

# LECTURES IN PhysICS OF Semiconductor

University of Ninevah

**DEPARTMENT of ELECTRONICS** 

**College of Electronic Engineering** 

# **Energy bands in Solids**

All matters are made of atoms; and all atoms consist of electrons, pro- tons, and neutrons. In this chapter, you will learn about the structure of the atom, electron orbits and shells, valence electrons, ions, and the semi- conductive materials. Semi conductive material is important because the configuration of certain electrons in an atom is the key factor in determining how a given material conducts electrical current.



Figure 1.1: Atomic structure

# **1.1** The energy-band theory of crystals

As we have seen, all the electrons of a given atom having the same value of *n* belong to the same prescribed bands (electronic shell). Each shell around the nucleus corresponds to a certain energy band and is separated from adjacent shells by energy gaps, in which no electron can exist.

A crystal is a solid consisting of a regular and repetitive arrangement of atoms or molecules (strictly speaking, ions) in space. If the positions of the atoms in the crystal are represented by points, called lattice points, we get a crystal lattice. The distance between the atoms in a crystal is fixed and is termed the lattice constant of the crystal. To discuss the behavior of electrons in a crystal, we consider an isolated atom of the crystal. If Z is the atomic number, the atomic nucleus has a positive charge Ze.

At a distance r from the nucleus, the electrostatic potential due to the nuclear charge is (in SI units).

$$V\left(r\right) = \frac{Ze}{4\pi\epsilon_{o}r} \tag{1}$$

Since an electron carries a negative charge, the potential energy of an electron at a distance r from the nucleus is:

V(r) is positive while  $E_p(r)$  is negative. Both V(r) and  $E_p(r)$  are zero at an infinite distance from the nucleus. Figs. 1.3(a) and (b) show the variation of V(r) and  $E_p(r)$ , respectively with r.

Now, consider two identical atoms placed close together. The net potential energy of an electron is obtained as the sum of the potential energies due to the two individual nuclei. In the region between the two nuclei, the net potential energy is clearly smaller than the potential energy for an isolated nucleus (see Fig. 1.2).



Figure 1.2: Variation of (a) Potential in the field of a nucleus with distance, (b) Potential energy of an electron with its distance from the nucleus.



Figure 1.3: Potential energy variation of an electron with distance between two identical nuclei.

The potential energy along a line through a row of equispaced atomic nuclei, as in a crystal, is diagrammatically shown in figure 1.4. The potential energy between the nuclei is found to consist of a series of humps. The separation between the split-off energy levels is very small. This large number of discrete and closely spaced energy levels forms an *energy band*. Energy bands are represented schematically by shaded regions in figure 1.4(b).

The width of an energy band is determined by the parent energy level of the isolated atom and the atomic spacing in the crystal. The lower energy levels are not greatly affected by the interaction among the neighboring atoms, and hence form narrow bands. The higher energy levels are greatly affected by the interatomic interactions and produce wide bands.



Figure 1.4: Splitting of energy levels of isolated atoms into energy bands as these atoms are brought close together to produce a crystal.

The lower energy bands are normally completely filled by the electrons since the electrons always tend to occupy the lowest available energy states. The higher energy bands may be completely empty or may be partly filled by the electrons. The interatomic spacing, although fixed for a given crystal, is different for different crystals. The width of an energy band thus depends on the type of the crystal, and is larger for a crystal with a small interatomic spacing. The lower energy bands are normally completely filled by the electrons since the electrons always tend to occupy the lowest available energy states. The higher energy bands may be completely empty or may be partly filled by the electrons. The lower energy band calls the valence band and the first, unfilled or partially filled, band above the valence is called conduction band. The energy gap between the valence and conduction can be calculated as:

On the basis of the band structure, crystals can be classified into metals, insulators, and semiconductors.



Figure 1.5: Energy band structure of (a) metal, (b) insulator, and (c) semiconductor.

### **1.1.1 Metals**

A crystalline solid is called a metal if the uppermost energy band is partly filled [figure 1.5(a)] or the uppermost filled band and the next unoccupied band overlap in energy. The electrons in the uppermost band find neighboring vacant states to move in, and thus behave as free particles. In the presence of an applied electric field, these electrons gain energy from the field and produce an electric current, so that a metal is a good conductor of electricity. The partly filled band is called the conduction band. The electrons in the conduction band are known as free electrons or conduction electrons.

# **1.1.2 Insulators**

When the forbidden energy gap between the valence band and the conduction band, is very large, only a few electrons can acquire enough thermal energy to move from the valence band into the conduction band. Such solids are known as insulators. Since only a few free electrons are available in the conduction band, an insulator is a bad conductor of electricity. The energy band structure of an insulator is schematically shown in figure 1.5(b).

#### **1.1.3 Semiconductors**

A material for which the width of the forbidden energy gap between the valence and the conduction band is relatively small (1 eV) is referred to as a semiconductor. As the forbidden gap is not very wide, some of the valence electrons acquire enough thermal energy to go into the conduction band. These electrons then become free and can move about under the action of an applied electric field. The absence of an electron in the valence band is referred to as a hole. The holes also serve as carriers of electricity. The electrical conductivity of a semiconductor is less than that of a metal but greater than that of an insulator. The band diagram of a semiconductor is given in figure 1.5(c).

At 0  $^{o}K$  the semiconductor becomes insulator because the electrons do not has energy to jump to conduction band.

# **1.2** Fermi–Dirac distribution function

Fermi Dirac distribution function describes the energies of single particles in a system comprising many identical particles that obey the Pauli exclusion principle. Electrons are Fermions, and thus follow Fermi Dirac distribution function.

At room temperature, the thermal energy of the atoms may allow a small number of electrons to participate in the conduction process in semiconductor. The probability for filling the band by electrons depends on temperature.

where f(E) is the probability of occupancy of the state with energy E,  $E_F$  is a char-

acteristic energy for a particular solid and is referred to as the Fermi level, *T* is the absolute temperature in  ${}^{o}K$  and *k* is Boltzmann's constant ( $k = 1.38 \times 10^{-23} J K^{-1} = 8.614 \times 10^{-5} eV K^{-1}$ ). Fermi energy can be defined as the energy at which there would be a fifty percent chance of finding an electron.

Figure 1.6 shows the probability f(E) against  $E/E_F$  for T=0, 300 and 2000 K.



Figure 1.6: f(E) as a function of  $E/E_F$  for different values of T

From Fermi Dirac function, equation (4) and figure 1.6, it can be conclude that:

- 1. At the absolute zero of temperature, i.e. at T = 0 K, equation 1.16 shows that f(E) = 1 for  $E < E_F$  and f(E) = 0 for  $E > E_F$ . Thus all the energy states below  $E_F$  are occupied by the electrons and all the energy states above  $E_F$  are completely empty. (The probability of finding electron above Fermi level at zero  ${}^{o}K$  is zero).
- 2. At temperatures greater than the absolute zero, f(E) > 0 for  $E > E_F$ , as shown in figure 1.6. This means that at a finite temperature, some of the electrons in the quantum states below EF acquire thermal energy to move into states above  $E_F$ . The probability of electron above Fermi level at T>0  $^{o}K$  is given by:

3. The probability of electron to fill a state below Fermi level at T>0 <sup>*o*</sup>K is given by:

$$f(E) = 1 - exp\left(\frac{-\left(|E - E_f|\right)}{kT}\right)$$
.....

