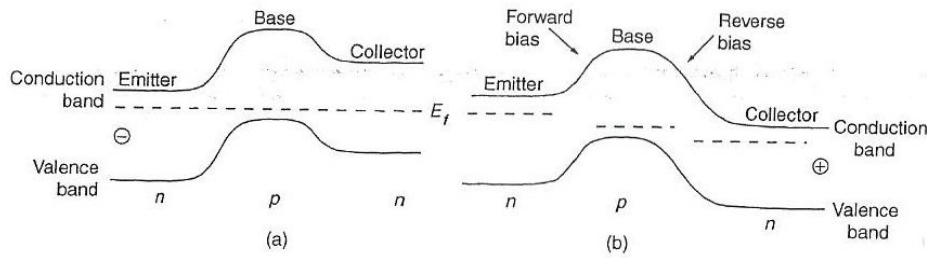
Figure 2.30 (a) Energy band structure of an *n-p-n*bipolar transistor with no applied bias and (b) when the voltage is applied the emitter is made negative with respect to the collector.

Alternatively, it is defined as a sandwich of three alternately doped layers of semiconductor. The middle layer is referred to as the *base (B)*and the other two layers as the emitter *(E)*and the collector *(C)*. A picture of a bimodal transistor is shown in Fig. 2.29.

Let us try to understand the working of a *p-n-p*and *n-p-n*bipolar transistor, on the basis of a energy band diagram shown in Fig. 2.30.

Since the emitter is more heavily doped than the base and collector, we note that the contact potential between the emitter and base is greater than that between the base and collector. From Fig. 2.30b it may be seen that the emitter-base junction is forward-biased and the collector-base junction is reverse-biased. This means that a sizable number of the conduction electrons in the emitter can flow into the base region.

Since the base region is quite small (narrow) and the doping concentration is much lower than that of the emitter, only a small proportion of these electrons recombine with the holes in the base. The remaining electrons are swept down into the lower energy states in the collector. Hence, in this process a substantial amount of electronic current flows from the emitter to the base.

When the emitter-base junction is forward-biased, the current enters the transistor through the emitter terminal for a *p-n-p*transistor and leaves the transistor through the emitter terminal for an *n-p-n*transistor. In both the

cases, the emitter current (I_e), base current (I_b)and collector currents (I_c)are assumed positive when the currents go into the transistor. This is shown in Fig 1.31. The symbols V_{eb}, V_{cb} and V_{ce} Present respectively the emitter-base, collector-base and collector-emitter voltages. These are assumed positive when the terminal marked by the first subscript is positive with respect to the terminal marked by the second subscript. Transistors are generally fabricated with the following techniques:

1. Growth

2. Diffusion

3. Epitaxial

4. Fused technique
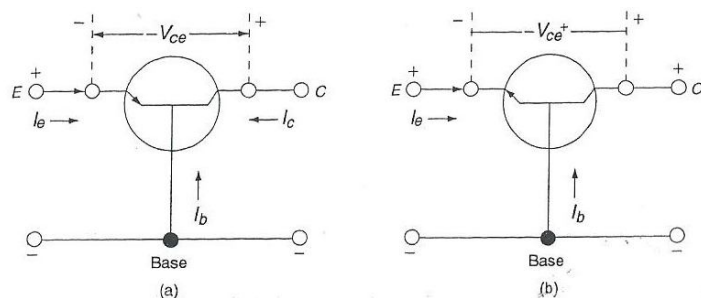
Figure 2.31 Schematic presentation of current symbols with reference to the current direction and voltage polarities for: (a) *p-n-p*and (b) *n-p-n* transistor [3] .

2-15Field effect transistor (FET):

FET is quite similar to the BJT in that it consists of three distinct regions with alternate doping. The current in an FET is carried predominantly by one type of carrier while in BJT, there are two types of carriers, i.e., electrons and holes. Therefore, an FET is also known as unipolar (or un junction) transistor (UJT). These are of many types but by far the most common are junction field

effect transistor (JFET) and Metal Oxide Semiconductor Field Transistor (MOSFET).

The principle of operation in both these types is through three regions which are known as the *source, drain* and *gate.* Figure **2**.32 presents a schematic picture of an n-channel JFET.

In this type of transistor the semiconductor bar is n-type. Therefore, depending upon the type of bar ($p$or n)it is known as either $p$or n-channel JFET. Two sides of the semiconductor bar are doped with impurities which are opposite to that of the bar. In an n-channel JFET, we term all the three regions, i.e., source, drain and gate as p^+, n andp^+(+ represents the impurity current loaded heavily). If we apply a potential V_{dd}between the ends of the semiconductor bar, the current starts flowing along the length of the bar. The central n-region, through which the electrons flow from the source to the collector or drain, $(d)$is known as the channel. The p^+regions form the gate. At each of the pn-junctions there is a depletion layer extending into the n-region. These layers penetrate to a large extent as the reverse bias $(V_{gg})$is increased. This allows the control of flow of electrons in the channel, i.e., the drain current (I_d) ischecked. Figure 2.33 presents the current-voltage characteristics of an n-channel JFET.

When the drain current (I_d) increases from zero (at constant gate-source potential, V_{gs})**,** the increase initially remains linear, conforming to Ohm's law. Further increase in drain-source voltage (V_{ds})results in the current attaining a saturation level. This level is known as *pinch*-off region.

The name field effect is used for the device because the transverse field produced by the gate gives the effect of controlling the drain current. The most popular mode of operation of a device of this kind is a switch. Since the input
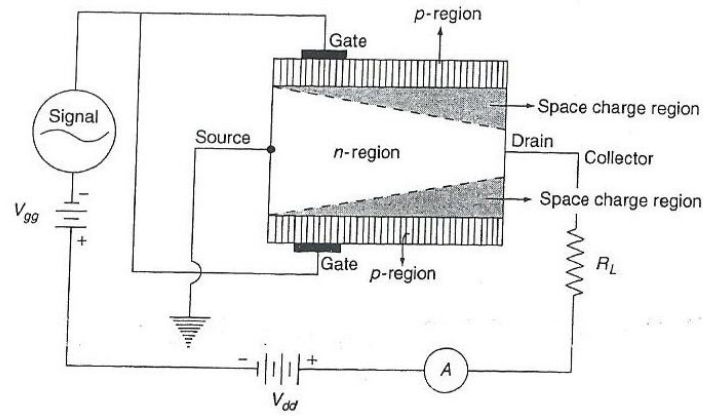
Figure 2.32the basic structure of an n-channel JFET
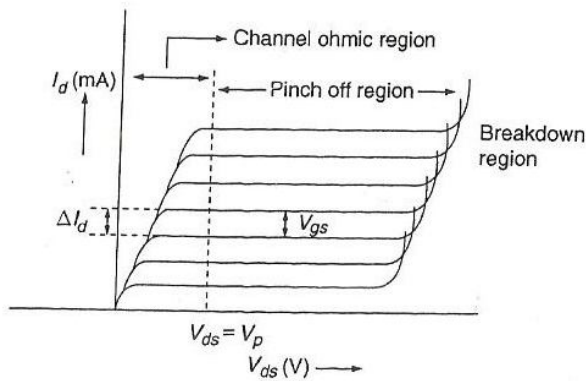
Figure 2.33Current-voltage $(I_d - V_{ds})$characteristics of an n-channel JFET.

Resistance of JFET is quite high; a lower switching time in switching devices can be achieved.

Another type of a field effect transistor is MOSFET, in which the metal contact above the gate region is separated from the semiconductor substrate by a thin oxide layer (usually silicon dioxide) which acts as an electrical insulator. A line-diagram depicting the structure of an n-channel MOSFET is shown in Fig. 2.34a.

Let us visualize what happens when a voltage is applied to the metal contact above the gate. Following are the possibilities:

1. When the gate voltage is positive then the holes in the p-type semiconductor directly below the gate are repelled from the surface, and at

the same time the minority carrier (conduction electrons) in the p-type material are attracted to the surface. It is depicted in Fig. 2.34b.

(a)
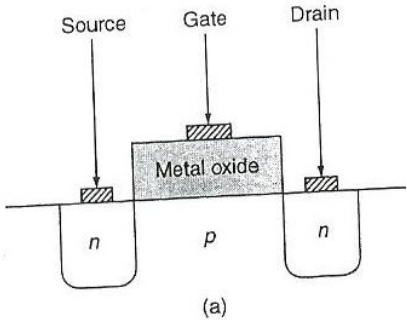
Figure 2.34 (a) The structure of an n-channel MOSFET.

(b)
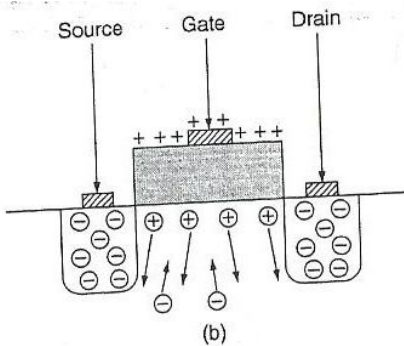
Figure 2.34 (b) When a positive voltage is applied to the gate, the holes in the p-type semiconductor are repelled from the surface and the minority carrier conduction electrons are attracted to the surface.

(c)
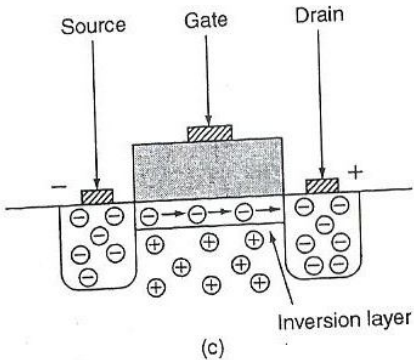
Figure 2.34 (c) When the gate voltage exceeds the threshold value then an inversion layer is created near the surface.

2. When the gate voltage crosses the threshold then in a region close to the surface, the concentration of conduction electrons exceeds the concentration of holes. It is shown in Fig. 2.34c.

Although the material is doped with acceptor, it behaves as if it is an n-type semiconductor. This region is known as an inversion layer which can be explained better on the basis of the energy band structure at the metal-oxide-semiconductor (M-O-S) interface in a MOSFET (Fig. 2.35).
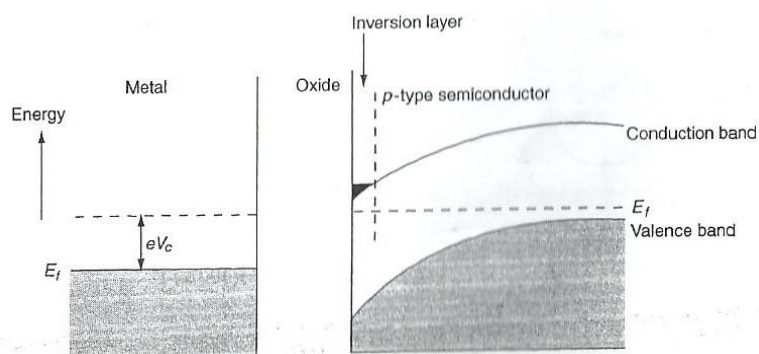
Figure 2.35 the energy band structure at the M-O-S interface in a MOSFET.

In this figure, for a p-type semiconductor at a distance well below the interface with the oxide layer, the Fermi energy is expectedly close to the valence band edge. However, the electron energies, closer to the surface of the semiconductor, are lowered by the presence of the positive charge on the other side of the oxide layer. This is termed as band bending .In this region the semiconductor exhibits n-type behaviour if the Fermi energy is closer to the conduction band than to the valence band, and hence, the degree of band bending determines whether or not inversion takes place.

Based on the same principle we can make a p-type MOSFET in which the current is carried by the holes if we make the gate w-type and source and drain p-type. Generally, n-type MOSFETs are preferred because of the fact that the mobility due to electrons in a semiconductor is much higher than that of the holes.[3] .

Chapter Three

Charge Carriers in Semiconductors

3-1 Introduction:

Current is the rate at which charge flows.

In a semiconductor, two types of charge carrier, the electron and the hole, can contribute to a current.

Since the current in a semiconductor is determined largely by the number of electrons in the conduction band and the number of holes in the valence band, an important characteristic of the semiconductor is the density of these charge carriers[1]

3.1-1 Equilibrium Distribution of Electrons and Holes:

The distribution (with respect to energy) of electrons in the conduction band is given by the density of allowed quantum states times the probability that a state is occupied by an electron.

