ELECTRONICS I

The Atom:

The atom is a basic unit of matter. It is composed of a nucleus, which contain positively charged protons and neutral neutrons, and negatively charged electrons that, in the classical sense, orbit the nucleus. Electrons in the outermost shell are called **valence electrons**, and the chemical activity of a material is determined primarily by the number of such electrons.

For example the silicon (Si) atom:

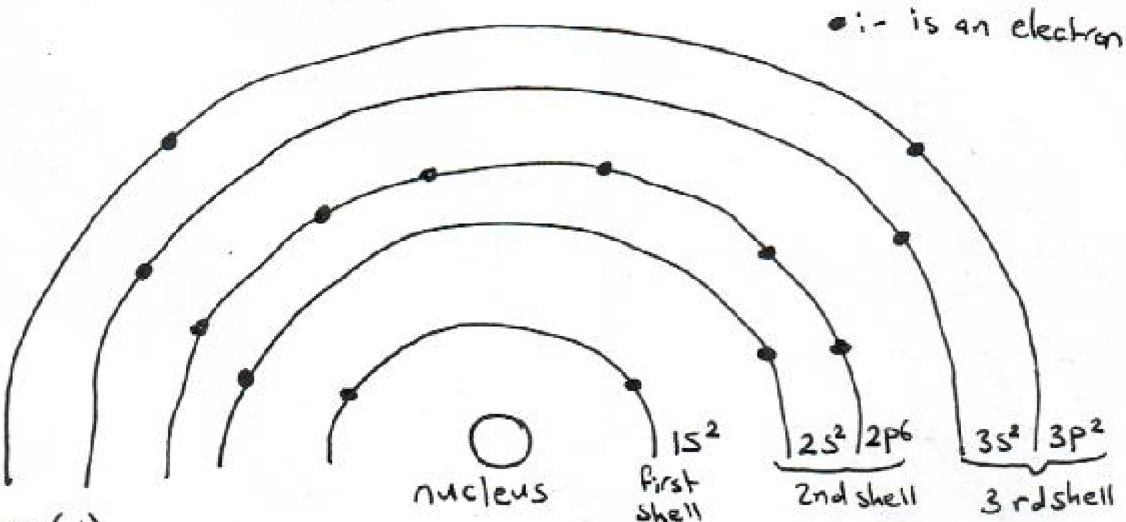


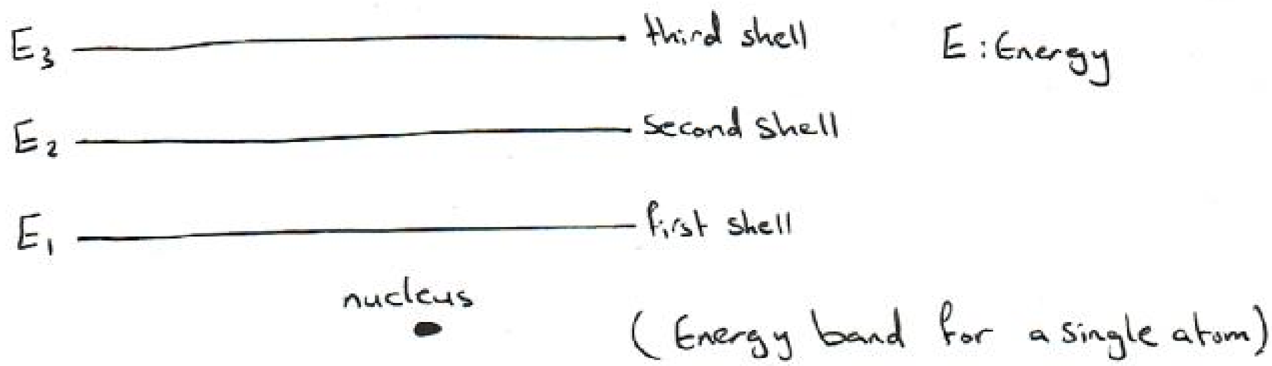
Figure (1)

Number of electrons = 14

These circles are not orbits. The electrons are not moving around the nucleus along the circles. Instead, the circles represent energy levels.

The electrons on the circle closest to the nucleus (first shell) have the lowest energy. The eight electrons on the next circles (second shell) have a higher energy, and the one on the outer circle has the highest energy.

