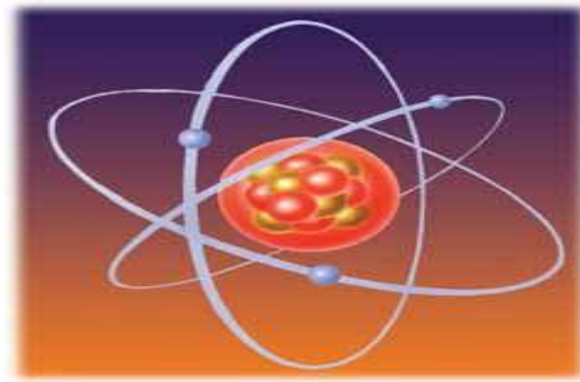
UNIT-1

REVIEW OF SEMICONDUCTOR PHYSICS

Atomic Structure

According to the modern theory, All the materials are composed of very small particles called *atoms*. The atoms are the building bricks of all matter.

Various scientists have given different theories regarding the structure of atom. However, for the purpose of understanding electronics, the study of Bohr's atomic model is adequate.



Bohr's Atomic Model

In 1913, Neils Bohr, Danish Physicist gave clear explanation of atomic structure. According to Bohr:

(i) An atom consists of a positively charged nucleus around which negatively charged electrons revolve in different *circular orbits.*

(ii) The electrons can revolve around the nucleus only in certain permitted orbits *i.e.* orbits of certain radii are allowed.

The number of electrons in any orbit is given by $2n^2$ where n is the number of the orbit. For example,

First orbit contains $2 \times 1^2 = 2$ electrons

Second orbit contains $2 \times 2^2 = 8$ electrons

Third orbit contains $2 \times 3^2 = 18$ electrons

(iii) The electrons in each permitted orbit have a certain fixed amount of energy. The larger the orbit (*i.e.* larger radius), the greater is the energy of electrons.

(iv) If an electron is given additional energy (*e.g.* heat, light etc.), it is lifted to the higher orbit. The atom is said to be in a state of *excitation.* This state does not last long, because the electron soon falls back to the original lower orbit. As it falls, it gives back the acquired energy in the form of heat, light or other radiations.

Fig. shows the structure of silicon atom. It has 14 electrons. Two electrons revolve in the first orbit, 8 in the second orbit and 4 in the third orbit. The first, second, third orbits etc. are also known as *K*, *L*, *M* orbits respectively.

These electrons can revolve only in permitted orbits (*i.e.* orbits of *radii r_1, r_2 and r_3) and not in any arbitrary orbit. Thus, all radii between r_1 and r_2 or between r_2 and r_3 are forbidden. Each orbit has fixed amount of energy associated with it.

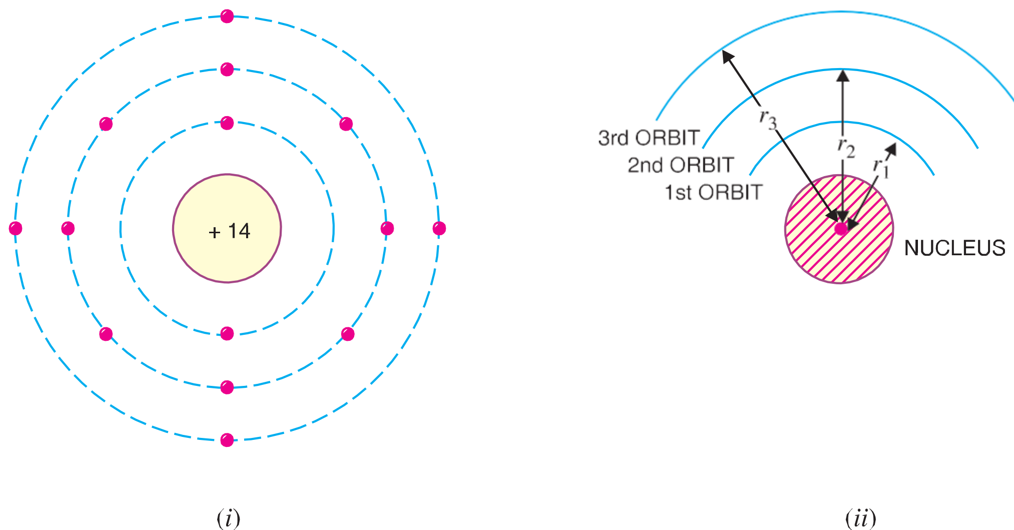


Fig. 4.1

Energy Levels

It has already been discussed that each orbit has fixed amount of energy associated with it. The electrons moving in a particular orbit possess the energy of that orbit. The larger the orbit, the greater is its energy. It becomes clear that outer orbit electrons possess more energy than the inner orbit electrons.

A convenient way of representing the energy of different orbits is shown in Fig. 4.2 (*ii*). This is known as energy level diagram. The first orbit represents the *first energy level*, the second orbit indicates the *second energy level* and so on. The larger the orbit of an electron, the greater is its energy and higher is the energy level.

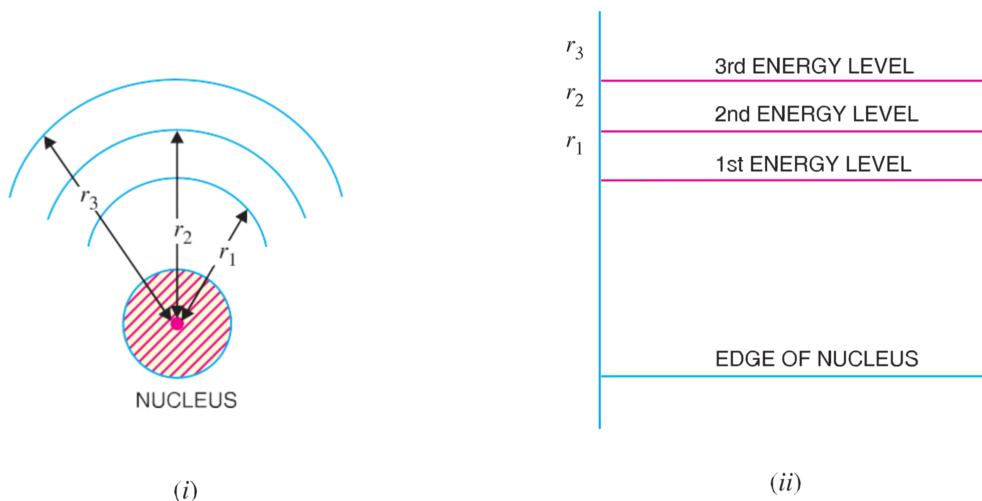


Fig. 4.2

Energy Bands

In case of a single isolated atom, the electrons in any orbit possess definite energy. However, an atom in a solid is greatly influenced by the closely-packed neighbouring atoms. The result is that the electron in any orbit of such an atom can have a range of energies rather than a single energy. This is known as *energy band.*

The range of energies possessed by an electron in a solid is known as **energy band.**

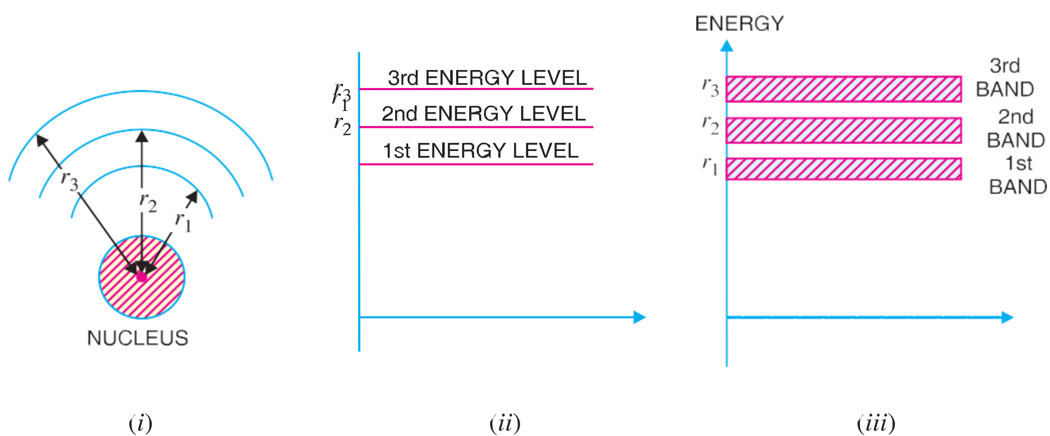


Fig. 4.3

The concept of energy band can be easily understood by referring to Fig. 4.3. Fig. 4.3 (*ii*) shows the energy levels of a single isolated atom of silicon. Each orbit of an atom has a single energy. Therefore, an electron can have only single energy corresponding to the orbit in which it exists. However, when the atom is in a solid, the electron in any orbit can have a range of energies. For instance, electrons in the first orbit have slightly different energies because no two electrons in this orbit see exactly the same charge environment. Since there are millions of first orbit electrons, the slightly different energy levels form a band, called 1st energy band [See Fig. 4.3 (*iii*)]. The electrons in the first orbit can have any energy range in this band. Similarly, second orbit electrons form second energy band and so on.

Important Energy Bands in Solids

As discussed before, individual *K*, *L*, *M* etc. energy levels of an isolated atom are converted into corresponding bands when the atom is in a solid. Though there are a number of energy bands in solids, the following are of particular importance [See Fig. 4.4] :

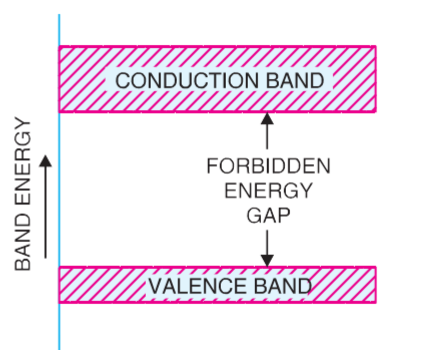


Fig. 4.4

(v) Valence band. *The range of energies (i.e. band) possessed by valence electrons is known as* **valence band.**

The electrons in the outermost orbit of an atom are known as valence electrons. In a normal atom, valence band has the electrons of highest energy. This band may be completely or partially filled. For instance, in case of inert gases, the valence band is full whereas for other materials, it is only partially filled. The partially filled band can accommodate more electrons.

(vi) Conduction band. In certain materials (*e.g.* metals), the valence electrons are loosely attached to the nucleus. Even at ordinary temperature, some of the valence electrons may get detached to become free electrons. In fact, it is these free electrons which are responsible for the conduction of

current in a conductor. For this reason, they are called *conduction electrons.*

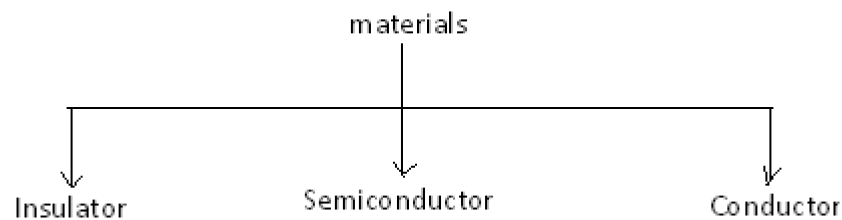
The range of energies (*i.e. band*) *possessed by conduction band electrons is known as* **conduction band.**

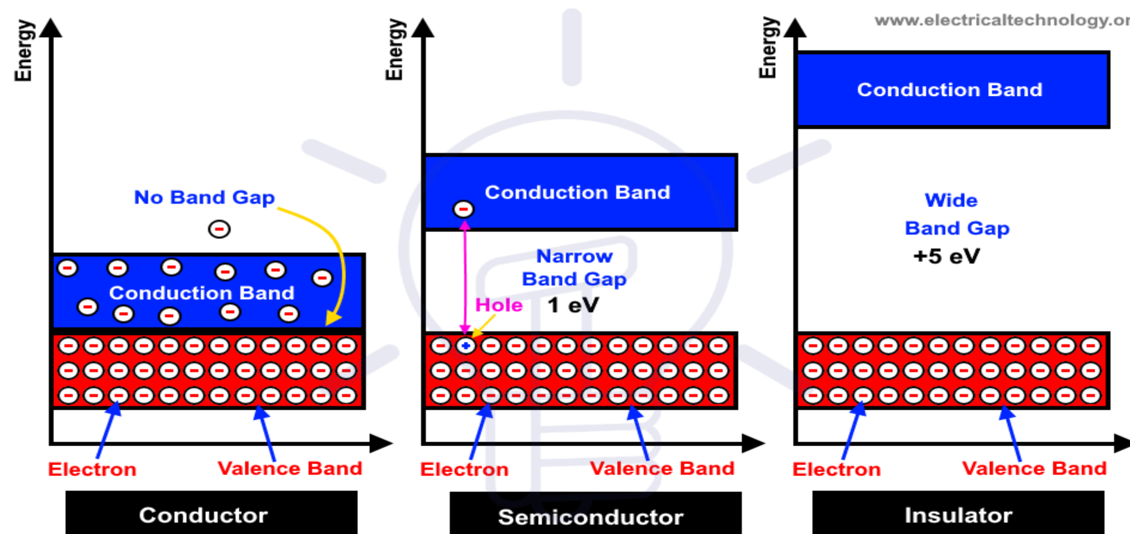
All electrons in the conduction band are free electrons. If a substance has empty conduction band, it means current conduction is not possible in that substance. Generally, insulators have empty conduction band. On the other hand, it is partially filled for conductors.

(vii) Forbidden energy gap. *The separation between conduction band and valence band on the energy level diagram is known as* **forbidden energy gap.**

No electron of a solid can stay in a forbidden energy gap as there is no allowed energy state in this region. The width of the forbidden energy gap is a measure of the bondage of valence electrons to the atom. The greater the energy gap, more tightly the valence electrons are bound to the nucleus. In order to push an electron from valence band to the conduction band (*i.e.* to make the valence electron free), external energy equal to the forbidden energy gap must be supplied.

Based on the electrical conductivity all the materials in nature are classified as insulators, semiconductors, and conductors.





PARAMATER	CONDUCTORS	SEMICONDUCTORS	INSULATORS
Conduction	The conduction in conductors is due to the free electrons in metal bonding.	The conduction in semiconductor is due to the movement of electron & holes.	There are no free electrons or holes thus, there is no conduction.
Band gap	There is no or low energy gap between the conduction & valance band of a conductor. It does not need extra energy for the conduction state.	The band gap of semiconductor is greater than the conductor but smaller than an insulator i.e. 1 eV. Their electrons need a little energy for conduction state.	The band gap in insulator is huge (+5 eV), which need an enormous amount of energy like lightning to push electrons into the conduction band.
Valence Electron in Outer Shell	1 Valence electron in outer shell.	4 Valence electron in outer shell.	8 Valence electron in outer shell.
Conductivity	High (10-7 mho/m)	Medium (10-7 to 10-13 mho/m)	Very Low (10-3 mho/m) Almost negligible.
Resistivity	Low	Moderate	High
Temperature coefficient of resistance	Positive	Negative	Negative
Charge carriers in conduction band	Completely filled	Partially filled	Completely vacant
Charge carriers in valence band	Almost vacant	Partially filled	Completely filled
Example	Copper, Aluminium, graphite etc.	Silicon, Germanium, arsenic etc.	Paper, rubber, glass, plastic etc.
Application	The metals like iron & copper etc. that can conduct electricity are made into wires and cable for carrying electric current.	Semiconductors are used every day electronic devices such as cellphone, computer, solar panel etc as switches, energy converter, amplifiers, etc.	The insulators are used for protection against high voltages & prevention of electrical short between cables in circuits.

SEMICONDUCTORS

- **Semiconductors are the materials which have 4 electrons in its outer most orbit . OR**
- **Semiconductor are materials whose electrical conductivity lies between conductor and an insulator.**

Some common semiconductors

elemental

- **Si - Silicon (most common)**
- **Ge - Germanium**

compound

- **GaAs - Gallium arsenide** **GaP - Gallium phosphide**
- **AlAs - Aluminum arsenide** **AlP - Aluminum phosphide**
- **InP - Indium Phosphide**
- **There are also three-element (ternary) compounds (GaAsP) and four-elements (quaternary) compounds such as InGaAsP.**

Compounds are widely used in high-speed devices and devices requiring the emission or absorption of light.

(i) Germanium. Germanium has become the model substance among the semiconductors; the main reason being that it can be purified relatively well and crystallised easily. Germanium is an earth element and was discovered in 1886. It is recovered from the ash of certain coals or from the flue dust of zinc smelters. Generally, recovered germanium is in the form of germanium dioxide powder which is then reduced to pure germanium.

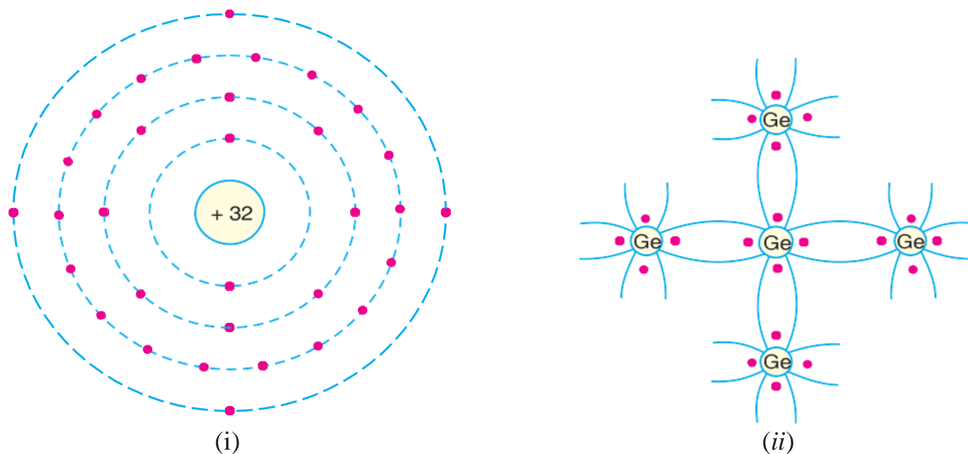


Fig. 5.2

The atomic number of germanium is 32. Therefore, it has 32 protons and 32 electrons. Two electrons are in the first orbit, eight electrons in the second, eighteen electrons in the third and four electrons in the outer or valence orbit [See Fig. 5.2 (*i*)]. It is clear that germanium atom has four valence electrons *i.e.*, it is a tetravalent element. Fig. 5.2 (*ii*) shows how the various germanium atoms are held through co-valent bonds. As the atoms are arranged in an orderly pattern, therefore, germanium has crystalline structure.

(*ii*) **Silicon.** Silicon is an element in most of the common rocks. Actually, sand is silicon dioxide. The silicon compounds are chemically reduced to silicon which is 100% pure for use as a semiconductor.

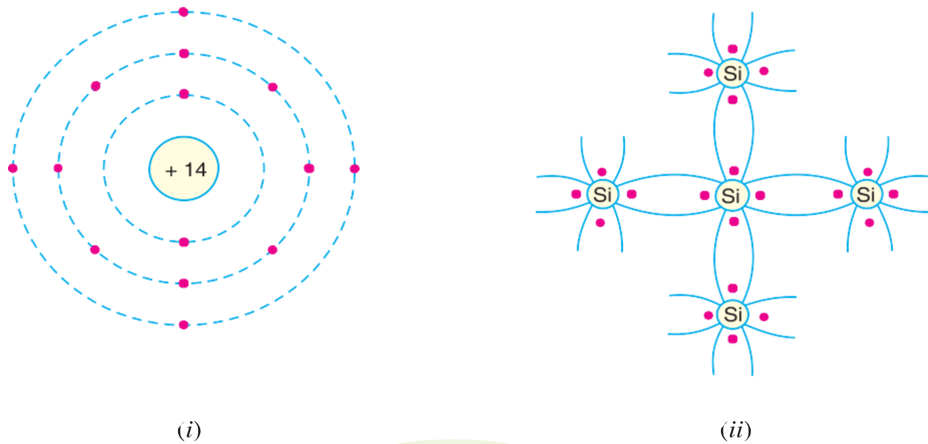


Fig. 5.3

The atomic number of silicon is 14. Therefore, it has 14 protons and 14 electrons. Two electrons are in the first orbit, eight electrons in the second orbit and four electrons in the third orbit [See Fig. 5.3 (*i*)]. It is clear that silicon atom has four valence electrons *i.e.* it is a tetravalent element. Fig. 5.3 (ii) shows how various silicon atoms are held through co-valent bonds. Like germanium, silicon atoms are also arranged in an orderly manner. Therefore, silicon has crystalline structure.