This statement is written in equation form as

$$n(E) = g_c(E)f_F(E) \tag{3.1}$$

Where $g_c(E)$ is the density of quantum states in the conduction band and $f_F(E)$ is the Fermi-Dirac probability function. The total electron concentration per unit volume in the conduction band is found by integrating Equation (3.1) over the entire conduction-band energy. The distribution (with respect to energy) of holes in the valence band is the density of allowed quantum states in the valence band multiplied by the probability that a state is not occupied by an electron:

$$p(E) = g_v(E)[1 - f_F(E)] \tag{3.2}$$

The total hole concentration per unit volume is found by integrating this function over the entire valence-band energy. To find the thermal-equilibrium electron and hole concentrations, we need to determine the position of the Fermi energy E_F, with respect to the bottom of the conduction-band energy E_c and the top of the valence-band energy E_v.

To address this question, we will initially consider an intrinsic semiconductor. An ideal intrinsic semiconductor is a pure semiconductor with no impurity atoms and no lattice defects in the crystal (e.g., pure silicon).

For an intrinsic semiconductor at $T = 0\,K$, all energy states in the valence band are filled with electrons and all energy states in the conduction band are empty of electrons.

The Fermi energy must, therefore, be somewhere between E_c and E_v.

The Fermi energy does not need to correspond to an allowed energy. As the temperature begins to increase above $0\,K$, the valence electrons will gain thermal energy.

A few electrons in the valence band may gain sufficient energy to jump to the conduction band.

As an electron jumps from the valence band to the conduction band, an empty stale, or hole, is created in the valence band.

In an intrinsic semiconductor, then, electrons and holes are created in pairs by the thermal energy so that the number of electrons in the conduction bond is equal to the number of boles in the valence band.

Figure 3.1 shows a plot of the density of states function in the conduction band $g_c(E)$, the density of states function in the valence band $g_v(E)$, and the Fermi-Dirac probability function for $T > 0\,K$ when E_F is approximately halfway between E_c and E_v.

If we assume, for the moment, that the electron and hole effective masses are equal, then $g_c(E)$ and $g_v(E)$ are symmetrical functions about the midgap energy. We noted previously that the function $f_F(E)$ for $E > E_F$ is symmetrical to the function $1 - f_F(E)$ for $E < E_F$ about the energy $E = E_F$.

This also means that the function $f_F(E)$ for $E = E_F + dE$ is equal to the function $1 - f_F(E)$ for $E = E_F - dE$.
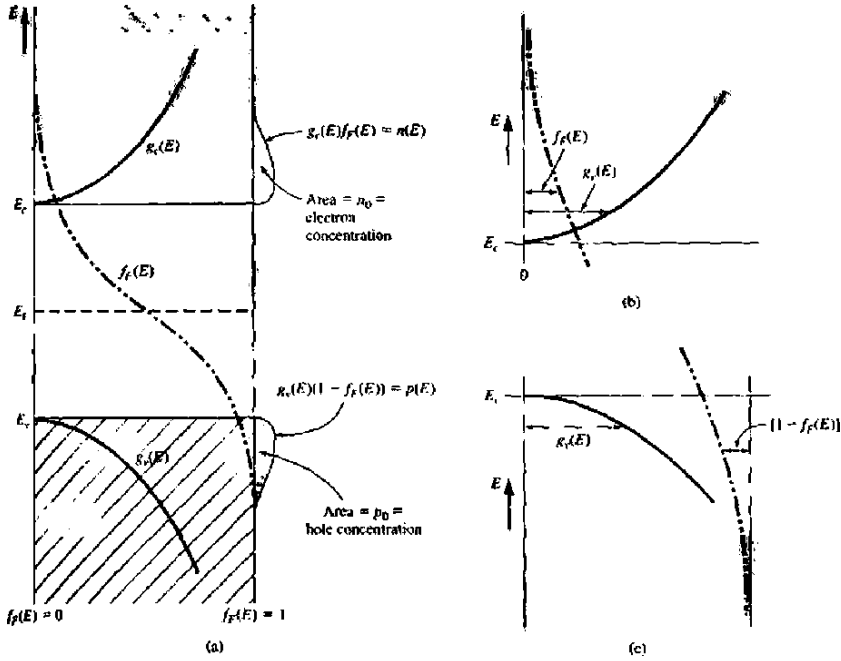
Figure 3.1(a) Density of states functions, Fermi-Dirac probability function, and areas representing electron and hole concentrations for the case when E_F is near the midgap energy energy. (b) Expanded view near the conduction band energy, and (c) expanded view near the valence band energy.

Figure 3.1b is an expanded view of the plot in Figure 3.1, showing $f_F(E)$ an $g_c(E)$ above the conduction band energy E_c.

The product of $g_c(E)$ and $f_F(E)$ is the distribution of electrons $n(E)$ in the conduction band given by Equation (3.1).

This product is plotted in Figure 3.1a.

Figure 3.1c is an expanded view of the plot in Figure 3.1a showing $[1 - f_F(E)]$ and $g_v(E)$ below the valence band energy E_v. The product of $g_v(E)$ and $[1 - [f_F(E)]$ is the distribution of holes $p(E)$ in the valence band given by Equation (2).

This product is also plotted in Figure1a.

The areas under these curves are then the total density of electrons in the conduction band and the total density of holes in the valence band.

From this we see that if $g_c(E)$ and $g_v(E)$ are symmetrical, the Fermi energy must be at the mid gap energy in order obtain equal electron and hole concentrations

If the effective masses of the electrons and hole are not exactly equal, then the effective density of states functions $g_c(E)$ and $g_v(E)$ will not be exactly symmetrical about the mid gap energy.

The Fermi energy for the intrinsic semiconductor will then shift slightly from the mid gap energy in order to obtain equal electron and hole concentrations[1].

3.2 The n_0 and p_0 Equations:

We will assume initially that the Fermi level remains within the band gap energy.

The equation for the thermal-equilibrium concentration of electrons may be found by integrating Equation 1 over the conduction band energy, or

$$n_0 = \int g_c(E) f_F(E) dE \tag{3.3}$$

The lower limit of integration is E_C and the upper limit of integration should be the top of the allowed conduction band energy.

However, since the Fermi probability function rapidly approaches zero with increasing energy as indicated in Figure1a, we can take the upper limit of integration to be infinity.

We are assuming that the Fermi energy is within the forbidden-energy band gap.

For electrons in the conduction band, we have $E \gg E_c$.

If $(E_c - E_F) \gg kT$ then $(E - E_F) \gg kT$, so that the Fermi probability function reduces to the Boltzmann approximation, which is

$$f_F(E) = \frac{1}{1 + \exp\frac{E-E_F}{kT}} \approx \exp\frac{-(E - E_F)}{kT} \tag{3.4}$$

Applying the Boltzmann approximation to Equation (3.3), the thermal-equilibrium density of electrons in the conduction band is found from

$$n_0 = \int_{E_c}^{\infty} \frac{4\pi(2m_n^*)^{3/2}}{h^3} \sqrt{E - E_c} \exp\left[\frac{-(E - E_F)}{kT}\right] dE \tag{3.5}$$

The integral of Equation (3.5) may be solved more easily by making a change of variable:

$$\eta = \frac{E - E_c}{kT} \tag{3.6}$$

Then Equation (3.5) becomes

$$n_0 = \frac{4\pi(2m_n^* kT)^{3/2}}{h^3} \exp\left[\frac{-(E_c - E_F)}{kT}\right] \int_0^{\infty} \eta^{1/2} \exp(-\eta)d\eta \tag{3.7}$$

The integral is the gamma function, with a value of

$$\int_0^{\infty} \eta^{1/2} \exp(-\eta)d\eta = \frac{1}{2}\sqrt{\eta} \tag{3.8}$$

Then Equation (3.7) becomes

$$n_0 = 2 \left(\frac{2\pi m_n^* kT}{h^2} \right)^{3/2} \exp \left[\frac{-(E_c - E_F)}{kT} \right] \tag{3.9}$$

We may define a parameter N_c as

$$N_c = 2 \left(\frac{2\pi m_n^* kT}{h^2} \right)^{3/2} \tag{3.10}$$

The value of n_0

Thermal-equilibrium electron concentration in the conduction band

$$n_0 = N_c \exp \left[\frac{-(E_c - E_F)}{kT} \right] \tag{3.11}$$

The parameter N_c is called the effective density of states function in the conduction band.

If $m_n^* = m_0$ then the value of the effective density of states function at $T = 300\ K$ is $N_c = 2.5 \times 10^{19} \text{cm}^{-3}$, which is the order of magnitude of N_c for most semiconductors.

If the effective mass of the electron is larger or smaller than m_0 then the value of the effective density of states function changes accordingly, but is still of the same order of magnitude.

Example 3.1 Calculate the probability that a state in the conduction band is occupied by an electron and calculate the thermal equilibrium electron concentration in Silicon at $T = 300\ K$. Assume the Fermi energy is $0.25\ eV$ below the conduction band. The value of N_C for silicon at $T = 300\ K$ is $N_c = 2.8 \times 10^{19} cm^{-3}$.

$$f_F(E) = \frac{1}{1 + \exp \left(\frac{E_c - E_F}{kT} \right)} \approx \exp \left[\frac{-(E_C - E_F)}{kT} \right]$$

or

$$f_F(E) = \exp\left(\frac{-0.25}{0.0259}\right) = 6.43 \times 10^{-5}$$

Example 3.2, the electron concentration is given by

$$n_0 = N_c \exp\left[\frac{-(E_c - E_F)}{kT}\right] = (2.8 \times 10^{19})\exp\left(\frac{-0.25}{0.0259}\right)$$

or

$$n_0 = 1.8 \times 10^{15} cm^{-3}$$

The probability of a state being occupied can be quite small, but the fact that there are a large number of states means that the electron concentration is a reasonable value.

The thermal-equilibrium concentration of holes in the valence band is found by integrating Equation (3.2) over the valence band energy, or

$$p_0 = \int g_v(E)[1 - f_F(E)]dE \tag{3.12}$$

We may note that

$$1 - f_F(E) = \frac{1}{1 + \exp\left(\frac{E_F - E}{kT}\right)} \tag{3.13}$$

For energy states in the valence band E < Ev.

If $(E_F - E_v) \gg kT$ then we have slightly different form of the Boltzmann approximation :

$$1 - f_F(E) = \frac{1}{1 + \exp\left(\frac{E_F - E}{kT}\right)} \approx \exp\left[\frac{-(E_F - E)}{kT}\right] \tag{3.14}$$

Applying the Boltzmann approximation of Equation (3.14) to Equation (3.12), we find the thermal-equilibrium concentration of holes in the valence band is

$$p_0 = \int_{-\infty}^{E_v} \frac{4\pi(2m_n^*)^{3/2}}{h^3} \sqrt{E_v - E} \exp\left[\frac{-(E_F - E)}{kT}\right] dE \qquad (3.15)$$

where the lower limit of integration is taken as minus infinity instead of the bottom of the valence band.

The exponential term decays fast enough so that this approximation is valid. Equation (3.15) may be solved more easily by again making a change of variable:

$$\eta' = \frac{E_v - E}{kT} \qquad (3.16)$$

the Equation (3.15) becomes

$$p_0 = \frac{-4\pi(2m_n^* kT)^{3/2}}{h^3} \exp\left[\frac{-(E_F - E_v)}{kT}\right] \int_{+\infty}^{0} (\eta')^{1/2} \exp(-\eta') d\eta' \qquad (3.17)$$

where the negative sign comes from the differential $dE = -kTd\eta'$.

Note that the lower limit of η' becomes $+\infty$ when $E = -\infty$.

If we change the order of integration, we introduce another minus sign.

From Equation (3.8), Equatio n (3.17) becomes

$$p_0 = 2\left(\frac{2\pi m_p^* kT}{h^2}\right)^{3/2} \exp\left[\frac{-(E_F - E_v)}{kT}\right] \qquad (3.18)$$

We may define a parameter N_v as

$$N_v = 2\left(\frac{2\pi m_p^* kT}{h^2}\right)^{3/2} \qquad (3.19)$$

The value of p_0 is

Thermal-equilibrium holes concentration in the valence band

$$p_0 = N_v \exp\left[\frac{-(E_F - E_v)}{kT}\right] \qquad (3.20)$$

The parameter N_v is called the effective density of states function in the valence band.

The magnitude of N_v is also on the order of $10^{19} cm^{-3}$ at $T = 300\ K$ for most semiconductors.

The effective density of states functions, N_c and N_v, are constant for a given semiconductor material at a fixed temperature .