Figure (1) can be drawn as in the following:



Energy bands:

In solids the energy band is a set of very closely spaced energy levels of slightly different energy.

There are two types of energy bands:

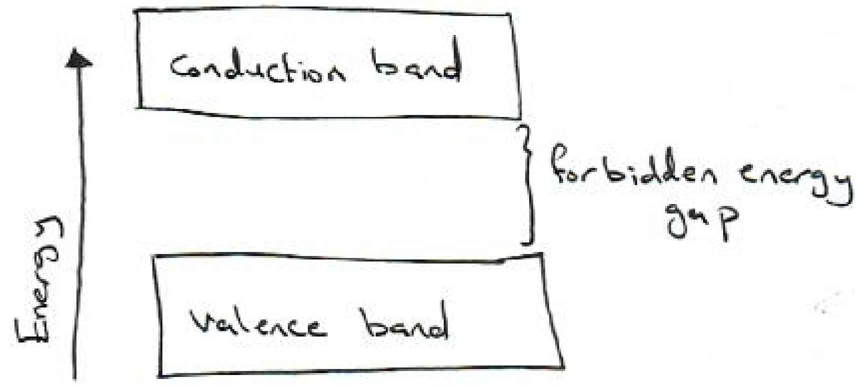
1) The valence band:

It is a band of energy levels that is occupied by the valance electrons. It may be completely filled or partially filled with electrons but never empty. When the electrons in this band get enough energy it releases from the atom and jump to the conduction band.

2) The conduction band:

It is a band of energy levels higher than the valence band, and may either be empty or partially filled with electrons. In the conduction band, electrons can move freely and hence known as conduction electrons.

The forbidden energy gap: It is a gap between the valence band and the conduction band. It does not contain energy levels. The width of this gap depends on the type of material and on temperature.



Insulators, Conductors, and Semiconductors:

The electrical conduction properties of different materials can be explained in terms of the electrons having energies in the valence and conduction bands. The electrons lying in the lower energy bands, which are normally filled, play no part in the conduction process.

1) **Insulators**: are those materials in which valence electrons are bound very tightly to their parent atoms. In other words, insulators have no free electrons available with them under normal conditions.

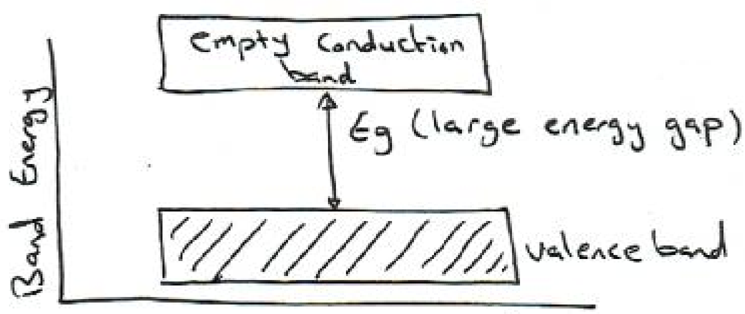
Insulators have:

i) A full valence band.

ii) An empty conduction band.

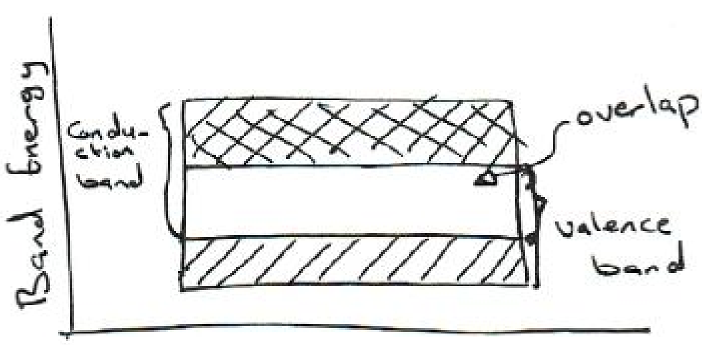
iii) A large energy gap (of several ev). (ev: electron volt)

iv) At ordinary temperature, the probability of electron jumping from valence band to conduction band is slight.