.....(6)

#### Solved problems

1. Find the probability of an electron to occupy a level (0.1 eV)above Fermi level at 27  $^{o}C$ ?

Solution:

$$f(E) = exp\left(\frac{-(E-E_f)}{kT}\right) = exp\left(\frac{-(0.1)}{8.614 \times 10^{-5} \times 300}\right) = 0.0209$$

2. The probability for an electron to occupy a level at 120  ${}^{o}C$  is $(2 \times 10^{-6})$ . Find the location of this level with respect to Fermi level?

#### Solution

$$f(E) = \frac{1}{1 + exp\left(\frac{E - E_f}{kT}\right)} = \frac{1}{1 + exp\left(\frac{E - E_f}{8.614 \times 10^{-5} \times 300}\right)} = 2 \times 10^{-6}$$

 $E - E_f = 0.444 eV$  above Fermi level.

# **Transport Phenomena in Semiconductor**

The current is defined as the flow of charged particles. In metal the current results from the flow of negative charges (electrons), whereas the current in a semiconductor results from the motion of both electrons and positive charges (holes). A pure semiconductor may be doped with impurity atoms so that the current is due predominantly either to electrons or to holes. The transport of the charges, i.e. conductivity, in a crystal under the influence of an electric field (a drift current), and also as a result of a nonuniform concentration gradient (a diffusion current), is investigated in this chapter.

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# 2.1 <u>Mobility and Conductivity</u>

As it is observed in the preceding chapter, according to the energy band theory, the materials can be classified into three types: insulators, conductors, and semiconductors. A conductor is a solid in which an electric current flows under the influence of the electric field. By contrast, the application of an electric field produces no current in an insulator

The energy gap for an insulator is so wide that hardly any electrons are acquired enough to jump to the conduction band. If a constant electric field is applied to the metal, the electrons will move with acceleration equal:

$$a = \frac{e E}{m} \tag{2.1}$$

where, *E* is the electric field in a unit ( $Vm^{-1}$ )

But the electron suffering from collisions with other particles in metal and it speed between two successive collisions is (*at*). *t*: is the relaxation time. The distance between two successive collisions is called the *mean free path* and is equal to:

$$l = v_d t \tag{2.2}$$

Electrical mobility is the ability of charged particles (i.e. electrons) to move through a medium in response to an electric field that is pulling them. The external electrical field gives electron drift velocity and acceleration, therefore the drift velocity is equal to:

$$v_d = \mu E \tag{2.3}$$

where  $\mu$  is the electron mobility in a unit ( $m^2 V^{-1} s^{-1}$ ) and it is equal to (*et/m*). The minus sign means the drift velocity is in the direction opposite to that of the external electric field.

*Electrical Conductivity:* Electrical conductivity is a measure of a material's ability to conduct an electric current. It is commonly represented by the Greek letter  $\sigma$ . The following figure shows a box of metal with length *L* and cross-section area *A*. The voltage *V* was applied on the ends of the box. According to Ohm's law: *V* = *I R* and;

$$R = \rho \frac{L}{A} \tag{2.4}$$

Where  $\rho$  is the resistivity in a unit ( $\Omega m$ ). Since R = V/IThen 2.4 become:

 $(I/A) = (1/\rho) \times (V/L) = J$  (Current density) but (V/L) = E and  $(1/\rho) = \sigma$ , then:

# 2.1 Mobility and Conductivity



Figure 2.1: Box of metal

$$J = \sigma E \tag{2.5}$$

Where *J* represents the drift current density.

Now, consider that the metal contains (n) of free electrons per unit volume, then the total free electrons inside the metal is:

$$q = -n \ e \ A \ L \tag{2.6}$$

but  $I = (q/t) = q \times (v_d/L)$ , where  $v_d = (L/t)$ Since  $I = J \times A$  and from 2.5 we have  $J = \sigma E$ , then it can be written:

$$\sigma E = -q \frac{v_d}{L \times A} = -n \, e \, v_d \tag{2.7}$$

Substituting 2.7 in equation 2.3, we can obtain:

$$\sigma = -n \, e \, \mu \tag{2.8}$$

This equation shows that the conductivity depends on the density of the free electrons and the mobility of these electrons. Equation 2.8 can be written in a new form as shown below:

$$\sigma = \frac{n \ e^2 l}{m \ v_d} \tag{2.9}$$

# 2.2 Diffusion Current

In addition to a conduction current, the transport of charges in a semiconductor may be accounted for by a mechanism called diffusion, not ordinarily encountered in metals. The essential features of diffusion are now discussed. It is possible to have no uniform concentration of particles in a semiconductor. As indicated in figure 2.2, the concentration *n* of electrons varies with distance *x* in the semiconductor, and there exists a concentration gradient, dn/dx, in the density of carriers. The existence of a gradient implies the density of electrons immediately on one side of the surface is larger than the density on the other side. The electrons are in a random motion as a result of their thermal energy. Accordingly, electrons will continue to move back. The net transport of electrons across the surface constitutes a current in the positive *X* direction.



Figure 2.2: A no uniform concentration n(x) results in a diffusion current

It should be noted that this net transport of charge is not the result of mutual repulsion among charges of like asign, but is simply the result of a statistical phenomenon. This diffusion is exactly analogous to *the* at which occurs in a neutral gas if a concentration gradient exists in the gaseous container. The diffusion electron-current density  $J_n$  (amperes per square meter) is proportional to the concentration gradient and is given by:  $J_{diff} \propto (dn/dx)$ also,  $J_{diff} \propto D$ 

where *D* is diffusion constant ( $m^2 sec^{-1}$ )

$$J_{diff} = eD \frac{dn}{dx}$$
(2.10)

*D* and  $\mu$  are related by Einstein's relation:

$$D = \frac{kT}{e}\mu\tag{2.11}$$

where T is the temperature in  ${}^{o}K$ 

Total Current: Both a potential gradient and a concentration gradient can exist simultaneously within a semiconductor. In such a situation the total hole current is the sum of the drift current 2.5 and the diffusion current 2.10;

$$J_{tot} = eD\frac{dn}{dx} + \sigma E$$
(2.12)

# 2.3 <u>Work Function</u>

A free electron moves in metal by random motion in the absent external operator or in addition to drift and /or diffusion motion. The kinetic energy makes electrons reach the Fermi level. Then the energy required rising electron to a state outside the metal is  $E_s$  (surface energy), therefore the work function ( $\varphi$ ) is given as:

$$\varphi = E_s - E_f \tag{2.13}$$

The **work function** is the minimum energy (usually measured in electron volts) needed to remove an electron from a solid to a point immediately outside the solid surface (or energy needed to move an electron from the Fermi level into avacuum). Here "immediately" means that the final electron position is far from the surface on the atomic scale but still close to the solid on the macroscopic scale. The work function is a characteristic property of any solid phase of a substance with a conduction band (whether empty or partly filled). For a metal, the Fermi level is inside the conduction band, indicating that the band is partly filled. For an insulator, the Fermi level lies within the band gap, indicating an empty conduction band; in this case, the minimum energy to remove an electron is about the sum of half the band gap and the electron affinity. When the electron absorbs energy *E* then the *K.E.* for this electron outside the metal will be:

$$\frac{1}{2}m v^2 = E - \varphi$$
 (2.14)

This is called **electronic emission**. There are four types of electronic emissions: *Thermionic Emission, Photo Emission, Field Emission, and Secondary Emission*. If thermal energy is supplied to the electrons in the metal, then the energy distribution of the electrons changes, because of the increase in the temperature. The thermal energy given to the charge carrier overcomes the binding potential (work function) and can release it from the metal surface. This is called **Thermionic emission.** According to the *Richardson-Dushman* equation the emitted electron current density,  $J(A.m^{-2})$ , is related to the absolute temperature *T* by the equation:

$$J = A_o T^2 exp(\frac{-\phi}{kT}) \tag{2.15}$$

where  $(A_o)$  is the Richardson-Dushman constant. As mentioned before, the work function is the minimum energy that must be given to an electron to liberate it from the sur- face of a particular substance. In the photoelectric effect, electron excitation is achieved by the absorption of a photon. If the photon's energy is greater than the substance's work

function, **photoelectricemission** occurs and the electron is liberated from the surface. Excess photon energy results in a liberated electron with non-zero kinetic energy. The photoelectric work function is:

$$\varphi = hf_o$$

 $f_o$  is the minimum (threshold) frequency of the photon required to produce photoelectric emission.