Table 3.1 gives the values of the density of states function and of the effective masses for silicon, gallium arsenide and germanium.

Note that the value of N_c for gallium arsenide is smaller than the typical $10^{19} cm^{-3}$ value. This difference is due to the small electron effective mass in gallium arsenide[1] .

Table 3.1: Effective density of states function and effective mass values

	$N_c\ (cm^{-3})$	$N_c\ (cm^{-3})$	m_n^*/m_0	m_p^*/m_0
Silicon	2.8 x 10^{19}	1.04 x 10^{19}	1.08	0.56
Gallium Arsenide	4.7 x 10^{17}	7.0 x 10^{18}	0.067	0.48
Germanium	1.04 x 10^{19}	6.0 x 10^{18}	0.55	0.37

3.3 The Intrinsic Carrier Concentration:

For an intrinsic semiconductor, the concentration of electrons in the conduction band is equal to the concentration of holes in the valence band.

We may denote n_i and p_i as the electron and hole concentrations, respectively . in the intrinsic semiconductor.

These parameters are usually referred to as the intrinsic electron concentration and the intrinsic hole concentration.

However $n_i = p_i$ so normally we use only the parameter n_i which refer to either intrinsic electron or hole concentration.

The Fermi energy level for the intrinsic semiconductor is called the intrinsic Fermi energy, or $E_F = E_{Fi}$.

If we apply Equations (3.11) and (3.20) to the intrinsic semiconductor, then we can write

$$n_0 = n_i = N_c \exp\left[\frac{-(E_c - E_{Fi})}{kT}\right] \tag{3.21}$$

and

$$p_0 = p_i = n_i = N_v \exp\left[\frac{-(E_{Fi} - E_v)}{kT}\right] \tag{3.22}$$

If we take the product of Equations (3.21) and (3.22), we obtain

$$n_i^2 = N_c N_v \exp\left[\frac{-(E_c - E_{Fi})}{kT}\right] \exp\left[\frac{-(E_{Fi} - E_v)}{kT}\right] \tag{3.23}$$

or

$$n_i^2 = N_c N_v \exp\left[\frac{-(E_c - E_v)}{kT}\right] = N_c N_v \exp\left[\frac{-E_g}{kT}\right] \tag{3.24}$$

where E_g is the bandgap energy.

For a given semiconductor material at a constant temperature, the value of n is a constant, and independent of the Fermi energy. The intrinsic carrier concentration for silicon at $T = 300\ K$ may be calculated by using the effective density of states function values from Table 3.1.

The value of n calculated from Equation (3.24) for $E_g = 1.12\ eV$ is $n = 6.95 \times 10^{19} cm^{-3}$.

The commonly accepted value of n for silicon at T = 300 K is approximately $1.5 \times 10^{10} cm^{-3}$. This discrepancy may arise from several sources.

First, the values of the effective masses are determined at a low temperature where the cyclotron resonance experiments are performed.

Since the effective mass is an experimentally determined parameter, and since the effective mass is a measure of how well a particle moves in a crystal, this parameter may be a slight function of temperature. Next, the density of states function for a semiconductor was obtained by generalizing the model of an electron in a three-dimensional infinite potential well.

This theoretical function may also not agree exactly with experiment.

However, the difference between the theoretical value and the experimental value of n_i is approximately a factor of 2, which, in many cases, is not significant. Table 3.2 lists the commonly accepted values of n_i for silicon, gallium arsenide, and germanium at $T = 300\ K$.

The intrinsic carrier concentration is a very strong function of temperature.

Table 3.2: Commonly accepted values of n_i at $T = 300\ K$.

Silicon	$1.5 \times 10^{10} cm^{-3}$
Gallium Arsenide	$1.8 \times 10^{6} cm^{-3}$
Germanium	$2.4 \times 10^{13} cm^{-3}$

Figure 3.2 is a plot of n from Equation (3.24) for silicon, gallium arsenide, and germanium as a function of temperature.

As seen in the figure, the value of n_i for these semiconductors may easily vary over several orders of magnitude as the temperature changes over a reasonable range[1] .
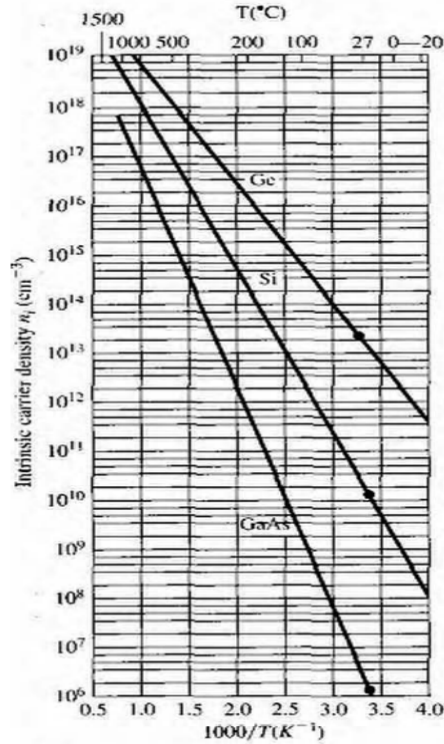
Figure 3.2: The intrinsic carrier concentration as a function of temperature.

3.4   The Intrinsic Fermi-Level Position:

We have qualitatively argued that the Fermi energy level is located near the center of the forbidden band gap for the intrinsic semiconductor.

We can specifically calculate the intrinsic Fermi- level position.

Since the electron and hole concentrations m equal, setting Equations (3.21) and (3.22) equal to each other, we have

$$N_c \exp\left[\frac{-(E_c - E_{Fi})}{kT}\right] = N_v \exp\left[\frac{-(E_{Fi} - E_v)}{kT}\right] \tag{3.25}$$

If we take the natural log of both sides of this equation and solve for E_{Fi} we obtain

$$E_{Fi} = \frac{1}{2}(E_c + E_v) + \frac{1}{2}kT \ln\frac{N_v}{N_c} \tag{3.26}$$

From the definitions for N_c and N_v given by Equations (3.10) and (3.19) Equation (3.26) may be written as

$$E_{Fi} = \frac{1}{2}(E_c + E_v) + \frac{3}{4}kT \ln \frac{m_p^*}{m_n^*}$$ (3.27)

so that

Intrinsic Fermi level

$$E_{Fi} = E_{midgap} + \frac{3}{4}kT \ln \frac{m_p^*}{m_n^*}$$ (3.28)

If the electron and hole effective masses are equal so that $m_n^* = m_p^*$ then the intrinsic Fermi level is exactly in the center of the band gap.

If $m_p^* > m_n^*$ the intrinsic Fermi level is slightly above the center, and if $m_p^* < m_n^*$, it is slightly below the center of the bandgap. The density of states function is directly related to the carrier effective mass; thus a larger effective mass means a larger density of stales function.

The intrinsic Fermi level must shift away from the band with the larger density of states in order to maintain equal numbers of electrons and holes[1] .

3.5 Dopant Atoms and Energy Levels:

The intrinsic semiconductor may be an interesting material, but the real power or semiconductors is realized by adding small, controlled amounts of specific dopant, or impurity, atoms.

The doped semiconductor, called an extrinsic material, is the primary reason we can fabricate the various semiconductor devices[3] .

3.5.1 Qualitative Description:

In the previous chapter we discussed the covalent bonding of silicon and considered the simple two-dimensional representation of the single-crystal silicon lattice as shown in Figure.

Now consider adding a group V element, such as phosphorus, as a substitutional impurity. The group V element has five valence electrons.

Four of these will contribute to the covalent bonding with the silicon atoms, leaving the fifth more loosely bound to the phosphorus atom.

This effect is schematically shown in Figure 3.4. We refer to the fifth valence electron as a donor electron. The phosphorus atom without the donor electron is positively charged.
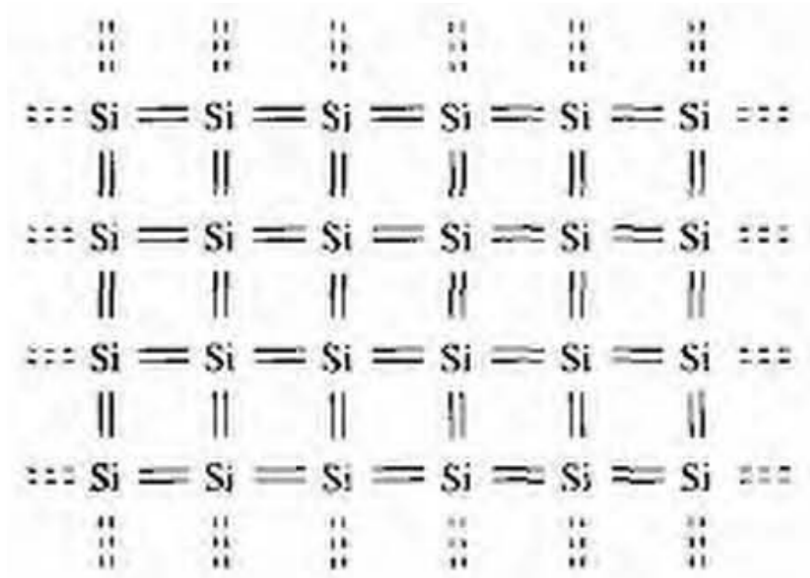
Figure 3.3 Two-dimensional representation of the intrinsic silicon lattice.
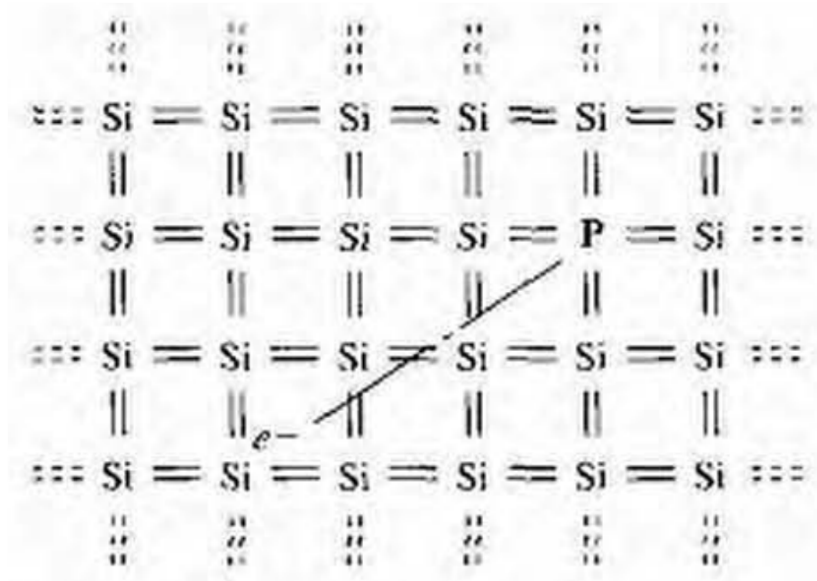
Figure 3.4 Two-dimensional representation of the silicon lattice doped with a phosphorus atom.

At very low temperatures, the donor electron is bound to the phosphorus atom.

However, by intuition, it should seem clear that the energy required to elevate the donor electron into the conduction band is considerably less than that for the electrons involved in the covalent bonding.

Figure 3.5 shows the energy-band diagram that we would expect.

The energy level, E_d, is the energy state of the donor electron. If a small amount of energy, such as thermal energy, is added to the donor electron, it can be elevated into the conduction band, leaving behind a positively charged phosphorus ion.

The electron in the conduction band can now move through the crystal generating a current, while the positively charged ion is fixed in the crystal. This type of impurity atom donates an electron to the conduction band and so is called a donor impurity atom.

Figure 3.5the energy-band diagram showing (a) the discrete donor energy state and (b) the effect of a donor state being ionized.

The donor impurity atom adds electrons to the conduction band without creating holes in the valence band.

The resulting material is referred to as an n-type semiconductor (n for the negatively charged electron). Now consider adding a group III element, such as boron, as a substitution impurity to silicon. The group III element has three valence electrons, which are all taken up in the covalent bonding. As shown in Figure 6a, one covalent bonding position appears to be empty.