Energy Band Description of Semiconductors

It has already been discussed that a semiconductor is a substance whose resistivity lies between conductors and insulators. The resistivity is of the order of 10^{-4} to 0.5 ohm metre. However, a semiconductor can be defined much more comprehensively on the basis of energy bands as under :

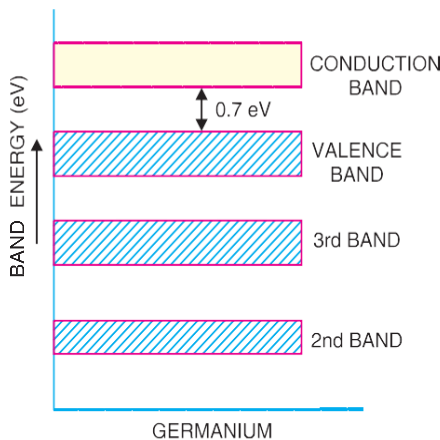


Fig. 5.4

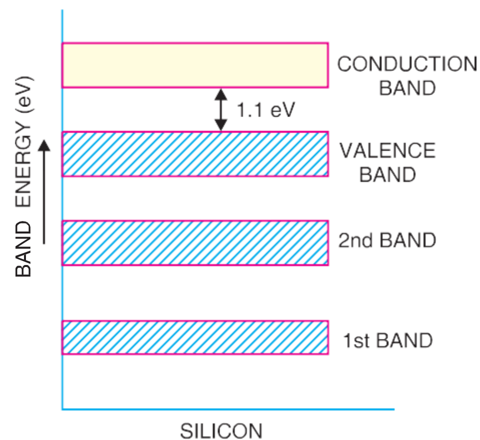


Fig. 5.5

A **semiconductor** *is a substance which has almost filled valence band and nearly empty conduction band with a very small energy gap (j 1 eV) separating the two.*

Figs. 5.4 and 5.5 show the energy band diagrams of germanium and silicon respectively. It may be seen that forbidden energy gap is very small; being 1.1 eV for silicon and 0.7 eV for germanium. Therefore, relatively small energy is needed by their valence electrons to cross over to the conduction band. Even at room temperature, some of the valence electrons may acquire sufficient energy to enter

into the conduction band and thus become free electrons. However, at this temperature, the number of free electrons available is very *small. Therefore, at room temperature, a piece of germanium or silicon is neither a good conductor nor an insulator. For this reason, such substances are called *semi-conductors.*

The energy band description is extremely helpful in understanding the current flow through a semiconductor. Therefore, we shall frequently use this concept in our further discussion.

Effect of Temperature on Semiconductors

The electrical conductivity of a semiconductor changes appreciably with temperature variations. This is a very important point to keep in mind.

(i) At absolute zero. At absolute zero temperature, all the electrons are tightly held by the semiconductor atoms. The inner orbit electrons are bound whereas the valence electrons are engaged in co-valent bonding. At this temperature, the co-valent bonds are very strong and there are no free electrons. Therefore, the semiconductor crystal behaves as a perfect insulator [See Fig. 5.6 (*i*)].

In terms of energy band description, the valence band is filled and there is a large energy gap between valence band and conduction band. Therefore, no valence electron can reach the conduction band to become free electron. It is due to the non-availability of free electrons that a semiconductor behaves as an insulator.

(ii) Above absolute zero. When the temperature is raised, some of the covalent bonds in the semiconductor break due to the thermal energy supplied. The breaking of bonds sets those electrons *free* which are engaged in the formation of these bonds. The result is that a few free electrons exist in the semiconductor. These free electrons can constitute a tiny electric current if potential difference is

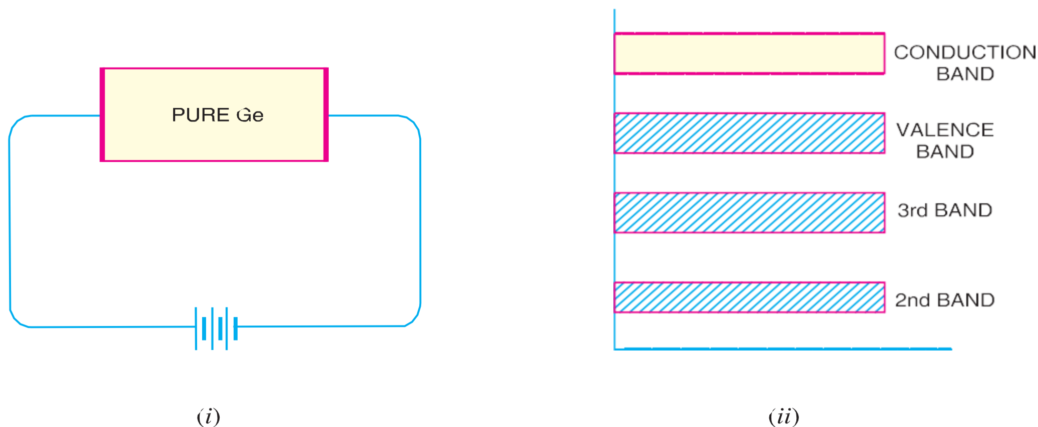


Fig. 5.6

applied across the semiconductor crystal [See Fig. 5.7 (*i*)]. *This shows that the resistance of a semi-conductor decreases with the rise in temperature i.e.* it has negative temperature coefficient of resistance. It may be added that at room temperature, current through a semiconductor is too small to be of any practical value.

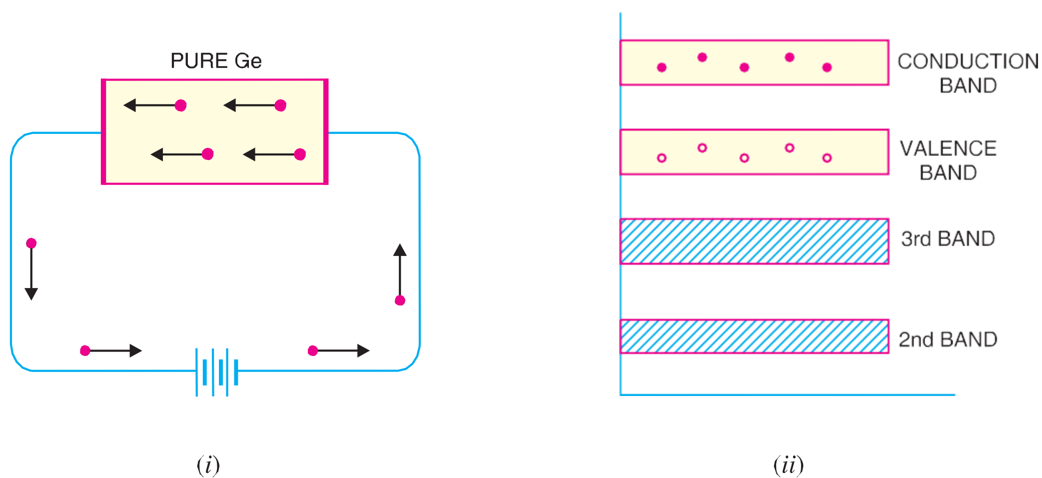


Fig. 5.7

Fig. 5.7 (*ii*) shows the energy band diagram. As the temperature is raised, some of the valence electrons acquire sufficient energy to enter into the conduction band and thus become free electrons. Under the influence of electric field, these free electrons will constitute electric current. It may be noted that each time a valence electron enters into the conduction band, a *hole* is created in the valence band. As we shall see in the next article, holes also contribute to current. In fact, hole current is the most significant concept in semiconductors.

Properties of Semiconductor

- The resistivity lies between insulator and conductor
- Doping increases conductivity of semiconductor
- At absolute zero, it behaves as perfect insulator
- At room temperature it behaves as conductor.
- It has negative temperature coefficient of resistance, i.e., the resistance of semiconductor decreases with increase in temperature and vice versa

Hole Current

At room temperature, some of the co-valent bonds in pure semiconductor break, setting up free electrons. Under the influence of electric field, these free electrons constitute electric current. At the

same time, another current – the hole current – also flows in the semiconductor. When a covalent bond is broken due to thermal energy, the removal of one electron leaves a vacancy *i.e.* a missing electron in the covalent bond. This missing electron is called a *hole which acts as a positive charge. For one electron set free, one hole is created. Therefore, thermal energy creates *hole-electron pairs*; there being as many holes as the free electrons. The current conduction by holes can be explained as follows :

The hole shows a missing electron. Suppose the valence electron at *L* (See Fig. 5.8) has become free electron due to thermal energy. This creates a hole in the co-valent bond at *L*. The hole is a strong centre of attraction **for the electron. A valence electron (say at *M*) from nearby co-valent bond comes to fill in the hole at *L*. This results in the creation of hole at *M*. Another valence electron (say at *N*) in turn may leave its bond to fill the hole at *M*, thus creating a hole at *N*. Thus the hole having a positive charge has moved from *L* to *N i.e.* towards the negative terminal of supply. This constitutes *hole current.*

It may be noted that hole current is due to the movement of ***valence electrons from one co-valent bond to another bond. The reader may wonder why to call it a hole current when the conduction is again by electrons (of course *valence electrons* !). The answer is that the basic reason for current flow is the presence of holes in the co-valent bonds. Therefore, it is more appropriate to consider the current as the movement of holes.

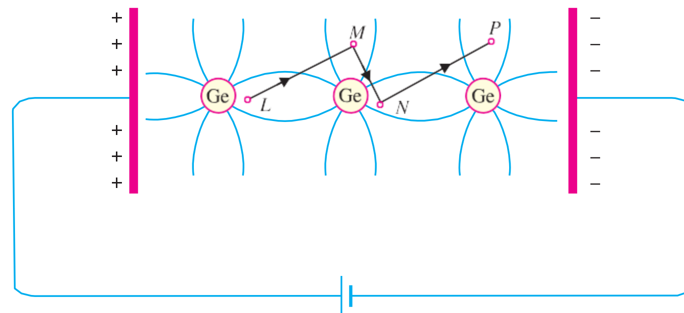


Fig. 5.8

Energy band description. The hole current can be beautifully explained in terms of energy bands. Suppose due to thermal energy, an electron leaves the valence band to enter into the conduction band as shown in Fig. 5.9.

This leaves a vacancy at *L*. Now the valence electron at *M* comes to fill the hole at *L*. The result is that hole disappears at *L* and appears at *M*. Next, the valence electron at *N* moves into the hole at *M*. Consequently, hole is created at *N*. It is clear that valence electrons move along the path *PNML* whereas holes move in the opposite direction *i.e.* along the path *LMNP*.

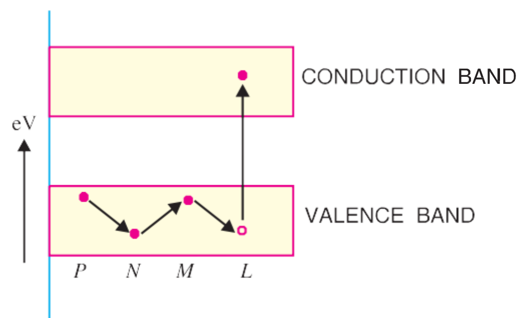


Fig. 5.9

Intrinsic Semiconductor

A semiconductor in an extremely pure form is known as an **intrinsic semiconductor**.

In an intrinsic semiconductor, even at room temperature, hole-electron pairs are created. When electric field is applied across an intrinsic semiconductor, the current conduction takes place by two processes, namely ; by *free electrons* and *holes* as shown in Fig. 5.10. The free electrons are produced due to the breaking up of some covalent bonds by thermal energy. At the same time, holes are created in the covalent bonds. Under the influence of electric field, conduction through the semiconductor is by both free electrons and holes. Therefore, the total current inside the semiconductor is the sum of currents due to free electrons and holes.

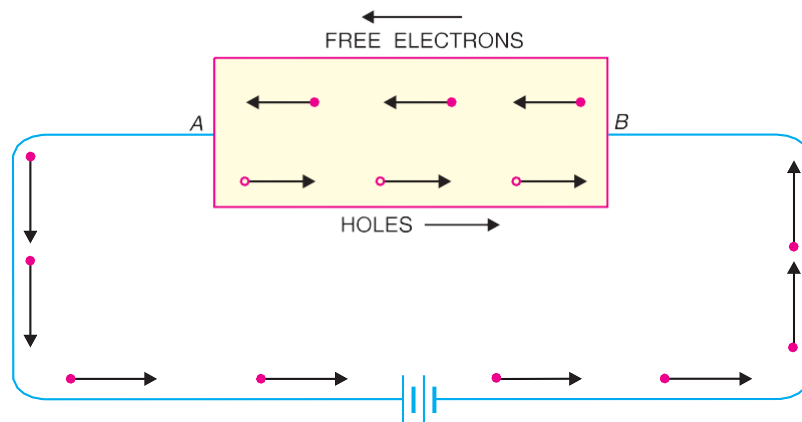


Fig. 5.10

It may be noted that current in the external wires is fully electronic *i.e.* by electrons. What about the holes ? Referring to Fig. 5.10, holes being positively charged move towards the negative terminal of supply. As the holes reach the negative terminal *B*, electrons enter the semiconductor crystal near the terminal and combine with holes, thus cancelling them. At the same time, the loosely held electrons near the positive terminal *A* are attracted away from their atoms into the positive terminal. This creates new holes near the positive terminal which again drift towards the negative terminal.

5.6 9 Extrinsic Semiconductor

The intrinsic semiconductor has little current conduction capability at room temperature. To be useful in electronic devices, the pure semiconductor must be altered so as to significantly increase its conducting properties. This is achieved by adding a small amount of suitable impurity to a semiconductor. It is then called *impurity* or *extrinsic semiconductor*. The process of adding impurities to a semiconductor is known as *doping*. The amount and type of such impurities have to be closely controlled during the preparation of extrinsic semiconductor. Generally, for 10^8 atoms of semiconductor, one impurity atom is added.

The purpose of adding impurity is to increase either the number of free electrons or holes in the semiconductor crystal. As we shall see, if a pentavalent impurity (having 5 valence electrons) is added to the semiconductor, a large number of free electrons are produced in the semiconductor. On the other hand, addition of trivalent impurity (having 3 valence electrons) creates a large number of holes in the semiconductor crystal. Depending upon the type of impurity added, extrinsic semiconductors are classified into:

(i) *n*-type semiconductor **(*ii*)** *p*-type semiconductor

5.7 0 *n*-type Semiconductor

When a small amount of pentavalent impurity is added to a pure semiconductor, it is known as

n-type semiconductor.

The addition of pentavalent impurity provides a large number of free electrons in the semiconductor crystal. Typical examples of pentavalent impurities are *arsenic* (At. No. 33) and *antimony* (At. No. 51). Such impurities which produce *n*-type semiconductor are known as *donor impurities* because they donate or provide free electrons to the semiconductor crystal.

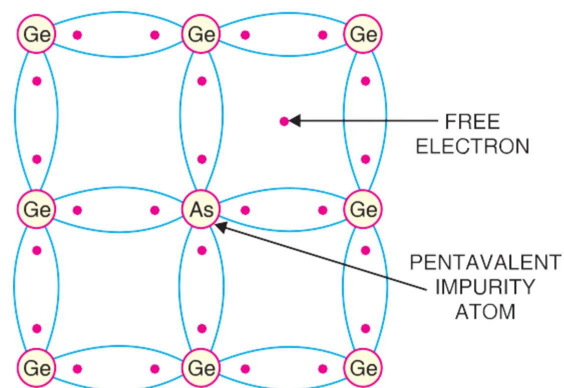


Fig. 5.11

To explain the formation of *n*-type semiconductor, consider a pure germanium crystal. We know that germanium atom has four valence electrons. When a small amount of pentavalent impurity like arsenic is added to germanium crystal, a large number of free electrons become available in the crystal. The reason is simple. Arsenic is pentavalent *i.e.* its atom has five valence electrons. An arsenic atom fits in the germanium crystal in such a way that its four valence electrons form covalent bonds with four germanium atoms. The *fifth* valence electron of arsenic atom finds no place in co-valent bonds and is thus free as shown in Fig. 5.11. Therefore, for each arsenic atom added, one free electron will be available in the germanium crystal. Though each arsenic atom provides one free electron, yet an extremely small amount of arsenic impurity provides enough atoms to supply millions of free electrons.

Fig. 5.12 shows the energy band description of *n*-type semi-conductor. The addition of pentavalent impurity has produced a number of conduction band electrons *i.e.*, free electrons. The four valence electrons of pentavalent atom form covalent bonds with four neighbouring germanium atoms. The fifth left over valence electron of the pentavalent atom cannot be accommodated in the valence band and travels to the conduction band. The following points may be noted carefully :

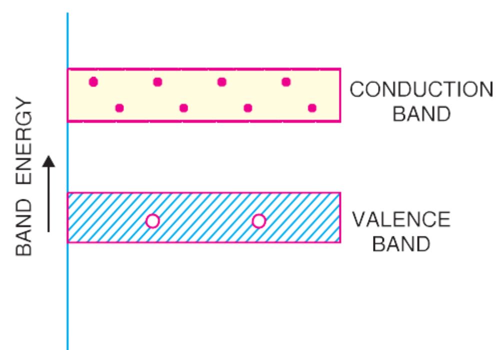


Fig. 5.12

(i) Many new free electrons are produced by the addition of pentavalent impurity.

(ii) Thermal energy of room temperature still generates a few hole-electron pairs. However, the number of free electrons provided by the pentavalent impurity far exceeds the number of holes. It is due to this predominance of electrons over holes that it is called *n*-type semiconductor (*n* stands for negative).

n-type conductivity. The current conduction in an *n*-type semiconductor is *predominantly* by free electrons *i.e.* negative charges and is called *n-type* or *electron type conductivity*. To understand *n*-type conductivity, refer to Fig. 5.13. When p.d. is applied across the *n*-type semiconductor, the free electrons (donated by impurity) in the crystal will be directed towards the positive terminal, constituting electric current. As the current flow through the crystal is by free electrons which are carriers of negative charge, therefore, this type of conductivity is called negative or *n*-type conductivity. It may be noted that conduction is just as in ordinary metals like copper.

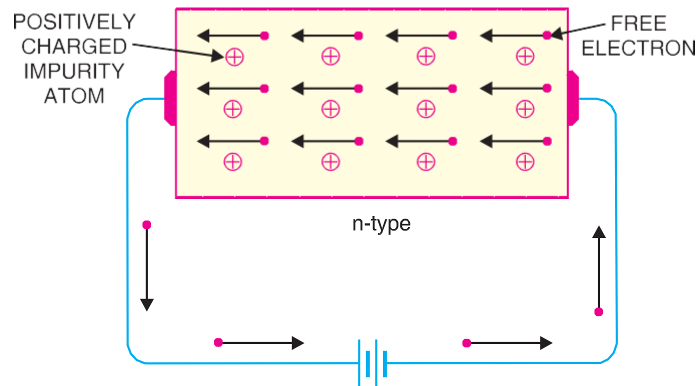


Fig. 5.13

5.8 1 *p*-type Semiconductor

When a small amount of trivalent impurity is added to a pure semiconductor, it is called **p-type semiconductor.**

The addition of trivalent impurity provides a large number of holes in the semiconductor. Typical examples of trivalent impurities are *gallium* (At. No. 31) and *indium* (At. No. 49). Such impurities which produce *p*-type semiconductor are known as *acceptor impurities* because the holes created can accept the electrons.