Field emission ( $F_E$ ) (also known as field electron emission and electron field emission) is the emission of electrons induced by an electrostatic field. Field emission in pure metals occurs in high electric fields and is strongly dependent upon the work function. The emission current density is given as:

$$J \propto exp\left(\frac{-\phi}{e E x_o}\right) \tag{2.16}$$

*x*<sup>*o*</sup> is the gap thickness.

Secondary electron emission is a phenomenon where primary incident electrons of sufficient energy when hitting a surface of thematerial, induce the emission of secondary electrons. It was found experimentally the number of secondary electrons depends on the following the number and the energy of primary electrons, the angle of incidence of the particles on the material, the type of the material, and the physical condition of the surface. The secondary emission ratio ( $\delta$ ) is defined as:

$$\delta = \frac{\text{no. of the secondary emitted electron}}{\text{no. of the primary incident electron}}$$
(2.17)

#### Solved problems

1. A silicon crystal having a cross section area of  $(0.001cm^2)$  and a length of  $(10^{-3}cm)$  is connected at its ends to (10V) battery at a temperature  $(300^{\circ}K)$ . Find the resistivity and the conductivity of the siliconcrystal if the current passing through the crystal is (100mA).

**Solution** 

$$J = \sigma E \Rightarrow \sigma = \frac{J}{E} = \frac{I/A}{V/L}$$
$$\sigma = \frac{100 \times 10^{-2}/0.001 \times 10^{-4}}{10/(10^{-3} \times 10^{-2})} = 10 \ (\Omega m)^{-1}$$
$$\rho = \frac{1}{\sigma} = \frac{1}{10} = 0.1 \ \Omega m$$

.....

2. Calculate the average drift velocity of a hole in a bar of silicon with a cross sectional area  $(10^{-4}cm^2)$ , containing a holes concentration of  $(4.5 \times 10^{15}cm^{-3})$  and carrying a current of (45mA)?

**Solution** 

$$v_{d} = \mu E \dots (a)$$

$$\sigma = pe \ \mu \dots (b)$$

$$= \sigma E \implies \sigma = \frac{J}{E \dots} (c)$$

Therefore equation (b) becomes:

J

$$\frac{J}{E} = pe\mu \implies \mu = \frac{J}{pe\mu...}(d)$$

From equations (a and d),

$$v_d = \left(\frac{J}{peE}\right) \times E = \frac{J}{pe} = \frac{I/A}{pe} = \frac{45 \times 10^{-3}/10^{-4} \times 10^{-4}}{4.5 \times 10^{15} \times 10^6 \times 1.6 \times 10^{-19}} = 6250 \ ms^{-1}$$

3. A current of  $1\mu A$  passing through an intrinsic silicon bar has 3mm length and  $50 \times 100 \mu m^2$  cross-section. The resistivity of the bar is  $2.3 \times 10^5 \Omega cm$  at  $300^{\circ} K$ . Find the voltage across the bar?

**Solution** 

$$J_{d} = \frac{I}{A} = \sigma E$$

$$E = \frac{J_{d}}{\sigma} = \frac{I}{A} \times \frac{1}{\sigma} = \frac{I}{A} \times \rho$$

$$E = \frac{10^{-6}}{50 \times 10^{-6} \times 100 \times 10^{-6}} \times 2.3 \times 10^{5} \times 10^{-2} = 4.6 \times 10^{5} V.m^{-1}$$

$$V_{bar} = E \times L = 4.6 \times 10^{5} \times 3 \times 10^{-3} = 1380 V$$

4. The electron density variation along the x-axis is given as  $[10^{28} exp(-10^{-6}x)]$ . Find the diffusion current at (x = 0) and  $(x = 10^{-5}m)$  if themobility of the electron is  $(4 \times 10^{-3}m^2V^{-1}s^{-1})$  at  $T = 300^{\circ}K$ ?

**Solution** 

$$J_{diff} = eD\frac{dn}{dx}$$

$$D = \frac{kT}{e}\mu = \frac{1.38 \times 10^{-23} \times 300}{1.6 \times 10^{-19}} \times 4 \times 10^{-3} = 1.035 \times 10^{-4}m^2sec^{-1}$$

$$\frac{dn}{dx} = -10^{28} \times 10^{-6} \times exp(-10^{-6}x)$$

$$J_{diff} = 1.6 \times 10^{-19} \times 1.035 \times 10^{-4} \times [-10^{28} \times 10^{-6} \times exp(-10^{-6}x)]$$

$$1.J_{diff(at \, x=0)} = -1.6 \times 10^{-11} \, Am^{-2}$$

$$2.J_{diff(at \, x=10^{-5})} = 1.035 \times 10^{-4} \times 1.6 \times 10^{-19} \times [-10^{28} \times 10^{-6} \times exp(-10^{-6} \times 10^{-5})]$$

$$= 1.76 \times 10^{11} \, Am^{-2}$$

5. A bar of copper of (2cm) length and resistively of  $(1.8 \times 10^{-8}\Omega m)$  is connected to a power supply of (10V). Find the mobility and drift velocity of the electrons if electron density in copper is  $(8.5 \times 10^{28} m^{-3})$ ? <u>Solution</u>

$$\sigma = n \, e \, \mu \ \Rightarrow \ \mu = \frac{1}{n \, e \, \rho}$$

$$\mu = \frac{1}{8.5 \times 10^{28} \times 1.6 \times 10^{-19} \times 1.8 \times 10^{-8}} = 4.08 \times 10^{-3} m^2 V^{-1} s^{-1}$$

2.4 Generation and Recombination of Charges

 $\mathcal{V}_{d=??}$ 

Generation = break up of covalent bond to form electron and hole pairs. A pure silicon crystal at room temperature derives heat (thermal) energy from the surrounding environment, causing some valence electrons to gain sufficient energy to jump the gap from the valence band into the conduction band, becoming free electrons. When an electron jumps to C.B., a vacancy is left in the valence band. This vacancy is called a hole. If *n* and *p* is the free electron and hole concentration, respectively, per volume unit,



Figure 2.3: Free charge carrier generation in semiconductor

at equilibrium status  $n=p=n_i$ . Where  $n_i$  is the carrier concentration. Recombination occurs when a conduction-band electron loses energy and falls back into a hole in the valence band.

To summarise, a piece of an intrinsic semiconductor at room temperature has, at any instant , a number of conduction-band (free) electrons that are unattached to any atom and are essentially drifting randomly throughout the material. There is also an equal number of holes in the valence band created when these electrons jump into the conduction band.

#### **Electron and Hole Current**

When a voltage is applied across a piece of intrinsic silicon the thermally generated free electrons in the conduction band, which are free to move randomly in the crystal structure, are now easily attracted toward the positive end. This movement of free electrons is one type of current in a semiconductor material and is called *electroncurrent*.