If an electron were to occupy this empty position its energy would have to be greater than that of the valence electrons, since the net charge state of the boron atom would now be negative. However the electron occupying

69
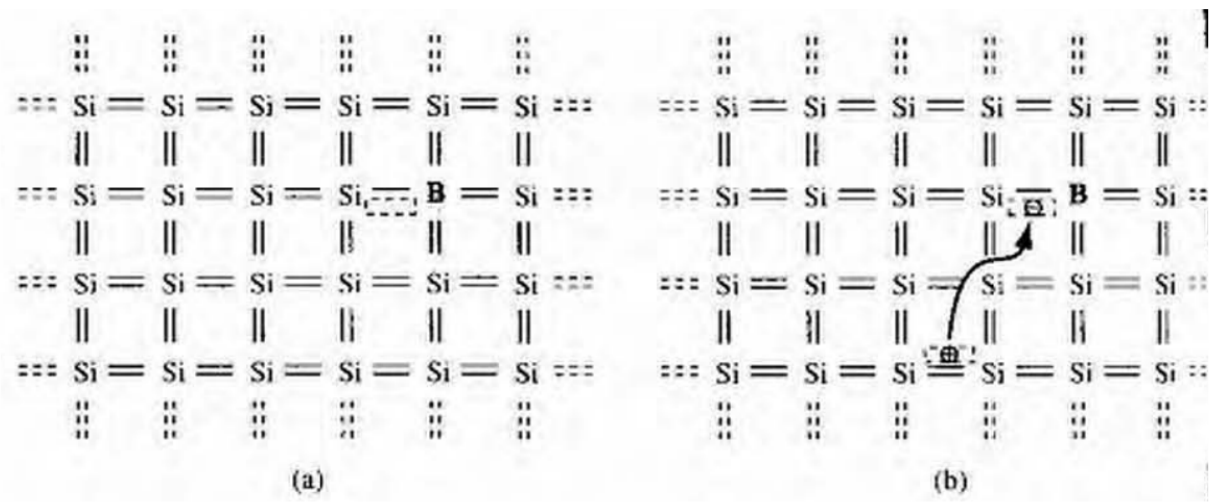
Figure 3.6 Two dimensional representation of a silicon lattice (a) doped with

A boron atom and (b) showing the ionization of the boron atom resulting in a hole

This empty position does not have sufficient energy to be in the conduction band, so its energy is far smaller than the conduction-band energy.

Figure 6b shows how valence electrons may gain a small amount of thermal energy and move about in the crystal.

The "empty" position associated with the boron atom becomes occupied, and other valence electron positions become vacated.

These other vacated electron positions can be thought of as holes in the semiconductor material.

Figure 3.7 shows the expected energy state of the "empty" position and also the formation of a hole in the valence band. The hole can move through the crystal generating a current, while the negatively charged boron atom is fixed in the crystal.
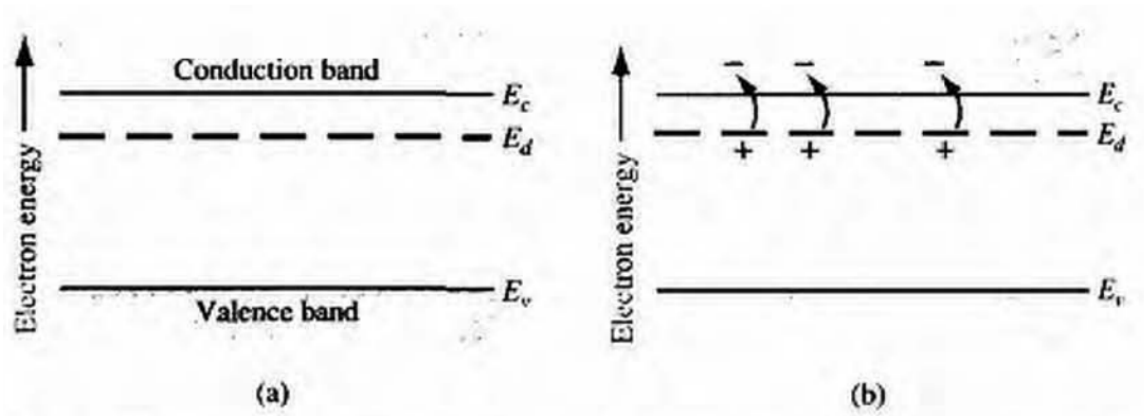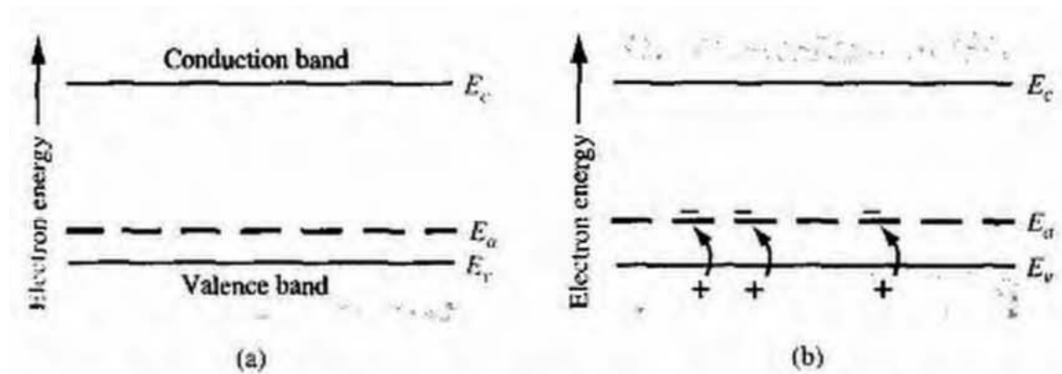
Figure 3.7 the energy-band diagram showing (a) the discrete acceptor energy states and (b) the effect or an acceptor state being ionized.

The group III atom accepts an electron from the valence band and so is referred to as an acceptor impurity atom.

The acceptor atom can generate holes in the valence band without generating electrons in the conduction band .This type of semiconductor material is referred to as a p-type materi-al (p for the positively charged hole).

The pure single-crystal semiconductor material is called an intrinsic material.

Adding controlled amounts of dopant atoms, either donors or acceptors, creates a material called an extrinsic semiconductor.

An extrinsic semiconductor will have either a preponderance of electrons (n −type) or a preponderance of holes (p- type)[3] .

3.6 The Extrinsic Semiconductor:

We defined an intrinsic semiconductor as a material with no impurity atoms present in the crystal.

An extrinsic semiconductor is defined as a semiconductor in which controlled amounts of specific dopant or impurity atoms have been added so that thermal equilibrium electron and hole concentrations are different from the intrinsic carrier concentration.

One type of carrier will predominate in an extrinsic semiconductor[3] .

3.6.1 Equilibrium Distribution of Electrons and Holes:

Adding donor or acceptor impurity atoms to a semiconductor will change the distribution of electrons and holes in the material.

Since the Fermi energy is related to the distribution function, the Fermi energy will change as dopant atoms are added. If the Fermi energy changes from near the mid gap value, the density of electrons in the conduction band and the density of holes in the valence band will change. These effects are shown in Figures 3.8 and 3.9.

Figure 3.8 shows the case for $E_F > E_{Fi}$ and Figure 3.9 shows the case for $E_F < E_{Fi}$.

When $E_F > E_{Fi}$, the electron concentration is larger than the hole concentration, and when $E_F < E_{Fi}$, the hole concentration is larger than electron concentration. When the density of electrons is greater than the density of holes, the semiconductor is n type; donor impurity atoms have been added.
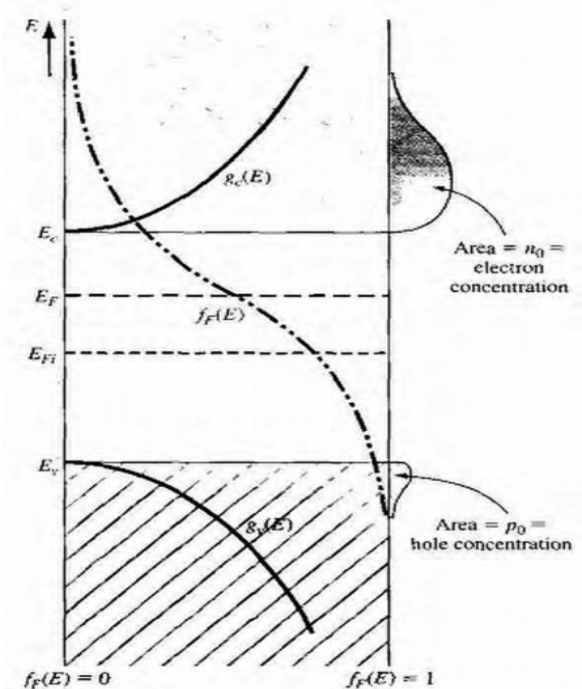
Figure 3.8 Density of states functions, Fermi-Dirac probability function, and areas representing electron and hole concentrations for the case when E_{Fi} is above the intrinsic Fermi energy.
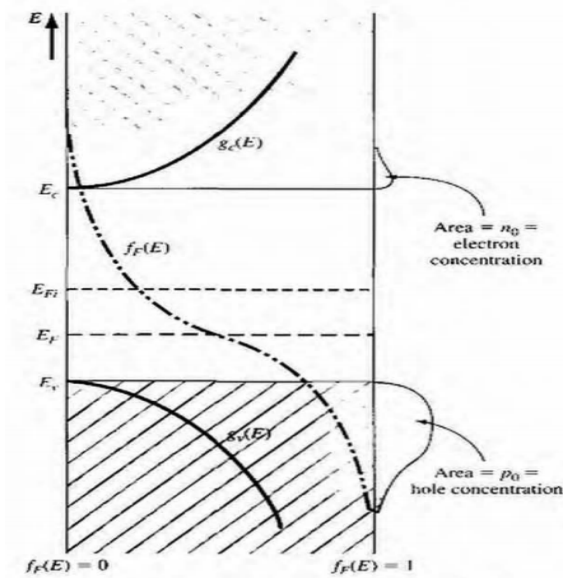
Figure 3.9 Density of states functions, Fermi-Dirac probability function, and areas representing electron and hole concentrations for the case when E_{Fi} is below the intrinsic Fermi energy.

When the density of holes is greater than the density of electrons, the semi-conductor is p-type; acceptor impurity atoms have been added.

The Fermi energy level in a semiconductor changes as donor and acceptor impurity are added. The expressions previously derived for the thermal-equilibrium concentration electrons and holes, given by Equations (3.11) and (3.20) are general equations for n_0 and p_0 in terms of the Fermi energy.

These equations are again

$$n_0 = N_c \exp\left[\frac{-(E_c - E_F)}{kT}\right] \tag{3.29}$$

And

$$p_0 = N_v \exp\left[\frac{-(E_F - E_v)}{kT}\right] \tag{3.30}$$

In an n-type semiconductor, electrons are referred to as the majority carrier and holes as the minority carrier. In a p-type semiconductor it will be the inverse.

We may derive another form of the equations for the thermal-equilibrium concentrations of electrons and holes. If we add and subtract an intrinsic Fermi energy in the exponent of Equation (3.11), we can write

$$n_0 = N_c \exp\left[\frac{-(E_c - E_{Fi}) + (E_F - E_{Fi})}{kT}\right] \tag{3.31}$$

or

$$n_0 = N_c \exp\left[\frac{-(E_c - E_{Fi})}{kT}\right] \exp\left[\frac{-(E_F - E_{Fi})}{kT}\right] \tag{3.32}$$

The intrinsic carrier concentration is given by

$$n_i = N_c \exp\left[\frac{-(E_c - E_{Fi})}{kT}\right] \tag{3.33}$$

so that the thermal-equilibrium electron concentration can be written as

Thermal-equilibrium electron concentration (expressed in terms of intrinsic concentration)

$$n_0 = n_i \exp\left[\frac{-(E_F - E_{Fi})}{kT}\right] \tag{3.34}$$

Similarly, if we add and subtract an intrinsic Fermi energy in the exponent of Equation (3.20) we obtain

Thermal-equilibrium hole concentration (expressed in terms of intrinsic concentration)

$$p_0 = n_i \exp\left[\frac{-(E_F - E_{Fi})}{kT}\right] \tag{3.35}$$

As we will see, the Fermi level changes when donors and acceptors are added, but Equations (3.34) and (3.35) show that, as the Fermi level changes from the intrinsic Fermi level, n_0 and p_0 change from the n_i value.

If $E_F > E_{Fi}$ then we will have $n_0 > n_i$ and $p_0 < p_i$, thus $n_0 > p_0$.

Similarly, in a p-type semiconductor, $E_F < E_{Fi}$ so that $p_0 > n_i$ and $n_0 < n_i$, thus $p_0 > n_0$[1] .