To explain the formation of *p*-type semiconductor, consider a pure germanium crystal. When a small amount of trivalent impurity like gallium is added to germanium crystal, there exists a large number of holes in the crystal. The reason is simple. Gallium is trivalent *i.e.* its atom has three valence electrons. Each atom of gallium fits into the germanium crystal but now only three co-valent bonds can be formed. It is because three valence electrons of gallium atom can form only three single co-valent bonds with three germanium atoms as shown in Fig. 5.14. In the fourth co-valent bond, only germanium atom contributes one valence electron while gallium has no valence electron to contribute as all its three valence electrons are already engaged in the co-valent bonds with neighbouring germanium atoms. In other words, fourth bond is incomplete; being short of one electron. This missing electron is called a *hole*. Therefore, for each gallium atom added, one hole is created. A small amount of gallium provides millions of holes.

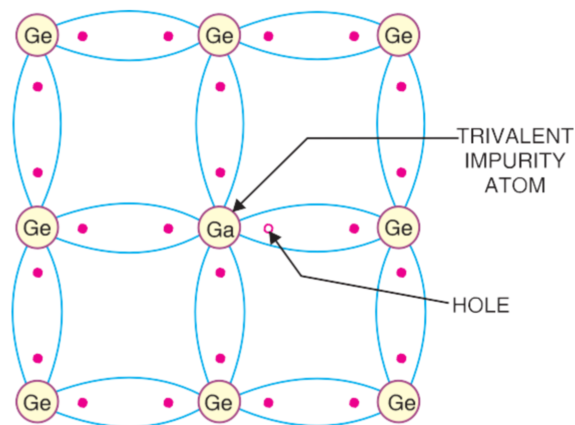
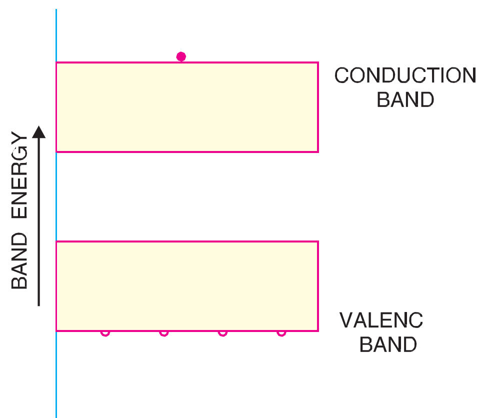


Fig. 5.14

Fig. 5.15 shows the energy band description of the *p*-type semiconductor. The addition of trivalent impurity has produced a large number of holes. However, there are a few conduction band electrons due to thermal energy associated with room temperature. But the holes far outnumber the conduction band electrons. It is due to the predominance of holes over free electrons that it is called *p*-type semiconductor (*p* stands for positive).



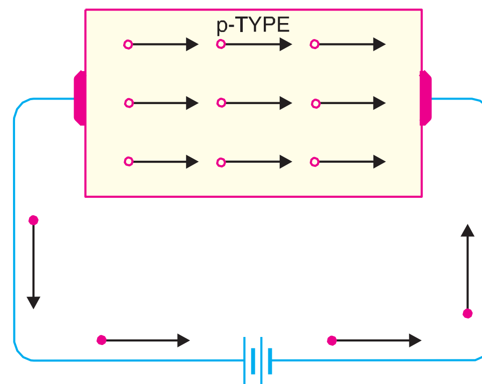


Fig. 5.15

Fig. 5.16

p-type conductivity. The current conduction in *p*-type semiconductor is predominantly by holes *i.e.* positive charges and is called *p-type* or *hole-type conductivity*. To understand *p*-type conductivity, refer to Fig. 5.16. When *p.d.* is applied to the *p*-type semiconductor, the holes (donated by the impurity) are shifted from one co-valent bond to another. As the holes are positively charged, therefore, they are directed towards the negative terminal, constituting what is known as hole current. It may be noted that in *p*-type conductivity, the valence electrons move from one co-valent bond to another unlike the *n*-type where current conduction is by free electrons.

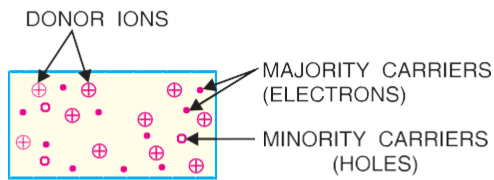
5.9 2 Charge on *n*-type and *p*-type Semiconductors

As discussed before, in *n*-type semiconductor, current conduction is due to excess of electrons whereas in a *p*-type semiconductor, conduction is by holes. The reader may think that *n*-type material has a net negative charge and *p*-type a net positive charge. But this conclusion is wrong. It is true that *n*-type semiconductor has excess of electrons but these extra electrons were supplied by the atoms of donor impurity and each atom of donor impurity is electrically neutral. When the impurity atom is added, the term "excess electrons" refers to an excess with regard to the number of electrons needed to fill the co-valent bonds in the semiconductor crystal. The extra electrons are free electrons and increase the conductivity of the semiconductor. The situation with regard to *p*-type semiconductor is also similar. *It follows, therefore, that n-type as well as p-type semiconductor is electrically neutral.*

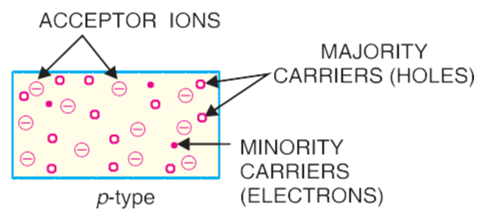
5.10 3 Majority and Minority Carriers

It has already been discussed that due to the effect of impurity, *n*-type material has a large number of free electrons whereas *p*-type material has a large number of holes. However, it may be recalled that even at room temperature, some of the co-valent bonds break, thus releasing an equal number of free electrons and holes. An *n*-type material has its share of electron-hole pairs (released due to breaking of bonds at room temperature) but in addition has a much larger quantity of free electrons due to the effect of impurity. These impurity-caused free electrons are not associated with holes. Consequently, an *n*-type material has a large number of free electrons and a small number of holes as shown in Fig. 5.17 (*i*). The free electrons in this case are considered *majority carriers* — since the majority portion of current in *n*-type material is by the flow of free electrons — and the holes are the *minority carriers.*

Similarly, in a *p*-type material, holes outnumber the free electrons as shown in Fig. 5.17 (*ii*). Therefore, holes are the majority carriers and free electrons are the minority carriers.



(*i*)



(*ii*)

Differences Between N-Type and P-type Semiconductors

Parameter	P-Type	N-Type
Impurity doped	Trivalent impurity	Pentavalent impurity
Also known as	Acceptor atom because of presence of additional hole.	Donor atom due to the existe additional electron.
Doped group	Group III elements. For eg - boron, gallium, indium, aluminium etc.	Group V elements. for eg - a antimony, bismuth, phospho
Majority carriers	Holes	Electrons
Minority carriers	Electrons	Holes
Conductivity	Due to presence of holes.	Due to presence of electrons
Presence of fermi level	Fermi level appears closer to the valence than the conduction band.	Fermi level is present nearer conduction band than the va
Concentration of electrons	Low	Very high as compared to p t semiconductor
Concentration of holes	High	Comparatively less than p ty semiconductor.

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Difference Between Intrinsic and Extrinsic semicoductors

Parameter	Intrinsic Semiconductor	Extrinsic Semiconduct
Form of semiconductor	Pure form of semiconductor.	Impure form of semico
Conductivity	It exhibits poor conductivity.	It possesses comparati better conductivity tha intrinsic semiconducto
Band gap	The band gap between conduction and valence band is small.	The energy gap is high than intrinsic semicon
Fermi level	It is present in the middle of forbidden energy gap.	The presence of Fermi level varies according the type of extrinsic semiconductor.
Dependency	The conduction relies on temperature.	The conduction depen on the concentration o doped impurity and temperature.
Carrier concentration	Equal amount of electron and holes are present in conduction and valence band.	The majority presence electrons and holes depends on the type of extrinsic semiconducto
Type	It is not further classified.	It is classified as p type and n type semiconduc

Example	Si, Ge etc.	GaAs, GaP etc.

So instead of the presence of widely separated energy levels as that of the isolated atoms, the closely spaced energy levels are present in a solid, which are called energy bands.

Out of all the energy bands, three bands are most important to understand the behaviour of solids. These bands are,

1] Valence band 2] Conduction band 3] Forbidden band or gap

Key Point: *The energy band formed due to merging of energy levels associated with the valence electrons i.e. electrons in the last shell, is called **valence band.***

As mentioned earlier in normal condition, valence electrons form the covalent bonds and are not free. But when certain energy is imparted to them, they become free.

Key Point: *The energy band formed due to merging of energy levels associated with the free electrons is called **conduction band.***

Under normal condition, the conduction band is empty and once energy is imparted, the valence electrons jump from valence band to conduction band and become free.

While jumping from valence band to conduction band, the electrons have to cross an energy gap.

Key Point: *The energy gap which is present separating the conduction band and the valence band is called **forbidden band or forbidden gap.***

The energy imparted to the electrons must be greater than the energy associated with the forbidden gap, to extract the electrons from valence band and transfer them to conduction band. The energy associated to forbidden band is denoted as E_G.

Key Point: *The electrons cannot exist in the forbidden gap.*

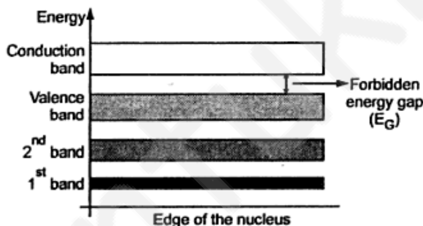

Fig. 7.3 Energy band diagram

The graphical representation of the energy bands in a solid is called **energy band diagram.** Such an energy band diagram for a solid silicon is shown in the Fig. 7.3.

The electrons in the various orbits revolving around the nucleus occupy the various bands including fully or partly occupied valence band. The conduction band which is normally empty carries the electrons which get drifted from the valence band. These electrons present in the conduction band are free electrons and they drift about in the spaces between the atoms.

For any given type of material the forbidden energy gap may be large, small or nonexistent. The classification of materials as insulators, conductors or semiconductors is mainly dependent on the widths of the forbidden energy gap. Let us see the classification of materials as insulators, conductors and semiconductors based on energy band diagram. Before that let us see the unit in which energy associated with the bands is measured.

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7.3.1 The eV, Unit of Energy

The energy is measured in joules (J) in the M.K.S. system. As mentioned earlier, each electron has an energy level associated with it. The unit joule is very large for the discussion of such energies associated with electrons. Hence such energies associated with the electrons are measured in electron volts denoted as eV.

The charge on a single electron is 1.6×10^{-19} coulomb. So **one electron volt is defined as the energy required by an electron to fall through a potential of one volt.**

$$\therefore \quad 1 \text{ eV} = 1.6\times10^{-19} \text{ (C)} \times 1 \text{ (V)} = 1.6\times10^{-19} \text{ J}$$

$$\therefore \quad \boxed{\mathbf{1\ eV = 1.6\times10^{-19}\ J}}$$

7.4 Classification of Materials Based on Energy Band Theory

Based on the ability of various materials to conduct current, the materials are classified as conductors, insulators and the semiconductors.

A metal which is very good carrier of electricity is called conductor. A very poor conductor of electricity is termed as insulator. A metal having conductivity which is between conductor and an insulator is called semiconductor. The copper and aluminium are good examples of a conductor. The glass, wood, mica, diamond are the examples of an insulator which does not conduct current. The silicon and germanium are the examples of a semiconductor which does not conduct current at low temperatures but as temperature increases these materials behave as good conductors. Let us see the energy band diagrams for these three types of metals.

7.4.1 Conductors

It has been mentioned earlier that a material having large number of free electrons can conduct very easily. For example, copper has 8.5×10^{28} free electrons per cubic metre which is a very large number. Hence copper is called good conductor. In fact, in the metals like copper, aluminium there is no forbidden gap between valence band and conduction band. **The two bands overlap.** Hence even at room temperature, a large number of electrons are available for conduction. So without any additional energy, such metals contain a large number of free electrons and hence called good **conductors.** An energy band diagram for a conductor is shown in the Fig. 7.4 (a).

7.4.2 Insulators

An insulator has an energy band diagram as shown in the Fig. 7.4 (b). In case of such insulating material, there exists a large forbidden gap in between the conduction band and the valence band. Practically it is impossible for an electron to jump from the valence band to the conduction band. Hence such materials cannot conduct and called **insulators.** The forbidden gap is very wide, approximately of about 7 eV is present in insulators. For a diamond, which is an insulator, the forbidden gap is about 6 eV. Such materials may

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conduct only at very high temperatures or if they are subjected to high voltage. Such a conduction is rare and is called breakdown of an insulator. The other insulating materials are glass, wood, mica, paper etc.

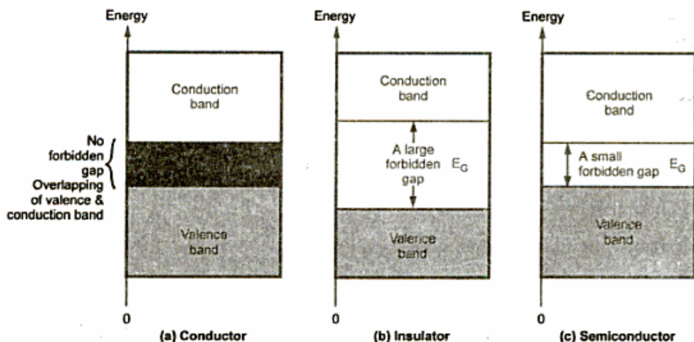

Fig. 7.4 Energy band diagrams

7.4.3 Semiconductors

Now let us come to an important category of materials, which are neither insulators nor conductors. The forbidden gap in such materials is very narrow as shown in Fig. 7.4 (c). Such materials are called **semiconductors.** The forbidden gap is about 1 eV. In such materials, the energy provided by the heat at room temperature is sufficient to lift the electrons from the valence band to the conduction band. Therefore at room temperature, semiconductors are capable of conduction. But at 0 °K or absolute zero (– 273 °C), all the electrons of semiconductor materials find themselves locked in the valence band. Hence at 0° k, the semiconductor materials behave as perfect insulators. In case of semiconductors, forbidden gap energy depends on the temperature. For silicon and germanium, this energy is given by,

$$E_G = 1.21 - 3.6 \times 10^{-4} \times T \quad \text{eV (for Silicon)}$$

$$E_G = 0.785 - 2.23 \times 10^{-4} \times T \text{ eV} \quad \text{(for Germanium)}$$

where T = Absolute temperature in °K

Assuming room temperature to be 27 °C i.e. 300 °K, the forbidden gap energy for Si and Ge can be calculated from the above equations. The forbidden gap for the germanium is 0.72 eV while for the silicon it is 1.12 eV at room temperature. The silicon and germanium are the two widely used semiconductor materials in electronic devices, as mentioned earlier.

Key Point : *While calculating* E_G, *substitute T in* °K.

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Why Silicon is most widely used ?

Looking at the structure of silicon and germanium atom, it can be seen that valence shell of silicion is 3rd shell while valence shell of germanium is 4th shell. Hence valence electrons of germanium are at larger distance from nucleus than valence electrons of silicon. Hence valence electrons of germanium are more loosely bound to the nucleus than those of silicon. Thus valence electrons of germanium can easily escape from the atom, due to very small additional energy imparted to them. So at high temperature, germanium becomes unstable than silicon and and hence silicon is widely used semiconductor material.

➠ **Example 7.1 :** *Calculate the value of forbidden gap for silicon and germanium at the temperature of 35 °C.*

Solution : Forbidden gap for silicon is given by,

$$E_G = 1.21 - 3.6\times 10^{-4}\times T$$

Now $$T = 35 + 273 = 308\ ^\circ K$$

$$\therefore \quad E_G = 1.21 - 3.6\times 10^{-4}\times 308 = \mathbf{1.099\ eV}$$

While forbidden gap for germanium is given by,

$$E_G = 0.785 - 2.23\times 10^{-4}\times T = 0.785 - 2.23\times 10^{-4}\times 308$$

$$= \mathbf{0.7163\ eV}$$

7.5 Intrinsic Semiconductors

A sample of semiconductor in its purest form is called an **intrinsic semiconductor.** The impurity content in intrinsic semiconductor is very very small, of the order of one part in 100 million parts of semiconductor. For achieving such a pure form, the semiconductor materials are carefully refined. To understand the conduction in an intrinsic semiconductor let us study the crystalline structure of an intrinsic semiconductor.

7.5.1 Crystal Structure of Intrinsic Semiconductor

Consider an atomic structure of an intrinsic semiconductor material like silicon. An outermost shell of an atom is capable of holding eight electrons. It is said to be completely filled and stable, if it contains eight electrons. But the outermost shell of an intrinsic semiconductor like silicon has only four electrons. Each of these four electrons form a bond with another valence electron of the neighbouring atoms. This is nothing but sharing of electrons. Such bonds are called **covalent bonds.** The atoms align themselves to form a three dimensional uniform pattern called **a crystal.**

The crystal structure of germanium and silicon materials consists of repetitive occurrence in three dimensions of a unit cell. This unit cell is in the form of a tetrahedron with an atom at each vertex. But such a three dimensional structure is very difficult to

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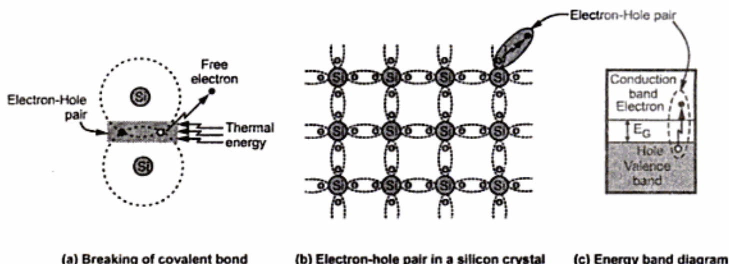

(a) Breaking of covalent bond (b) Electron-hole pair in a silicon crystal (c) Energy band diagram

Fig. 7.6 Thermal generation

The concentration of free electrons and holes is always equal in an intrinsic semiconductor. The hole also serves as a carrier of electricity similar to that of free electron. **An electron is negatively charged particle. Thus a hole getting created due to electron drift is said to be positively charged.**

> **Key Point**: *Thus in an intrinsic semiconductors both holes as well as free electrons are the charge carriers.*

7.5.3 Conduction by Electrons and Holes

The electrons and holes generated due to thermal generation move randomly and hence cannot constitute any current. Now consider that battery is connected across the intrinsic semiconductor.

Under the influence of applied voltage there is electron as well as hole motion in one particular direction, causing the flow of current.

The free electrons which are available in the conduction band are moved under the influence of applied voltage. The electrons as negatively charged get repelled from the negative terminal of battery and attracted towards the positive terminal. Thus there is an electric current due to the movement of electrons in conduction band. This is called **electron current** .

There are electrons present in the valence band which are involved in forming the covalent bonds. Some holes are also present in the valence band due to escape of electrons from valence to conduction band. Under the influence of applied voltage, the electrons involved in covalent bonds break the covalent bonds and try to fill the holes present. The electron breaking the covalent bond jumps to the hole of neighbouring atom, leaving a hole behind. This is illustrated in the Fig. 7.7 (a), (b) and (c).

The atom x has a hole due to escape of an electron to the conduction band. The electron from atom y breaks its covalent bond and fill the hole of atom x. Now the hole is

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7.5.6 Recombination of Electrons and Holes

The movement of holes in the valence band is always random and similarly the movement of free electrons in the conduction band is also random. Thermal agitation continues to produce new hole-electron pairs. Occasionally, a free electron approaches a hole and falls into it. This merging of a free electron and a hole is called **recombination.** After the recombination, an electron-hole pair gets disappeared. Due to recombination the number of charge carriers decreases. **The amount of time between the creation and disappearence of a free electron or hole is called the mean life time of the charge carrier.**

At any temperature, at any instant, the free electrons and holes, the two types of charge carriers are present in equal numbers. This concentration is called **intrinsic concentration**. Mathematically this is indicated as,

$$\boxed{n = p = n_i} \quad \text{... (2)}$$

where n = Number of free electrons per unit volume

p = Number of holes per unit volume

and n_i = Intrinsic concentration.