Energy band diagram for insulators

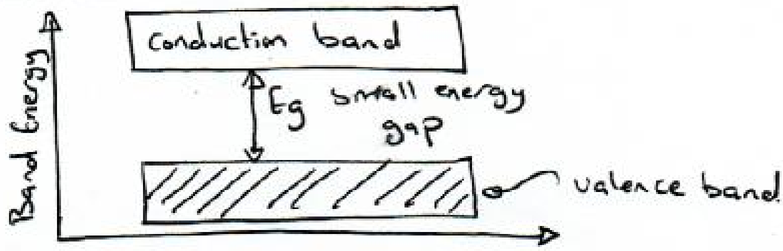
2) **Conductors**: are those materials that have plenty of free electrons for electric conduction. In conductors the valence band and the conduction band are overlapped (there is no forbidden gap).



Energy band diagram for conductors

3) **Semiconductors**: A semiconductor material is one whose electrical properties lie in between those of insulators and good conductors. Example germanium (Ge) and silicon (Si).

Semiconductors have a very narrow energy gap (of the order of 1ev) between the valence band and the conduction band. At 0°K, there are no electrons in the conduction band and the valence band is completely filled. However, with increase in temperature some of the electrons jump from the valence band to the conduction band.



Energy band diagram for semiconductors

Semiconductors crystal structure:

Semiconductors like germanium and silicon, have crystalline structure. Their atoms are arranged in an ordered array known as crystal lattice. Both these materials are tetravalent i.e. each has four valence electrons in its outermost shell. The neighboring atoms form covalent bonds by sharing four electrons with each other. A two dimensional view of the silicon crystal lattice is shown in figure (2).

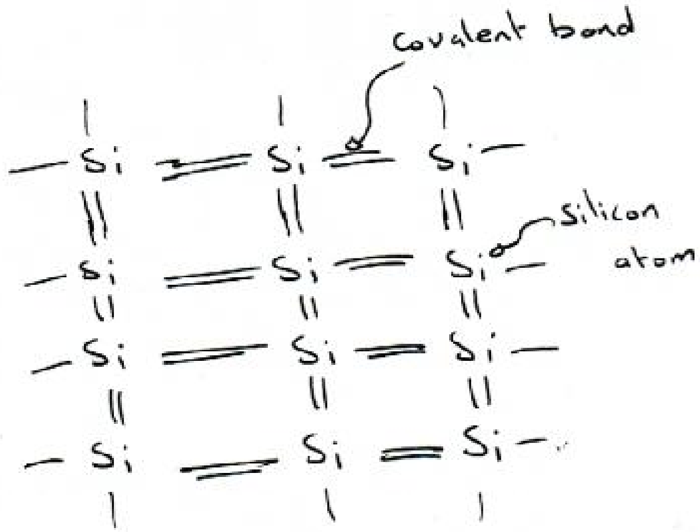
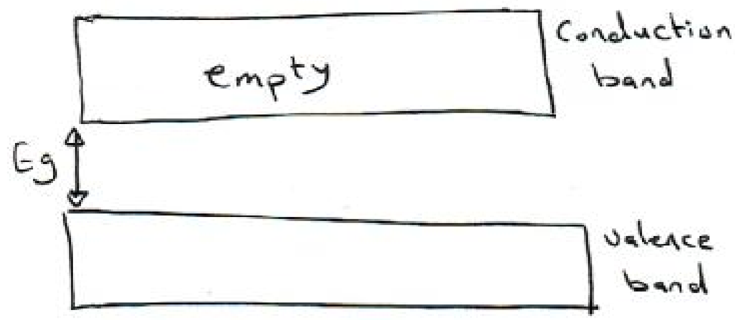


Figure (2) Two dimentional view of the silicon crystal lattice

A t T = 0 K all of the valence electrons shown in Figure (2) are in the valence band and the upper energy band, the conduction band, is completely empty.



As the temperature increases above 0 K, a few valence band electrons may gain enough thermal energy to break the covalent bond and jump into the conduction band. Figure (3a) shows a two-dimensional representation of this bond-breaking effect and Figure (3b) shows a simple line representation of the energy-band model.