3.6.2 The $n_0 p_0$ product:

We may take the product of the general expressions for n_0 and p_0 as given in Equations (3.11) and (3.20), respectively:

$$n_0 p_0 = N_c N_v \exp\left[\frac{-(E_c - E_F)}{kT}\right] \exp\left[\frac{-(E_F - E_v)}{kT}\right] \tag{3.36}$$

which may be written as

$$n_i = N_c N_v \exp\left[\frac{-E_g}{kT}\right] \tag{3.37}$$

As Equation (3.37) was derived for a general value of Fermi energy, the values of n_0 and p_0 are not necessarily equal.

However, Equation (3.37) is exactly the same as Equation (3.24), which we derived for the case of an intrinsic semiconductor.

We then have that, for the semiconductor in thermal equilibrium, $n_0 p_0$ Equation

$$n_0 p_0 = n_i^2 \tag{3.38}$$

Equation (3.38) states that the product of n_0 and p_0 is always a constant for a given semiconductor material at a given temperature.

Although this equation seems very simple, it is one of the fundamental principles of semiconductors in thermal equilibrium.

It is important to keep in mind that Equation (3.38) was derived using the Boltzmann approximation.

If the Boltzmann approximation is not valid, then Equation (3.38) is not valid. An extrinsic semiconductor in thermal equilibrium does not, strictly speaking, contain an intrinsic carrier concentration, although some thermally generated carriers are present.

The intrinsic electron and hole carrier concentrations are modified by the donor or acceptor impurities[1] .

3.6.3 Degenerate and No degenerate Semiconductors:

In our discussion of adding do-pant atoms to a semiconductor, we have implicitly assumed that the concentration of do-pant atoms added is small when compared to the density of host or semiconductor atoms.

The small number of impurity atoms are spread far enough apart so that there is no interaction between donor electrons for example in an n-type material .

We have assumed that the impurities introduce discrete no interacting donor energy states in the n-type semiconductor and discrete, non interacting acceptor states in the p-type semiconductor.

These types of semiconductors are referred to as non degenerate semiconductors. If the impurity concentration increases, the distance between the impurity atoms decreases and a point will be reached when donor electrons, for example, will begin to interact with each other.

When this occurs, the single discrete donor energy will split into a band of energies. As the donor concentration further increases, the band of donor states widens and may overlap the bottom of the conduction band.

This overlap occurs when the donor concentration becomes comparable with the effective density of states.

When the concentration of electrons in the conduction band exceeds the density of states N_c, the Fermi energy lies within the conduction band.

This type of semiconductor is called a degenerate n-type semiconductor. In a similar way, as the acceptor doping concentration increases in a p-type semiconductor, the discrete acceptor encegy states will split into a band of energies and may overlap the top of the valence band.

The Fermi energy will lie in the valence band when the concentration of holes exceeds the density of states N_v.

This type semiconductor is called a degenerate p-type semiconductor. Schematic models of the energy-band diagrams for a degenerate n-type and degenerate p-type semiconductors are shown in Figure 3.10.

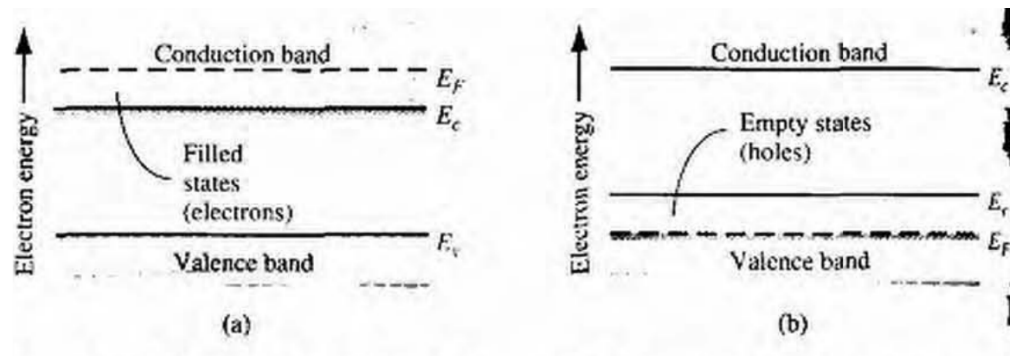Figure 3.10 Simplified energy-band diagrams for degenerately doped (a) n-type and (b) p-type semiconductors.

The energy states below E_F are mostly filled with electrons and the energy state above E_F are mostly empty.

In the degenerate n-type semiconductor, the states between E_F and E_c are mostly filled with electrons, thus, the electron concentration in the conduction band is very large.

Similarly, in the degenerate p-type semiconductor, the energy states between E_v and E_f are mostly empty thus, the hole concentration in the valence band is very large[3] .

3.7 Statistics of Donors and Acceptors:

We discussed the Fermi-Dirac distribution function, which give the probability that a particular energy state will be occupied by an electron.

We need to reconsider this function and apply the probability statistics to the donor and acceptor energy states[3] .

3.7.1   Probability Function:

One postulate used in the derivation of the Fermi-Dirac probability function was the Pauli Exclusion Principle, which states that only one particle is permitted in quantum state.

The Pauli Exclusion Principle also applies to the donor and acceptor states. Suppose we have N_i electrons and g_i quantum states, where the subscript i indicates the ith energy level.

There are g_i ways of choosing where to put the first particle.

Each donor level has two possible spin orientations for the donor electron: thus each donor level has two quantum states.

The insertion of an electron into one quantum state, however, precludes putting an electron into the second quantum state. By adding one electron, the vacancy requirement of the atom is satisfied, and the addition of a second electron in the donor level is not possible.

The distribution function of donor electrons in the donor energy states is then slightly different than the Fermi-Dirac function.   The probability function of electrons occupying the donor state is

$$n_d = \frac{N_d}{1 + \frac{1}{2}\exp\left(\frac{E_d - E_F}{kT}\right)} \tag{3.39}$$

where n_d is the density of electrons occupying the donor level and E_d is the energy of the donor level. The factor 1/2 is a direct result of the spin factor just mentioned.

The 1/2 factor is sometimes written as $1/g$ where g is called a degeneracy factor. Equation (3.39) can also be written in the form

$$n_d = N_d - N_d^+ \tag{3.40}$$

where N_d^+ is the concentration of ionized donors.

In many applications we will be interested more in the concentration of ionized donors than in the concentration of electrons remaining in the donor state.

If we do the same type of analysis for acceptor atoms .we obtain the expression

$$p_a = \frac{N_a}{1 + \frac{1}{g}\exp\left(\frac{E_F - E_a}{kT}\right)} = N_a - N_a^- \tag{3.41}$$

where N_a is the concentration of acceptor atoms, E_a is the acceptor energy level, p_a is the concentration of holes in the acceptor states and N_a^- is the concentration of ionized acceptors . A hole in an acceptor state corresponds to an acceptor atom that is neuturally charged and still has an "empty" bonding position.

The parameter g is, again a degeneracy factor.

The ground state degeneracy factor g is normally taken as four for the acceptor level in silicon and gallium arsenide because of the detailed band structure.

3.7.2 Complete Ionization and Freeze-Out:

The probability function for electrons in the donor energy state was just given by Equation (3.39).

If we assume that $E_d - E_p \gg kT$ then

$$n_d \approx \frac{N_d}{\frac{1}{2}\exp\frac{E_d - E_F}{kT}} = 2N_d \exp\frac{-(E_d - E_F)}{kT} \tag{3.42}$$

If $(E_d - E_F) \gg kT$, then the Boltzmann approximation is also valid for the electrons in the conduction band so from Equation (3.11):

$$n_0 = N_c \exp\left[\frac{-(E_c - E_F)}{kT}\right] \tag{3.43}$$

We can determine the relative number of electrons in the donor state compared with the total number of electrons, therefore we can consider the ratio of electrons in the donor state to the total number of electrons in the conduction band plus donor state.

Using the expressions of Equations (3.43) and (3.11), we write

$$\frac{n_d}{n_d + n_0} = \frac{2N_d \exp\left[\frac{-(E_d - E_F)}{kT}\right]}{2N_d \exp\left[\frac{-(E_d - E_F)}{kT}\right] + N_c \exp\left[\frac{-(E_c - E_F)}{kT}\right]} \tag{3.44}$$

Dividing by the numerator term we obtain:

$$\frac{n_d}{n_d + n_0} = \frac{1}{1 + \frac{N_c}{2N_d}\exp\left[\frac{-(E_c - E_d)}{kT}\right]} \tag{3.45}$$

The factor $E_c - E_d$ is just the ionization energy of the donor electrons. At room temperature, then, the donor states are essentially completely ionized.

At room temperature, there is also essentially complete ionization of the acceptor atoms.

This ionization effect and the creation of electrons and holes in the conduction band and valence band, respectively, are shown in Figure 3.11. The opposite of complete ionization occurs at $T = 0\,K$: all electrons are
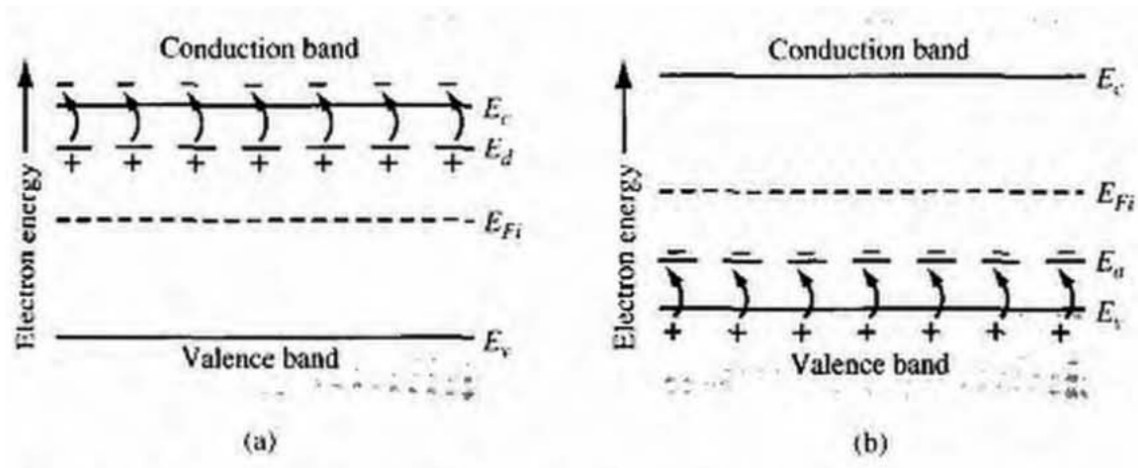

Figure 3.11: Energy-band diagrams showing complete ionization of (a) donor states and (b) acceptor states.

in their lowest possible energy state; that is, for an n-type semiconductor, each donor state must contain an electron. Therefore $n_d = N_d$ or $N_d^+ = 0$.

We must have, then, from Equation (3.39) that $\exp(E_d - E_F)/kT = 0$.

Since $T = 0\,K$, this will occur for $\exp(-\infty) = 0$, which means that $E_p > E_d$. The Fermi energy level must be above the donor energy level at absolute zero.

In the case of a p-type semiconductor at absolute zero temperature, the impurity atom will not contain any electrons, so that the Fermi energy level must be below the acceptor energy state.
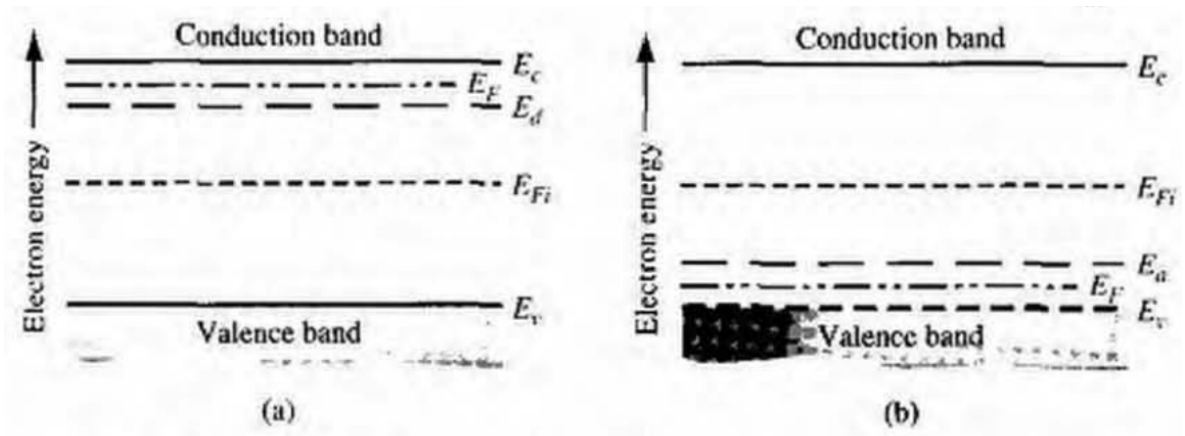
Figure 3.12 Energy-band diagrams at $T = 0\,K$ for (a) n-type and (b) p-type semiconductors.