The concentration is measured in the units **number per m^3 or per cm^3.**

7.6 Drift Current

When a voltage is applied to a semiconductor, the free electrons try to move in a straight line towards the positive terminal of the battery. The electrons, moving towards positive terminal collide with the atoms of semiconductor and connecting wires, along its way. Each time the electron strikes an atom, it rebounds in a random direction. But still the applied voltage make the electrons drift towards the positive terminal. This drift causes current to flow in a semiconductor, under the influence of the applied voltage. This current produced due to drifting of free electrons is called **drift current** and the velocity with which electrons drift is called **drift velocity**. Thus drift current means the flow of current due to bouncing of electrons from one atom to another, travelling from negative terminal to positive terminal of the applied voltage.

Key Point : *The direction of conventional current is always opposite to the direction of drifting electrons.*

This is shown in the Fig. 7.10.

The conventional current direction is always from positive terminal to the negative terminal of the battery. But the operating principle of many semiconductor devices is generally explained considering the direction of flow of electrons rather than the conventional current.

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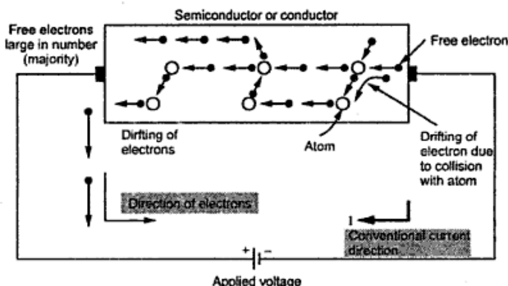

Fig. 7.10 Drift mechanism causing drift current

7.7 Mobility of Charged Particle

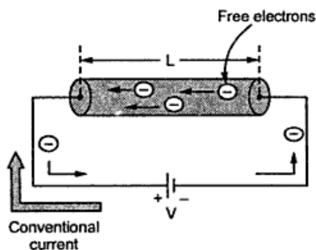

Fig. 7.11 Concept of mobility

Consider a material having a large number of free electrons. It is electrically neutral i.e. number of electrons is equal to number of protons. All the free electrons move around randomly inside the material. As the motion is random, on an average, the number of electrons passing through unit area in a given time in any direction inside the material is same as the number of electrons passing in opposite direction. Hence net movement of the electrons is cancelled. And hence **without electric field, there cannot be any drift current in the material.**

Consider a material of length L, subjected to the voltage V as shown in the Fig. 7.11. The electric field to which it is subjected is given by,

$$E = \frac{V}{L} \text{ V/m} \quad \text{... (1)}$$

The free electrons drift inside the material constituting the drift current.

Finally a steady state condition is reached where electrons continue to move with a finite steady velocity. Such a speed attained by the electrons under the influence of applied electric field in steady state condition is called as **drift speed** or **drift velocity**. It is denoted by v measured in metres per second. **The magnitude of the drift velocity is proportional to the electric field E**, so mathematically we can write

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$$v \propto E$$

$$\therefore \quad \boxed{v = \mu E} \quad \text{... (2)}$$

where v = Drift velocity in m/sec.

E = Applied electric field in V/m

where μ is constant of proportionality and is called **mobility** of the electrons. This is applicable to the free electrons as well as the holes whichever are the majority carriers.

So in general,

$$\mu = \text{Mobility of a charged particle} = \frac{v}{E}$$

$$\therefore \quad \boxed{\text{Units of } \mu = \frac{\text{m / sec}}{\text{V / m}} = \frac{\text{m}^2}{\text{V - sec}}} \quad \text{... (3)}$$

So it is measured in square metres per volt-second. Such steady movement of majority charge carriers with drift velocity constitutes a current. This current is called **drift current**.

7.8 General Expression for Conductivity

Consider a tube of metal with large number of free elecrons as shown in the Fig. 7.12.

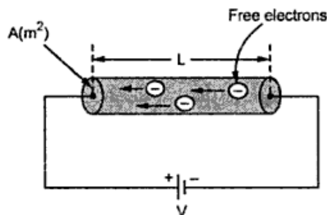

Fig. 7.12 Tube of metal subjected to voltage

Let, A = Cross-sectional area in m^2

L = Length in m

V = Voltage applied in volts

T = Time required by an electron to travel distance of 'L' m

$$\therefore \quad v = \text{Drift velocity of electron} = \frac{L}{T} \quad \text{...(1)}$$

$$E = \frac{V}{L} = \text{Electric field} \quad \text{...(2)}$$

$$v = \mu E \quad \text{where } \mu = \text{Mobility of electrons} \quad \text{...(3)}$$

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Consider any cross-section as shown in the Fig. 7.13.

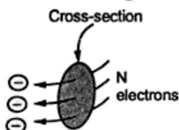

Fig. 7.13 N electrons crossing in T

Let N be the number of electrons passing through area A in time T. So number of electrons crossing the area A in **unit time** is $\frac{N}{T}$.

If $$e = \text{Charge on each electron} = 1.6 \times 10^{-19}\ \text{C}$$

then the total charge crossing the cross-section area A in **unit time** is,

$$dq = \text{Charge on each electron} \times \frac{N}{T} = \frac{Ne}{T}\ \text{C}$$

But charge passing per unit time through a cross-section is the **current**.

$$\therefore \quad I = \frac{\text{Charge passing}}{\text{Unit time}} = \frac{\frac{Ne}{T}}{(1\text{sec.})}$$

$$\therefore \quad I = \frac{Ne}{T}\ \text{A} \qquad \text{... (4)}$$

The **current density** J for the bar is current per unit cross-sectional area of the conducting material.

$$\therefore \quad J = \frac{I}{A}\ \text{A/m}^2 \qquad \text{... (5)}$$

$$\therefore \quad J = \frac{Ne}{TA} \quad \text{but } T = \frac{L}{v} \qquad \text{... from (1)}$$

$$\therefore \quad J = \frac{Ne}{\frac{L}{v} \times A} = \frac{Nev}{LA}$$

But $$LA = \text{Volume of the tube}$$

$$\therefore \quad n = \text{Concenration of free electrons}$$

$$= \text{Number of elecrons per unit volume}$$

$$\therefore \quad n = \frac{N}{LA}\ /\text{m}^3$$

$$\therefore \quad J = nev \quad \text{but } v = \mu E$$

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$$\therefore \quad \boxed{J = ne\mu E \quad A/m^2} \qquad \text{... (6)}$$

This is the general expression for current density in a given material.

The current density is related to electric field E by the relation,

$$\therefore \quad \boxed{J = \sigma E} \qquad \text{... (7)}$$

where σ = Conductivity of the material in $(\Omega\text{-m})^{-1}$

Key Point: *The conductivity indicates the ease with which current can flow through the given material.*

Comparing (6) and (7)

$$\therefore \quad \boxed{\sigma = ne\mu \ (\Omega - m)^{-1}} \qquad \text{... (8)}$$

This is the general expression for the conductivity of the given material

$$\therefore \quad \boxed{\rho = \text{resistivity} = \frac{1}{\sigma} \ (\Omega - m)} \qquad \text{... (9)}$$

Key Point: *The resistivity* ρ *is the reciprocal of the conductivity.*

7.9 Conductivity of an Intrinsic Semiconductor

In a semiconductor, there are two charged particles. One is negatively charged free electrons while the other is positively charged holes. These particles move in opposite direction, under the influence of an electric field but as both are of opposite sign, they constitute current in the same direction.

For the semiconductor,

n = Concentration of free electrons/m^3

p = Concentration of holes/m^3

μ_n = Mobility of electrons in m^2/V-s

μ_p = Mobility holes in m^2/V-s

then the current density is given by,

$$\therefore \quad \boxed{J = (n\mu_n + p\mu_p) \ e \ E \ A/m^2} \qquad \text{... (1)}$$

This can be obtained from the general expression for J derived in last section, equation (6).

Hence the conductivity for a semiconductor is given by,

$$\therefore \quad \boxed{\sigma = (n\mu_n + p\mu_p) \ e \ (\Omega - m^{-1})} \qquad \text{... (2)}$$

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7.9.2 Effect of Light on Semiconductor

The effect of light on a semiconductor is exactly similar to the effect of heat on a semiconductor. Just as thermal energy causes electrons to break their covalent bonds, similarly the light energy also causes electrons to break their covalent bonds. Under the influence of light energy, electron-hole pairs get generated in a semiconductor, increasing its conductivity.

When not illuminated there are few free electrons in a semiconductor and its resistance is high called **dark resistance.** As the light is incident on a semiconductor and it is illuminated it imparts light energy to the electrons. The electrons breaking their bonds move from valence band to conduction band and the conduction can take place readily. Thus there is decrease in resistance of a semiconductor. When illumination increases, a semiconductor may behave comparable to a conductor.

Thus effect of light on a semiconductor is to cause increase in the conductivity of a semiconductor.

Key Point : *Both heat and light are responsible to generate electron-hole pairs and hence to increase the conductivity of a semiconductor.*

➠ **Example 7.2 :** *Find the resistivity of an intrinsic silicon at 300 °K if intrinsic concentration of silicon at 300 °K is* 1.5×10^{10} *per* cm^3 *while* $\mu_n = 1300\ cm^2/V\text{-}sec$ *and* $\mu_p = 500\ cm^2/V\text{-}sec$. *Assume* $e = 1.6\times 10^{-19} C$.

Solution : The given values are, $n_i = 1.5\times10^{10}/cm^3$

$$\therefore \quad n_i = \frac{1.5\times 10^{10}}{10^{-6}} /m^3$$

$$= 1.5\times 10^{16} /m^3$$

And $$\mu_n = 1300\times10^{-4}\ m^2/V\text{-sec}$$

$$\mu_p = 500\times10^{-4}\ m^2/V\text{-sec}$$

Now $$\sigma_i = n_i(\mu_n + \mu_p)\, e$$

$$= 1.5\times 10^{16}[1300 + 500]\times 10^{-4}\times 1.6\times 10^{-19}$$

$$= 0.000432\ (\Omega\text{ - m})^{-1} \qquad \text{... conductivity}$$

$$\therefore \quad \rho = \frac{1}{\sigma_i}$$

$$= \frac{1}{0.000432} = \mathbf{2314.8148\ \Omega\text{ - m}}$$

This is the required resistivity.

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Example 7.3 : *A bar of intrinsic silicon has a cross-sectional area of* 2.5×10^{-4} m^2*. The electron density is* 1.5×10^{16} *per* m^3*. How long the bar be in order that the current in the bar will be 1.2 mA when 9 volts are applied across it ?*

Assume : $\mu_n = 0.14\ m^2/V\text{-}s,\ \mu_p = 0.05\ m^2/V\text{-}s.$

Solution : Electron density = n_i = Carrier intrinsic concentration

$$\therefore \quad n_i = 1.5\times10^{16}/m^3,$$

For intrinsic semiconductor,

$$\sigma_i = n_i(\mu_n + \mu_p)\, e$$

where e = Charge on one electron = 1.6×10^{-19} C

$$\therefore \quad \sigma = 1.5\times10^{16}\,(0.14 + 0.05)\,1.6\times10^{-19}$$

$$= 4.56\times10^{-4} = \text{Conductivity in } (\Omega\text{-m})^{-1}$$

$$\therefore \quad \rho = \text{Resistivity} = \frac{1}{\sigma}$$

$$= 2192.982\ \Omega\text{ - m}$$

Now
$$R = \frac{\rho l}{A}$$

$$\therefore \quad \frac{V}{I} = \frac{\rho l}{A}$$

$$\therefore \quad \frac{9}{1.2\times10^{-3}} = \frac{2192.982\times l}{2.5\times10^{-4}}$$

$$\therefore \quad l = 8.55\times10^{-4}\text{m} = \mathbf{0.855\ mm}$$

This is the length of the bar.

Example 7.4 : *Estimate the value of resistivity of intrinsic Germanium at 300 °K given :*
Intrinsic concentration = $2.5\times10^{13}\ cm^3$

Electron mobility = $3800\ cm^2/V\text{-}s$

Hole mobility = $1800\ cm^2/V\text{-}s$

Electron charge = 1.6×10^{-19} C

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Solution : Given values are

$$n_i = 2.5 \times 10^{13} / cm^3$$

$$\therefore \quad n_i = \frac{2.5 \times 10^{13}}{10^{-6}} = 2.5 \times 10^{19} / m^3$$

$$\mu_n = 3800 \ cm^2/V\text{-}s = 3800 \times 10^{-4} \ m^2 / V\text{-}s$$

$$\mu_p = 1800 \ cm^2/V\text{-}s = 1800 \times 10^{-4} \ m^2 / V\text{-}s$$

$$\sigma_i = (\mu_n + \mu_p) \, n_i \, e$$

$$= (3800 + 1800) \times 1.8 \times 10^{-19} \times 10^{-4} \times 2.5 \times 10^{19}$$

$$= 2.24 \ (\Omega - m)^{-1}$$

$$\rho_i = \frac{1}{\sigma_i} = \frac{1}{2.24} = \mathbf{0.4464 \ \Omega\text{ - }cm}$$

$$= \mathbf{0.4464 \ \Omega\text{ - }cm}$$

7.10 Law of Mass Action

If n is the concentration of free electrons and p is the concentration of holes then the law of mass action states that **the product of concentrations of electrons and holes is always constant, at a fixed temperature.**

Mathematically it is expressed as,

$$\mathbf{np = n_i^2} \quad \text{... (1)}$$

where n_i is intrinsic concentration.

Important Observations

1. The law can be applied to both intrinsic and extrinsic semiconductors.
2. As n_i depends on temperature, the law is applicable at a fixed temperature.
3. In case of extrinsic semiconductors, n_i is the intrinsic concentration of the basic semiconductor material used.

Key Point : *The law can be used to find the electron and hole densities in intrinsic semiconductors.*

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7.11 Extrinsic Semiconductors

In order to change the properties of intrinsic semiconductors a small amount of some other material is added to it. The process of adding other material to the crystal of intrinsic semiconductors to improve its conductivity is called **doping**. The impurity added is called **dopant**. Doped semiconductor material is called **extrinsic semiconductor.** The doping increases the conductivity of the basic intrinsic semiconductors hence the extrinsic semiconductors are used in practice for manufacturing of various electronic devices such as diodes, transistors etc.

Depending upon the type of impurities, the two types of extrinsic semiconductors are,

1. n-type and 2. p-type

7.11.1 Types of Impurities

The impurity material having five valence electrons is called **pentavalent atom**. When this is added to an intrinsic semicondcutor, it is called **donor doping** as each impurity atom donates one free electron to an intrinsic material. Such an impurity is called **donor impurity**. The examples of such impurity are arsenic, bismuth, phosphorous etc. This creates an extrinsic semiconductor with large number of free electrons, called **n-type semiconductor.**

Another type of impurity used is **trivalent atom** which has only three valence electrons. Such an impurity is called **acceptor impurity**. When this is added to an intrinsic semiconductor, it creates more holes and ready to accept an electron hence the doping is called **acceptor doping**. The examples of such impurity are gallium, indium and boron. The resulting extrinsic semiconductor with large number of holes is called **p-type semiconductor.**

7.12 n-Type Semiconductor

When a small amount of pentavalent impurity is added to a pure semiconductor, it is called **n-type semiconductor**. The pentavalent impurity has five valence electrons. These elements are such as arsenic, bismuth, phosphorous and antimony. Such an impurity is called **donor impurity.**

Consider the formation of n-type material by adding arsenic (As) into silicon (Si). The arsenic atom has five valence electrons. An arsenic atom fits in the silicon crystal in such a way that its four valence electrons form covalent bonds with four adjacent silicon atoms. The fifth electron has no chance of forming a covalent bond. This spare electron enters the conduction band as a free electron.

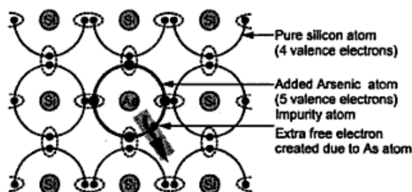

Fig. 7.15 n-type material formation

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Such n-type material formation is represented in the Fig. 7.15. This means that **each arsenic atom added into silicon atom gives one free electron.** The number of such free electrons can be controlled by the amount of impurity added to the silicon. Since the free electrons have negative charges, the material is known as n-type material and an impurity donates a free electron hence called donor impurity.

Key Point: *One donor impurity atom donates one free electron in n-type material. The free electrons are majority charge carriers.*

7.12.1 Conduction in n-Type Semiconductor

When the voltage is applied to the n-type semiconductor, the free electrons which are readily available due to added impurity, move in a direction of positive terminal of voltage applied. This constitutes a current. Thus the conduction is predominantly by free electrons. The holes are less in number hence electron current is dominant over the hole current. Hence in n-type semiconductors free electrons are called **majority carriers** while the holes which are small in number are called **minority carriers**. The conduction in n-type material is shown in the Fig. 7.16.

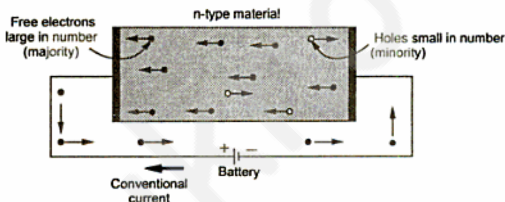

Fig. 7.16 Conduction in n-type material

7.13 p-Type Semiconductor

When a small amount of trivalent impurity is added to a pure semiconductor, it is called **p-type semiconductor**. The trivalent impurity has three valence electrons. These elements are such as gallium, boron or indium. Such an impurity is called **acceptor impurity.**

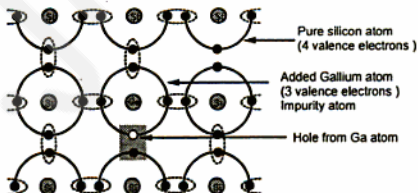

Fig. 7.17 p-type material formation

Consider the formation of p-type material by adding gallium (Ga) into silicon (Si). The gallium atom has three valence electrons. So gallium atom fits in the silicon crystal in such a way that its three valence electrons form covalent bonds with the three adjacent

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silicon atoms. Being short of one electron, the fourth covalent bond in the valence shell is incomplete. The resulting vacancy is called a hole. Such p-type material formation is represented in the Fig. 7.17. This means that **each gallium atom added into silicon atom gives one hole**. The number of such holes can be controlled by the amount of impurity added to the silicon. As the holes are treated as positively charged, the material is known as p-type material.

At room temperature, the thermal energy is sufficient to extract an electron from the neighbouring atom which fills the vacancy in the incomplete bond around impurity atom. But this creates a vacancy in the adjacent bond from where the electron had jumped, which is nothing but a hole. This indicates that a hole created due to added impurity is ready to accept an electron and hence is called acceptor impurity. Thus even for a small amount of impurity added, large number of holes get created in the p-type material.

Key Point : *One acceptor impurity creats one hole in a p-type material. The holes are majority charge carriers.*

7.13.1 Conduction in p-Type Semiconductor

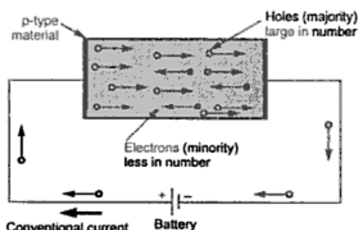

Fig. 7.18 Conduction in p-type material

If now such p-type material is subjected to an electric field by applying a voltage then the holes move in a valence band and are mainly responsible for the conduction. So the current conduction in p-type material is predominantly due to the holes. The free electrons are also present in conduction band but are very less in number. Hence holes are the **majority carriers** while electrons are **minority carriers** in p-type material. The conduction in p-type material is shown in the Fig. 7.18.

7.14 Conductivity of Extrinsic Semiconductor

In an extrinsic semiconductors, there are two types of materials n-type and p-type. Let us obtain the expressions for the conductivity of n-type and p-type materials.

7.14.1 Conductivity of n-Type Material

It is known that in n-type material, the free electrons are majority carriers while the holes are minority carriers.