Figure(3a)

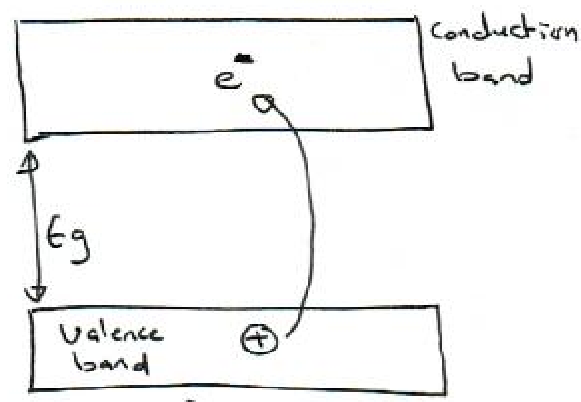
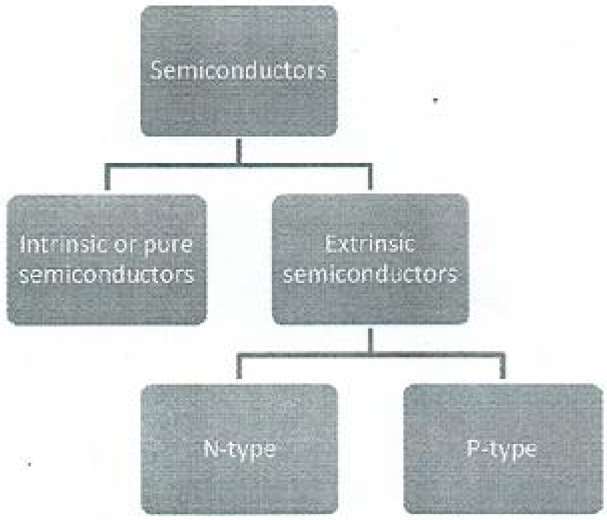


Figure (3b)

The semiconductor is neutrally charged. This means that, as the negatively charged electron breaks away from its covalent bonding position, a positively charged "empty state" or "holes" is created in the original covalent bonding position in the valence band as shown in figure (3a). As the temperature further increases, more covalent bonds are broken, more electrons jump to the conduction hand, and more positive "empty states" are created in the valence band

In order to break the covalent bond, the valence electron must gain a minimum energy Eg (band gap energy). The electrons that gained that minimum energy now exist in the conduction band and are said to be free electrons.

Types of semiconductors:



1) Intrinsic Semiconductors

   An intrinsic semiconductor is one which is made of the semiconductor material in its extremely pure form. For example pure germanium and silicon which have forbidden energy gaps of 0.72 ev and 1.1ev respectively. The energy gap is so small that even at ordinary room temperature, there are many electrons which posses sufficient energy to jump across the small energy gap between the valence and the conduction bands.

2) Extrinsic Semiconductors

   Are those intrinsic semiconductors to which some suitable impurity or doping agent or dopant has been added in extremely small amounts (about 1 part in 10^8).

   The impurity atoms are:

   i) Pentavalent atoms having <u>five</u> valence electrons (Arsenic, antimony, phosphorus). Pentavalent atoms are known as **donor** atoms because it donates or contributes one electron to the conduction band of a pure (silicon or germanium).

ii) Trivalent atoms having three valence electrons (gallium , indium, aluminum, boron). The trivalent atom is called accepter atom because it accepts one electron from the silicon or germanium atom .

Extrinsic semiconductors can be sub-divided into two classes:

a) N-type extrinsic semiconductor , b) P-type extrinsic semiconductor

a) N-type extrinsic semiconductor: this type of semiconductor is obtained when a pentavalent material like Phosphorus (P) is added to pure silicon crystal. As shown in figure (4a), each Phosphorus atom forms covalent bonds with the surrounding four silicon atoms with the help of four of its five valence electrons. The fifth electron is loosely bound to the phosphorus atom. Hence it can be easily excited from the valence band to the conduction band by the application of electric field or increase in thermal energy. Thus practically every phosphorus atom introduced into the silicon lattice creates a free electron without creating a positive hole.
By giving away its one valence electron, the donor atom becomes a positively charged ion as shown in figure (4b).