The distribution of electrons among the various energy states, and hence the Fermi energy, is a function of temperature. A detailed analysis shows that at $T = 0\,K$ the Fermi energy is halfway between E_c and E_d for the n-type material and halfway between E_a and E_v for the p-type material.

Figure 3.12 shows these effects.

No electrons from the donor states are thermally elevated into the conduction band; this effect is called freeze-out.

Similarly, when no electrons from the valance band are elevated into the acceptor states, the effective also called freeze-out.

Between $T = 0\,K$, freeze-out, and $T = 300\,K$, complete ionization, we have partial ionization of donor or acceptor atoms[3] .

3.8 Charge Neutrality:

In thermal equilibrium the semiconductor crystal is electrically neutral.

The electrons are distributed among the various energy stats, creating negative and positive charges, but the net charge density is zero.

This charge-neutrality condition is used determine the thermal-equilibrium electron and hole concentrations as a function of the impurity doping concentration[3] .

3.8.1 Compensated Semiconductor:

A compensated semiconductor is one that contains both donor and acceptor impurity atoms in the same region.

A compensated semiconductor can be formed. for example. by diffusing acceptor impurities into an n-type material or viceversa.

An n-type compensated semiconductor occurs when $N_d > N_a$ and a p-type compensated semiconductor occurs when $N_a > N_d$.

If $N_d = N_a$ we have a completely compensated semiconductor that has, as we will show, the characteristics of an intrinsic material[3] .

3.8.2 Equilibrium Electron and Hole Concentrations:

Figure 3.13 shows the energy-band diagram of a semiconductor when both donor and acceptor impurity atoms are added to the same region to form a compensated semiconductor. The figure shows how the electrons and
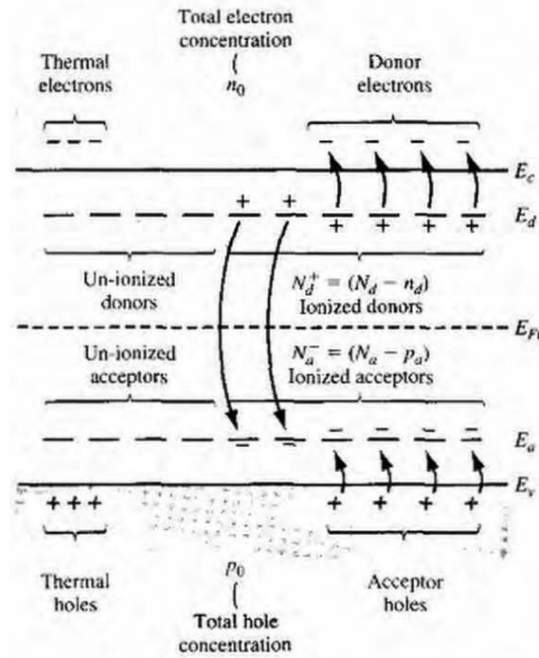
Figure 3.13 Energy-band diagram of a compensated semiconductor showing ionized and un-ionized donors and acceptors.

holes can be distribute among the various states. The charge neutrality condition is expressed by equating the density of negative charges to the density of positive charges:

$$n_0 + N_a^- = p_0 + N_d^+ \tag{3.46}$$

or

$$n_0 + (N_a - p_a) = p_0 + (N_d - n_d) \tag{3.47}$$

where n_0 and p_0 are the thermal-equilibrium concentrations of electrons and holes in the conduction band and valence band.

The parameter n_d is the concentration of electrons in the donor energy states, so $N_d^+ = N_d - n_d$ is the concentration of positively charged donor states.

Similarly, p_a is the concentration of holes in the acceptor states, so $N_a^- = N_a - p_a$ is the concentration of negatively charged acceptor states.

We have expressions for n_0, p_0, n_d and p_a in terms of the Fermi energy and temperature. If we assume complete ionization, n_d and p_a are both zero, and Equation (3.47) becomes

$$n_0 + N_a = p_0 + N_d \tag{3.48}$$

we express p_0 as n_i^2/n_0 then Equation (3.48) can be written as

$$n_0 + N_a = \frac{n_i^2}{n_0} + N_d \tag{3.49}$$

which in turn can be written as

$$n_0^2 - (N_d - N_a)n_0 - n_i^2 = 0 \tag{3.50}$$

The electron concentration no can be determined using the quadratic formula

Equilibrium electron concentration in compensated semiconductor

$$n_0 = \frac{N_d - N_a}{2} + \sqrt{\left(\frac{N_d - N_a}{2}\right)^2 + n_i^2} \tag{3.51}$$

The positive sign in the quadratic formula must be used, since, jn the limit of an intrinsic semiconductor when $N_a = N_d = 0$, the electron concentration must be a positive quantity or $n_0 = n_i$. Equation (3.51) is used to calculate the electron concentration in an n-type semiconductor, or when $N_d > N_a$.

Although Equation (3.51) was derived for a compensated semiconductor, the equation is also valid for $N_a = 0$. The concentration of electrons in the conduction band increases above the intrinsic carrier concentration as we add donor impurity atoms.

At the same time, the minority carrier hole concentration decreases below the intrinsic carrier concentration as we add donor atoms.

We must keep in mind that as we add donor impurity atoms and the corresponding donor electrons, there is a redistribution of electrons among available energy stales.

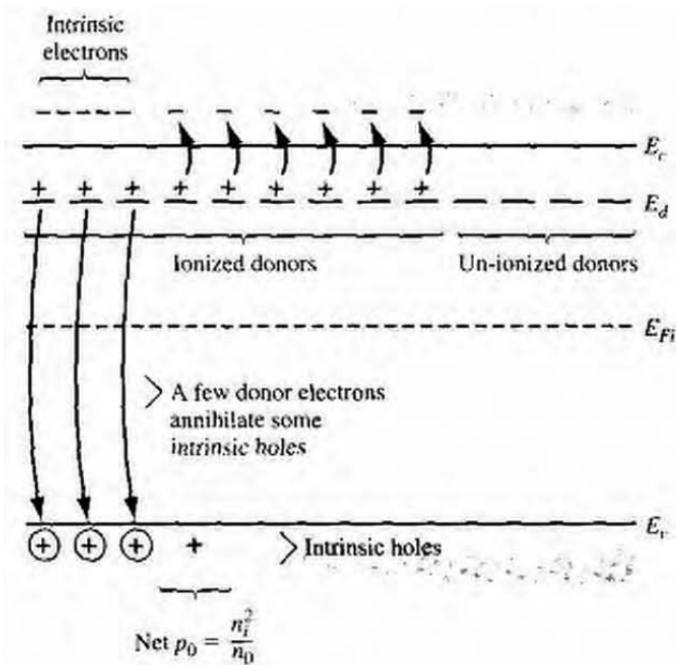Figure ??shows a schematic of this physical redistribution.

Figure 3.14: Energy-band diagram showing the redistribution of electrons when donors are added.

A few of the donor electrons will fall into the empty states in the valence band and, in doing so, will annihilate some of the intrinsic holes.

The minority carrier hole concentration will therefore decrease.

At the same time, because of this redistribution, the net electron concentration in the conduction band is not simply equal to the donor concentration plus the intrinsic electron concentration. We have seen that the intrinsic carrier concentration n is a very strong function of temperature.

As the temperature increases, additional electron-hole pairs are thermally generated so that the n_i^2 term in Equation (3.51) may begin to dominate.

The semiconductor will eventually lose its extrinsic characteristics.

Figure 3.15 shows the electron concentration versus temperature in silicon doped with 5 x 10^{14} donors per cm^3. As the temperature increases, we can see where the intrinsic concentration begins to dominate.

Also shown is the partial ionization, or the onset of freeze-out, at the low temperature. For the case of holes we obtain in an analogous way

Equilibrium hole concentration in compensated semiconductor

$$p_0 = \frac{N_d - N_a}{2} + \sqrt{\left(\frac{N_d - N_a}{2}\right)^2 + n_i^2} \qquad (3.52)$$

where the positive sign must be used.

Equation (3.52) is used to calculate the thermal equilibrium majority carrier hole concentration in a p-type semiconductor, or when $N_a > N_d$.
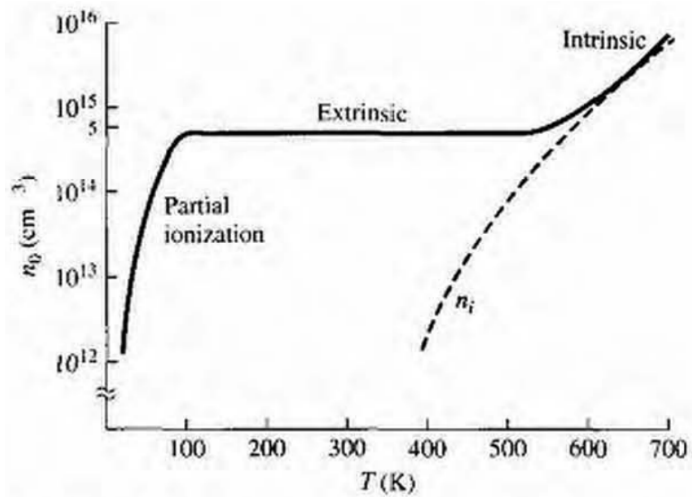

Figure 3.15 Electron concentration versus temperature showing the three regions: partial ionization, extrinsic and intrinsic.

This equation also applies for $N_d = 0$. Equations (3.51) and (3.52) are used to calculate the majority carrier electron concentration in an n-type semiconductor and majority carrier hole concentration in a p-type semi conductor.

The minority carrier hole concentration an n-type semicon-ductor could theoretically be calculated from Equation (3.52). However we would be sub stracting two numbers two big numbers which from a practical point of view is not possible.

The minority carrier concentrations are calculated from $n_0 p_0 = n_i^2$ once the majority carrier concentration has been determined[1] .

3.9 Position of the Fermi Energy Level:

We discussed how the electron and hole concentrations change as the Fermi energy level moves through the band gap energy.

We calculated the electron and hole concentrations as a function of donor and acceptor impurity concentrations.

We can now determine the position of the Fermi energy level as a function of the doping concentrations and as a function of temperature[3] .

3.9.1 Mathematical Derivation:

If we assume the Boltzmann approximation to be valid, then from Equation (3.11) we have $n_0 = N_c \exp[-(E_c - E_F)/kT]$.

We can solve for $E_c - E_F$ from this equation and obtain

$$E_c - E_F = kT \ln\left(\frac{N_c}{n_0}\right) \tag{3.53}$$

where n_0 is given by Equation (3.51).

If we consider an n-type semiconductor in which $N_d \gg n_i$ then $n_0 \approx N_d$ so that

$$E_c - E_F = kT \ln\left(\frac{N_c}{N_d}\right) \tag{3.54}$$

We may note that if we have a compensated semiconductor, then the N_d term in Equation (3.54) is simply replaced by $N_d - N_a$ or the net effective donor concentration.

We may develop a slightly different expression for the position of the Fermi level. We had from Equation (3.34) that $n_0 = n_2 \exp[(E_F - E_{Fi})/kT]$. We can solve for $E_F - E_{Fi}$ as

$$E_F - E_{Fi} = kT \ln\left(\frac{n_0}{n_i}\right) \tag{3.55}$$

Equation (55) can be used specifically for an n-type semicon-ductor, where n_o is given by Equation (3.51) to find the difference between the Fermi level and the intrinsic Fermi level as a function of the donor concentration.

We may note that, if the net effective donor concentration is zero, that is, $N_d - N_a = 0$ then $n_0 = n_i$ and $E_F = E_{Fi}$.