Another type of current occurs in the valence band, where the holes created by the free electrons exist. Electrons remaining in the valence band are still attached to their atoms and are not free to move randomly in the crystal structure as are the free electrons. However, a valence electron can move into a nearby hole with little change in its energy level. thus leaving another hole where it came from. Effectively the hole has moved from one place to another in the crystal structure. as illustrated in Figure 2.4 This is called *hole current*.



Figure 2.4: Hole current in intrinsic silicon

#### 2.4.1 <u>Electrons and Holes Density in an Intrinsic Semiconductor</u>

In a pure (*intrinsic*) semiconductor the number of holes is equal to the number of free electrons and the electrical properties determined by host martial. In intrinsic semiconductor the carrier concentration can be determined from Fermi-Dirac function distribution:

$$n = N_c \exp\left(-\frac{E_c - E_f}{kT}\right) \tag{2.18}$$

$$p = N_v \exp\left(-\frac{E_f - E_v}{kT}\right) \tag{2.19}$$

Where *n* and *p* are the electron and hole concentration, respectively.  $N_c$  is the active level density at C.B. and  $N_v$  is the active level density at V.B. and given by:

and

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

 $m_n^*$ : effective mass of the electron.  $m_p^*$ : effective mass of hole.

(*Effective mass*: When we apply an external force to an electron in a crystal, it may not respond as if it were a free electron. This is because of the interaction with the crystal lattice). Then the number of carriers is:

$$n_i = \sqrt{n p} = \sqrt{N_c N_v} \exp\left(-\frac{E_c - E_v}{2kT}\right)$$
(2.20)

but  $E_g = E_c - E_v$ , then;

$$n_i = \sqrt{n p} = \sqrt{N_c N_v} \exp\left(-\frac{E_g}{2kT}\right) \tag{2.21}$$

It can be observed that the concentration of electrons and holes in pure semiconductors is independent of the location of the Fermi level but it is depending on the temperature.

#### 2.4.2 Electrons and Holes Density in an Extrinsic Semiconductor

Semiconductor materials do not conduct current well and are of limited value in their intrinsic state. This is because of the limited number of free electrons in the conduction band and holes in the valence band. Intrinsic silicon (or germanium) must be modified by increasing the number of free electrons or holes to increase its conductivity and make it useful in electronic devices. This is done by adding impurities to the intrinsic material as you will learn in this section. Two types of extrinsic (impure) semiconductor materials, n-type and p-type, are the key building blocks for most types of electronic devices.

An extrinsic semiconductor can be formed by adding impurity atoms to the intrinsic semiconductor in a process known as doping. The electrical of an extrinsic semiconductor are determined properties by chemical impurities. For example, silicon has four valence electrons. Doping silicon with Aluminum (Al) will produce a hole. The dopant atoms have not enough number of electrons to share bonds with surrounding silicon atoms. One of the silicon atoms has a vacancy for an electron. It creates hole that contributes to the conduction process and the semiconductor is called p-type as shown in figure 2.5(a). The dopant atoms are called **acceptors**. While if the silicon is doped with Phosphor (P) or Arsenide (As), which have an extra electron in valence bands, the dopant atoms contribute an additional electron to the crystal and the semiconductor is called n-type as shown in figure 2.5(b). The dopant atoms are called **donors**.



Figure 2.5: Extrinsic s.c. (a) n-type s.c. (b) p-type s.c.

#### Determination of electrons density for n-type semiconductor

If, to intrinsic silicon, there is added a small percentage of phosphor (*P*) atoms, a doped, impure, or extrinsic, semiconductor is formed. The fifth electron of the phosphor (*P*) will be released by energy 0.05eV, which is the smallest energy required an electron of a silicon atom by 20 times ( $E_g$ = 1.1eV).

Then the density of electrons in the host semiconductor which is doped by  $N_D$  atoms is:

$$n = N_D$$

 $N_D$  is the concentration of donor atoms.

The increasing of the electron density in conduction band case shifting in Fermilevel up word to C.B, then the difference in energy between the old and new position of Fermi-level is:

$$\Delta E_n = E_{fn} - E_{fi}$$



Figure 2.6: Energy band structure in n-type s.c.

The concentration of the electrons in conduction band is:

(2  

$$n = N_D = N_c \exp\left(-\frac{E_c - E_{fn}}{kT}\right)$$
(2.22)

but,  $E_{fn} = \Delta E_n + E_{fi}$ then 2.22 becomes;

$$n = N_D = N_c \exp\left(-\frac{E_c - \Delta E_n - E_{fi}}{kT}\right)$$

$$n = N_D = N_c \exp\left(-\frac{E_c - E_{fi}}{kT}\right) \times \exp\left(\frac{\Delta E_n}{kT}\right)$$

Since;

$$n_i = N_c \exp\left(-\frac{E_c - E_{fi}}{kT}\right)$$

then,

$$n = N_D = n_i \exp\left(\frac{\Delta E_n}{kT}\right) \tag{2.23}$$

From the above equation the shift in Fermi level can be calculated as:

$$\Delta E_n = kT \ln\left(\frac{n}{n_i}\right) = kT \ln\left(\frac{N_D}{n_i}\right) \tag{2.24}$$

$$p = N_v \exp\left(-\frac{E_{fn} - E_v}{kT}\right) \tag{2.25}$$

but,  $E_{fn} = \Delta E_n + E_{fi}$  then 2.25 becomes;

$$p = N_v \exp\left(-\frac{E_{fi} - E_v + \Delta E_n}{kT}\right)$$
$$p = N_v \exp\left(-\frac{E_{fi} - E_v}{kT}\right) \times \exp\left(-\frac{\Delta E_n}{kT}\right)$$

Since;

$$n_i = N_v \exp\left(-\frac{E_{fi} - E_v}{kT}\right)$$

then,

$$p = n_i \exp\left(-\frac{\Delta E_n}{kT}\right) \tag{2.26}$$

It can be observe that the hole density decrease with Fermi level shifting upward:

$$n p = n_i^2$$

Since  $n = N_D$ , then;

$$p = n_i^2 / N_D$$

**Determination of holes density for p-type semiconductor** The doping solid is aluminum (**Al**) or boron (**B**), which have 3 valence electrons only, so the doping atom needs one additional electron to bond with the silicon structure, in this case, it's can be filled from the nearest bond electrons and this will cause break up the bond near vacancy. The energy required is (0.05 eV) for the boron (**B**) atoms, and the number of charge carriers is equal to the number of holes (doping atoms). The impurity atoms in this case called the acceptors atoms and their density is:

$$p = N_A$$

where  $N_A$  is the concentration of acceptor atoms.

The concentration of holes can be determined from the Fermi-Dirac function as below:

$$p = N_v \exp\left(-\frac{E_{fp} - E_v}{kT}\right) \tag{2.27}$$

new position of Fermi-level is:

$$\Delta E_p = E_{fi} - E_{fp}$$



Figure 2.7: Energy band structure in p-type s.c.

$$p = N_A = N_v \exp\left(-\frac{E_{fi} - \Delta E_p - E_v}{kT}\right)$$
$$p = N_v \exp\left(-\frac{E_{fi} - E_v}{kT}\right) \times \exp\left(\frac{\Delta E_p}{kT}\right)$$

Since;

$$n_i = N_v \exp\left(-\frac{E_{fi} - E_v}{kT}\right)$$

then,

$$p = n_i \exp\left(\frac{\Delta E_p}{kT}\right) \tag{2.28}$$

From the above equation the shift in Fermi level can be calculated as:

$$\Delta E_p = kT \ln\left(\frac{p}{n_i}\right) = kT \ln\left(\frac{N_A}{n_i}\right) \tag{2.29}$$

and the number of electrons is equal to:

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

1. The electron density in pure silicon is  $1.45 \times 10^{16} m^{-3}$  at  $300^{\circ} K$ . Find the electron density when the temperature change to  $350^{\circ} K$ , take  $E_g = 1.1 eV$ ?