Let n_n = Concentration of free electrons in n-type

p_n = Concentration of holes in n-type

N_D = Concentration of donor atoms

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Key Point: *In the symbol, main letter n or p indicates concentration of type of charge carrier electron or hole while the suffix indicates the type of material i.e. n-type or p-type. Thus* n_n *indicates electron concentration in n-type material while* n_p *indicates electron concentration in p-type material and so on.*

From the basic equation of conductivity, the conductivity of n-type material can be expressed as,

$$\sigma_n = (n_n \mu_n + p_n \mu_p)\, e \quad \text{... (1)}$$

But $p_n << n_n$ as holes are in minority hence,

$$\therefore \quad \boxed{\sigma_n \approx n_n \mu_n e} \quad \text{... (2)}$$

The number of free electrons is dominantly controlled by donor atoms added than the thermal generation at room temperature. Hence concentration of donor atoms N_D added can be approximately assumed to be equal to the concentration of free electrons n_n in n type materials.

Thus as $N_D >> n_i$ we can write,

$$n_n \approx N_D \quad \text{... (3)}$$

$$\therefore \quad \boxed{\sigma_n \approx N_D \mu_n e} \quad \text{... (4)}$$

7.14.2 Conductivity of p-Type Material

For a p-type material, holes are in majority and electrons are in minority.

Let n_p = Concentration of free electrons in p-type

p_p = Concentration of holes in p-type

N_A = Concentration of acceptor atoms

Thus the conductivity of p-type material can be expressed as,

$$\sigma_p = (n_p \mu_n + p_p \mu_p)\, e \quad \text{... (5)}$$

But $n_p << p_p$ as free electrons are in minority hence,

$$\boxed{\sigma_p \approx p_p \mu_p e} \quad \text{... (6)}$$

The number of holes is dominantly controlled by added acceptor impurity than the thermal generation. Each added impurity atom creats a hole hence $N_A >> n_i$. Thus all the holes generated p_p can be approximately assumed to be equal to the concentration of acceptor N_A. Thus,

$$p_p \approx N_A \quad \text{... (7)}$$

$$\therefore \quad \sigma_p \approx N_A \mu_p e \quad \text{... (8)}$$

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7.14.3 Law of Mass Action for Extrinsic Semiconductors

It is seen that, mathematically the law is expressed as,

$$\boxed{np = n_i^2} \quad \text{... (9)}$$

where n_i is intrinsic concentration.

Important Observations

1. The law can be applied to both intrinsic and extrinsic semiconductors.
2. In case of extrinsic semiconductors, n_i is the intrinsic concentration of the basic semiconductor material used.
3. For n-type material, $n = n_n$ while $p = p_n$ hence law can be stated as,

$$n_n p_n = n_i^2 \quad \text{... (10)}$$

4. For p-type material $n = n_p$ while $p = p_p$ hence law can be stated as,

$$n_p p_p = n_i^2 \quad \text{... (11)}$$

5. The law is applicable irrespective of amount of doping.
6. As n_i depends on temperature, the law is applicable at a fixed temperature.
7. The law can be used to find both majority and minority carrier concentrations in an extrinsic semiconductor.

7.14.4 Carrier Concentrations in Extrinsic Semiconductors

Let us obtain the concentrations of minority and majority carriers in n-type and p-type materials using Law of mass action.

n type material :

For n-type material it is seen that, $n_n \approx N_D$.

At any fixed temperature, according to law of mass action,

$$n_n \times p_n = n_i^2$$

where n_n is electrons i.e. majority carrier concentration while p_n is hole i.e. minority carrier concentration. Using $n_n \approx N_D$, we can write minority carrier concentration as,

$$N_D\, p_n = n_i^2$$

$$\therefore \quad \boxed{p_n = \frac{n_i^2}{N_D}} \quad \text{... (12)}$$

Knowing n_i and N_D, the **number of holes in n-type material i.e. minority carrier** concentration can be obtained.

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$$\therefore \quad n = \frac{-1 \times 10^{20} \pm \sqrt{(1 \times 10^{20})^2 - 4(-6.25 \times 10^{38})}}{2}$$

$$= 5.901 \times 10^{18} \text{ per m}^3 \quad \text{... neglecting negative value}$$

$$\therefore \quad p = 1 \times 10^{20} + n = 1.059 \times 10^{20} \text{ per m}^3$$

These are the actual concentrations of electrons holes in the sample. As $p > n$, holes are much more than electrons and sample will behave as **p-type** material

Example 7.7 : *If a donor impurity is added to the extent of one atom per 10^8 germanium atoms, calculate its resistivity at 300 °K. If its resistivity without addition of impurity at 300 °K is 44.64 Ω-cm, comparing two values, comment on the result.*
Assume : μ_n = 3800 cm²/V-sec.

Solution : Referring to the Table 7.2 of properties of germanium, germanium has 4.4×10^{22} atoms/cm³.

For 10^8 germanium atom there is 1 atom impurity added, as given.

Thus, for 4.4×10^{22} germanium atoms, we have,

$$= \frac{4.4 \times 10^{22}}{10^8} = 4.4 \times 10^{14} \text{ atoms of impurity/cm}^3$$

This is nothing but concentration of donor atoms i.e. N_D

$$\therefore \quad N_D = 4.4 \times 10^{14} \text{ per cm}^3 = \frac{4.4 \times 10^{14}}{10^{-6}} = 4.4 \times 10^{20} \text{ per m}^3$$

Now as donor impurity is added, n-type material will form,

$$\therefore \quad \sigma_n = n_n \mu_n q = N_D \mu_n q$$

where $n_n \cong N_D$ and $\mu_n = 3800 \text{ cm}^2/\text{V-sec} = 3800 \times 10^{-4} \text{m}^2/\text{V-sec}$

$$\therefore \quad \sigma_n = 4.4 \times 10^{20} \times 3800 \times 10^{-4} \times 1.6 \times 10^{-19} = 26.752 \ (\Omega\text{-m})^{-1}$$

$$\therefore \quad \text{Resistivity} = \rho_n = \frac{1}{\sigma_n} = \frac{1}{26.752} = 0.0373 \ \Omega\text{-m}$$

$$= 3.73 \ \Omega\text{-cm}$$

Comparing this with resistivity of intrinsic germanium it can be observed that resistivity reduces considerably due to addition of impurity. Hence conductivity of n-type material is much higher and hence it can carry more current as compared to the intrinsic semiconductor. By controlling amount of doping we can control the conductivity.

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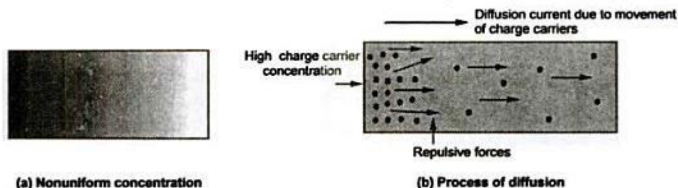
7.15 Diffusion Current

This is the current which is due to the transport of charges occurring because of nonuniform concentration of charged particles in a semiconductor.

Consider a piece of semiconductor which is nonuniformly doped. Due to such nonuniform doping, one type of charge carriers occur at one end of a piece of semiconductor. The charge carriers are either electrons or holes, of one type depending upon the impurity used. They have the same polarity and hence experience a force of repulsion between them. The result is that there is a tendency of the charge carriers to move gradually i.e. to diffuse from the region of high carrier density to the low carrier density. This process is called **diffusion**. This movement of charge carriers under the process of diffusion constitutes a current called **diffusion current**. This is shown in the Fig. 7.19.



(a) Nonuniform concentration (b) Process of diffusion

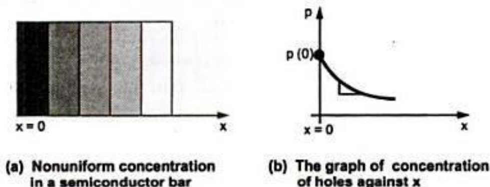
Fig. 7.19 Diffusion current

The diffusion current continues till all the carriers are evenly distributed throughout the material. A diffusion current is possible only in case of nonuniformly doped semiconductors while drift current is possible in semiconductors as well as conductors.

Key Point: *The diffusion current exists without external voltage applied while drift current can not exist without an external voltage applied.*

7.15.1 Concentration Gradient

Consider a p-type semiconductor bar which is nonuniformly doped. Along its length, in the direction of x as shown in Fig. 7.20 (a), there exists a nonuniform doping. As x increases, the doping concentration decreases.



(a) Nonuniform concentration in a semiconductor bar (b) The graph of concentration of holes against x

Fig. 7.20

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To form p-type of semiconductor, acceptor impurity is added which creates holes as the majority charged particles. Let p be the concentration of holes. But due to nonuniform doping it is not constant but is changing with respect to x.

Let concentration of holes at x = 0 is p = p(0) and is maximum as bar is heavily doped at x = 0. As x increases, the concentration of holes decreases. The nature of the variation in p against distance x is shown in the Fig. 7.20 (b).

The slope of the graph can be observed from the Fig. 7.20 (b) is the ratio of change in concentration to change in distance. It is called rate of change of concentration or **concentration gradient**.

$$\therefore \text{ Slope of graph } = \text{ Concentration gradient } = \frac{dp}{dx} \quad \dots (1)$$

Hence nonuniform doping produces a concentration gradient in a semiconductor. Due to such concentration gradient, holes move from the higher concentration area to the lower concentration area to adjust the concentration. Such a **movement of holes, due to the concentration gradient in a semiconductor is called diffusion.** Due to the movement of holes, current is constituted in a bar which is called **diffusion current.** There exists such a diffusion current in n-type semiconductor if it is nonuniformly doped, due to movement of electrons which are majority carriers.

Key Point: *Nonuniform doping creats concentration gradient, due to which diffusion of charge carriers exists.*

7.15.2 Diffusion Current Density

Consider a nonuniformly doped p-type semiconductor bar as shown in Fig. 7.21 (a).

The diffusion current density is proportional to the concentration gradient, which is responsible for the diffusion and hence the diffusion current.

$$\therefore \quad J_p \propto \frac{dp}{dx} \quad \dots (2)$$

where J_p = Diffusion current density due to holes

Hence the diffusion current density is expressed by,

$$J_p = e D_p \frac{dp}{dx}$$

where D_p = Diffusion constant for holes expressed in square metres per second. (m^2/sec).

Note : The current due to holes is in the direction of the conventional current and hence treated as positive. But slope of the graph i.e. $\frac{dp}{dx}$ is negative giving the negative diffusion current density for holes. But to get positive sign for holes, an additional

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negative sign is used to compensate for negative sign of $\frac{dp}{dx}$. Hence diffusion current density for holes is mathematically expressed as,

$$J_p = -e D_p \frac{dp}{dx} \quad \dots (3)$$

In case of n-type bar, such diffusion current is due to the electrons. Current due to the electrons is in opposite direction to the conventional current and mathematically treated to be negative. The concentration gradient $\frac{dn}{dx}$ is negative where n is concentration of electrons.

Hence diffusion current density to electrons is expressed by,

$$J_n = +e D_n \frac{dn}{dx} \quad \dots (4)$$

where D_n = Diffusion constant for electrons in square metres per second (m^2/sec).

The Fig. 7.21 (a) shows the direction of diffusion of holes and corresponding diffusion current density. The Fig. 7.21 (b) shows the direction of diffusion of electrons and corresponding diffusion current density.

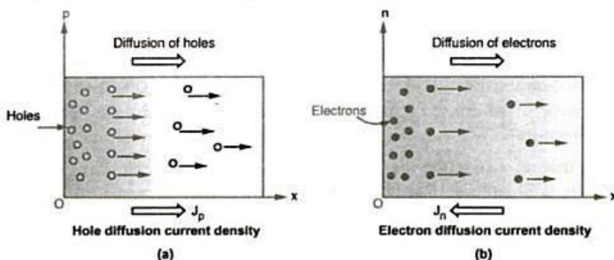

Fig. 7.21 Diffusion current densities

Observe that the charge carriers whether it is hole or electron, always **move from high concentration area towards low concentration area.** Hence direction of diffusion is same in both the cases. But resulting current densities have opposite directions.

7.15.3 Total Current Density Due to Drift and Diffusion

We have seen that the drift current is due to the applied voltage while the diffusion current is due to the concentration gradient. But in semiconductor it is very much possible that both the types of currents may exist simultaneously. In practice in such situation there exists four components of current as the drift current due to electrons and due to holes, while the diffusion current due to electrons and due to holes.

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Drift current density for electrons and holes can be expressed as,

$$J_n = n e \mu_n E \text{ and } J_p = p e \mu_p E$$ (Refer section 7.8)

Diffusion current density due to the electrons and holes can be expressed from equations (3) and (4) as,

$$J_n = + e D_n \frac{dn}{dx} \text{ and } J_p = - e D_p \frac{dp}{dx}$$

∴ **Total current density due to the electrons** can be expressed as,

$$\boxed{J_n = n e \mu_n E + e D_n \frac{dn}{dx}} \quad \ldots (5)$$

and **Total current density due to the holes** can be expressed as,

$$\boxed{J_p = p e \mu_p E - e D_p \frac{dp}{dx}} \quad \ldots (6)$$

And hence the total current density due to the electrons and holes (drift + diffusion) is,

$$\boxed{J = J_n + J_p} \quad \ldots (7)$$

7.15.4 Einstein's Relationship

It is now known that drift current density is proportional to the mobility (μ) while diffusion current density is proportional to the diffusion constant (D). There exists a fixed relation between these two constants which is called **Einstein's relation.**

It states that, at a fixed temperature, the ratio of diffusion constant to the mobility is constant. This is Einstein's relation. Mathematically it is expressed as,

$$\boxed{\frac{D_p}{\mu_p} = \frac{D_n}{\mu_n} = kT = \text{constant at fixed temperature.}} \quad \ldots (8)$$

where T is the temperature in °K

And k is the Boltzmann's constant = 8.62×10^{-5} eV/°K

7.15.5 Voltage Equivalent of Temperature

In the equation (8), the product kT is called **voltage equivalent of temperature.**

The voltage equivalent of temperature is denoted by V_T.

$$\boxed{V_T = kT = \text{Voltage equivalent of temperature}} \quad \ldots (9)$$

At room temperature i.e. at 27 °C,

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$$T = 273 + 27 = 300\ °K$$

$$\therefore \quad V_T = kT = 8.62 \times 10^{-5} \times 300 = 0.02586\ V \approx 26\ mV \text{ at } 300\ °K$$

Key Point: *The value of V_T = 26 mV at 27 °C i.e. 300 °K is very commonly used while solving the examples.*

Substituting this in equation (8) we get,

$$\frac{D_n}{\mu_n} = \frac{D_p}{\mu_p} = V_T = 0.02586 \quad \text{at room temperature}$$

$$\therefore \quad \boxed{\mu_n = 39\ D_n} \text{ and } \boxed{\mu_p = 39\ D_p} \text{ at room temperature.} \quad \text{... (10)}$$

In general we can express the relation between mobility and diffusion constant as,

$$\boxed{\mu = 39\ D \quad \text{at room temperature}} \quad \text{... (11)}$$

7.16 The p-n Junction Diode

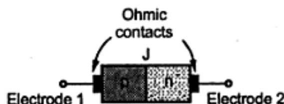
The p-n junction forms a popular semiconductor device called **p-n junction diode.** The p-n junction has two terminals called **electrodes,** one each from p-region and n-region. Due to the two electrodes it is called diode i.e. di + electrode.

To connect the n and p regions to the external terminals, a metal is applied to the heavily doped n and p-type semiconductor regions. Such a contact between a metal and a heavily doped semiconductor is called **ohmic contact.** Such an ohmic contact has two important properties,

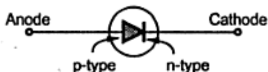
1. It conducts current equally in both the directions.
2. The drop across the contact is very small, which do not affect the performance of the device.

Thus ohmic contacts are used to connect n and p-type regions to the electrodes.

The Fig. 7.22 (a) shows schematic arrangement of p-n junction diode while the Fig. 7.22 (b) shows the symbol of p-n junction diode. The **p-region** acts as **anode** while the **n-region** acts as cathode. The arrowhead in the symbol indicates the direction of the conventional current, which can flow when an external voltage is connected in a specific manner across the diode.



(a) Two electrodes



(b) Symbol of a diode

Fig. 7.22

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The large number of majority carriers constitute a current called **forward current.** Once the conduction electrons enter the p-region, they become valence electrons. Then they move from hole to hole towards the positive terminal of the battery. The movement of valence electrons is nothing but movement of holes in opposite direction to that of electrons, in the p-region. So current in the p-region is the movement of holes which are majority carriers. This is the **hole current.** While the current in the n-region is the movement of free electrons which are majority carriers. This is the **electron current.** Hence the overall forward current is due to the majority charge carriers. The action is shown in the Fig. 7.24. These majority carriers can then travel around the closed circuit and a relatively large current flows. The direction of flow of electrons is from negative to positive of the battery. While direction of the conventional current is from positive to negative of the battery as shown in the Fig. 7.24.

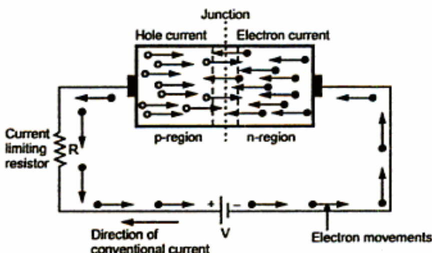

Fig. 7.24 Forward current in a diode

Key Point : *The direction of flow of electrons and conventional current is opposite to each other.*

7.17.2 Effect on the Depletion Region

Due to the forward bias voltage, more electrons flow into the depletion region, which reduces the number of positive ions. Similarly flow of holes reduces the number of negative ions. This reduces the width of the depletion region. This is shown in the Fig. 7.25.

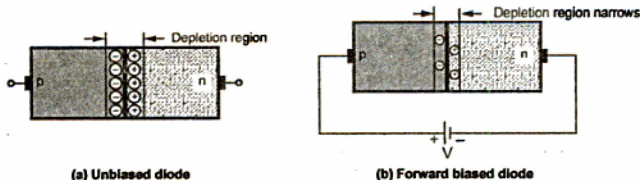

Fig. 7.25

Key Point : *Depletion region narrows due to forward bias voltage.*

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creates more positive ions and hence more positive charge in the n-region and more negative ions and hence more negative charge in the n-region. This is because the applied voltage helps the barrier potential. This is shown in the Fig. 7.27.

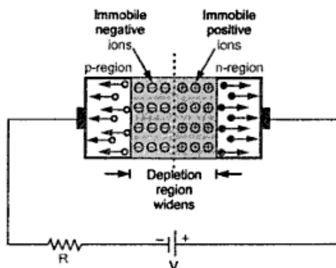

Fig. 7.27 Depletion region widens in reverse bias

Key Point: *Reverse biasing increases the width of the depletion region*

As depletion region widens, barrier potential across the junction also increases. However, this process cannot continue for long time. In the steady state, majority current ceases as holes and electrons stop moving away from the junction.

The polarities of barrier potential are same as that of the applied voltage. Due to increased barrier potential, the positive side drags the electrons from p-region towards the positive of battery. Similarly negative side of barrier potential drags the holes from n-region towards the negative of battery. The electrons on p-side and holes on n-side are minority charge carriers, which constitute the current in reverse biased condition. Thus reverse conduction takes place.

The reverse current flows due to minority charge carriers which are small in number. Hence reverse current is always very small.

Key Point : *The generation of minority charge carriers depends on the the temperature and not on the applied reverse bias voltage. Thus the reverse current depends on the temperature i.e. thermal generation and not on the reverse voltage applied.*

For a constant temperature, the reverse current is almost constant though reverse voltage is increased upto a certain limit. Hence it is called **reverse saturation current** and denoted as I_0.

Key Point : *Reverse saturation current is very small of the order of few microamperes for germanium and few nanoamperes for silicon p-n junction diodes.*

The reverse current and its direction is shown in the Fig. 7.28.

