# Chapter Two Semiconductors

## 2.1: Introduction to Semiconductor

Certain substances like **germanium**, **silicon**, **carbon** <u>is</u> neither good conductors like copper nor insulators like glass. Such substances are classified as **semiconductors**.

Semiconductors <u>have</u> some useful properties and are being extensively <u>used</u> in electronic circuits.

For instance, **transistor**: a **semiconductor device** <u>is</u> fast replacing bulky vacuum tubes in almost all applications.

In this chapter, we shall focus our attention on the different aspects of semiconductors.

- <u>Low</u> resistivity => "*conductor*".
- <u>High</u> resistivity => "*insulator*".
- <u>Intermediate</u> resistivity => "*semiconductor*".
- Resistivity  $(\rho = R \frac{A}{l})$  or Conductivity  $(\sigma = \frac{1}{\rho})$  lies between that of conductors and insulators.
- Semiconductors <u>are</u> materials which have electrical conductivities lying between those of good conductors and insulators.
- The resistivity of semiconductors varies from  $10^{-5}$  to  $10^{+4} \Omega m$  as compared to the values ranging from  $10^{-8}$  to  $10^{-6} \Omega m$  for conductors and from  $10^7$  to  $10^8 \Omega m$  for insulators.
- There are **elemental semiconductors** <u>such as</u> *Germanium* and *Silicon* which belong to group IV of the periodic table and have **resistivity** of about 0.6 and  $1.5 \times 10^3 \Omega m$  respectively.
- Besides these, there are certain **compound semiconductors** <u>such as</u> *Galiumarsnide* (*GaAs*), *Indium sulphide* (*InP*), *Cadmium sulphide* (*CdS*), etc. which are formed from the combination of the elements of group III and V, or group II and VI.



- Another important characteristic of the **semiconductors** is that they <u>have</u> **small band gap**.
- The **band gap of semiconductors** varies **from 0.2 to 2.5 eV** which <u>is</u> quite **small** <u>as</u> <u>compared</u> to that of **insulators**.
- The band gap of a typical insulator such as diamond is about 6 eV.

#### **Q1**: Why is Diamond important?!!!!

**Answers**: This property determines the **wavelength** of radiation which <u>can be</u> **emitted** or **absorbed** by the semiconductor and hence helps to construct devices such as **light emitting diodes** (LEDs) and **lasers**.

### **Properties of Semiconductors:**

- (i) The **resistivity of a** *semiconductor* is less than an *insulator* but more than a *conductor*.
- (ii) Semiconductors <u>have</u> negative temperature coefficient of resistance i.e. the resistance of a semiconductor <u>decreases</u> with the <u>increase</u> in temperature and vice versa.

For example, **germanium** is actually an **insulator** at **low temperatures** but it becomes a **good conductor** at **high temperatures**.

- (iii) When a suitable metallic impurity (e.g. arsenic, gallium etc.) <u>is added</u> to a **semiconductor**, its current conducting **properties change** appreciably. This property is most important and is <u>discussed</u> later in detail.
- The **band gap energies** for the elements of group IV at **0K** are as follows:

Elements	<b>Band gap Energies</b>	
C (Diamond)	5.51 eV	
Ge (Germanium)	0.75 eV	
Si (Silicon)	1.16 eV	
Sn (Grey) (Tin) (from Latin: Stannum)	0.08 eV	
Pd (Palladium)	0 eV	N.

- At room temperature, diamond behaves <u>as</u> an *insulator*, Ge and Si <u>as</u> *semiconductors* and Sn and Pd <u>as</u> *conductors*.
- The *importance of semiconductors* is further <u>increased</u> due to the fact that the **conductivity** and the effective **band gaps** of these materials <u>can be</u> modified by the <u>introduction</u> of impurities which strongly <u>affect</u> their **electronic and optical properties**.
- The process of <u>adding</u> impurities to a semiconductor <u>is known</u> as <u>doping</u>.

### **Doping:**

Depending on the nature of impurities added, the semiconductors are classified as follows:

- Pure or Intrinsic semiconductors
- Impurity or extrinsic semiconductors
- The intrinsic semiconductors are pure semiconductors in which no impurity atoms are added.
- The extrinsic semiconductors are doped semiconductors in which suitable impurity atoms are added to modify the properties.

In the present, the effect of <u>impurities</u> and <u>charge carrier concentrations</u> in semiconductors are discussed.

## 2.2: Pure or Intrinsic Semiconductors

As stated above, the intrinsic semiconductors such as pure Ge or Si are un-doped semiconductor.

The electrical conductivity of this type of semiconductor is solely determined by thermally generated carriers.

To <u>understand</u> the **mechanism of conduction**, we <u>consider</u> the bonding between atoms in these semiconductors.

Consider, for example, the case of **silicon** with **atomic number 14**. <u>Each</u> **silicon atom** <u>has</u> **four valance electrons** and <u>can form</u> **four covalent bonds** with our <u>neighboring</u> silicon atoms which are directed along the corners of a regular tetrahedron.



#### Silicon Structure

Figure (1): (a) A two-dimensional representation of Si crystal.

(b) Electron-hole pairs in a silicon crystal. Free electrons are being generated continuously while some recombine with holes.

Apparently, all the **valence bonds** and <u>no electron</u> are <u>free</u> to cause conduction particularly <u>at</u> <u>**OK**</u>.

<u>As the temperature increases above 0K</u>, some of the valence electrons <u>may</u> acquire sufficient thermal energy <u>to break their covalent bonds</u> and become free from the influence of cores of the atoms.

The electrons <u>move randomly</u> in the crystal and are referred to as the conduction electrons. Each escaped electron <u>leaves</u> behind an empty space called a hole which also acts as a current carrier.

Thus, <u>when</u> a valence electron <u>breaks away</u> from a covalent bond, an electron hole pair <u>is</u> <u>generated</u> and two carriers of electricity <u>are produced</u> as shown in figure (1b).

Thus, the **motion of an electron** <u>may</u> also <u>be regarded</u> as the **motion of a hole** in the **opposite direction**.



Q2: How to create the current in semiconductor?

created at the **initial position of electron**.

**Answers**: These **electrons and holes** <u>move</u> in **opposite direction** under the effect of an external **electric field** and <u>constitute</u> the **current**.

**Q**ADD: Why the current in semiconductor is small?

The energy band diagram of the intrinsic semiconductor is shown in figure (2).