.....

$$\begin{aligned} \underline{Solution} \\ n_{i1} &= \sqrt{N_c N_v} \exp\left(-\frac{E_g}{2kT_1}\right) \dots (1) \\ n_{i2} &= \sqrt{N_c N_v} \exp\left(-\frac{E_g}{2kT_2}\right) \dots (2) \\ \frac{n_{i1}}{n_{i2}} &= \frac{\exp\left(-\frac{E_g}{2kT_1}\right)}{\exp\left(-\frac{E_g}{2kT_2}\right)} \\ n_{i2} &= n_{i1} \frac{\exp\left(\frac{E_g}{2kT_2}\right)}{\exp\left(\frac{E_g}{2kT_2}\right)} \\ n_{i2} &= n_{i1} \exp\left(\frac{E_g}{2k}\left[\frac{1}{T_1} - \frac{1}{T_2}\right]\right) = 1.45 \times 10^{16} \exp\left(\frac{1.1}{2 \times 8.62 \times 10^{-5}} \times \left[\frac{1}{300} - \frac{1}{350}\right]\right) \\ n_{i2} &= 3.03 \times 10^{17} \, m^{-3} \end{aligned}$$

2. Pure semiconductor with energy gap of 1.42 *eV* and charge carrier den- sity of  $1.79 \times 10^{12} m^{-3}$  at 300 °*K*. Determine the position of the Fermi level with respect of the mid of gap if  $N_c = 4.7 \times 10^{23} m^{-3}$ . What is the value of  $N_v$ ? *Solution* 

\_\_\_\_\_

Since the charge concentration in pure semiconductor is equal to electron concentration, so:

$$n = N_c \exp\left(-\frac{E_c - E_f}{kT}\right)$$

$$E_c - E_f = kT \ln \frac{N_c}{n} = \frac{1.38 \times 10^{-23}}{1.6 \times 10^{-19}} \times 300 \times \ln \left(\frac{4.7 \times 10^{23}}{1.79 \times 10^{12}}\right) = 0.68 \, eV$$

under the  $E_c$ . Therefore the position of Fermi level would be 0.03 eV above the mid of the gap.

\_\_\_\_

\*\* Home work  $\Rightarrow$  Find  $N_{\nu}$  \*\*

3. Pure silicon has electron concentration  $1.45 \times 10^{16} m^{-3}$  at 300 °*K* wasdoped with  $10^{22}m^{-3}$  phosphor (*P*) atoms. Find the electron and hole densities at 300 °*K* and 500 °*K*?

#### **Solution**

Г

 $n_i = 1.45 \times 10^{16} m^{-3}$  before doping at 500  $^{o}K$  the doping solid is phosphor (*P*) which is donor atoms, then;  $n = N_D = 10^{22}m^{-3}$  the density of the solid after doping at 300  $^{o}K$ 

$$\begin{aligned} \frac{n_{i1}}{n_{i2}} &= \frac{exp\left(-\frac{E_g}{2kT_1}\right)}{exp\left(-\frac{E_g}{2kT_2}\right)} \\ n_{i2} &= n_{i1}\frac{exp\left(\frac{E_g}{2kT_1}\right)}{exp\left(\frac{E_g}{2kT_2}\right)} \\ n_{i2} &= n_{i1} \times exp\left(\frac{E_g}{2k}\left[\frac{1}{T_1} - \frac{1}{T_2}\right]\right) = 1.45 \times 10^{16} \times exp\left(\frac{1.1}{2 \times 8.62 \times 10^{-5}} \times \left[\frac{1}{300} - \frac{1}{500}\right]\right) \\ n_{i2} &= 7.2 \times 10^{19} \, m^{-3} \\ p_2 &= \frac{n_{i2}^2}{N_D} = 5.2 \times 10^{17} \, m^{-3} \end{aligned}$$

4. The electron concentration in pure silicon is  $1.5 \times 10^{16} m^{-3}$  at 300 °K. The silicon was doped with  $10^{22}m^{-3}$  donor atoms. Find the electron and hole densities after doping and calculate the position of the newFermi level with to the initial position?

#### **Solution**

After doping the density of electron is  $n = N_D = 10^{22} m^{-3}$ , while the hole density is given as;

$$p = \frac{n_i^2}{N_D} = \frac{1.5 \times 10^{16^2}}{10^{22}} = 2.25 \times 10^{10} \ m^{-3}$$
$$\Delta E_n = kT \ln\left(\frac{N_D}{n_i}\right)$$
$$\Delta E_n = \frac{1.38 \times 10^{-23}}{1.6 \times 10^{-19}} \times 300 \ \times \ln\left(\frac{10^{22}}{1.5 \times 10^{16}}\right) = 0.347 \ eV$$

The new position of Fermi level is above the initial position by 0.347 eV

5. If the position of Fermi level in impure semiconductor at 0.3 *eV* above the mid of the energy gap at 300 °*K*, where the  $E_g = 1.1 \ eV$  and  $n_i = 1.45 \times 10^{16} m^{-3}$ .

What is type of the impurities and what are its concentration?

**Solution** 

Since the Fermi level location is above the mid of the energy gap, therefore the semiconductor would be from n-type. So the impurities are donor atoms.

$$N_D = n_i \times exp\left(\frac{\Delta E_n}{kT}\right)$$

$$N_D = 1.45 \times 10^{16} \times exp\left(\frac{0.3}{8.614 \times 10^5 \times 300}\right) = 1.58 \times 10^{21} \ m^{-3}$$

# 2.5 <u>Electrical conduction in semiconductor</u>

As it was seen that the electron motion and the electrical conduction in metal depend on several parameters which describe the electrical motion in metal, this description for the electron motion and the electrical conduction is thesame as these in semiconductors but takes care of the ratio of doping.

# 2.5 Electrical conduction in semiconductor

#### 2.5.1 Electrical conduction in intrinsic semiconductor

The electrical conduction in the intrinsic semiconductor is the same as the general formula of conductivity in metal:

$$\sigma = ne\mu$$

Applied this formula on an intrinsic semiconductor, the electrons and holes contribute to electrical conduction then:

$$\sigma_i = ne \ \mu_n + p \ e \ \mu_p \tag{2.30}$$

where;

*n*=concentration of electrons  $(m^{-3})$   $\mu_n$ =electron mobility  $(m^2 V^{-1} s^{-1})$  *p*=concentration of holes  $(m^{-3})$  $\mu_p$ =hole mobility  $(m^2 V^{-1} s^{-1})$ 

In a pure semiconductor the concentration of electrons is equal to the concentration of holes; i.e.,  $p=n=n_i$ , then equation 2.30 can be written as;

$$\sigma_i = n_i e \left(\mu_n + \mu_n\right) \tag{2.31}$$

and  $n_i$  is;

$$n_i = \sqrt{N_c N_v} \exp\left(-\frac{E_g}{2kT}\right)$$

$$n_{i} = \sqrt{\left[\frac{2\pi m_{n}^{*} k T}{h^{2}}\right]^{3/2}} \times \left[\frac{2\pi m_{p}^{*} k T}{h^{2}}\right]^{3/2}} \times \left[exp\left(-\frac{E_{g}}{2kT}\right)\right]$$
$$n_{i} = \left[\frac{2\pi k}{h^{2}}\right]^{3/2} \times \left[m_{n}^{*} m_{p}^{*}\right]^{3/4} \times T^{3/2} \times \left[exp\left(-\frac{E_{g}}{2kT}\right)\right]$$
$$n_{i} \propto T^{3/2} \times \left[exp\left(-\frac{E_{g}}{2kT}\right)\right]$$

Since it is known that;

$$\mu_n = \frac{e t_n}{m_n^*}$$

and

$$\mu_p = \frac{e \, t_p}{m_p^*}$$

where,  $t_n$  and  $t_p$  are the relaxation time of electrons and holes respectively.