The reverse biasing produces a voltage drop across the diode denoted as V_R which is almost equal to applied reverse voltage.

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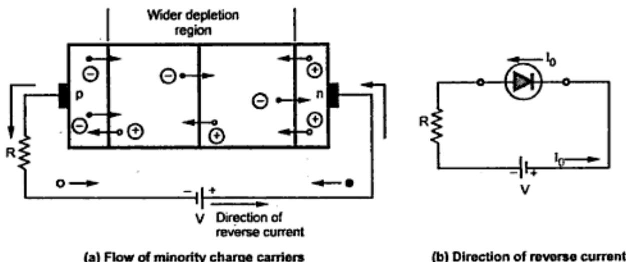

(a) Flow of minority charge carriers (b) Direction of reverse current

Fig. 7.28 Reverse biased diode

7.18.2 Breakdown in Reverse Biased

Though the reverse saturation current is not dependent on the applied reverse voltage, if reverse voltage is increased beyond particular value, large reverse current can flow damaging the diode. This is called **reverse breakdown** of a diode. Such a reverse breakdown of a diode can take place due to the following two effects,

1. Avalanche effect and 2. Zener effect.

Breakdown Due to the Avalanche Effect

Though reverse current is not dependent on reverse voltage, if reverse voltage is increased, at a particular value, velocity of minority carriers increases. Due to the kinetic energy associated with the minority carriers, more minority carriers are generated when there is collision of minority carriers with the atoms. The collision make the electrons to break the co-valent bonds. These electrons are available as minority carriers and get accelerated due to high reverse voltage. They again collide with another atoms to generate more minority carriers. This is called **carrier multiplication.** Finally large number of minority carriers move across the junction, breaking the p-n junction. These large number of minority carriers give rise to a very high reverse current. This effect is called **avalanche effect** and the mechanism of destroying the junction is called **reverse breakdown** of a p-n junction. The voltage at which the breakdown of a p-n junction occurs is called **reverse breakdown voltage.** The series resistance must be used to avoid breakdown condition, limiting the reverse current.

Breakdown Due to the Zener Effect

The breakdown of a p-n junction may occur because of one more effect called **zener effect.** When a p-n junction is heavily doped the depletion region is very narrow. So under reverse bias conditions, the electric field across the depletion layer is very intense. Electric field is voltage per distance and due to narrow depletion region and high reverse voltage, it is intense. Such an intense field is enough to pull the electrons out of the valence bands

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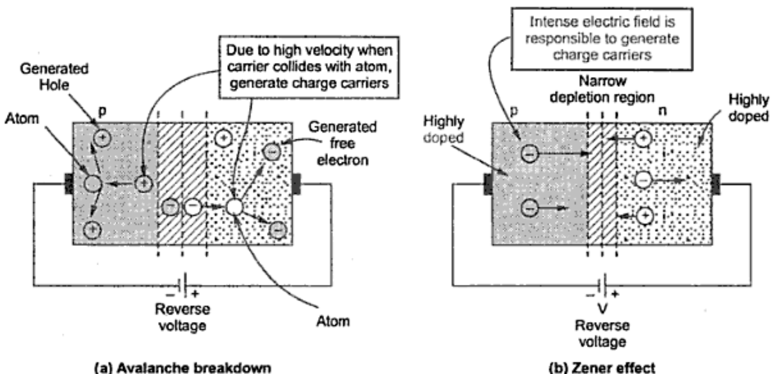
of the stable atoms. So this is not due to the collision of carriers with atoms. Such a creation of free electrons is called **zener effect** which is different than the avalanche effect. These minority carriers constitute very large current and mechanism is called **zener breakdown.**

> **Key Point**: *The normal p-n junction diode is practically not operated in reverse breakdown region though may be operated in reverse biased condition.*

The breakdown effects are not required to be considered for p-n junction diode. These effects are required to be considered for special diodes such as zener diode as such diodes are always operated in reverse breakdown condition.

The Fig. 7.29(a) shows the avalanche effect while the Fig. 7.29 (b) shows the zener effect.



(a) Avalanche breakdown (b) Zener effect

Fig. 7.29 Breakdown mechanisms

7.19 The Current Components in a p-n Junction Diode

It is indicated earlier that when a p-n junction diode is forward biased a large forward current flows, which is mainly due to majority carriers. The depletion region near the junction is very very small, under forward biased condition. In forward biased condition holes get diffused into n-side from p-side while electrons get diffused into p-side from n-side. So on p-side, the current carried by electrons which is diffusion current due to minority carriers, decreases exponentially with respect to distance measured from the junction. This current due to electrons, on p-side which are minority carriers is denoted as I_{np}. Similarly holes from p-side diffuse into n-side carry current which decreases exponentially with respect to distance measured from the junction. This current due to holes on n-side, which are minority carriers is denoted as I_{pn}. If distance is denoted by x then,

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I_{np} (x) = Current due to electrons in p-side as a function of x

I_{pn} (x) = Current due to holes in n-side as a function of x

At the junction i.e. at x = 0, electrons crossing from n-side to p-side constitute a current, $I_{np}(0)$ in the same direction as holes crossing the junction from p-side to n-side constitute a current, $I_{pn}(0)$.

Hence the current at the junction is the total conventional current I flowing through the circuit.

$$\therefore \quad \boxed{I = I_{pn}(0) + I_{np}(0)} \quad \text{... (1)}$$

Now $I_{pn}(x)$ decreases on n-side as we move away from junction on n-side. Similarly $I_{np}(x)$ decreases on p-side as we move away from junction on p-side.

But as the entire circuit is a series circuit, the total current must be maintained at I, independent of x. This indicates that on p-side there exists one more current component which is due to holes on p-side which are the majority carriers. It is denoted by $I_{pp}(x)$ and the addition of the two currents on p-side is total current I.

$$I_{pp}(x) = \text{Current due to holes in p-side.}$$

Similarly on n-side, there exists one more current component which is due to electrons on n-side, which are the majority carriers. It is denoted as $I_{nn}(x)$ and the addition of the two currents on n-side is total current I.

$$I_{nn}(x) = \text{Current due to electrons in n-side.}$$

On p-side, $$\boxed{I = I_{pp}(x) + I_{np}(x)} \quad \text{... (2)}$$

On n-side, $$\boxed{I = I_{nn}(x) + I_{pn}(x)} \quad \text{... (3)}$$

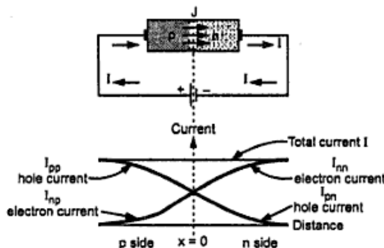

Fig. 7.30 Current components

These current components are plotted as a function of distance in the Fig. 7.30.

The current I_{pp} decreases towards the junction, at the junction enters the n-side and becomes I_{pn} which further decreases exponentially. Similarly the current I_{nn} decreases towards the junction, at the junction enters the p-side and becomes I_{np} which also further decreases exponentially.

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Key Point : *In forward bias condition, the current enters the p-side as a hole current and leaves the n-side as an electron current, of the same magnitude.*

So sum of the currents carried by electrons and holes at any point inside the diode is always constant equal to total forward current I. But the proportion due to holes and electrons in constituting the current varies with the distance, from the junction.

7.20 The Volt-Ampere (V-I) Characteristics of a Diode

The response of a diode when connected in an electrical circuit, can be judged from its characteristics known as Volt-Ampere commonly called **V-I characteristics.** The V-I characteristics in the forward biased and reverse biased condition is the graph of voltage across the diode against the diode current.

7.20.1 Forward Characteristics of p-n Junction Diode

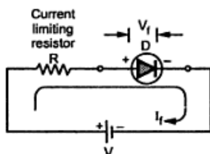

Fig. 7.31 Forward biased diode

The response of p-n junction can be easily indicated with the help of characteristics called **V-I characteristics** of p-n junction. It is the graph of voltage applied across the p-n junction and the current flowing through the p-n junction.

The Fig. 7.31 shows the forward biased diode. The applied voltage is V while the voltage across the diode is V_f. The current flowing in the circuit is the forward current I_f. The graph of forward current I_f against the forward voltage V_f across the diode is called **forward characteristics** of a diode.

The forward characteristics of a diode is shown in the Fig. 7.32.

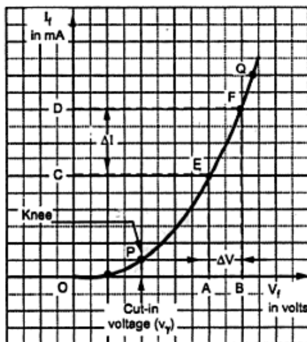

Fig. 7.32 Forward characteristics of a diode

Basically forward characteristics can be divided into two regions :

1. **Region O to P :** As long as V_f is less than cut-in voltage (V_γ) , the current flowing is very small. Practically this current is assumed to be zero.

2. **Region P to Q and onwards :** As V_f increases towards V_γ the width of depletion region goes on reducing. When V_f exceeds V_γ i.e. cut-in voltage, the depletion region becomes very thin and current I_f increases suddenly. This increase in the current is **exponential** as shown in the Fig. 7.32 by the region P to Q.

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The point P, after which the forward current starts increasing exponentially is called **knee** of the curve.

Key Point: *The normal forward biased operation of the diode is above the knee point of the curve. i.e. in the region P-Q.*

The forward current is the conventional current, hence it is treated as positive and the forward voltage V_f is also treated positive. Hence the forward characteristics is plotted in the **first quadrant.**

Forward Resistance of a Diode

The resistance offered by the p-n junction diode in forward biased condition is called **forward resistance.** The forward resistance is defined in two ways :

1) Static Forward Resistance :

This is the forward resistance of p-n junction diode when p-n junction is used in d.c. circuit and the applied forward voltage is d.c. This resistance is denoted as R_F and is calculated at a particular point on the forward characteristics.

Thus at a point E shown in the forward characteristics, the static resistance R_F is defined as the ratio of the d.c. voltage applied across the p-n junction to the d.c. current flowing through the p-n junction.

$$R_F = \frac{\text{Forward d.c. voltage}}{\text{Forward d.c. current}} = \frac{OA}{OC} \text{ at point E}$$

2) Dynamic Forward Resistance :

The resistance offered by the p-n junction under a.c. conditions is called **dynamic resistance** denoted as r_f.

Key Point: *The dynamic resistance is reciprocal of the slope of the forward characteristics.*

Consider the change in applied voltage from point A to B shown in the Fig. 1.18. This is denoted as ΔV. The corresponding change in the forward current is from point C to D. It is denoted as ΔI. Thus the slope of the characteristics is $\Delta I/\Delta V$. The reciprocal of the slope is dynamic resistance r_f.

$$r_f = \frac{\Delta V}{\Delta I} = \frac{1}{(\Delta I/\Delta V)} = \frac{1}{\text{Slope of forward characteristics}}$$

Key Point : *Generally the value of r_f is very small of the order of few ohms, in the operating region i.e. above the knee.*

7.20.2 Reverse Characteristics of p-n Junction Diode

The Fig. 7.33 shows the reverse biased diode. The reverse voltage across the diode is V_R while the current flowing is reverse current I_R flowing due to minority charge carriers. The graph of I_R against V_R is called **reverse characteristics** of a diode.

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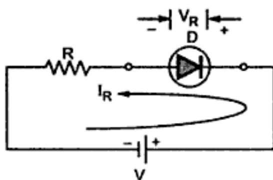

Fig. 7.33 Reverse biased diode

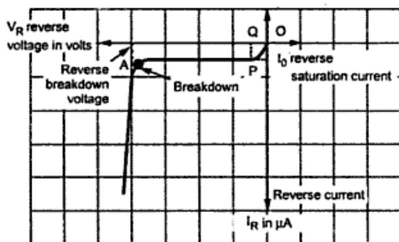

Fig. 7.34

The polarity of reverse voltage applied is opposite to that of forward voltage. Hence in practice reverse voltage is taken as negative. Similarly the reverse saturation current is due to minority carriers and is opposite to the forward current. Hence in practice reverse saturation current is also taken as negative. Hence the reverse characteristics is plotted in the **third quadrant** as shown in the Fig. 7.34.

Key Point : *Typically the reverse breakdown voltage is greater than 50 V for normal p-n junctions.*

As reverse voltage is increased, reverse current increases initially but after a certain voltage, the current remains constant equal to reverse saturation current I_0 though reverse voltage is increased. The point A where breakdown occurs and reverse current increases rapidly is called knee of the reverse characteristics.

Reverse Resistance of a Diode

The p-n junction offers large resistance in the reverse biased condition called **reverse resistance.** This is also defined in two ways.

1. Reverse static resistance :

This is reverse resistance under d.c. conditions, denoted as R_r. It is the ratio of applied reverse voltage to the reverse saturation current I_0.

$$\therefore \quad \boxed{R_r = \frac{OQ}{I_0} = \frac{\text{Applied reverse voltage}}{\text{Reverse saturation current}}}$$

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2. Reverse dynamic resistance :

This is the reverse resistance under the a.c. conditions, denoted as r_r. It is the ratio of incremental change in the reverse voltage applied to the corresponding change in the reverse current.

$$\therefore \quad r_r = \frac{\Delta V_R}{\Delta I_R} = \frac{\text{Change in reverse voltage}}{\text{Change in reverse current}}$$

The dynamic resistance is most important in practice whether the junction is forward or reverse biased.

7.20.3 Complete V-I Characteristics of a Diode

The complete V-I characteristics of a diode is the combination of its forward as well as reverse characteristics. This is shown in the Fig. 7.35.

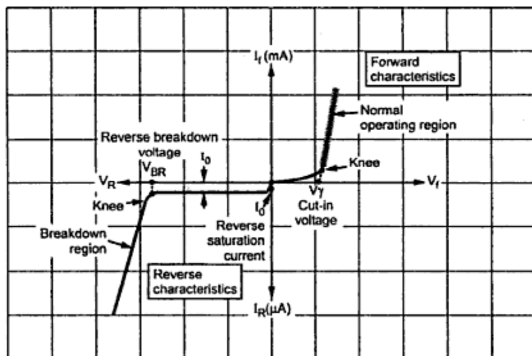

Fig. 7.35 Complete V-I characteristics of a diode

In forward characteristics, it is seen that initially forward current is small as long as the bias voltage is less that the barrier potential. At a certain voltage close to barrier potential, current increases rapidly. The voltage at which diode current starts increasing rapidly is called as cut-in voltage. It is denoted by V_γ. Below this voltage, current is less than 1% of maximum rated value of diode current. The cut-in voltage for germanium is about 0.2 V while for silicon it is 0.6 V.

It is important to note that the breakdown voltage is much higher and practically diodes are not operated in the breakdown condition. **The voltage at which breakdown occurs is called reverse breakdown voltage denoted as V_{BR}.**

Key Point : *Reverse current before the breakdown is very very small and can be practically neglected.*

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The factor η is called **emission coefficient** or **ideality factor**. This factor takes into account the effect of recombination taking place in the depletion region. The effect is dominant in silicon diodes and hence for silicon $\eta = 2$. The range of factor is from 1 to 2.

The **voltage equivalent of temperature** indicates dependence of diode current on temperature. The voltage equivalent of temperature V_T for a given diode at temperature T is calculated as,

$$\boxed{V_T = kT \text{ volts}} \qquad \ldots (2)$$

where k = Boltzmann's constant = 8.62×10^{-5} eV/°K

T = Temperature in °K.

At room temperature of 27 °C i.e. T = 27 + 273 = 300 °K and the value of V_T is 26 mV, as seen earlier.

The value of V_T also can be expressed as,

$$\boxed{V_T = \frac{T}{\left(\frac{1}{k}\right)} = \frac{T}{\left(\frac{1}{8.62 \times 10^{-5}}\right)} = \frac{T}{11600}} \qquad \ldots (3)$$

Key Point : *The diode current equation is applicable for all the conditions of diode i.e. unbiased, forward biased and reverse biased.*

When unbiased, $V = 0$ hence we get,

$$I = I_0 [e^0 - 1] = 0 \text{ A}$$

Thus there is no current through diode when unbiased.

Key Point: *For forward biased,* ***V must be taken positive*** *and we get current I positive which is forward current. For reverse biased,* ***V must be taken negative*** *and we get negative current I which indicates that it is reverse current.*

If both sides of diode current equation is divided by cross-sectional area A of the junction,

$$\frac{I}{A} = \frac{I_0}{A}\left[e^{V/\eta V_T} - 1\right]$$

i.e.

$$\boxed{J = J_0\left[e^{V/\eta V_T} - 1\right] \text{A/m}^2} \qquad \ldots (4)$$

where J = Forward current density

J_0 = Reverse saturation current density

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Example 7.9 : *The voltage across a silicon diode at room temperature of 300 °K is 0.71 V when 2.5 mA current flows through it. If the voltage increases to 0.8 V, calculate the new diode current.*

Solution : The current equation of a diode is

$$I = I_0 \left(e^{V/\eta V_T} - 1\right)$$

At 300 °K, $V_T = 26 \text{ mV} = 26 \times 10^{-3}$ V

$V = 0.71$ V for $I = 2.5$ mA and $\eta = 2$ for silicon

$\therefore \quad 2.5 \times 10^{-3} = I_0 \left[e^{(0.71/2 \times 26 \times 10^{-3})} - 1 \right]$

$\therefore \quad I_0 = 2.93 \times 10^{-9}$ A

Now V = 0.8 V

$\therefore \quad I = 2.93 \times 10^{-9} \left[e^{(0.8/2 \times 26 \times 10^{-3})} - 1 \right]$

$= 0.0141$ A = **14.11 mA**

Example 7.10 : *A germanium diode has a reverse saturation current of 3 μA. Calculate the forward bias voltage at the room temperature of 27 °C and 1% of the rated current is flowing through the forward biased diode. The diode forward rated current is 1 A.*

Solution : The given values are, $I_0 = 3\ \mu A$, T = 27 °C = 27 +273 = 300 °K , $\eta = 1$

Now $I_{rated} = 1$ A for diode

and $I = 1\%$ of I_{rated} at 27 °C

$\therefore \quad I = \frac{1}{100} \times (1) = 0.01$ A

$V_T = kT = 8.62 \times 10^{-5} \times 300 = 0.026$ V

According to diode equation, $I = I_0 [e^{V/\eta V_T} - 1]$

$\therefore \quad 0.01 = 3 \times 10^{-6} [e^{V/1 \times 0.026} - 1]$

$\therefore \quad 3333.333 = e^{V/0.026} - 1$

$\therefore \quad e^{V/0.026} = 3334.3333$

$\therefore \quad ln\,[e^{V/0.026}] = ln\,[3334.3333]$ ... taking natural log

$\therefore \quad \frac{V}{0.026} = 8.112$

$\therefore \quad V =$ **0.2109 V**

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Example 7.11 : *A diode operating at 300 °K at a forward voltage of 0.4 V carries a current of 10 mA. When voltage is changed to 0.42 V, the current becomes twice. Calculate the value of reverse saturation current and* η *for the diode.*

Solution : At $V_1 = 0.4$ V, $I_1 = 10$ mA and at $V_2 = 0.42$ V, $I_2 = 2\,I_1 = 20$ mA

Now $$I = I_0[e^{V/\eta V_T} - 1]$$

$$\therefore \quad 10\times10^{-3} = I_0\left[e^{0.4/\eta\times26\times10^{3}} - 1\right] \quad ...(1)$$

and $$20\times10^{-3} = I_0\left[e^{0.42/\eta\times26\times10^{3}} - 1\right] \quad ...(2)$$

In forward bias condition $1 << e^{V/\eta V_T}$, $\therefore$ Neglecting 1

$$10\times10^{-3} = I_0\,e^{\frac{15.384}{\eta}} \quad ...(3)$$

and $$20\times10^{-3} = I_0\,e^{\frac{16.153}{\eta}} \quad ...(4)$$

Dividing the two equations (3) and (4) ,

$$\frac{1}{2} = \frac{e^{15.384/\eta}}{e^{16.153/\eta}}$$

$$\therefore \quad e^{16.153/\eta} = 2e^{15.384/\eta}$$

Taking natural logarithm of both sides,

$$\therefore \quad \frac{16.153}{\eta} = ln2 + \frac{15.384}{\eta}$$

$$\therefore \quad \frac{1}{\eta}(16.153-15.384) = 0.6931$$

$$\therefore \quad \eta = 1.109$$

Hence $$I_0 = 9.45 \text{ nA}$$

7.22 Effect of Temperature on Diode

The temperature has following effects on the diode parameters,

1. The cut-in voltage decreases as the temperature increases. The diode conducts at smaller voltages at large temperature.
2. The reverse saturation current increases as temperature increases.