Figure (2): Energy band diagram of an intrinsic semiconductor showing generation and <u>recombination</u> of an electron and a hole.

<u>At 0K</u>, the valence band is <u>completely filled</u> and the conduction band is <u>completely</u> <u>empty</u>. Therefore, the *semiconductor* <u>behaves as</u> an *insulator*. The electrons present in the valence band <u>do not conduct</u> <del>as</del> these are bound to their cores</del>.

<u>As temperature increases</u>, <u>some</u> of the valence band electrons <u>acquire sufficient</u> thermal energy to jump to the conduction band <u>leaving behind an equal</u> number of holes in the valence band. The electron <u>in</u> the conduction band and hole <u>in</u> valence band <u>behave as</u> free carriers and <u>increase</u> the conductivity of the material. The <u>conditions</u> for the **movement of electrons** are <u>different</u> from the <u>conditions</u> for **movement of holes**: the **electrons move** <u>when</u> the **conduction band** <u>is nearly empty</u> and the **holes move** <u>when</u> the **valence band** <u>is nearly full</u>.

Thus, the **electrons move** <u>mainly under</u> the influence of the **applied field** <u>while</u> the holes move <u>under</u> the <u>combined</u> effect of the **applied electric field** and the **ionic field** of the **lattice**.

Thus, the prosperities such as **effective mass, mobility**, etc. of a **hole** are quite <u>different</u> from the corresponding properties of **electrons**.

For example, a hole <u>has</u> larger effective mass and lower mobility than the corresponding values for an electron.

The charge of a hole is equal and opposite to that of an electron.

It is apparent that, in an **intrinsic semiconductor**, the **number of electrons**  $n_i$ , <u>in</u> the conduction band <u>is always equal to</u> the **number holes**  $p_i$ , <u>in</u> the valence band, i.e.,  $n_i = p_i$ , and either one of these is called the **intrinsic carrier concentration**.

Besides the generation of free electron-hole pairs, there is another process called recombination of carriers in *semiconductors*.

A free electron <u>moving</u> randomly <u>in</u> semiconductor <u>may encounter</u> a hole and <u>combine</u> with it so as to <u>reconstruct</u> the **broken covalent bond**.

Thus, the electron-hole pair <u>is destroyed</u> and the free electron <u>is converted</u> into the bound electron.

This **recombination process** is equivalent to an **electron jumping** from the conduction band to the valence band and occurs with the release of **energy** equal to the **band gap energy** in the form of **electromagnetic radiation** as shown previous in figure 2.

In intrinsic semiconductor, the rate of generation of carriers (g) depends on the temperature and nature of the material.

The recombination rate (R) on the other hand, <u>depends</u> on the concentration of electrons and holes in a material at that temperature. <u>In equilibrium</u>, the generation rate just <u>equals</u> the recombination rate, i.e.,

$$g = R = C n_i p_i$$

Where *C* is a **proportionality constant** which <u>depends</u> on the **nature of the material**. Since <u>in an intrinsic semiconductor  $n_i = p_i$ , we have:</u>

$$g = R = C n_i^2$$

For a given temperature, the quantity  $n_i$  is a constant and <u>depends</u> only on the **nature of the semiconductor**. It will be recognized later that the constant C is **related to the densities** of states of electrons and holes at the conduction band and valence band edged respectively.

### 2.3: Impurity or Extrinsic Semiconductors

The **intrinsic semiconductor** <u>has</u> little current conduction capability <u>at</u> **room temperature**. To be **useful** <u>in</u> electronic devices, the **pure semiconductor** <u>must be altered</u> so as to significantly <u>increase its conducting properties</u>.

This is achieved by <u>adding</u> a small amount of suitable impurity to a semiconductor. It is then called **impurity or extrinsic semiconductor**.

The process of <u>adding</u> impurities to a semiconductor <u>is known</u> as doping. The amount and type of such impurities have to be closely controlled during the preparation of extrinsic semiconductor. Generally, for 10° atoms of semiconductor, one impurity atom is added.

The purpose of <u>adding</u> impurity is to <u>increase</u> either the number of free electrons or holes in the semiconductor crystal. As we shall see, if a <u>pentavalent impurity</u> (<u>having</u> 5 valence electrons) is added to the semiconductor, a <u>large</u> number of free electrons are produced in the semiconductor. On the other hand, addition of trivalent impurity (<u>having</u> 3 valence electrons) *creates* a <u>large</u> number of holes in the semiconductor crystal.

Impurities that contribute to the carrier density of a semiconductor are called **donors** <u>if</u> they supply additional electrons to the conduction band, and <u>acceptors</u> <u>if</u> they supply additional holes to (i.e. capture electrons from) the valence band.

The <u>addition of doping</u> elements significantly <u>increases</u> the **conductivity of a semiconductor**. <u>In fact</u>, **impurity** <u>is accidentally</u> present in **semiconductors** (even <u>in</u> **low concentrations** like 1 atom in  $10^{12}$  atoms), which make it **extrinsic**.

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The impurity atoms <u>are referred</u> to as acceptor or p-type and donor or n-type impurities as they <u>contribute excess</u> holes and electrons respectively to the semiconducting material.

The *semiconductor* is accordingly <u>known</u> as **p-type** or **n-type** *semiconductor*. The **dopants** are <u>added</u> in the ratio of **about 1 in 10^6 to 10^8 atoms** of the semiconducting material.

Such a **small quantity of dopants** <u>does not bring about any structural changes</u> in the semiconductor <u>as</u> the impurity atoms replace the regular atoms in the crystal.

However, the conductivity of the semiconductor is greatly affected by such substitution.

### 2.3.1: Donor or n-Type Semiconductor

<u>When</u> a **pentavalent impurity atom** of group **V**, <u>such as</u> **Phosphorus**, **Arsenic** or **Antimony**, is <u>introduced</u> into silicon, *four* of its *five* valence electrons from covalent bonds with the **neighbouring** *four silicon* atoms <u>while</u> the **fifth** valence electron remain loosely bound to <u>its</u> **nucleus** as shown in figure (3a).





Figure (3a): A pentavalent Impurity atom (P) in a silicon crystal.

<u>A small but definite</u> amount of energy is required to detach this fifth electron from its nucleus and make it free to conduct. However, the energy required is quite small as compared to the energy required for breaking a covalent bond and can be easily provided by thermal agitation inside the crystal.