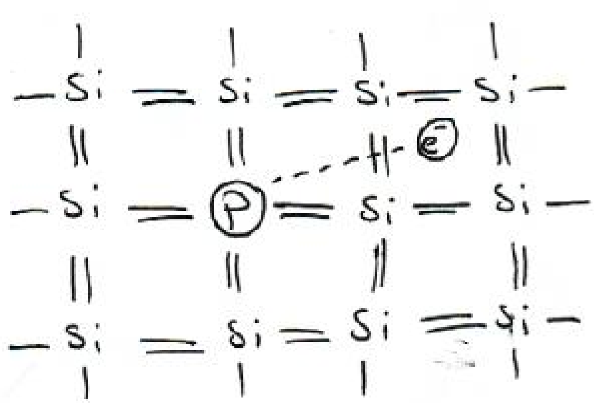


Figure (4a)

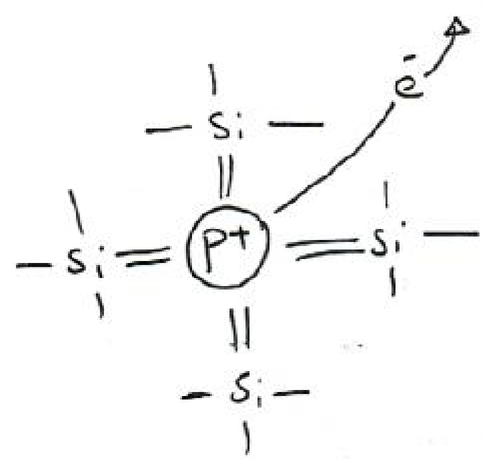


Figure (4b)
the positively charged phosphorous ion after the fifth valence electron has moved into the conduction band

In a N-type extrinsic semiconductor there are

- Electrons and holes intrinsically available
- conduction electrons from donor atoms

Hence, concentration of electrons in the conduction band is increased and exceeds the concentration of holes in the valence band.

In N-type semiconductors, electrons are the majority carriers while holes constitute the minority carriers.

b) P-type extrinsic semiconductor: This type of semiconductor is obtained when impurity atoms of a trivalent like boron (B) are added to a pure silicon crystal.

The three valence electrons of boron atom form covalent bonds with four surrounding silicon atoms but one bond is left incomplete and gives rise to a hole as shown in figure (5a) and (5b).

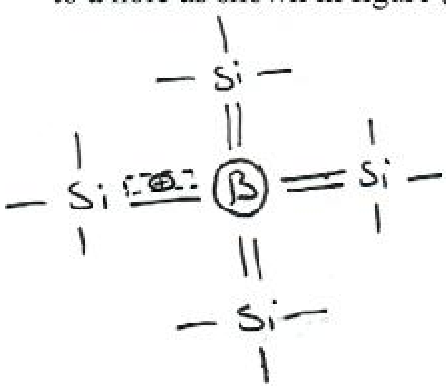


figure (5a)

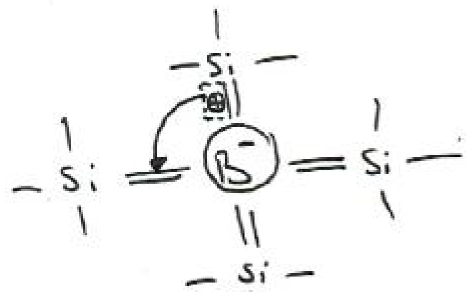


figure (5b)
the negatively charged boron ion after it has accepted an electron from the valence band

Thus, boron which is called an accepter impurity causes as many positive holes in silicon crystal as there are boron atoms thereby producing P-type (P for Positive) extrinsic semiconductor.

In this type of semiconductor, conduction is by the movement of holes in the valence band. Accordingly, holes form the majority carriers whereas electrons constitute minority carriers.

Charge Carriers

In a piece of pure semiconductor, at room temperature electron-hole pairs are produced. These are called thermally-generated charge carriers and are also known as intrinsically available charge carriers (n_i). Ordinarily, these electrons and holes are quite small.