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This increase in reverse current I_0 is such that it **doubles at every 10 °C rise in temperature.** Mathematically,

$$I_{02} = 2^{(\Delta T/10)} I_{01}$$

where I_{02} = Reverse current at T_2 °C

I_{01} = Reverse current at T_1 °C

$\Delta T = (T_2 - T_1)$

3. The voltage equivalent of temperature V_T also increases as temperature increases.
4. The reverse breakdown voltage increases as temperature increases.

This is shown in the Fig. 7.39.

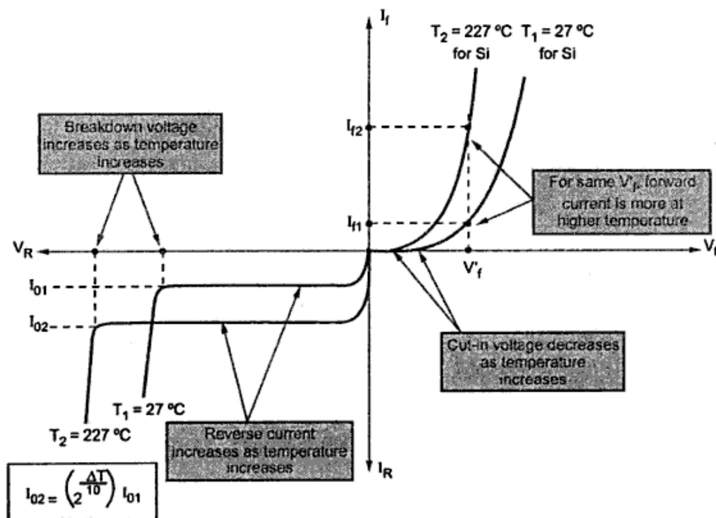

Fig. 7.39 Effect of temperature on diode

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vacancy. So because of the thermal agitation of the crystal lattice, an electron of another ion may come very close to the ion which has lost the electron. The ion which has lost the electron will immediately steal an electron from the closest ion, to fill its vacancy. The holes move from the first ion to the second ion. ***When no electric field is applied, the motion of free electron is random in nature***. But when electric field is applied, all the free electrons are lined up and they move towards the positive electrode. The ***life period of a free electron may be 1μ–sec to 1 millisecond*** after which it is absorbed by another ion.

2.9 MASS ACTION LAW

In an intrinsic Semiconductor number of free electrons $n = n_i$ = No. of holes $p = p_i$

Since the crystal is electrically neutral, $n_i p_i = n_i^2$.

Regardless of individual magnitudes of n and p, the product is always constant,

$$\therefore \quad np = n_i^2$$

$$n_i = AT^{\frac{3}{2}} e^{\frac{-E_{GO}}{2KT}} \quad \text{.......... (2.13)}$$

This is called ***Mass Action Law***.

2.10 LAW OF ELECTRICAL NEUTRALITY

Let N_D is equal to the concentration of donor atoms in a doped semiconductor. So when these donor atoms donate an electron, it becomes positively charged ion, since it has lost an electron. So positive charge density contributed by them is N_D. If '*p*' is the hole density then total positive charge density is $N_D + p$. Similarly if N_A is the concentration of acceptor ions, (say Boron which is trivalent, ion, accepts an electron, so that 4 electrons in the outer shell are shared by the Ge atoms), it becomes negatively charged. So the acceptor ions contribute charge = ($N_A + n$). Since the Semiconductor is electrically neutral, when no voltage is applied, the magnitude of positive charge density must equal that of negative charge density.

Total positive charge, $N_D + p$ = Total negative charge ($N_A + n$)

$$N_D + p = N_A + n$$

This is known as ***Law of Electrical Neutrality***.

Consider n-type material with acceptor ion density $N_A = 0$. Since it is n-type, number of electrons is >> number of holes.

So 'p' can be neglected in comparison with n.

$$\therefore \quad n_n \simeq N_D. \quad \text{(Since every Donor Atom contributes one free electron.)}$$

In n-type material, the free electron concentration is approximately equal to the density of donor atoms.

In n-type semiconductor the electron density $n_n = N_D$. Subscript n indicates that it is n-type semiconductor.

But $$n_n \times p_n = n_i^2$$

$$\therefore \quad p_n = \text{The hole density in n-type semiconductor} = \frac{n_i^2}{N_D}$$

$$p_n = \frac{n_i^2}{N_D} \quad \text{.......... (2.14)}$$

$A = 9.64 \times 10^{14}$

$E_G = 0.25$ ev

$n_i^2 = 6.25 \times 10^{26}/cm^3$

$N_A + n = N_D + p$

∴ Total negative charge = Total positive charge

or $p - n = N_A - N_D = (3 - 2) \times 10^{14} = 10^{14}$

or $p = n + 10^{14}$

Then $n(n + 10^{14}) = 6.25 \times 10^{26}$

or $n = 5.8 \times 10^{12}$ electrons. $/cm^3$

and $p = n + 10^{14} = 1.06 \times 10^{14}$ holes/cm^3

As $p > n$, this is p-type semiconductor.

Problem 2.17

Find the concentration of holes and electrons in a p type germanium at 300°K, if the conductivity is 100 Ω - cm. μ_p Mobility of holes in Germanium = 1800 cm^2 / V - sec.

Solution

∵ It is p-type $p >> n$.

∴ $\sigma_p = p \, e \, \mu_p$

$$p_p = \frac{\sigma}{e\mu_p} = \frac{100}{1.6 \times 10^{-19} \times 1800} = 3.47 \times 10^{17} \text{ holes/cm}^3$$

$n \times p = n_i^2$

$n_i = 2.5 \times 10^{13}/cm^3$

$$\therefore \quad n = \frac{(2.5 \times 10^{13})^2}{3.47 \times 10^{17}} = 1.8 \times 10^9 \text{ electrons/cm}^3$$

Problem 2.18

(a) Find the concentration of holes and electrons in p-type Germanium at 300°K, if $\sigma = 100$ υ/cm.

(b) Repeat part **(a)** for n-type Si, if $\sigma = 0.1$ υ/cm.

Solution

As it is p-type semiconductor, $p >> n$.

∴ $\sigma = pe\mu_p$

$$\therefore \quad p = \frac{\sigma}{e\mu_p} = \frac{100}{1.6 \times 10^{-19} \times 1800} = 3.47 \times 10^{17} \text{holes/cm}^3$$

$= 3.47 \times 10^{17}$ holes/cm^3

$n \times p = n_i^2$

$$n_i = AT^{\frac{3}{2}} e^{-\frac{E_{GO}}{2kT}} = 2.5 \times 10^{13}/cm^3$$

$p = 3.47 \times 10^{17}/cm^3$

$\therefore \quad n = \frac{n_i^2}{p} = \frac{(2.5\times10^{13})^2}{3.47\times10^{17}} = 1.8 \times 10^9$ electron/m^3

(b) $\sigma = ne\,\mu_n$;

$n = \frac{0.1}{1300\times1.6\times10^{-19}} = 4.81 \times 10^{14}/cm^3$

$= 4.81 \times 10^{14}/cm^3$

$n_i = 1.5 \times 10^{10}$;

$p = \frac{n_i^2}{n} = \frac{(1.5\times10^{10})^2}{4.81\times10^{14}} = 4.68 \times 10^{11}$ hole/m^3

Problem 2.19

A sample of Ge is doped to the extent of 10^{14} donor atoms/cm^3 and 7×10^{13} acceptor atoms/cm^3. At room temperature, the resistivity of pure Ge is 60 Ω-cm. If the applied electric field is 2 V/cm, find total conduction current density.

Solution

For intrinsic Semiconductor,

$n = p = n_i$

$\sigma_i = n_i e\,(\mu_p + \mu_n)$

$= \frac{1}{60}$ ʊ/cm.

μ_p for Ge is 1800 cm^2/V-sec ;

$\mu_n = 3800$ cm^2/V-sec.

$\therefore \quad n_i = \frac{\sigma_i}{e(\mu_p + \mu_n)} = \frac{1}{60(1.6\times10^{-19})(3800 + 1800)}$

$= 1.86 \times 10^{13}$ electron/cm^3

$p \times n = n_i^2 = (1.86 \times 10^{13})^2$ ....(1)

$N_A + n = N_D + p$

$N_A = 7 \times 10^{13}/cm^3$

$N_D = 10^{14}/cm^3$

$\therefore \quad (p - n) = N_A - N_D = -3 \times 10^{13}$ ....(2)

Solving (1) and (2) simultaneously to get p and n,

$p = 0.88 \times 10^{13}$

$n = 3.88 \times 10^{13}$

$J = (n\mu_n + p\mu_p).\,e\varepsilon$

$= \{(3.88)(3800) + (0.88)(1800)\} \times 10^{13}.\,e\varepsilon$

$= 52.3$ mA/cm^3

Problem 2.20

Determine the concentration of free electrons and holes in a sample of Germanium at 300°K which has a concentration of donor atoms = 2×10^{14} atoms /cm^3 and a concentration of acceptor atoms = 3×10^{14} atoms/cm^3. Is this *p-type* or *n-type* Ge ? In other words, is the conductivity due primarily to holes or electrons ?

Solution

$$n \times p = n_i^2$$

$$N_A + n = P + N_D$$

Solving (a) and (b) to get n and p,

$$p - n = N_A - N_D$$

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

$$\therefore \quad \frac{n_i^2}{n} - n = (N_A - N_D)$$

or
$$\frac{n_i^2 - n^2}{n} = (N_A - N_D)$$

$$n_i^2 - n^2 = n \times (N_A - N_D)$$

or
$$n^2 + n(N_A - N_D) - n_i^2 = 0$$

This is in the form $ax^2 + bx + c = 0$

$$\therefore \quad x = -\frac{b}{2} \pm \sqrt{\frac{b^2 - 4ac}{2a}}$$

$$\therefore \quad n = -\frac{(N_A - N_D)}{2} + \sqrt{\frac{(N_A - N_D)^2 - 4n_i^2}{2}} = 0$$

Negative sign is not taken into consideration since electron or hole concentration cannot be negative.

$$\therefore \quad n > 0 \text{ and } p > 0.$$

$$N_A = 3 \times 10^{14}/\text{cm}^{30}$$

$$N_D = 2 \times 10^{14}/\text{cm}^3$$

$$n_i \text{ at } 300°K = 2.5 \times 10^{13} / \text{cm}^3$$

$$n_i = AT^{\frac{3}{2}} e^{\frac{-E_G}{2KT}}$$

$$E = 0.72 \text{ eV}$$

$$n_i^2 = 6.25 \times 10^{26}/\text{cm}^3$$

$\therefore$ n can be calculated. Similarly p is also calculated.

$$n = 5.8 \times 10^{18}/\text{cm}^3$$

$$p = 10.58 \times 10^{19}/\text{m}^3$$

as **p > n**, it is *p-type* semiconductor.

Problem 2.21

Calculate the intrinic concentration of Germanium in carries/m^3 at a temperature of 320°K given that ionization energy is 0.75 eV and Boltzman's Constant K = 1.374 × 10^{-23}J / °K. Also calculate the intrinsic conductivity given that the mobilities of electrons and holes in pure germanium are 0.36 and 0.17 m^2/ volt-sec respectively.

Solution

$$n_i = AT^{\frac{3}{2}} e^{\frac{-e E_{GO}}{2\bar{K}T}}$$

$\bar{K}$ = Boltzman's Constant in J / °K
K = Boltzman's Constant in eV / °K

$$= 9.64 \times 10^{21} \times (320)^{3/2} \cdot e^{\frac{-1.6\times10^{-19}\times0.75}{2\times1.37\times10^{-23}\times320}}$$

$n_i = 6.85 \times 10^{19}$ electrons (or holes)/m^3.

In intrinsic semiconductor, $n = p = n_i$.

$\therefore \quad \sigma_i = en_i(\mu_n + \mu_p)$

$= 1.6 \times 10^{-19} \times 6.85 \times 10^{19} (0.36 + 0.17) = 5.797$ ʋ/m

Problem 2.22

Determine the resistivity of intrinsic Germanium at room temperature

Solution

T = 300 °K
A = 9.64 × 10^{21}
E = 0.75 eV.

$n_i = AT^{\frac{3}{2}} e^{\frac{-E_{GO}}{2KT}} = 2.5 \times 10^{19}$ electrons (or holes) /m^3.

$\mu_n = 0.36 m^2 / V - sec$

$\mu_p = 0.17 m^2 / V - sec$

$\sigma_i = en_i(\mu_n + \mu_p)$

$= 1.6 \times 10^{-19} \times 2.5 \times 10^{19} (0.35 + 0.17) = 2.13$ ʋ/m

$$\rho = \frac{1}{\sigma} = \frac{1}{2.13} = 0.47\ \Omega\text{-m}$$

2.11 THE FERMI DIRAC FUNCTION

N(E) = Density of states.

i.e., The number of states per ev per cubic meter (number of states/eV/m^3)

The expression for

$N(E) = \gamma E^{1/2}$ where γ is a constant.

$$\gamma = \frac{4\pi}{h^3}(2m)^{3/2}(1.6 \times 10^{-19})^{3/2} = 6.82 \times 10^{27}$$

m = Mass of Electron in Kgs

h = Planck's Constant is Joule-secs.

The equation for $f(E)$ is called the ***Fermi Dirac Probability Function***. It specifies the fraction of all states at energy E (eV) occupied under conditions of thermal equilibrium. From Quantum Statistics, it is found that,

$$f(E) = \frac{1}{1 + e^{\frac{(E-E_F)}{kT}}} \qquad \text{........ (2.16)}$$

where k = Boltzmann Constant, $eV/^oK$

T = Temp ^oK

E_F = Fermi Level or Characteristic Energy

The momentum of the electron can be uncertain. Heisenberg postulated that there is always uncertainty in the position and momentum of a particle, and the product of these two uncertainities is of the order of magnitude of Planck's constant 'h'.

If Δ_p is the Uncertainty in the Momentum of a particle, Δ_n is the uncertainty in the position of a particle

$$\Delta_p \times \Delta x \approx h.$$

2.11.1 Effective Mass

When an external field is applied to a crystal, the free electron or hole in the crystal responds, as if its mass is different from the true mass. This mass is called the ***Effective Mass*** of the electron or the hole.

By considering this effective mass, it will be possible to remove the quantum features of the problem. This allows us to use Newton's law of motion to determine the effect of external forces on the electrons and holes within the crystal.

2.11.2 Fermi Level

Named after ***Fermi***, ***it is the Energy State, with 50% probability of being filled if no forbidden band exists***. In other words, it is the mass energy level of the electrons, at 0^oK.

If $E = E_f$,

$f(E) = ½$ From Eq.(2.17).

If a graph is plotted between $(E - E_F)$ and $f(E)$, it is shown in Fig. 2.7

At $T = 0^oK$, if $E > E_F$ then, $f(E) = 0$.

That is, there is no probability of finding an electron having energy $> E_F$ at $T = 0^0 K$. Since fermi level is the max. energy possessed by the electrons at 0^ok. $f(E)$ varies with temperature as shown in Fig. 2.7.

2.11.6 Fermi Level in Intrinsic Semiconductor

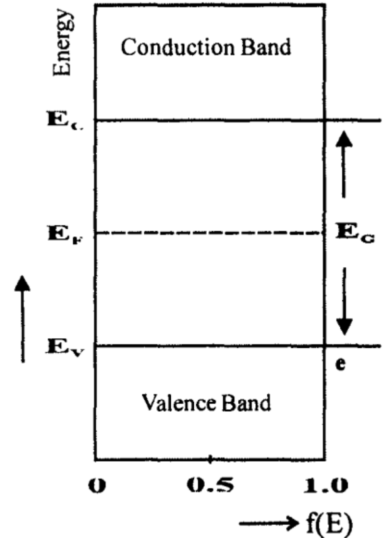


Fig. 2.8 Energy band diagram.

$$n = p = n_i$$

$$n = N_C\, e^{-(E_C - E_F)/KT}$$

$$p = N_V\, e^{-(E_F - E_V)/KT}$$

$$n = p$$

or $$N_C\, e^{-(E_C - E_F)/KT} = N_V\, e^{-(E_F - E_V)/KT}$$

Electrons in the valence bond occupy energy levels up to 'E_F'. E_F is defined that way. Then the additional energy that has to bo supplied so that free electron will move from valence band to the conduction band is E_C

$$\frac{N_C}{N_V} = e^{\frac{-(E_F - E_V)}{KT} + \frac{(E_C + E_F)}{KT}}$$

$$= e^{\frac{-2E_F + E_C + E_V}{KT}}$$

Taking logarithms on both sides,

$$\ln \frac{N_C}{N_V} = \frac{E_C + E_V - 2E_F}{KT}$$

$$\therefore \quad E_F = \frac{E_C + E_V}{2} - \frac{KT}{2} \ln \frac{N_C}{N_V}$$

$$N_C = 2\left(\frac{2\pi m_n \overline{K}T}{h^2}\right)^{\frac{3}{2}} \qquad \text{.......... (2.18)}$$

$$N_V = 2\left(\frac{2\pi m_p . \overline{K}T}{h^2}\right)^{\frac{3}{2}} \qquad \text{.......... (2.19)}$$

where $m_n$and m_p are effective masses of holes and electrons. If we assume that $m_n = m_p$, (though not valid),

$$N_C = N_V$$

$$\therefore \quad \ln \frac{N_C}{N_V} = 0$$

$$\therefore \quad E_F = \frac{E_C + E_V}{2} \qquad \text{.......... (2.20)}$$

The graphical representation is as shown in Fig. 2.8. ***Fermi Level in Intrinsic Semiconductor lies in the middle of Energy gap E_G.***

Problem 2.23

In p-type Ge at room temperature of 300 °K, for what doping concentration will the fermi level coincide with the edge of the valence bond ? Assume $\mu_p = 0.4$ m.

Solution

$$E_F = E_V$$

when $N_A = N_V$

$$\therefore \quad E_F = E_V + kT \ln . \frac{N_V}{N_A}$$

$$\therefore \quad N_V = 4.82 \times 10^{15}\left(\frac{mp}{m}\right)^{\frac{3}{2}} \times T^{3/2} = 4.82 \times 10^{15}(0.4)^{3/2}(300)^{3/2}$$

$$= 6.33 \times 10^{18}.$$

$\therefore$ Doping concentration $N_A = 6.33 \times 10^{18}$ atoms/cm^3.

Problem 2.24

If the effective mass of an electron is equal to twice the effective mass of a hole, find the distance in electron volts (ev) of fermi level in as intrunsic semiconductor from the centre of the forbidden bond at room temperature.

Solution

For Intrunsic Semiconductor,

$$E_F = \left[\left(\frac{E_C + E_V}{2}\right) - \frac{KT}{2}\ln\left(\frac{N_C}{N_V}\right)\right]$$

If $m_p = m_n$

then $N_C = N_V$.

Hence E_F will be at the centre of the forbidden band. But if $m_p \neq m_n$. E_F will be away from the centre of the forbidden band by

$$\frac{KT}{2} \ln . \frac{N_C}{N_V} = ¾ \frac{kT}{2} .\ln \frac{m_n}{m_p}$$

$$\therefore \quad N_C = 2\left(\frac{2\pi m_n \overline{K}T}{n^2}\right)^{3/2}$$

$$N_V = 2\left(\frac{2\pi m_p \bar{k}T}{n^2}\right)^{3/2}$$

$$= \frac{3}{4} \times 0.026\, ln\, (2)$$

$$= 13.5 \text{ m. eV}$$

2.11.7 Fermi Level in a Doped Semiconductor

$$\sigma = (\mu_n n + \mu_p p)e,$$

So the electrical characteristics of a semiconductor depends upon '*n*' and '*p*', the concentration of holes and electrons.