The mobility depends on the related time and effective mass of moving charges.

Heating the semiconductor causes vibration of atoms and this will affect electron motion inside the crystal structure hence the collision of the electrons with atoms will increase due to the vibration of atoms and therefore the *mobility will decrease*.

$$\mu\,\propto\,T^{-3/2}$$

Then it can be conclude that:

$$\sigma \propto n_i \Longrightarrow \sigma \propto T^{3/2} \times \left[ exp\left( -\frac{E_g}{2kT} \right) \right]$$

and;

 $\sigma \propto \mu \implies \sigma \propto T^{3/2}$ 

As a result of that the semiconductor conductivity affected by temperature as:

$$\sigma_i = \sigma_o \exp\left(-\frac{E_g}{2kT}\right) \tag{2.32}$$

where,  $\sigma_o$  is a constant and **independent of temperature**. Equation 2.32 can also be written as:

$$ln\left(\sigma_{i}\right) = ln\left(\sigma_{o}\right) - \frac{E_{g}}{2kT}$$

The semiconductor conductivity changes strongly with temperature variation.

$$\frac{1}{\sigma_i}\frac{d\sigma_i}{dT} = -\frac{E_g}{2kT} \tag{2.33}$$

#### 2.5.2 Electrical conduction in an extrinsic semiconductor

When the semiconductor is doped by impurities has  $N_D$  concentration (n >> p):

$$\sigma_{(n)} = ne \ \mu_n + p \ e \ \mu_p \tag{2.34}$$

In other words, equation 2.34 can be written as;

$$\sigma_{(n)} = \sigma_n + \sigma_p$$

But  $n \times p = n^2_i = \Rightarrow N_D \times p = n^2_i \Rightarrow p = (n_i^2 / N_D)$ , then equation 2.34 can also be written as;

$$\sigma_{(n)} = N_D \, e \, \mu_n + \frac{n_i^2}{N_D} \, e \, \mu_p \tag{2.35}$$

::  $N_D = n >> n_i$  that is meaning the *p* concentration has no effect and  $(\sigma_n >> \sigma_p)$ , so:  $\sigma_{(n)} = N_D e \mu_n$  In the same manner if the semiconductor is doped by impurities have  $N_A$  acceptor atoms concentration  $(N_A = p >> n_i)$ :  $\sigma_{(p)} = N_A e \mu_p$ 

# 2.6 Diffusion and Drift currents density in semiconductor

There are two mechanisms by which holes and electrons move through a silicon crystal diffusion and drift.

**Diffusion current density:** As aforementioned, the diffusion current density is given as:

$$J_{diff} = -eD \frac{dn}{dx}$$
(2.36)

Since the diffusion current density in a semiconductor is due to electrons and holes motion, then:

$$J_{diff} = J_{diff(n)} + J_{diff(p)} = -e \left( D_n \frac{dn}{dx} + D_p \frac{dp}{dx} \right)$$
(2.37)

Drift current density: As aforementioned the drift current density is given as:

$$J_d = -e n \mu_n \tag{2.38}$$

The free electrons will drift in the direction opposite to that of E. **The total drift current density** is obtained by combining the two charge carriers:

$$J_{drift} = J_d = e E (n\mu_n + p \mu_p)$$
(2.39)

# 2.7 <u>Photo-conductivity</u>

When the semiconductor exposure to an electromagnetic wave has energy (*hf* ) then this energy will cause a generation of new charge carriers to contribute to the electrical conduction process, this iscalled *Photo-conductivity*: If the energy of exposure photon is:  $hf \ge E_g$ . In other words, the minimum wavelength of the absorbed electromagnetic radiation which can produce a new charge carrier will be given as:

$$\lambda \le \frac{1.24}{E_g} \ (\mu m) \tag{2.40}$$

The ability of the semiconductor to absorb photons depend on its nature and  $\sum_{k=1}^{\infty} \sum_{k=1}^{\infty} \sum_{k=1}^{\infty}$ 

$$n_{ph(x)} = n_{ph(o)}.exp(-\alpha x)$$
(2.41)

 $\alpha$ : is the absorption constant.  $\alpha$  proportion to the absorption of solid ability to photons, so if  $\alpha$  is large the solid has a good ability to absorb.

#### Solved problems

- 1. Pure germanium has  $(4 \times 10^{22}) atom. cm^{-3}$  doped by indium atoms, the impurity is added to the extent of 1 part in  $(10^8)$  germanium atoms, if the intrinsic concentration of germanium  $2.5 \times 10^{13} cm^{-3}$ , note that  $\mu_n = 3800 cm^2 (Vs)^{-1}$  and  $\mu_p = 1800 cm^2 (Vs)^{-1}$ .
  - (a) Find the conductivity and the resistivity before the doping?
  - (b) Find the conductivity and the resistivity after the doping?
  - (c) What can you conclude from 1 and 2?

#### <u>Solution</u>

1. The conductivity of pure semiconductor (before doping) is given by:

$$\sigma = ne\mu_n + pe\mu_p$$

since the semiconductor is intrinsic then,  $n = p = n_i$ 

$$\sigma = n_i e \left( \mu_n + \mu_p \right)$$

$$\sigma = 2.5 \times 10^{13} \times 1.6 \times 10^{-19} \times (3800 + 1800) = 0.0224 \, S \, cm^{-1}$$
$$\rho = \frac{1}{\sigma}$$
$$\rho = \frac{1}{0.0224} = 44.64 \, \Omega \, cm$$

2. Doping pure germanium with indium will produce increasing in hole density, so:

$$N_A = \frac{4 \times 10^{22}}{10^8} = 4 \times 10^{14} cm^{-3}$$
$$n \times p = n_i^2 \Rightarrow n \times N_A = n_i^2 \Rightarrow n = \frac{n_i^2}{N_A}$$
$$n = \frac{(2.5 \times 10^{13})^2}{4 \times 10^{14}} = 1.56 \times 10^{12} cm^{-3}$$

The conductivity of the germanium increased more than 5 times after doping with indium.

2. Pure silicon doped by antimony has a concentration equal to  $2 \times 10^{15}$  *atom.*  $cm^{-3}$ , until  $N_D - N_A 2n_i$ , note that they represent the replacement of less than  $10^{-5}$ % of the atoms in the silicon. Find the conductivities  $\sigma_{(n)}$ ,  $\sigma_{(p)}$  and  $\sigma$  and the resistivity  $\rho$  of the silicon? note that  $\mu_n = 1260 \ cm^2 \ (V \ s)^{-1}$  and  $\mu_p = 460 \ cm^2 \ (V \ s)^{-1}$ .