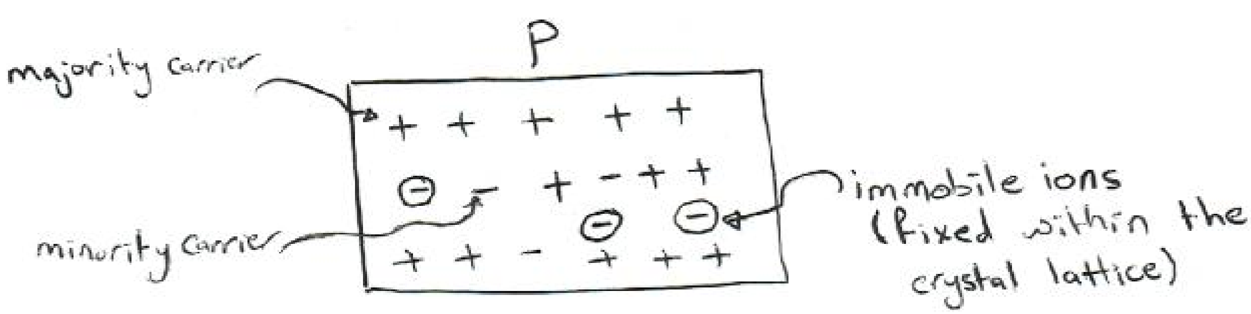
While in p-type material contains the following charge carriers:

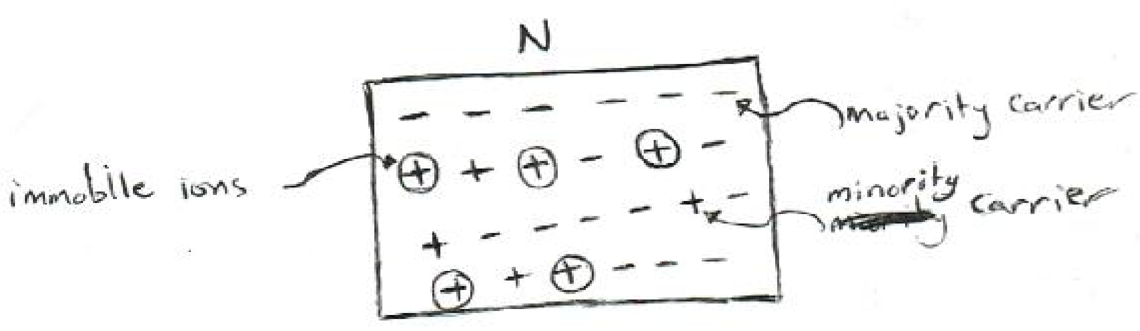
a) Large number of positive holes (most of them being the added impurity holes with only a very small number of thermally generated ones).

b) A very small number of thermally generated electrons (the companions of the thermally generated holes mentioned above).

Similarly, in n-type material, the number of electrons (both added and thermally generated) is much larger than the number of thermally generated holes.

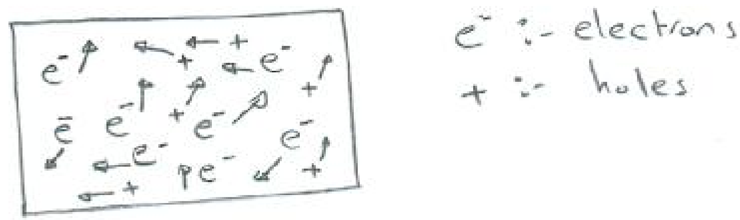
Mobile charge carriers and immobile Ions:



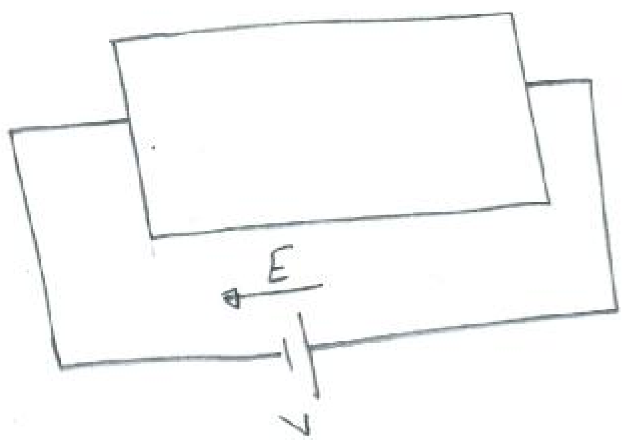


Drift Motion and Mobility:-

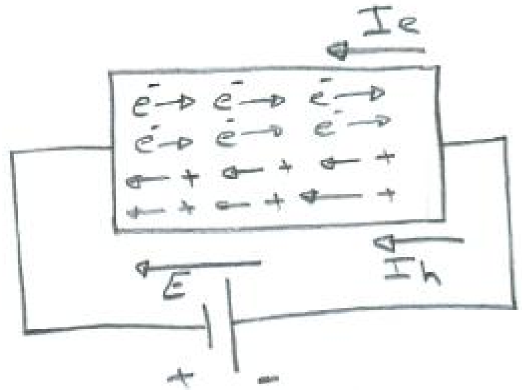
Suppose we have a piece of semiconductor as shown below:-