A completely compensated semiconductor has the characteristics of an intrinsic material in terms of carrier concentration and Fermi level position. For the case of a p-type semiconductor we obtain in a similar way the formula

$$E_F - E_v = kT \ln\left(\frac{N_v}{p_0}\right) \tag{3.56}$$

which, in the case $N_a \gg n_i$ becomes

$$E_F - E_v = kT \ln\left(\frac{N_v}{N_a}\right) \tag{3.57}$$

It's have also

$$E_{Fi} - E_F = kT \ln\left(\frac{p_0}{n_i}\right) \tag{3.58}$$

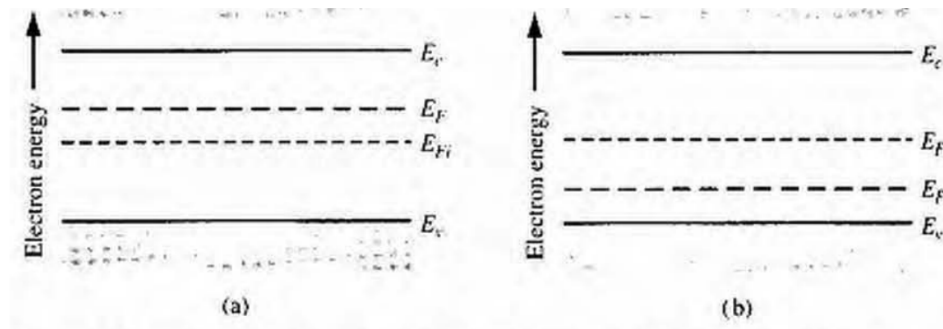These results are schematically shown in figure 3.16

Figure 3.16 Position of Fermi level for an (a) n-type ($N_d > N_a$) and (b) p-type ($N_a > N_d$) semiconductor[3] .

3.9.2 Variation of E_F with Doping Concentration and Temperature :

We may plot the position of the Fermi energy level as a function of the doping concentration.

Figure 3.17 shows the Fermi energy level as a function of donor concentration (n-type) and as a function of acceptor concentra-tion (p-type) for silicon at $T = 300 \ K$.

As the doping level increases the Fermi energy level moves closer to conduction band for the n-type material and closer to the valence band for the p-type material. The intrinsic carrier concentration is a strong function of temperature, so that E_F is a function of temperature also.

Figure 3.18 shows the variation of the Fermi energy level in silicon with temperature for several donor and acceptor concentrations.

As the temperature increases, n_2 increases and E_F moves closer to the intrinsic Fermi level. At high temperature the semiconductor material begins to lose its extrinsic characteristics and begins to behave more like an intrinsic semiconductor.
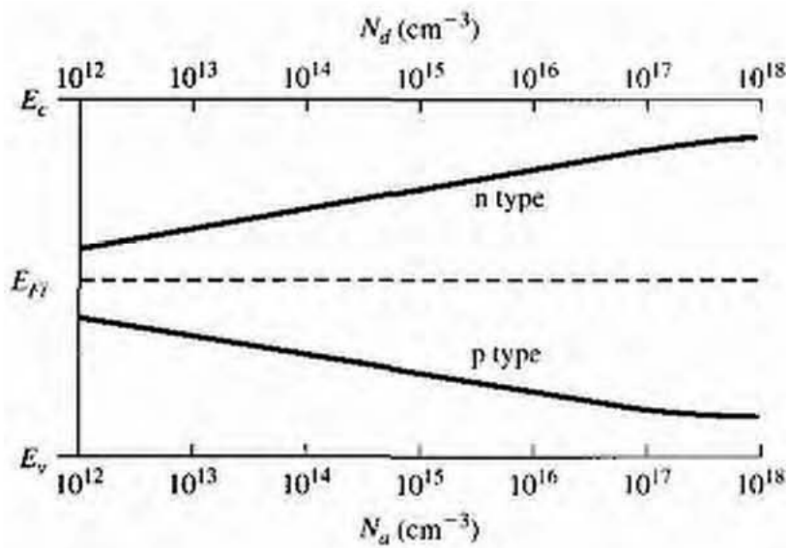
Figure 3.17 Position of Fermi level as a function of donor concentration (*n*-type) and acceptor concentration (*p*-type).
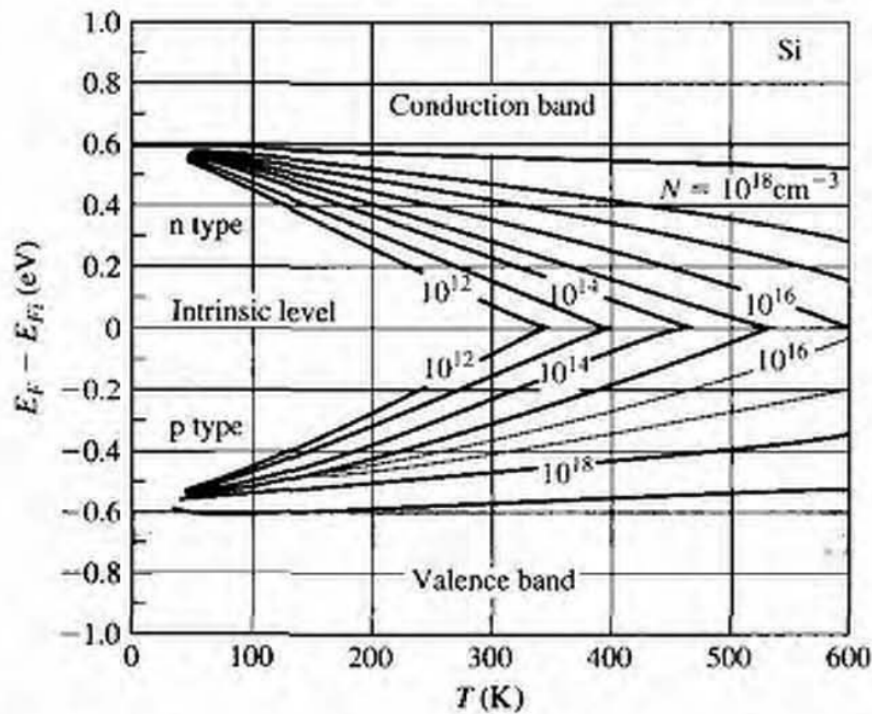

Figure 3.18 Position of Fermi level as a function of temperature for various doping concentrations.

At the very low temperature freeze-out occurs: the Boltzmann approximation is no longer valid and the equations we derived for the Fermi-level position no longer apply.

At the low temperature where freeze-out occurs the Fermi level goes above E_d for the n-type material and below E_a for the p-type material.

3.9.3 Relevance of the Fermi Energy :

An important point is that in thermal equilibrium, the Fermi energy level is a constant throughout a system.

We will not prove this statement. but we can intuitively see its validity by considering the following example.

Suppose we have a particular material, A, whose electrons are distributed in the energy states of an allowed band as shown in Figure 3.19a.

Most of the energy states below E_{FA} contain electrons and most of the energy states above E_{FA} are empty of electrons.
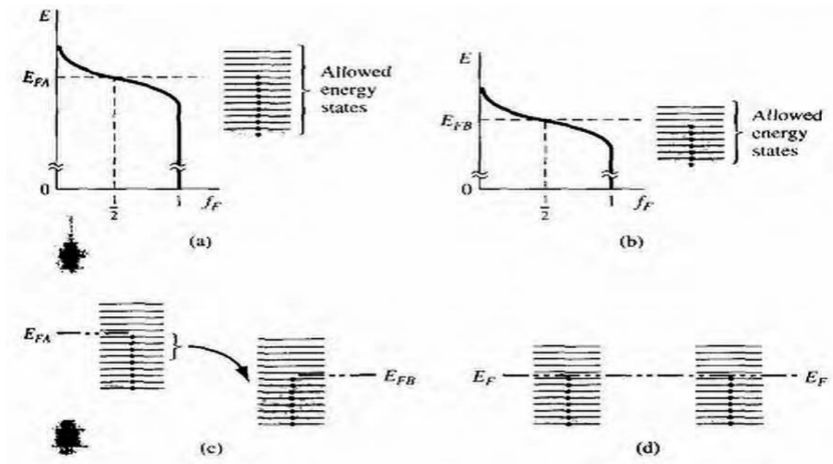

Figure 3.19 The Fermi energy of (a) material A in thermal equilibrium, (b) material B in thermal equilibrium, (c) materials A and B at the instant they are placed in contact and (d) materials A and B in contact at thermal equilibrium[3] .

Chapter four

Experiment

4.1 Introduction:

In a material whose electrical conduction results from migration of a unique charge carrier species, Either electrons or ions, the electrical conductivity $\sigma = n_e e \mu$, where n_e is the effective charge carrier concentration, (e) is the charge for the single

In the case of ion conductive glasses ,the absence of experimental data on n_e and μ leads to different interpretation, assuming that either all the ions move simultaneously with a low mobility or only a small fraction of them move with a higher mobility at any time .

The charge carrier concentration of most electronic conductors such as semiconductors can be determined separately by measuring both Hall's coefficient .however, in ionic conductors, the mobility of ions is lower than that of electrons in semiconductors.[5]

4.2 Aim of experiment:

Calculate concentration of charge carriers and the energy gab in semiconductor.

4.3 The Theory:

In semiconductors the resistance is given by:

$$R_T = R_0 * Exp\left(-\frac{E_g}{2} * KT\right)$$

$$LnR_T = LnR_0\left(-\frac{E_g}{2k}\right) * \frac{1}{T}$$

From this relation we find the concentration:

$$n_i = n_0 \, Exp(-\frac{E_g}{2KT})$$

$$R_T = the\ unknown\ resistant$$

$$R_0 = known\ resistant$$

$$\frac{R_T}{100} = \frac{l_1}{l_2}$$

$$RT = 100\frac{l_1}{l_2}$$

$$so\ that$$

$$n_i = \frac{100\ l_1}{l_2}$$

$$n_i \quad is\ concentration$$

$$l = the\ length\ of\ wire$$

4.4 The Apparatus:

_sample of semiconductor(as shown figure below) place within a glass tube thin walls installed on the base metal, resistance of this sample(200Ω) in the degree($20\ ^0c$).

_bridge: the bridge consist of the unknown resistance(the sample)and known resistance 100 ohm(resistor tray) and two resistance both wire and installed on a ruler and holder of three stalls.