The energy level <u>corresponding to</u> the fifth valence electron lies in the band gap just below the conduction band edge as shown in figure (3b). This level is called the donor level. The <u>depth</u> of the donor level below the conduction band <u>is</u> merely about 0.01 eV for Ge and 0.03 eV for silicon.



Figure (3b): Energy level diagram of an n-type semiconductor.

The electrons are, therefore, easily <u>transferred to</u> the conduction band leaving behind positively charged immobile impurity ions. Thus, each pentavalent impurity atom <u>donates</u> one free electron to the <u>semiconductor</u>.

Such **impurities** are, therefore, <u>known as</u> **donor or n-type** impurities and the semiconductor <u>containing</u> such impurity atoms is <u>known as</u> **n-type semiconductor**.

In these semiconductors, the current is carried mainly by electrons which are called majority carriers.

The thermally generated holes are called minority carriers. The electron concentration (n) is obviously quite large <u>as compared</u> to hole concentration (p), <u>but</u> their product always remains constant.

i.e.,

 $np = n_i p_i = n_i^2$ 

Where  $n_i$  and  $p_i$  are the intrinsic values of the carrier concentration. This relationship is called the law of mass – action and will be derived later.

CONDUCTION

BAND

VALENCE BAND

BAND ENERGY

## **2.3.2: Acceptor or p-Type Semiconductor**

If a **trivalent impurity atom** of group **III**, <u>such as</u> **Boron**, **Aluminum**, **Gallium** or **Indium**, is <u>introduced</u> into silicon, it forms <u>three</u> covalent bonds with the **neighbouring** <u>three</u> silicon atoms <u>while</u> the **fourth** bond <u>is not completed</u> due to the <u>deficiency</u> of one electron. This <u>incomplete</u> bond is <u>shown</u> by **broken line** in figure (4a) where the small circle (marked a) <u>represents</u> the **electron deficiency**.



Figure (4a): A trivalent impurity atom (B) in a silicon crystal.

Thus, the **trivalent impurity atom** <u>has a tendency</u> to **accept one electron (Say b)** from a neighbouring silicon atom <u>to complete</u> the **fourth** covalent bond. This process <u>requires a</u> <u>small amount of energy</u> which is easily provided by the **thermal** agitation in the crystal. The **transferred electron** <u>leaves</u> behind a broken covalent bond, i.e., a **hole at position** "b" <u>on</u> the silicon atom which <u>acts</u> as a **current carrier**.

The energy level <u>corresponding to</u> the electron deficiency of the type á' is located just above the valence band and is called the acceptor level. The acceptor levels are located at a distance of about 0.01eV above the top of the valence band in Ge and about 0.046 to 0.16 eV in Si.

An **electron** can be easily <u>transferred from</u> the **valence band** to the acceptor level by providing this <u>small amount of energy</u>. This <u>creates</u> **a hole** in the valence band which acts <u>as</u> a **mobile current carrier**.

The negatively charged impurity atom, however, <u>remains immobile</u> and <u>does not contribute</u> to conduction. Thus, each trivalent impurity atom <u>can</u> accept an electron from a neighbouring silicon atom <u>to produce</u> a hole <u>in</u> the <u>semiconductor</u>.



Figure (4b): Energy level diagram of a P-type semiconductor.

Such **impurities** are, therefore, <u>known as</u> **acceptor or p-type impurities** and the semiconductor <u>containing</u> such impurity atoms is <u>known as</u> a **p-type semiconductor**.

In these semiconductors, holes are the majority carriers and thermally generated electrons are the minority carriers.

In this case, hole concentration (p) is quite large <u>as compared</u> to <u>electron concentration</u> (n), <u>but</u> the law of mass action still holds.

i.e.,



It <u>may also be noted</u> that in either type of semiconductors, the overall **charge neutrality** is maintained as <u>no charge</u> is **added to or removed from the material**.

## 2.4: Drift Velocity, Mobility and Conductivity of Intrinsic Semiconductors

### 2.4.1: Drift Velocity

If an electric field  $\vec{E}$  (V/m) is applied to a metal, an electrostatic force is exerted on the free electrons which causes a conduction current to flow. (The arrow indicates a vector quantity.)

The force on an individual electron is given by  $\vec{F} = -q\vec{E}$  (N),

where (q) is the electronic charge ( $q = 1.602 \times 10^{-19}$  C). The electrostatic forces cause the electrons to be accelerated in a direction opposite to that of the applied field.



Figure (5): Electric field applied on various metal shape.

Figure below illustrates the path that an individual electron might take under the influence of the electric field. If the electron did not collide with the bound ions, its velocity would increase indefinitely. However, energy is lost with each collision so that the average velocity approaches a constant or steady-state value. The average velocity  $\vec{v}_d$  (m/s) is called the drift velocity.



Figure (6): Path taken by a free electron in a metal under the influence of an applied electric field.

The drift velocity is proportional to the applied field  $(\vec{v}_d \propto \vec{E})$  and is given by:

$$\vec{p}_d = -\mu_e \vec{E}$$

Where  $\mu_e$  (m<sup>2</sup> V<sup>-1</sup> s<sup>-1</sup>) is the electron mobility.

(The **minus sign** <u>is required</u> because the **negative charge on the electron** causes it <u>to move</u> is a <u>direction opposite to the field</u>.)

The average <u>distance</u> that the electron travels between <u>collisions</u> with the <u>bound ions</u> is called the mean free path.

<u>As the temperature increases</u>, the **bound ions** <u>vibrate</u> with <u>increasing</u> **intensity**, causing the **mean free path** between collisions to <u>decrease</u>.

This effect causes the **drift velocity** ( $\vec{v}$ ) to <u>decrease</u>, which is modeled by a <u>decrease</u> in the **electron mobility** ( $\mu_e$ ) with temperature.

## **2.4.2:** Charge Density (*ρ*)

The charge density  $\rho(C/m^3)$  in a conductor is defined as the free charge per unit volume. To <u>relate</u> the charge density in a metal to the density of free electrons, let n be the number of electrons per m<sup>3</sup>. Because the charge per electron is -q, it follows that the free charge per unit volume in the metal is given by

$$\rho = -nq$$

# **2.4.3:** Current Density $(\vec{J})$

The current density  $\vec{J}$  (A/m<sup>2</sup>) in a conductor is defined as the current per unit area flowing in a particular direction.



$$\vec{J} = \frac{1}{A}\hat{a}$$

To <u>relate</u> the current density in a conductor to the drift velocity of the moving charges, consider a section of wire of length  $\Delta l$  in which a current I is flowing.