If a Voltage difference (V) is applied across that piece, then an electric field will be applied to the piece as shown below:-



Now due to the electric field the free electrons and holes will experience a force (f). Due to the force caused by the electric field the electrons and holes will move with an average velocity (v) as shown in the following figure, this motion is called the <u>drift motion</u>.



I_e is the electron current.
I_h is the hole current.

Note:-

The motion of the electrons is in a direction opposite to the applied field (E) due to its -ve charge, while the holes move in the same direction of the electric field since it has a +ve charge.

This motion will cause two currents:- I_h and I_e.

I_h :- the current due to the motion of holes.
I_e :- the current due to the motion of holes.

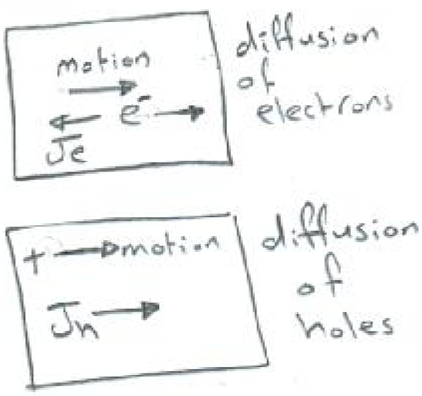
$$I_T = I_h + I_e$$

I_T :- the total current.

Diffusion :-

In addition to the drift mechanism, there is the diffusion mechanism that results from the continual random thermal motion of the carriers. To understand the diffusion mechanism see figure (5). In figure (5) a piece of semiconductor is shown with non-uniform carrier concentration. As shown the concentration C of the carrier varies with the distance X in the semiconductor and there is a concentration gradient $\frac{dc}{dx}$, in the density of carriers. This will cause the carrier to transport from the region of high concentration to the region of low concentration. This transport of carriers will cause a current called the diffusion current in the X-direction.

Note :- the diffusion current is generated with no applied fields.



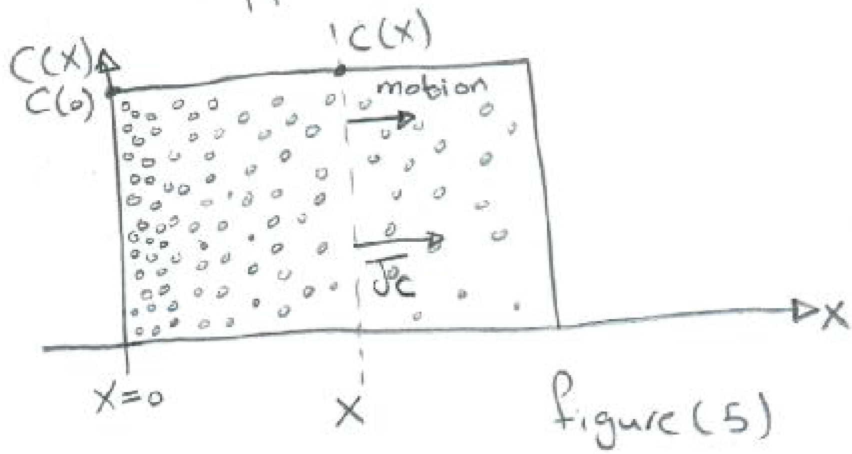


figure (5)

Recombination and Carrier Liftime:- (13)

In addition to drift and diffusion, there is the recombination phenomenon. In Semiconductors, hole-electron pairs disappear due to recombination, in other words, free electrons fall into empty covalent bonds, resulting in the loss of an electron-hole pair. A hole and electron will exist for a time τ before recombination, τ is called carrier lifetime.