**Solution** 

When pure silicon doped with antimony atoms means doping by donor atoms:

$$N_D = 2 \times 10^{15} atom \ cm^{-3}$$
  

$$\therefore 10^{-5} \times 2 \times 10^{15} - 0 \gg 2n_i$$
  

$$n_i = 10^{10} atom \ cm^{-3}$$
  

$$n.p = n_i^2$$
  

$$p \ N_D = n_i^2 \Longrightarrow p = (n_i^2)/N_D$$
  

$$p = (10^{10})^2/(2 \times 10^{15}) = 5 \times 10^4 \ atoms \ cm^{-3}$$
  

$$\sigma_n = N_D \ e \ \mu_n = 2 \times 10^{15} \times 1.6 \times 10^{-19} \times 1260 = 0.403 \ S \ cm^{-1}$$
  

$$\sigma_p = p \ e \ \mu_p = 5 \times 10^4 \ \times 1.6 \times 10^{-19} \times 460 = 368 \times 10^{-14} \ S \ cm^{-1}$$
  

$$\sigma = \sigma_n + \sigma_p$$

$$\therefore \sigma_n \gg \sigma_p$$
$$\therefore \sigma = \sigma_n$$
$$\sigma = 0.403 \ S \ cm^{-1}$$
$$\rho = \frac{1}{\sigma} = \frac{1}{0.403} = 2.48 \ \Omega \ cm$$

# Chapter Three: Junction- Diode Characteristics

# 3.1 P-N Junction in Equilibrium (Zero Bias)

In a p - n junction, without an external applied voltage, an equilibrium condition is reached in which a potential difference forms across the junction. This potential difference is called built in potential V<sub>D</sub>.

Consider the special case indicated in Fig. 3.1. The left half of the bar is *p*type with a constant concentration  $N_A$ , whereas the right half is *n*-type with a uniform density  $N_D$ . The dashed plane is a metallurgical (p-n) junction separating the two sections with different concentration. This type of doping, where the density changes abruptly from *p*- to *n*-type, is called step grading. The step-graded junction is located at the plane where the concentration is zero.



**Fig. 3.1** Zero Bias (p - n) Junction.

$$V_D = V_{21} = V_T \ln \frac{p_p}{p_n}$$

where  $p_p = N_A$  and  $p_n = \frac{{n_i}^2}{N_D}$ 

1

$$V_D = V_T \ln \frac{N_A N_D}{{n_i}^2}$$

 $V_{\rm T} = KT/e = T/11600$ 

If donor impurites are introduced into one side and acceptors into the other side of a single crystal of a semiconductor, a p-n junction is formed, as in Fig. 3.1. Such a system is illustrated in more schematic detail in Fig. 3.2. The donor ion is represented by a plus sign because, after this impurity atom "donates" an electron, it becomes a positive ion. The acceptor ion is indicated by a minus sign because, after this atom "accepts" an electron, it becomes a negative ion. Initially, there are nominally only p-type carriers to the left of the junction and only n-type carriers to the right.



Fig. 3.2 A schematic diagram of P-N junction.

The region of the junction is depleted of mobile charges, it is called the *depletion region*, the *space charge region*, or the *transition region*.

The thickness of this region is of the order of the wavelength of visible light (0.5 micron =  $0.5\mu m$ ). Within this very narrow space charge layer there

are no mobile carriers. To the left of this region the carrier concentration is  $p=N_A$  and to its right it is  $n=N_D$ .

The space charge density is zero at the junction. It is positive to the right and negative to the left of the junction.

The two terminal device (called a junction diode), as shown in Fig. 3.3, is a device that conducts current in only one direction.



Fig. 3.3 Diode schematic symbol.

# 3.2 P-N Junction Bias

If the external potential of **V volt** is applied across the P-N junction this will bias the diode. There are two type of diode bias :

# **3.2.1 Forward Bias**

**Forward Bias** An external voltage applied with the polarity shown in Fig. 3.4. Where Connecting the positive terminal of the external voltage source to the p-side and the negative terminal to the n-side will cause a forward bias for the junction

The application of **Forward Bias** potential **V** will cause an injection of electrons from n-side and hole from p-side in opposite direction across the junction region and some of these carriers will recombine with the ions near the boundary region and reduce the width of depletion region.

On being injected across the junction, these carriers immediately become minority carriers.



Fig 3.4 P-N Junction biased in the forward direction.

# **3.2.2 Reverse Bias**

**Reverse Bias** If the positive terminal of the applied voltage connect to the n-type and the negative terminal to p-type, as shown in Fig. 3.5, the junction will bias in reverse direction. The depletion region has been winded, that result to overcome the region from the majority carrier more and more carriers.

The current in reverse-bias condition called **Reverse Saturation Current** (Is).



Fig 3.5 P-N Junction biased in the reverse direction.

# Example 1:

A PN junction was formed from two pieces of silicon contain  $N_D = 10^{24} m^{-3}$  and  $N_A = 10^{20} m^{-3}$  at 300°K. Calculate the built in potential of the p-n junction where  $n_i = 1.45 \times 10^{16} m^{-3}$ .

Sol:

$$V_D = \frac{kT}{e} \ln \frac{N_D N_A}{n_i^2}$$
$$= \frac{1.38 \times 10^{-23} \times 300}{1.6 \times 10^{-19}} \ln \frac{10^{24} \times 10^{20}}{(1.45 \times 10^{16})^2} = 0.7 \text{ volt}$$

# Example 2:

The conductivity of n-side in the Ge PN junction is  $10^4 \text{ s/m}$  and for the p-side is  $10^2 \text{ s/m}$ . Find the built in potential for the junction at  $300^{\circ}$ K? where  $n_i = 2.5 \times 10^{19} \text{m}^{-3}$ ,  $\mu_n = 0.36 \text{ m}^2/\text{v.s}$  and  $\mu_p = 0.16 \text{ m}^2/\text{v.s}$ . *sol:* 

#### At n-side:

$$\sigma_{(n)} = n_n e \mu_n + p_n e \mu_p = N_D e \mu_n + \frac{n_i^2}{N_D} e \mu_p$$

$$10^{4} = 1.6 \times 10^{-19} \left( 0.36 \,\mathrm{N_{D}} + \frac{(2.5 \times 10^{19})^{2}}{\mathrm{N_{D}}} \times 0.16 \right)$$

$$N_D = 1.7 \times 10^{23} m^{-3}$$

At p-side:

$$\sigma_{(p)} = p_p e\mu_p + n_p e\mu_n = N_A e \mu_p + \frac{n_i^2}{N_A} e \mu_n$$

$$10^{2} = 1.6 \times 10^{-19} \left( 0.16 \,\mathrm{N}_{\mathrm{A}} + \frac{(2.5 \times 10^{19})^{2}}{\mathrm{N}_{\mathrm{A}}} \times 0.36 \right)$$

5

$$N_A = 3.9 \times 10^{21} m^{-3}$$

$$V_{\rm D} = \frac{kT}{e} \ln \frac{N_{\rm D} N_{\rm A}}{n_{\rm i}^2}$$
$$= \frac{1.38 \times 10^{-23} \times 300}{1.6 \times 10^{-19}} \ln \frac{1.7 \times 10^{23} \times 3.9 \times 10^{21}}{(2.5 \times 10^{19})^2}$$
$$= 0.36 \text{volt}$$

# 3.3 The Volt - Ampere Characteristics of Diode

The relationship between the current that passed through the diode and the voltage applied at its ends is exponential relationship, where the expression for the diode current  $\mathbf{I}$  is :

Where : V : the applied voltage.