The charge in the section is  $\Delta Q = \rho \Delta V = \rho A \Delta l$ , where  $(\rho)$  is the charge density and (A) is the cross-sectional area of the wire.

Let  $(\Delta t)$  be the time required for the charge in the section to move the distance  $(\Delta l)$ . The velocity of the charge is  $\vec{v} = \Delta l / \Delta t \hat{a}$ , where  $\hat{a}$  is a unit vector in the direction of current flow.

The current *I* flowing in the area (*A*) is  $I = \Delta Q / \Delta t$ .

It follows that the current density  $(\bar{j})$  can be <u>related</u> to the drift velocity  $(\bar{v}_d)$  as follows:

$$\vec{j} = \frac{l}{A}\hat{a} = \frac{1}{A}\frac{\Delta Q}{\Delta t}\hat{a} = \frac{\rho A \Delta l}{A \Delta t}\hat{a} = \rho \left(\frac{\Delta l}{\Delta t}\right)\hat{a} = \rho \vec{v}_d$$
 Prove it!

## **2.4.4:** Conductivity (*σ*)

We can <u>relate</u> the current density  $(\bar{j})$  to the electric field  $(\bar{E})$  in a metal as follows:

$$\vec{J} = \rho \vec{v} = (-nq) \left(-\mu_e \vec{E}\right)$$
$$\vec{J} = nq\mu_e \vec{E} = \sigma \vec{E}$$

This equation defines the **conductivity**  $\sigma$  ( $\Omega^{-1}$  m<sup>-1</sup>) of the metal. It is given by:

 $\boldsymbol{\sigma} = \boldsymbol{n}\boldsymbol{q}\boldsymbol{\mu}_{\boldsymbol{e}}$ 

## **2.4.5:** Conductivity of a Semiconductor ( $\sigma$ )

Where  $\sigma$  represents the **electronic conductivity** of the material, we get:

Similarly, we can write the expression for the conductivity due to holes in the valence band as:

 $\sigma_p = pq\mu_p$ 

The conductivity of a semiconductor is given by:

$$\sigma = \sigma_n + \sigma_p \quad \rightarrow \sigma = q(\mu_n n + \mu_p p)$$

Where  $\mu_n$  and  $\mu_p$  refer to the **mobilities of the electrons** and **holes**, and *n* and *p* refer to the **density of electrons** and **holes**, respectively.

For an intrinsic semiconductor:  $n = p = n_i$ Therefore, equation of total conductivity reduces:

### $\boldsymbol{\sigma} = \boldsymbol{n}_i \boldsymbol{q} (\boldsymbol{\mu}_n + \boldsymbol{\mu}_p)$

It is important to note that, in semiconductors, the movement of carriers or the flow of current is, in fact, the consequence of the following two processes:

1. **Drift of carriers** under the effect of an applied field; the resulting current is called the **drift current**.

2. **Diffusion of carriers** under the effect of concentration gradient of dopants presents inside the semiconductor; the corresponding current is called the **diffusion current**.

In the above treatment, we have considered only the drift current contribution. The diffusion current contribution is absent in semiconductor having a uniform distribution of impurities.

## **2.4.6: Resistance** (*R*)

The current density is:

$$\vec{J} = \frac{I}{A}\hat{a} = \frac{1}{A}\frac{\Delta Q}{\Delta t}\hat{a} = \frac{\rho A \Delta l}{A \Delta t}\hat{a} = \rho \left(\frac{\Delta l}{\Delta t}\right)\hat{a} = \rho \vec{v}_d = (-nq)(-\mu_e \vec{E}) = nq\mu_e \vec{E} = \sigma \vec{E}$$
  
we can write:  $\vec{J} = \sigma \frac{V}{M}\hat{a}$ 

we can write:  $J = \sigma_{\Delta l} a$ By equating the two relations for  $\vec{j}$ , we obtain:

$$\frac{I}{A}\hat{\boldsymbol{a}} = \boldsymbol{\sigma}\frac{\boldsymbol{V}}{\Delta \boldsymbol{l}}\hat{\boldsymbol{a}}$$

This equation can be solved for the resistance  $(R = \frac{V}{I})$  of the section of wire to obtain:

R

$$=\frac{\Delta l}{\sigma A}$$
 Prove it!

Thus, the resistance is directly proportional to the length of the wire and inversely proportional to its area. Because the conductivity  $\sigma$  decreases with temperature, it follows from this equation that **R** increases with temperature. In most metals, the resistance increases linearly with temperature ( $R_t = R_0(1 + \alpha \Delta T)$ ).

### **2.4.7: Variation of Conductivity with Temperature**

Assuming mobilities to be <u>independent</u> of temperature, the temperature <u>dependence</u> of conductivity arises because of the <u>variation</u> of intrinsic carrier concentration  $(n_i)$  with temperature. It will be proved that  $n_i$  is given by:

$$n_i = \frac{2(2\pi KT)^{\frac{3}{2}}}{h^3} (m_n m_p)^{\frac{3}{4}} e^{-(\frac{E_g}{2KT})}$$

Where  $m_n$  and  $m_p$  represent the effective masses of an electron and a hole respectively,  $E_g$  is the band gap, K is the Boltzmann's constant and T is the absolute temperature. Substituting  $n_i$  into total conductivity equation, we get:  $\sigma = n_i q(\mu_n + \mu_n)$ 

$$\sigma = e(\mu_n + \mu_p) \frac{2(2\pi KT)^{\frac{3}{2}}}{h^3} (m_n m_p)^{\frac{3}{4}} e^{-(\frac{E_g}{2KT})}$$

We take In for both sides, we get:

$$ln\sigma = -\left(\frac{E_g}{2K}\right)\frac{1}{T} + \frac{3}{2}lnT + constant$$

The **first term** on the right-hand side is the **dominant term**.

The plot of  $ln \sigma$  versus 1/T is a right line as shown in this figure. The <u>slope</u> of the line gives an <u>estimate</u> of the **band gap of the semiconductor**.



**Example 2.1:** Aluminum has three valence electrons per atom, an atomic weight of 0.02698 Kg/mol, a density of  $2700 \text{ Kg/m}^3$ , and a conductivity of  $3.54 \times 10^7 \text{ S/m}^{-1}$ . Calculate the electron mobility in aluminum. Assume that all three valence electrons in each atom are free.