Variable resistors tray (0-1111Ω)._

Thermometer its range from zero to 300%.
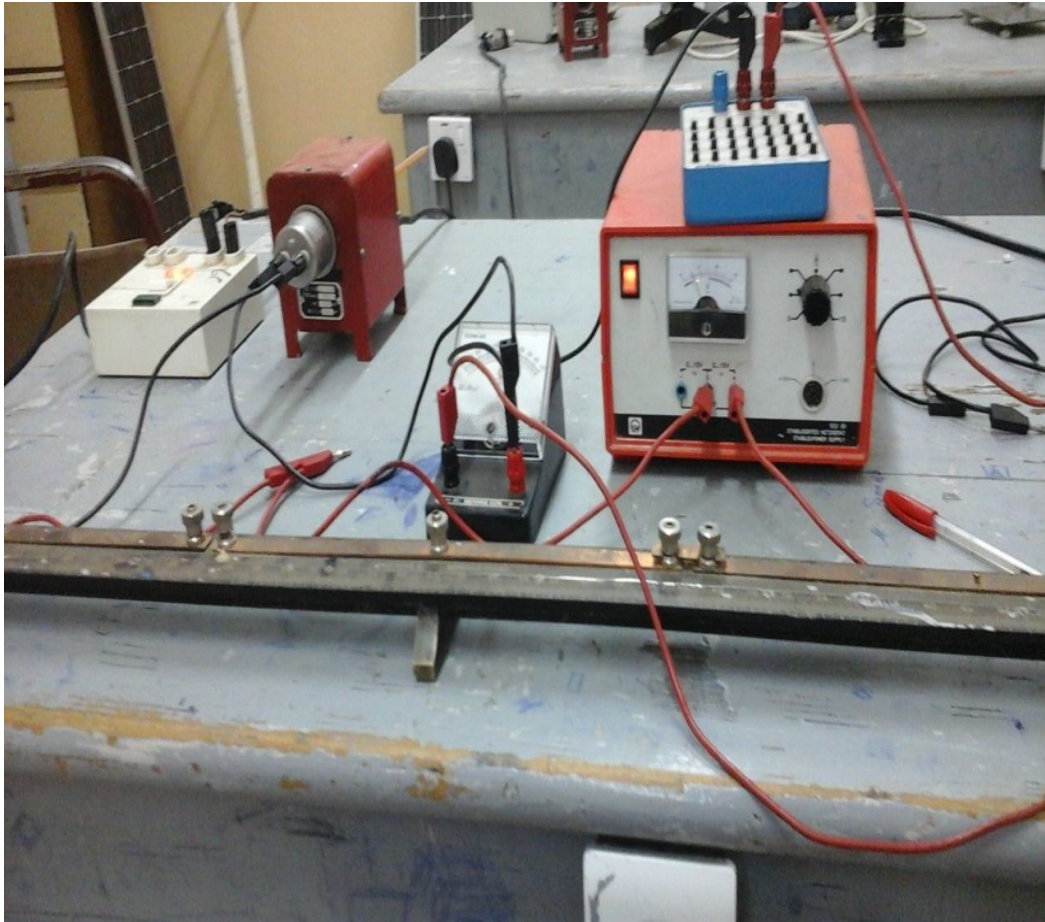
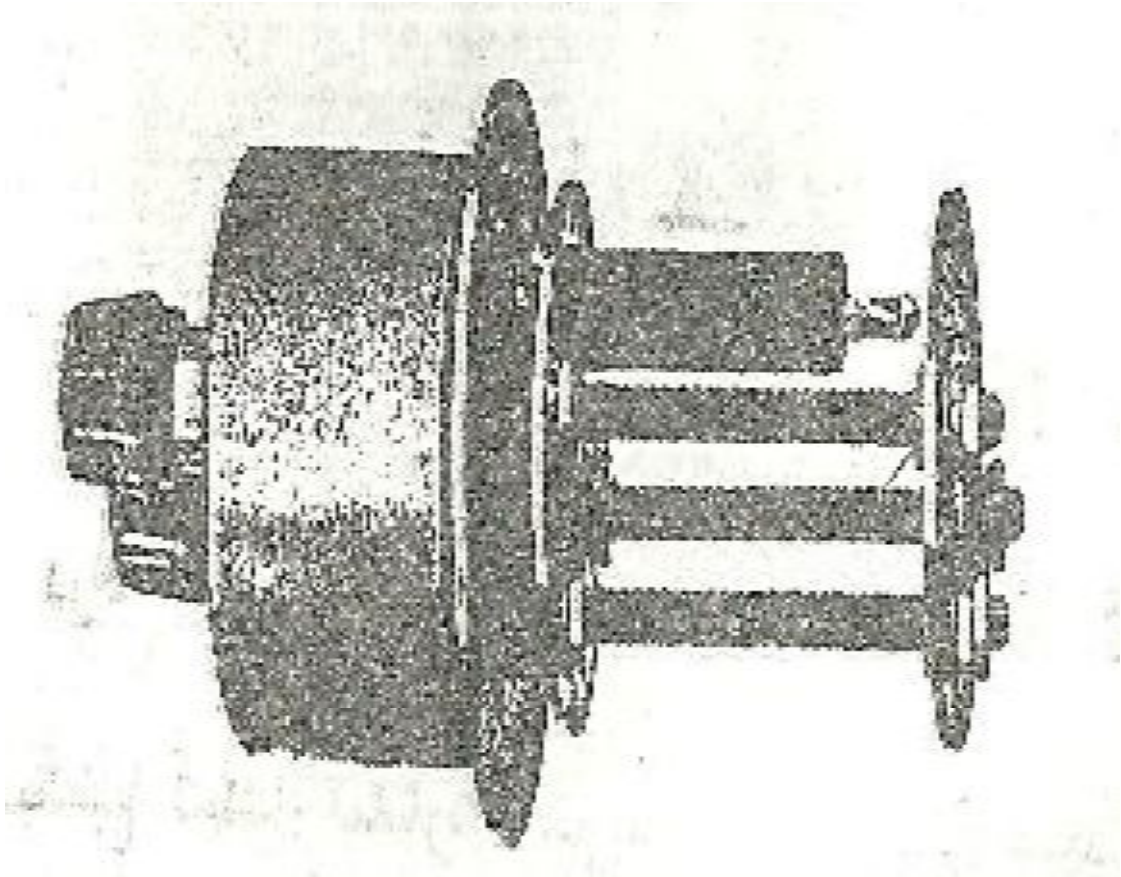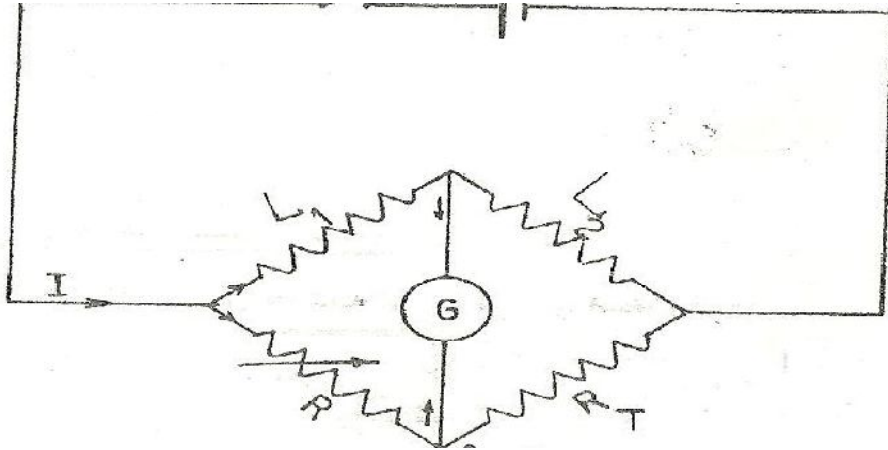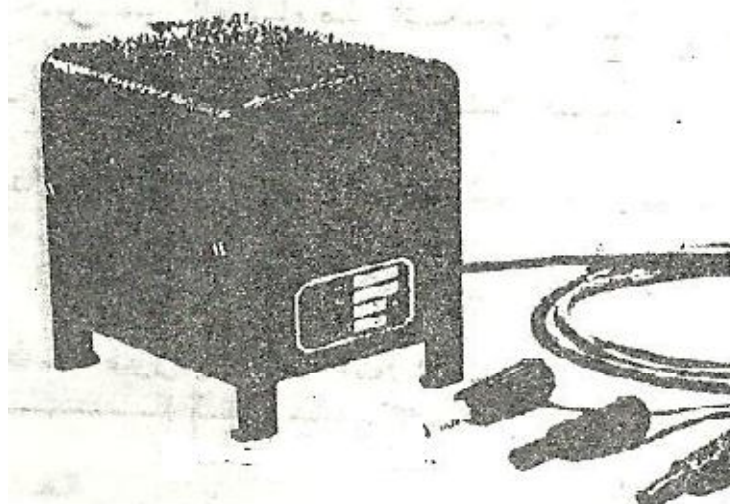Figure 4-1 the sample

Figure 4-2 the bridge

Figure 4-3 the oven

~glvanomitr light that indicates the balance of the bridge

~ oven for heating: is the electric oven being able to(200W) contains a cylindrical chamber heated length (10cm)in diameter(3.7cm) closing the gap nozzle holder metal sample. And also it contains slot backdrop diameter (1.5) hole to put the heat balance to measure the temperature and the cable feeding.

~connecting wires

4.5Results:

| T	L_1	L_2	N_i	N_s	$E_g \times 10^{-20}$	n_i
303	34	66	51.51	9968.4	2.09	-2.492×10^{-38}
313	41	59	69.49	10465.9	2.159	-2.616×10^{-38}
323	50	50	100	10971.4	2.228	-2.743×10^{-38}
333	58	42	138.09	11484.9	2.298	-2.871×10^{-37}
343	66	34	194.1	12006.1	2.366	-3.002×10^{-38}
353	72	28	257.1	12534.9	2.435	-3.134×10^{-38}
363	78	22	354.5	13071.4	2.505	-3.268×10^{-36}
373	82	18	455.6	13615.2	2.574	-3.404×10^{-36}
383	84	16	525	14166.4	2.643	-3.542×10^{-36}
393	86	14	614.3	14724.8	2.712	-3.681×10^{-36}
403	88	12	733.3	15290.4	2.781	-3.824×10^{-36}
413	92	8	1150	15863.1	2.849	-3.969×10^{-36}
423	96	4	2400	16442.7	2.919	-4.111×10^{-36}
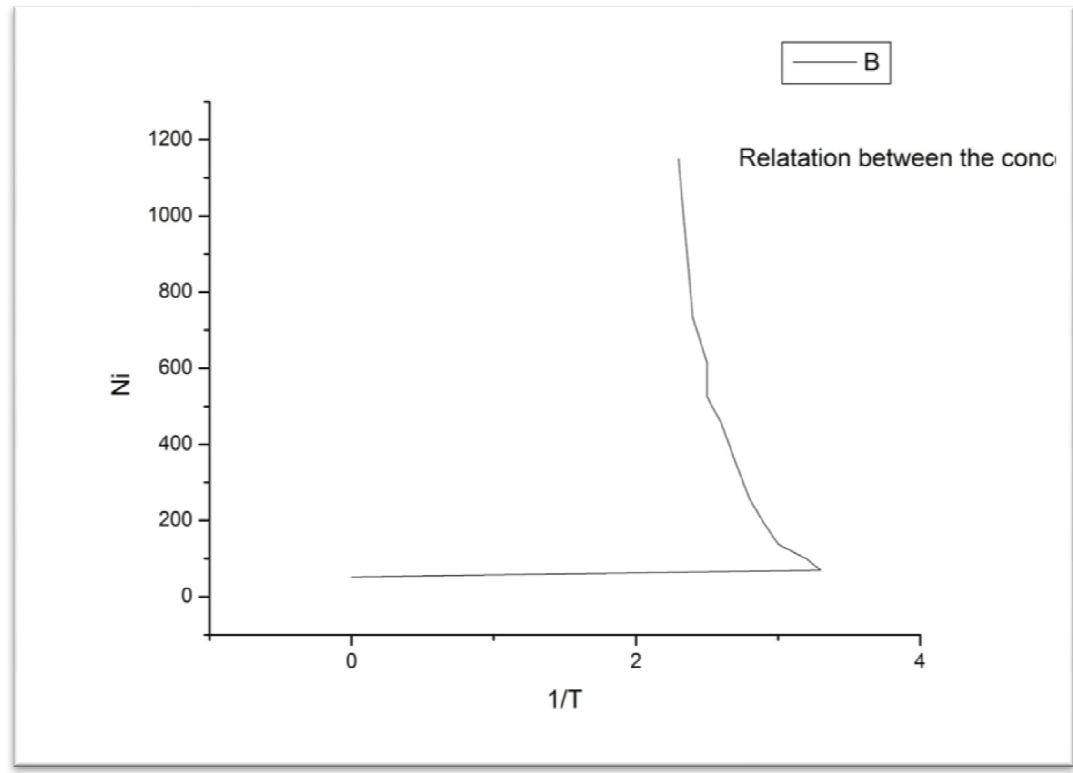
Figure (4.4) relation between concentration & temperature

4.6 Calculation:

The intrinsic charge carrier concentration:

$$N_i = N_s Exp(-E_g/2KT) \tag{4.1}$$

Then:

N_s = the number per unit volume of effectively available state.

E_g = energy gap.

K= Boltzmann constant.$(1.38 \times 10^{-23} J/Kelvin)$.

$$KT = \frac{E_g}{5} \tag{4.2}$$

$$E_g = 5 * kT \tag{4.3}$$

So that:

$$Ns = 2\left(m * \frac{kTh2}{2\pi}\right)^{1.5} = (m^*/m)^{1.5} * \left(\frac{T}{300K}\right)^{1.5} 2.5 \times \frac{10^{19}}{Cm^3} \tag{4.4}$$

Effective mass $= m^*$

m = The electron mass.(for silicon the rate of effective mass and electron mass is equal to 0.543).

Then:

$$Ns = [0.543]^{1.5}\left[\frac{T}{300}\right]^{1.5} \times 2.5 \times 10^{25}$$

$$= 0.400\left[\frac{1}{300}\right]^{1.5} T^{1.5} \times 2.5 \times 10^{25}$$

$$= 0.400 \times 1.89 \times 10^{-4} \times 2.5 \times 10^{25}$$

$$= 1.89T^{1.5} \tag{4.5}$$

4.7 Conclusion:

After conduct this study we conclusion :

-The concentration of electrons in the conduction band is equal to the concentration of holes in the valence band.

-Whenever increase the temperature decreased in the concentration and energy gap.

4.8 Recommendation:

Recommend advanced research in this area and find an easy alternative methods to calculated charge carriers concentration.

References

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[2]Neaman, D semiconductor physics and devices, 3rded ,NewYork :MC Graw –hill ,2003.

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[4]Shocktey ,w, electrons and holes in semiconductors ,Princeton, NJ: Van Nostrand , 1950.

[5]B.L.Anderson and R.L.A nderson ,fundamentals of semiconductors devices ,MC Graw hill,2005.