 $V_T$ : the volt equivalent of temperature and is given by :

 $V_T = T / 11600 = KT/e$ .

At room temperature (T =  $300^{\circ}$  K), V<sub>T</sub> = 0.026 V = 26 mV.

I<sub>s</sub> : Reverse saturation current.

 $\eta$  : constant , for Ge = 1 , Si = 2 .

The form of Volt -Ampere characteristic described by eqn. (3.1) is shown in Fig. 3.6.



Fig. 3.6 The Volt - Ampere characteristic of an ideal diode .

When the diode is **Reverse Biased** and V is several times  $V_T$ , then  $I \approx I_s$  as shown in the left side of Fig. 3.6. The reverse current is therefore constant, independent of the applied reverse bias.

In Forward Bias, the current beyond the  $V_D$  (Cut in or Threshold voltage) is rises very rapidly, as shown in the right side of Fig. 3.6.  $V_D$  is approximately 0.3 V for Ge and 0.7 for Si.

In forward bias, eqn. (3.1) can be written as :  $I_F = I_s \ e^{\frac{V}{\eta V_T}} \qquad \dots \dots (3.2)$ 

# 3.5 Diffusion Capacitance (CD)

Diffusion capacitance occurs in a forward biased p - n junction diode. The diffusion capacitance occurs due to stored charge of minority electrons and minority holes near the depletion region. When forward bias voltage is applied to the p - n junction diode, electrons (majority carriers) in the n-region will move into the p-region and recombines with the holes. In the similar way, holes in the p-region will move into the n-region and recombines with electrons. As a result, the width of depletion region decreases.

The electrons (majority carriers) which cross the depletion region and enter into the p-region will become minority carriers of the p-region similarly; the holes (majority carriers) which cross the depletion region and enter into the n-region will become minority carriers of the n-region.

A large number of charge carriers, which try to move into another region will be accumulated near the depletion region before the recombine with majority carriers. As a result, a large amount of charge is stored at both sides of the depletion region as shown in Fig. 3.8.



Fig. 3.8 Diffusion capacitance of p - n junction diode.

The accumulation of holes in the n-region and electrons in the p-region is separated by a very thin depletion region. This depletion region acts like insulator of the capacitor and charge stored at both sides of the depletion region acts like conducting plates of the capacitor. The formula for diffusion capacitance is given by:

$$C_D = \frac{dQ}{dV} \qquad \dots \dots (3.3)$$

Where :

dQ : the change in number of minority carriers storied outside the depletion region.

dV : the change in voltage applied across diode.

If  $\tau$  is mean life time of charge carriers, and is given by:

$$\tau = \frac{L^2}{D}$$

Where L is the diffusion length, and D is the diffusion constant.

Then a flow charge Q yields a diode current I is given as :

$$\mathbf{I} = \frac{Q}{\tau} \tag{3.4}$$

In case of forward bias current is given by :

$$I_F = I_S \ e^{\frac{V}{\eta V_T}}$$
  
Substitute eqn.(3.2) in eqn. (3.4) :

$$Q = \tau I_s e^{\frac{V}{\eta V_T}} \qquad \dots \dots (3.5)$$

So, diffusion capacitance C<sub>D</sub> in eqn.(3.3) will become :

$$C_D = \frac{dQ}{dV} = \frac{d(\tau I_s e^{\frac{V}{\eta V_T}})}{dV}$$
$$= \frac{\tau I_s e^{\frac{V}{\eta V_T}}}{\eta V_T}$$
$$\therefore C_D = \frac{\tau I_F}{\eta V_T} \qquad \dots (3.6)$$

# Example 3:

A silicon PN junction has a hole density in p-side  $10^{24}$ m<sup>-3</sup> and electron density in n-side  $10^{22}$ m<sup>-3</sup>, the cross-section area for the pn junction is  $10^{-6}$ m<sup>2</sup>, the mobility of the holes is  $0.2 \text{ m}^2/\text{v.s}$  and the mobility of the electrons is  $0.4 \text{ m}^2/\text{v.s}$ . The diffusion length of the minorities are (L<sub>n</sub> =  $300\mu\text{m}$  and L<sub>p</sub> =  $200\mu\text{m}$ ). If the reverse saturation current equal to  $0.04\mu$  A and  $n_i = 10^{19}\text{m}^{-3}$  at  $17^\circ$  C. Determine:

- 1) The density of majority and minority carriers and the conductivity?
- 2) The barrier potential?
- 3) The diffusion constant for the both types of the carriers?
- 4) The junction current when  $V_F = 0.25v$ ?
- 5) The junction current for the reverse bias, at high reverse voltage?
- 6) The diffusion capacitance of the junction?

# Sol:

# 1)

*At* p – side

$$\begin{split} n_p &= \frac{n_i^2}{p_p} = \frac{(10^{19})^2}{10^{24}} = 10^{14} m^{-3} \text{ electrons minority} \\ N_A &= 10^{24} m^{-3} \text{ holes majority} \\ \sigma_p &= e \ p_p \ \mu_p = 1.6 \times 10^{-19} \times 10^{24} \times 0.2 = 3.2 \times 10^4 \text{ s/m} \\ \sigma_n &= e \ n_p \ \mu_n \ = 1.6 * 10^{-19} * \ 10^{14} * 0.4 \\ \sigma_{(p)} &= \sigma_p + \sigma_n \end{split}$$

<u>At n – side</u>

$$\begin{split} p_n &= \frac{n_i^2}{n_n} = \frac{(10^{19})^2}{10^{22}} = 10^{16} \text{m}^{-3} \text{holes minority} \\ N_D &= 10^{22} \text{m}^{-3} \text{ electrons majority} \\ \sigma_n &= en_n \mu_n = 1.6 \times 10^{-19} \times 10^{22} \times 0.4 = 640 \text{ s/m} \\ \sigma_p &= ep_n \mu_p \\ \sigma_{(n)} &= \sigma_p + \sigma_n \end{split}$$

2) 
$$V_{\rm D} = \frac{kT}{e} \ln \frac{N_{\rm D} N_{\rm A}}{n_{\rm i}^2} = \frac{1}{40} \ln \frac{10^{22} \times 10^{24}}{(10^{19})^2} = 0.46 \text{ volt.}$$

3) 
$$D_n = \frac{kT}{e} \mu_n = \frac{1}{40} \times 0.4 = 0.01 \text{ m}^2/\text{s}$$
  
 $D_p = \frac{kT}{e} \mu_p = \frac{1}{40} \times 0.2 = 0.005 \text{ m}^2/\text{s}$   
4)  $I = I_s \left[ \exp\left(\frac{V}{\eta v_T}\right) - 1 \right]$   
 $V_T = \frac{T}{11600} = \frac{17+273}{11600} = 0.025$ 

I = 
$$0.04 \times 10^{-6} \left[ \exp\left(\frac{0.25}{2 * 0.025}\right) - 1 \right]$$

5) At high reverse voltage:

$$I_R = I_S = 0.04 \ \mu A$$

 $6) C_D = C_{Dn} + C_{Dp}$ 

$$L_p^2 = \tau_p D_p \longrightarrow \tau_p = L_p^2 / D_p$$
$$L_n^2 = \tau_n D_n \longrightarrow \tau_n = L_n^2 / D_n$$

$$C_{Dp} = \tau_p \frac{I_F}{\eta V_T}$$
$$C_{Dn} = \tau_n \frac{I_F}{\eta V_T}$$