#### **Solution:**

Recall from introductory chemistry that a mole of any substance is a quantity equal to its atomic weight and contains a number of molecules equal to **Avogadro's number** which is  $6.02 \times 10^{23}$ . It follows that the number of aluminum atoms per m<sup>3</sup> is:

$$n = \frac{N_A}{V} = \frac{N_A \rho}{m} = \frac{6.02 \times 10^{23} \frac{atoms}{mol} \times 2700 \frac{\text{Kg}}{\text{m}^3}}{0.02698 \frac{\text{Kg}}{mol}} = 6.024 \times 10^{28} \text{ m}^{-3}$$

Thus, the electron density in the aluminum is  $n=3\times6.024\times10^{28} = 1.807\times10^{29} \text{ m}^{-3}$ The mobility is given by:

$$\mu_e = \frac{\sigma}{nq} = \frac{3.54 \times 10^7}{1.807 \times 10^{29} \times 1.602 \times 10^{-19}} = 3.67 \times 10^{-3} m^2 V^{-1} s^{-1}$$

**Example 2.2:** The conductivity of copper is  $5.8 \times 10^7$  S/m. If a 1 m length of copper wire has a resistance of 1  $\Omega$ , what is the thickness of the wire? Assume a circular cross section.

#### **Solution:**

$$R = \frac{\Delta l}{\sigma A} \rightarrow A = \frac{\Delta l}{\sigma R} = \pi r^2 = \pi \left(\frac{d}{2}\right)^2 = \pi \frac{d^2}{4} \rightarrow d = 2\sqrt{\frac{\Delta l}{\pi \sigma R}} = 2\sqrt{\frac{1}{\pi \times 5.8 \times 10^7 \times 1}} = 0.0148 \, mm$$

**H.W: Q3**: A 20m length of cable has a cross-sectional area of  $1\text{mm}^2$  and a resistance of  $5\Omega$ . Calculate the conductivity of the cable. Data given: DC resistance, R=5 $\Omega$ , cable length L=20m, and the cross-sectional area of the conductor is  $1\text{mm}^2$  giving an area of: A=1×10<sup>-6</sup>m<sup>2</sup>.

**Solution:** 

## 2.5: Carrier Concentration and Fermi Level for Intrinsic Semiconductor

The **concentration of electrons and holes** <u>in</u> a semiconductor <u>can be obtained</u> from the knowledge of the **densities of available states** <u>in</u> the valence band and the conduction band as well as the **Fermi–Dirac distribution function**. The expression for the **Fermi energy** is then <u>obtained</u> from this **carrier concentration**.

### **2.5.1: Electron Concentration in the Conduction Band**

The **number of free electrons per unit volume** (dn) in an energy range E and (E + dE) can be written as:

$$dn = D_{(E)} f_{(E)} dE \dots (1)$$

Where  $D_{(E)}$  is the density of states defined as the total number of allowed electronic states per unit volume in a semiconductor and  $f_{(E)}$  is the Fermi distribution function representing the probability of occupation of a state with energy *E*.

The expression for  $f_{(E)}$  is given as:

$$f_{(E)} = \frac{1}{e^{\left(\frac{E-E_f}{KT}\right)} + 1} \dots (2) \text{ (Save it)}$$

Whereas that for  $D_{(E)}$ , which is strictly valid for free electrons, is obtained:

$$D_{(E)} = \frac{4\pi}{h^3} (2m)^{\frac{3}{2}} E^{\frac{1}{2}} \dots (3)$$

It apparent that an electron occupying an energy state E in the conduction band, in fact, possess the kinetic energy (E - Ec).

Thus, equation (1) becomes by using equations (2) and (3):

$$dn = \frac{4\pi}{h^3} (2m_n)^{\frac{3}{2}} (E - E_c)^{\frac{1}{2}} \frac{1}{e^{\left(\frac{E - E_f}{KT}\right)} + 1}} dE \dots (4)$$

Where  $m_n$  is the effective mass of the electron in the conduction band.

The concentration of electrons (*n*) in the conduction band is obtained by <u>integrating</u> equation (4) from  $E = E_c$  to  $E = \infty$ , i.e;

$$n = \frac{4\pi}{h^3} (2m_n^*)^{\frac{3}{2}} \int_{E_c}^{\infty} \frac{(E-E_c)^{\frac{1}{2}}}{e^{\left(\frac{E-E_f}{KT}\right)} + 1} dE \quad \dots (5)$$

Now, <u>near room temperature</u>,  $KT \approx 0.026 \, eV$ . Therefore, for <u>energies greater</u> than  $E_c$ ,  $\therefore e^{\left(\frac{E-E_f}{KT}\right)} + 1 \cong e^{\left(\frac{E-E_f}{KT}\right)}$  $n = \frac{4\pi}{h^3} (2m_n^*)^{\frac{3}{2}} \int_{E_c}^{\infty} (E - E_c)^{\frac{1}{2}} e^{-\left(\frac{E-E_f}{KT}\right)} dE$ 

Add; 
$$+E_{c} - E_{c}$$
  
 $n = \frac{4\pi}{h^{3}} (2m_{n}^{*})^{\frac{3}{2}} \int_{E_{c}}^{\infty} (E - E_{c})^{\frac{1}{2}} e^{\left[-\left(\frac{E - E_{f} + E_{c} - E_{c}}{KT}\right)\right]} dE$   
 $n = \frac{4\pi}{h^{3}} (2m_{n}^{*})^{\frac{3}{2}} e^{\left[-\left(\frac{E_{c} - E_{f}}{KT}\right)\right]} \int_{E_{c}}^{\infty} (E - E_{c})^{\frac{1}{2}} e^{\left[-\left(\frac{E - E_{c}}{KT}\right)\right]} dE$ 

Let 
$$\left(\frac{E-E_{c}}{KT}\right) = x_{i} dE = KT dx$$
, For  $E = E_{c}, x = 0$   
 $n = \frac{4\pi}{h^{3}} (2m_{n}^{*})^{\frac{3}{2}} e^{\left[-\left(\frac{E_{c}-E_{f}}{KT}\right)\right]} \int_{E_{c}}^{\infty} x^{\frac{1}{2}} [KT]^{\frac{1}{2}} e^{[-x]} KT dx_{i}$   
 $n = \frac{4\pi}{h^{3}} (2m_{n}^{*} KT)^{\frac{3}{2}} e^{\left[-\left(\frac{E_{c}-E_{f}}{KT}\right)\right]} \int_{0}^{\infty} x^{\frac{1}{2}} e^{-x} dx_{i}$   
Now:  $\int_{0}^{\infty} x^{\frac{1}{2}} e^{-x} dx = \left[\frac{\pi}{4}\right]^{\frac{1}{2}};$   
 $n = 2 \left[\frac{2\pi m_{n}^{*} KT}{h^{2}}\right]^{\frac{3}{2}} e^{-\left(\frac{E_{c}-E_{f}}{KT}\right)} \dots (6)$ 

From equation (2), the probability of occupancy of level  $E_c$  is given by: Therefore, equation (6) becomes:  $f_{(E_c)} = \frac{1}{e^{\left(\frac{E_c - E_f}{KT}\right)} + 1} \cong e^{-\left(\frac{E_c - E_f}{KT}\right)}$  $n = 2\left[\frac{2\pi m_n^* KT}{h^2}\right]^{\frac{3}{2}} f_{(E_c)} \dots (7)$ 

The first term on the right-hand side must <u>represent</u> the <u>effective density</u> of state of <u>electrons at</u> the conduction band edge. Denoting it by  $N_c = 2 \left[ \frac{2\pi m_n^* KT}{h^2} \right]^{\frac{3}{2}} \dots (9)$ , we have:  $n = N_c e^{-\left(\frac{E_c - E_f}{KT}\right)} \dots (8)$ For silicon;  $N_c = 2.8 \times 10^{25} \left[ \frac{T}{300} \right]^{\frac{3}{2}} m^{-3}$  **Example 2.3:** Calculate the energy relative to the Fermi energy for which the Fermi function equals 5%. Write the answer in units of *KT*.

**Solution:** The problems states that:

$$f_{(E)} = \frac{1}{e^{\left(\frac{E-E_f}{KT}\right)_{+1}}} = 0.05, e^{\left(\frac{E-E_f}{KT}\right)} + 1 = \frac{1}{00.5} = 20, \frac{E-E_f}{KT} = \ln (20-1),$$
  
Which can be solved vielding:  $E - E_f = \ln (19)KT = 3KT$ 

**Example 2.4:** Calculate the effective densities  $(N_c)$  of states in the conduction and valence bands of germanium at 300K.

**Solution:** The effective density of states in the conduction band of germanium equals:

$$N_{c} = 2 \left[ \frac{2\pi m_{n}^{*} KT}{h^{2}} \right]^{\frac{5}{2}},$$
  

$$N_{c} = 2 \left[ \frac{2\pi \times 0.55 \times 9.11 \times 10^{-31} \times 1.38 \times 10^{-23} \times 300}{(6.626 \times 10^{-34})^{2}} \right]^{\frac{3}{2}} = 1.02 \times 10^{19} cm^{-3}.$$

### 2.5.2: Hole Concentration in The Valence Band

An expression similar to equation (1) for the **number of holes per unit volume** in the energy range *E* and E + dE can be written as:

$$dp = D_{(E)} [1 - f_{(E)}] dE \dots (10)$$

Where we have <u>replaced</u>  $f_{(E)}$  by  $[1 - f_{(E)}]$  which <u>represents</u> the probability of an energy state E <u>not</u> to be occupied by an electron, i.e., the probability of finding a hole in the energy state E.

Now; 
$$1 - f_{(E)} = 1 - \frac{1}{e^{\left(\frac{E-E_f}{KT}\right)} + 1} = \frac{e^{\left(\frac{E-E_f}{KT}\right)}}{e^{\left(\frac{E-E_f}{KT}\right)} + 1}$$

In the valence band, since  $E < E_f$  the exponential term in the denominator may be neglected in comparison to unity. Thus, we get:

$$1 - f_{(E)} = e^{\left(\frac{E-E_f}{KT}\right)} \dots (11)$$

It follows that the probability of finding holes decreases exponentially with increase in depth into the valence band. Also, in the kinetic energy of a hole in the energy state in the valence band is  $(E_v - E)$ . Therefore, the **density of states per unit volume in the valence band** can be written as:

$$D_{(E)} = \frac{4\pi}{h^3} (2m_p^*)^{\frac{3}{2}} (E_v - E)^{\frac{1}{2}} \dots (12)$$

Where  $m_p^*$  is the effective mass of a hole in the valence band.

Using equations (11) and (12) in equation (10);

 $dp = \frac{4\pi}{h^3} (2m_p^*)^{\frac{3}{2}} (E_v - E)^{\frac{1}{2}} e^{\left(\frac{E-E_f}{KT}\right)} dE$ and integrating from  $E = \infty$  to  $E = E_v$ , we obtain the hole concentration in the valence band as:  $p = \frac{4\pi}{h^3} (2m_p^*)^{\frac{3}{2}} \int_{-\infty}^{E_v} (E_v - E)^{\frac{1}{2}} e^{\left[\left(\frac{E-E_f}{KT}\right)\right]} dE$ , Add;  $+E_v - E_v$  $p = \frac{4\pi}{h^3} (2m_p^*)^{\frac{3}{2}} \int_{-\infty}^{E_v} (E_v - E)^{\frac{1}{2}} e^{\left[\left(\frac{E-E_f+E_v-E_v}{KT}\right)\right]} dE$ ,

$$p = \frac{4\pi}{h^3} (2m_p^*)^{\frac{3}{2}} e^{\left[\left(\frac{E_v - E_f}{KT}\right)\right]} \int_{-\infty}^{E_v} (E_v - E)^{\frac{1}{2}} e^{\left[\left(\frac{E - E_v}{KT}\right)\right]} dE$$

Let 
$$\left(\frac{E_{v}-E}{KT}\right) = x$$
,  $dE = -KT \, dx$ , For  $E_{v} = E$ ,  $x = 0$   
 $p = \frac{4\pi}{h^{3}} (2m_{p}^{*})^{\frac{3}{2}} e^{\left[\left(\frac{E_{v}-E_{f}}{KT}\right)\right]} \int_{-\infty}^{0} x^{\frac{1}{2}} (KT)^{\frac{1}{2}} e^{-x} (-KT \, dx)$ ,  
 $p = \frac{4\pi}{h^{3}} (2m_{p}^{*})^{\frac{3}{2}} e^{\left[\left(\frac{E_{v}-E_{f}}{KT}\right)\right]} (KT)^{\frac{3}{2}} \int_{0}^{-\infty} x^{\frac{1}{2}} e^{-x} \, dx$ ,  
Now:  $\int_{0}^{-\infty} x^{\frac{1}{2}} e^{-x} \, dx = \left[\frac{\pi}{4}\right]^{\frac{1}{2}}$ ;  
 $p = \frac{4\pi}{h^{3}} (2m_{p}^{*}KT)^{\frac{3}{2}} e^{\left[\left(\frac{E_{v}-E_{f}}{KT}\right)\right]} \left(\frac{\pi}{4}\right)^{\frac{1}{2}}$ ,  
 $p = 2\left(\frac{2\pi m_{p}^{*}KT}{h^{2}}\right)^{\frac{3}{2}} e^{\left[-\left(\frac{E_{f}-E_{v}}{KT}\right)\right]} \dots (13)$ 

The first term on the right-hand side must represent the effective density of holes <u>at</u> the valance band edge. Denoting it by  $N_v = 2(\frac{2\pi m_p KT}{h^2})^{\frac{3}{2}} \dots (15)$ , we have:  $p = N_v e^{\left[-\left(\frac{E_f - E_v}{KT}\right)\right]} \dots (14)$ For silicon;  $N_v = 2.8 \times 10^{25} \left[\frac{T}{300}\right]^{\frac{3}{2}} m^{-3}$ 

The electron and hole concentrations  $(n_i, p_i)$  given by equations (8) and (14) respectively are valid for intrinsic and extrinsic materials. For intrinsic materials, these equations can also be written as:

$$\boldsymbol{n_i} = N_c e^{-\left(\frac{E_c - E_i}{KT}\right)}, \qquad \boldsymbol{p_i} = N_v e^{\left[-\left(\frac{E_i - E_v}{KT}\right)\right]} \dots (16)$$

Where the Fermi level  $E_f$  has been replaced by the intrinsic level  $E_i$ .

### 2.5.3: Fermi Level

For an intrinsic semiconductor,  $N = n_i = p_i$ Therefore, from equations (8) and (14), we get:

$$N_c e^{-\left(\frac{E_c - E_f}{KT}\right)} = N_v e^{-\left(\frac{E_f - E_v}{KT}\right)}$$

OR:  $e^{\frac{2E_f - E_c - E_v}{KT}} = \frac{N_v}{N_c},$   $\frac{2E_f - E_c - E_v}{KT} = \ln\left(\frac{N_v}{N_c}\right),$ 

$$E_f = \frac{E_c + E_v}{2} + \frac{KT}{2} \ln\left(\frac{N_v}{N_c}\right) \dots (17)$$

Using equations (9) and (15) in equation (17), we obtain:

$$E_{f} = \frac{E_{c} + E_{v}}{2} + \frac{3KT}{4} \ln\left(\frac{m_{p}^{*}}{m_{n}^{*}}\right) \dots (18)$$

At T = 0 K,  $E_f = \frac{E_c + E_v}{2}$  .... (19)

i.e., the **Fermi level** <u>lies</u> in the middle of the conduction band and valence band. This is also <u>true</u> at all other temperatures provided  $m_p^* = m_n^*$ .

However, in general,  $m_p^* > m_n^*$  and the **Fermi level** is raised slightly as *T* exceeds 0K. For Si <u>at</u> 300K, the <u>increase</u> in Fermi energy is about **0.01eV** only which <u>may be neglected</u> for all practical purposes.

### 2.5.4: Law of Mass Action and Intrinsic Carrier Concentration

For an intrinsic semiconductor,  $N = n_i = p_i$ The equations (8) and (14) yield:

$$\boldsymbol{np} = \boldsymbol{n}_i^2 = N_c N_v \boldsymbol{e}^{-\left(\frac{E_c - E_v}{KT}\right)}$$

Let 
$$E_c - E_v = E_g$$
  
 $n_i^2 = N_c N_v e^{-\left(\frac{E_g}{KT}\right)} \dots (20)$   
 $np = n_i^2 = 4\left(\frac{2\pi KT}{h^2}\right)^3 (m_p^* m_n^*)^{\frac{3}{2}} e^{-\frac{E_g}{KT}} \dots (21)$ 

This shows that, for a given semiconductor, the product of electron and hole concentration is a constant at a given temperature and is equal to the square of the intrinsic carrier concentration. This is called the law of mass action and holds for both intrinsic and extrinsic semiconductors. If impurity atoms are added to a semiconductor to increase n, there will be a corresponding decrease in p such that the product np remains constant. Thus, we always have:

$$np = n_i^2 \dots (22)$$

The intrinsic carrier concentration can be directly obtained from equation (20) Or (21) as:

$$n_{i} = (N_{c}N_{v})^{\frac{1}{2}}e^{-\left(\frac{E_{g}}{2KT}\right)} \dots (23)$$
  
$$n_{i} = 2\left(\frac{2\pi KT}{h^{2}}\right)^{\frac{3}{2}}(m_{p}^{*}m_{n}^{*})^{\frac{3}{4}}e^{-\frac{E_{g}}{2KT}} \dots (24)$$

For a pure Ge a 300K, the intrinsic electron concentration is about  $2.4 \times 10^{19} \text{m}^{-3}$  when the concentration of germanium atoms is  $4.4 \times 10^{28} \text{m}^{-3}$ . This shows that, at ordinary temperature, only about five covalent bonds per  $10^{10}$  atoms of germanium are broken and contribute to intrinsic conduction. On the other hand, in metals such as copper, about  $10^{28}$  electrons per cubic meter are a available for conduction.

As described earlier, the donor or acceptor levels are present in an extrinsic semiconductor depending on the type of impurity present. The concentration of donors or acceptors in semiconductor affect the Fermi energy, the carrier concentration and the conductivity of the semiconductor. We consider the following cases:

EF

Ed

## **2.6.1: N-Type Semiconductor**

The electron concentration must be equal to the sum of the concentration of ionized donors,  $N_d$ , in the donor levels and the concentration of thermally generated holes in the valence band, i.e.,

$$\boldsymbol{n} = \boldsymbol{N}_{\boldsymbol{d}}^{+} + \boldsymbol{p}$$

If a sufficient number of donors are present to produce electrons in the conduction band, the concentration of thermally generated holes gets suppressed as a consequence of the law of mass action. Thus, p may be neglected in above equation which, therefore becomes:


$$N_d^+ = N_d f(1 - E_d)$$

The free electron concentration in the conduction band is:

$$\boldsymbol{n} = \sqrt{N_c N_d} \boldsymbol{e}^{-\left(\frac{\Delta E}{2KT}\right)}$$

Where  $\Delta E = E_c - E_d$  represents the ionization energy of the donors.

The position of the **Fermi level** at moderate temperatures is given by:

$$E_f = \frac{E_d - E_c}{2} + \frac{KT}{2} \ln\left(\frac{N_d}{N_c}\right)$$

The only valid information obtainable from this equation is that the Fermi level lies somewhere near the middle of the donor level and the conduction band edge v at moderate temperatures.

The **electrical conductivity** of an n-type semiconductor can be calculated from:

$$\sigma_n = en\mu_n = eN_d^+\mu_n$$

Where  $\mu_n$  is the electron mobility.

### 2.6.2: P-Type Semiconductor

If n, p,  $N_a$  and  $N_a^-$  represents electron concentration in the conduction, hole concentration in the valence band, total acceptor concentration, and concentration of ionized acceptors respectively, then

 $p = N_a^- + n$ <u>Neglecting</u> n in comparison with for p-type  $\mathbf{E}_a$ semiconductor, we get:

 $p = N_a^-$ The concentration of ionized acceptors is given by:  $N^- = N_a f(F_a)$ 

$$N_a = N_a J(E_a)$$



Conduction band

The free hole concentration in the valence band is:

$$\boldsymbol{p} = \sqrt{N_v N_a} \boldsymbol{e}^{-\left(\frac{\Delta E}{2KT}\right)}$$

Where  $\Delta E = E_c - E_d$  represents the ionization energy of the donors.

$$E_f = \frac{E_a - E_v}{2} - \frac{KT}{2} \ln\left(\frac{N_a}{N_v}\right)$$

The **Fermi level** at moderate temperatures <u>lies</u> near the middle of the acceptor level and the top of the valence band.

The **electrical conductivity** of a *p*-type semiconductor is given by:

$$\sigma_p = ep\mu_p = eN_a^-\mu_p$$

Where  $\mu_p$  is the hole mobility.

### 2.6.3: Mixed Semiconductor

In semiconductor containing both n and p -type impurities, the law of electrical neutrality is written as:  $N_d^+ + p = N_a^- + n$ Taking and using equation  $(np = n_i^2)$ , we obtain:  $n = p = n_i$ 

This shows that, for equal concentrations of donors and acceptors, the semiconductor behaves as pure or intrinsic semiconductor. All the ionized acceptors combine with free electrons of the donors and all ionized donors combine with free holes of the acceptors to produce no net free carriers. For  $N_d^+ \neq N_a^-$  or simply  $N_d \neq N_a$  (donors and acceptors are assumed to be ionized), the semiconductor behaves as n-type or p-type depending on the relative magnitudes of Nd and Na, and the cases described above become applicable.

#### **REVIEW Yourself**!!!

#### H.W: Q4:

- 1. In an intrinsic semiconductor, the number of free electrons
  - (a) Equals than the number of holes
  - (c) Is less than the number of holes
- 2. In an intrinsic semiconductor.
  - (a) there are no free electrons
  - (c) there are only holes
- (e) answers (b) and (d)
- 3. The process of adding an impurity to an intrinsic semiconductor is called
  - (a) doping (b) recombination (c) atomic modification (d) ionization
- 4. A trivalent impurity is added to silicon to create
  - (a) germanium (b) a p-type semiconductor (c) an n-type semiconductor (d) a depletion region
- 5. The purpose of a pentavalent impurity is to
  - (a) reduce the conductivity of silicon (b) increase the number of holes
  - (c) increase the number of free electrons (d) create minority carriers
- 6. The majority carriers in an n-type semiconductor are
  - (a) holes (b) valence electrons (c) conduction electrons (d) protons
- 7. Holes in an n-type semiconductor are
  - (a) minority carriers that are thermally produced
  - (b) minority carriers that are produced by doping
  - (c) majority carriers that are thermally produced
  - (d) majority carriers that are produced by doping
- 8. In n-type semiconductors, holes are:

(a) majority carriers (b) minority carriers (c) absent (d) none of these

#### **05:** What is Intrinsic Semiconductor?

Pure form of semiconductors is said to be intrinsic semiconductor. Ex: germanium, silicon.

#### **O6:** What is Extrinsic Semiconductor?

If certain amount of impurity atom is added to intrinsic semiconductor the resulting semiconductor is Extrinsic or impure Semiconductor.

#### **Q7:** What are the types of Extrinsic Semiconductor?

1. p-type Semiconductor 2. n-Type Semiconductor.

- (b) Is greater than the number of holes
- (d) None of the above
- (b) the free electrons are thermally produced
- (d) there are as many electrons as there are holes

The Semiconductor which are obtained by introducing trivalent impurity atom (gallium, indium) are known as P-type Semiconductor.

#### **Q9:** What is n-type Semiconductor?

The Semiconductor which is obtained by introducing pentavalent impurity atom (phosphorus, Antimony) are known as N-type Semiconductor.

#### **Q10:** What is doping?

Process of adding impurity to a intrinsic semiconductor atom is doping. The impurity is called dopant.

#### **Q11:** Why n-type or pentavalent impurities are called as Donor impurities?

n- type impurities will donate the excess negative charge carriers (Electrons) and therefore they are referred to as donor impurities.

#### Q12: Why p-type or trivalent impurities are called as acceptor impurity?

p- type impurities make available positive carriers because they create holes which can accept electron, so these impurities are said to be as acceptor impurity.

#### **Q13: Define drift current?**

When an electric field is applied across the semiconductor, the holes move towards the negative terminal of the battery and electron move towards the positive terminal of the battery. This drift movement of charge carriers will result in a current termed as drift current.

#### **Q14:** Define the term diffusion current?

A concentration gradient exists, if the number of either electrons or holes is greater in one region of a semiconductor as compared to the rest of the region. The holes and electron tend to move from region of higher concentration to the region of lower concentration. This process in called diffusion and the current produced due this movement is diffusion current.

#### **Q15:** Define mean life time of a hole or an electron.

The electron hole pair created due to thermal agitation will disappear as a result of recombination. Thus, an average time for which a hole or an electron exist before recombination can be said as the mean life time of a hole or electron.