The expression for $n = N_C\, e^{-(E_C-E_F)/KT}$ and the expression for $p = N_V\, e^{-(E_F-E_V)/KT}$

These are valid for both intrinsic and extrinsic materials.

The electrons and holes, respond to an external field as if their mass is m^*($m^* = 0.6m$) and not 'm'. So this m^* is known as ***Effective Mass***.

With impurity concentration, only E_F will change. In the case of intrinsic semiconductors, E_F is in the middle of the energy gap, indicating equal concentration of holes and electrons.

If donor type impurity is added to the intrinsic semiconductor it becomes n-type. So assuming that all the atoms are ionized, each impurity atom contributes at least one free electron. So the first N_D states in the conduction band will be filled. Then it will be more difficult for the electrons to reach Conduction Band, bridging the gap between Covalent Bond and Valence Bond. So the number of electron hole pairs, thermally generated at that temperature will be decreased. ***Fermi level is an indiction of the probability of occupancy of the energy states***. Since Because of doping, more energy states in the ConductionBand are filled, the fermi level will move towards the Conduction Band.

Expression for E_G

$$n = N_C \times e^{\frac{-(E_C-E_F)}{KT}}$$

$$p = N_V \cdot e^{\frac{-(E_F-E_V)}{KT}}$$

$$n \times p = N_C \times N_V \times e^{\frac{-(E_C-E_V)}{KT}}$$

But $(E_C - E_V) = E_G$

and $n \times p = n_i^2$

$$\therefore \quad n_i^2 = N_C \times N_V \times e^{-\frac{E_G}{KT}}$$

$$\frac{n_i^2}{N_C \times N_V} = e^{-\frac{E_G}{KT}}$$

Taking logarithms,

$$\ln\left(\frac{n_i^2}{N_C N_V}\right) = -\frac{E_G}{KT}$$

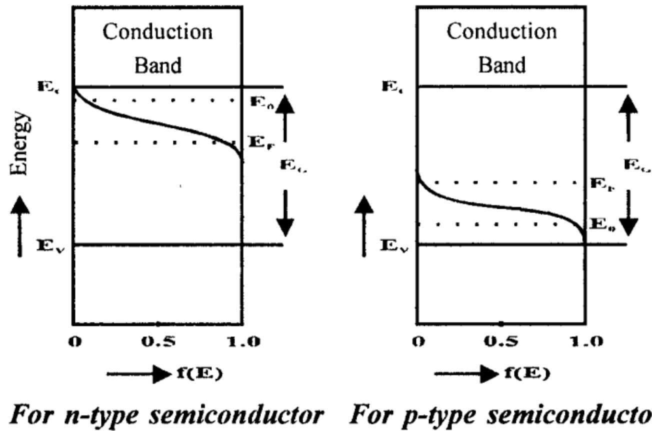
or

$$-\ln\left(\frac{N_C N_V}{n_i^2}\right) = -\frac{E_G}{KT}$$

or

$$\boxed{E_G = KT \ln\left(\frac{N_C N_V}{n_i^2}\right)} \quad \text{.......... (2.21)}$$

The position of Fermi Level is as shown in Fig. 2.9



For n-type semiconductor For p-type semiconductor

Fig. 2.9

Similarly, in the case of *p-type* materials, the Fermi level moves towards the valence band since the number of holes has increased. In the case of *n-type* semiconductor, the number of free electrons has increased. So energy in Covalent Bond has increased. Fermi Level moves to wards conduction band. ***Similarly in p-type semiconductors, fermi Level moves towards Valence Band.*** So it is as shown in Fig. 2.9.

To calculate the exact position of the Fermi Level in n-type Semiconductor:

In *n-type* semiconductor,

$$n \simeq N_D$$

But $$n = N_C \times e^{-(E_C - E_F)/KT}$$

$\therefore$ $$N_D = N_C \times e^{-(E_C - E_F)/KT}$$

or $$\frac{N_D}{N_C} = e^{-(E_C - E_F)/KT}$$

Taking logarithms,

$$\ln \frac{N_D}{N_C} = \frac{-(E_C - E_F)}{KT}$$

or $$KT \times \left\{ \ln \frac{N_D}{N_C} \right\} = -(E_C - E_F)$$

or $$\boxed{E_F = E_C - KT \times \left\{ \ln \frac{N_C}{N_D} \right\}} \qquad \text{.......... (2.22)}$$

So Fermi Level E_F is close to Conduction Band E_C in n-type semiconductor.

Similarly for p-type material,

$$p = N_A$$

But $$p = N_V \times e^{-(E_F - E_V)/KT}$$

$$\therefore \quad \frac{N_A}{N_V} = e^{-(E_F - E_V)/KT}$$

Taking Logarithms,

$$\ln \frac{N_A}{N_V} = -\frac{(E_F - E_V)}{KT}$$

$$KT \times \ln \frac{N_A}{N_V} = E_V - E_F$$

or $$\boxed{E_F = E_V + KT \times \ln \frac{N_V}{N_A}} \qquad \text{.......... (2.23)}$$

$$\therefore \quad N_A = N_V$$

Fermi Level is close to Valance Band E_V in p-type semiconductor.

Problem 2.25

In n type silicon, the donor concentration is 1 atom per 2 × 10^8 silicon atoms. Assuming that the effective mass of the electron equals true mass, find the value of temperature at which, the fermi level will coincide with the edge of the conduction band. Concentration of Silicon = 5 × 10^{22} atom/cm3.

Solution

Donor atom concentration = 1 atom per 2 × 10^8 Si atom.
Silicon atom concentration = 5 × 10^{22} atoms/cm^3

$$\therefore \quad N_D = \frac{5 \times 10^{22}}{2 \times 10^8} = 2.5 \times 10^{14}/\text{cm}^3.$$

For n-type, Semiconductor,

$$E_F = E_C - KT \ln \left(\frac{N_C}{N_D}\right)$$

If E_F were to coincide with E_C, then

$$N_C = N_D$$

$$N_D = 2.5 \times 10^{14} /\text{cm}^3.$$

$$N_C = 2\left\{\frac{2\pi m_n \overline{K} T}{h^2}\right\}^{\frac{3}{2}}$$

h = Plank's Constant; $\overline{K}$ = Boltzman Constant

m_n the effective mass of electrons to be taken as = m_E

$$\therefore \quad N_C = 2\left\{\frac{2 \times 3.14 \times 9.1 \times 10^{-31} \times \overline{K} \times T}{h^2}\right\}^{\frac{3}{2}}$$

$$= 4.28 \times 10^{15}\ T^{\frac{3}{2}}$$

Problem 2.27

In p-type Ge at room temperature of 300 °K, for what doping concentration will the fermi level coincide with the edge of the valence bond ? Assume $\mu_p = 0.4$ m.

Solution

$$E_F = E_V$$

when $N_A = N_V$

$$\therefore \quad E_F = E_V + kT \ln . \frac{N_V}{N_A}$$

$$\therefore \quad N_V = 4.82 \times 10^{15}\left(\frac{mp}{m}\right)^{\frac{3}{2}} \times T^{3/2} = 4.82 \times 10^{15}(0.4)^{3/2}(300)^{3/2}$$

$$= 6.33 \times 10^{18}.$$

$\therefore$ Doping concentration $N_A = 6.33 \times 10^{18}$ atoms/cm^3.

Problem 2.28

If the effective mass of an electron is equal to thrice the effective mass of a hole, find the distance in electron volts (ev) of fermi level in as intrunsic semiconductor from the centre of the forbidden bond at room temperature.

Solution

For Intrunsic Semiconductor,

$$E_F = \left[\left(\frac{E_C + E_V}{2}\right) - \frac{KT}{2}\ln\left(\frac{N_C}{N_V}\right)\right]$$

If $m_p = m_n$

then $N_C = N_V$.

Hence E_F will be at the centre of the forbidden band. But if $m_p \neq m_n$. E_F will be away from the centre of the forbidden band by

$$\frac{KT}{2} \ln . \frac{N_C}{N_V} = ¾ \frac{kT}{2} .\ln \frac{m_n}{m_p}$$

$$\therefore \quad N_C = 2\left(\frac{2\pi m_n \overline{K}T}{n^2}\right)^{3/2}$$

$$N_V = 2\left(\frac{2\pi m_p \bar{k}T}{n^2}\right)^{3/2}$$

$$= \frac{3}{4} \times 0.026\, ln\,(3) \quad = 21.4 \text{ meV}$$

2.12.2 Drift Current in p-Type Semiconductor

The mechanism is the same to as explained above. The holes in the acceptor type semiconductor moves towards the negative electrode and enter into it, pulling out one electron from the negative electrode from the acceptor atoms (Fig. 2.11), the hole has moved away, i.e. it has acquired an electron. So electrical neutrality or of its original condition is disturbed. This results in a electrons from the acceptor atom being pulled away. These free electrons enter the positive electrode. The acceptor atoms having lost one electron steal another electron from the adjoining atom resulting in a new hole. The new holes created thus drift towards negative electrode.

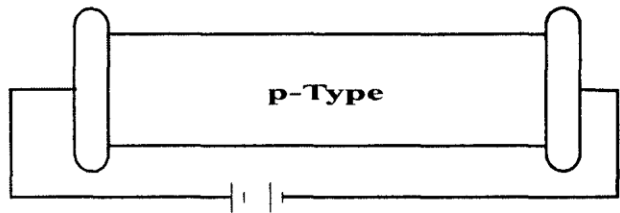


Fig. 2.11 Drift current in p-type semiconductor

2.12.3 Diffusion Current

This current results due to difference in the concentration gradients of charge carriers. That is, free electrons and holes are not uniformly distributed all over the semiconductor. In one particular area, the number of free electrons may be more, and in some other adjoining region, their number may be less. So the electrons where the concentration gradient is more move from that region to the place where the electrons are lesser in number. This is true with holes also.

Let the concentration of some carriers be as shown in the Fig 2.12. The concentration of carriers is not uniform and varies as shown along the semiconductor length. Area A_1 is a measure of the number of carriers between x_1 and x_2. Area A_2 is a measure of the number of carriers between x_2 and x_3. Area A_1 is greater than Area A_2. Therefore number of carriers in area A_1 is greater than the number of carriers in A_2. Therefore they will move from A_1 to A_2. If these

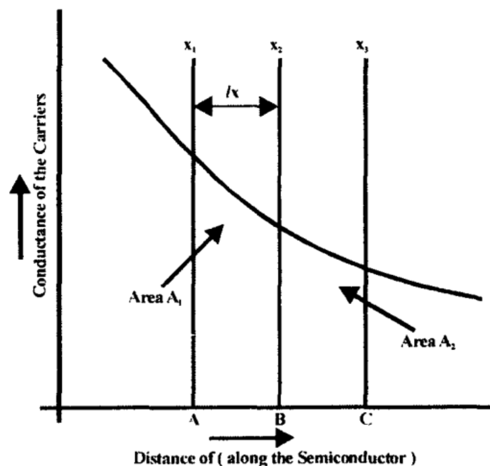


Fig. 2.12 Diffusion current.

where D_n is called Diffusion Constant for electrons. It is in m^2/sec. $\frac{dn}{dx}$ is concentration gradient.

D and μ are interrelated. It is given as,

$$\frac{D_n}{\mu_n} = \frac{D_p}{\mu_p} = V_T$$

where $$V_T = \frac{KT}{e} = \frac{T}{11{,}600} \qquad \text{.......... (2.24)}$$

where V_T is volt equivalent. of temperature. At room temperature, μ = 39D.

The thermal energy due to temperature T is expressed as electrical energy in the form of Volts.

2.12.4 Total Current

Both Potential Gradient and Concentration Gradient can exist simultaneously within a Semiconductor. Since in such a case the total current.is the sum of *Drift Current* and *Diffusion Current.*

$$J_p = e\,\mu_p\,p.\,E - e\,D_p\,.\frac{dp}{dx}$$

Drift Current $= e\mu_p pE$

Diffusion Current $= eD_p\frac{dp}{dx}$

Similarly the net electron current is

$$Jn = e\,\mu_n\,nE + e\,D_n\,\frac{dn}{dx}$$

Since Diffusion hole current is J_p

$$J_p = -eD_p\,\frac{dp}{dx}$$

p decreases with increase in x. So $\frac{dp}{dx}$ is negative. Negative sign is used for J_p, so that, J_p will be positive in the positive x direction. For electrons

$$J_n = +\,e\,.\,D_n\,.\frac{dn}{dx}$$

since the electron current is opposite to the directions of conventional current.

There exists a concentration gradient in a semiconductor. On account of this, it results in Diffusion Current. If you consider p-type semiconductor holes are the majority carriers. So the resulting Diffusion Current Density J_p is written as

$$J_p = -\,e \times D_p \times \frac{dp}{dx}$$

where D_p is called diffusion constant for holes. Since p the hole concentration is decreasing with x, $\frac{dp}{dx}$ is –ve. So –ve sign is used in the expression for J_p.

Similarly for electrons also the expression is similar and the slope is $-\frac{dn}{dx}$. But since the electron current is opposite to the conventional current,

$$J_n = \left(e.D_n \times \frac{dn}{dx}\right) + e \times D_n \frac{dn}{dx}$$

2.13 EINSTEIN RELATIONSHIP

D, the Diffusion Coefficient and μ are inter related as

$$\boxed{\frac{D_P}{\mu_P} = \frac{D_n}{\mu_n} = V_T} \qquad \text{.......... (2.25)}$$

where V_T is volt equivalent of temperature.

$$V_T = \frac{KT}{e} = \frac{T}{11{,}600}$$

$$\overline{K} = 1.6 \times 10^{-19}\ J/^oK$$

$$K = 8.62 \times 10^{-5}\ ev/^oK$$

$$K = 1.381 \times 10^{-23}\ J/^oK$$

$$\mu_p = \frac{D_p}{V_T} = \frac{D_p}{0.026} = 39D_p \qquad \text{.......... (2.26)}$$

$$\mu_p = 39D_p$$

$$\mu_n = 39D_n$$

or $$\mu = 39D \qquad \text{.......... (2.27)}$$

Therefore values of D_p and D_n for Si and Ge can be determined.

Problem 2.29

Determine the values of D_p and D_n for Silicon and Germanium at room temperature.

Solution

For Germanium at room temperature,

$$D_n = \mu_n \times V_T = 3{,}800 \times 0.026 = 99\ cm^2/sec$$

$$D_p = \mu_p \times V_T = 1800 \times 0.026 = 47\ cm^2/sec$$

For Silicon, $$D_n = 1300 \times 0.026 = 34\ cm^2/sec$$

$$D_p = 500 \times 0.026 = 13\ cm^2/sec$$

2.14 CONTINUITY EQUATION

Thus Continuity Equation describes how the carrier density in a given elemental volume of crystal varies with time.

If an intrinsic semiconductor is doped with n-type material, electrons are the majority carriers. Electron - hole recombination will be taking place continuously due to thermal agitation. So the concentration of holes and electrons will be changing continuously and this varies with time as well as distance along the semiconductor. We now derive the differential. equation which is based on the fact ***that charge is neither created nor destroyed***. This is called ***Continuity Equation***.

Consider a semiconductor of area A, length dx (x + dx – x = dx) as shown in Fig. 2.13. Let the average hole concentration be 'p'. Let E_p is a factor of x. that is hole current due to concentration is varying with distance along the semiconductor. Let I_p is the current entering the volume at x at time t, and (I_p + dI_p) is the current leaving the volume at (x + dx) at the same instant of time 't'. So when only I_p colombs is entering, (I_p + dI_p) colombs are leaving. Therefore effectively there is a decrease of ($I_p + dI_p - I_p$) = dI_p colombs per second within the volume. Or in other words, since more hole current is leaving than what is entering, we can say that more holes are leaving than the no. of holes entering the semiconductor at 'x'.

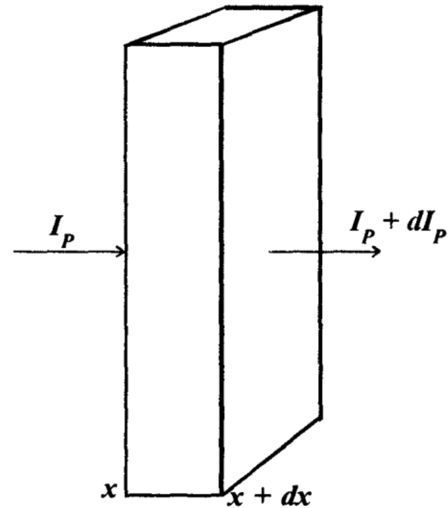


Fig 2.13 Charge flow in semiconductor

If dI_p is rate of change of total charge that is

$$dI_p = d\left(\frac{n \times q}{t}\right)$$

$\frac{dI_p}{q}$ gives the decrease in the number of holes per second with in the volume A × dx. Decrease in holes per unit volume (hole concentration) per second due to I_p is

$$\frac{dI_p}{A \times dx} \times \frac{1}{q}$$

But $$\frac{dI_p}{A} = \text{Current Density}$$

$$= \frac{1}{q} \times \frac{dJ_p}{dx}.$$

But because of thermal agitation, more number of holes will be created. If p_0 is the thermal equilibrium concentration of holes,(the steady state value reached after recombination), then, the increase per second, per unit volume due to thermal generation is,

$$g = \frac{p}{\tau_p}$$

Therefore, increase per second per unit volume due to thermal generation,

$$g = \frac{p_o}{\tau_p}$$

But because of recombination of holes and electrons there will be decrease in hole concentration.

The decrease $$= \frac{p}{\tau_p}$$

Charge can be neither created nor destroyed. Because of thermal generation, there is increase in the number of holes. Because of recombination, there is decrease in the number of holes. Because of concentration gradient there is decrease in the number of holes.

So the net increase in hole concentration is the algebraic sum of all the above.

$$\frac{\partial p}{\partial t} = \frac{p_0 - p}{\tau_p} - \frac{1}{q} \times \frac{\partial J_p}{\partial x}$$

Partial derivatives are used since p and Jp are functions of both time t and distance x. $\frac{dp}{dt}$ gives the variation of concentration of carriers with respect to time 't'.

If we consider unit volume of a semiconductor (*n-type*) having a hole density p_n, some holes are lost due to recombination. If p_{no} is equilibrium density, (i.e., density in the equilibrium condition when number of electron = holes).

The recombination rate is given as $\frac{p_n - p_{no}}{\tau}$. ***The expression for the time rate of change in carriers density is called the Continuity Equation.***

$$\text{Recombination rate } R = \frac{dp}{dt}$$

Life time of holes in n-type semiconductors

$$\tau_p = \frac{\Delta P}{R} = \frac{p_n - p_{no}}{dp/dt}$$

or

$$\frac{dp}{dt} = \left(\frac{p_n - p_{no}}{\tau_p}\right)$$

where p_n is the original concentration of holes in n-type semiconductors and p_{no} is the concentration after holes and electron recombination takes place at the given temperature. In other word p_{no} is the thermal equilibrium minority density. Similarly for a p-type semiconductors, the life time of electrons

$$\tau_n = \frac{n_p - n_{po}}{dx/dt} \; ; \; \frac{dx}{dt} = \frac{n_p - n_{no}}{\tau_n}.$$

2.15 THE HALL EFFECT

If a metal or semiconductor carrying a current I is placed in a perpendicular magnetic field B, an electric field E is induced in the direction perpendicular to both I and B. This phenomenon is known as the ***Hall Effect****. It is used to determine whether a semiconductor is p-type or n-type. By measuring conductivity σ, the mobility μ can be calculated using* ***Hall Effect.***

In the Fig. 2.14 current I is in the positive X-direction and B is in the positive Z-direction. So a force will be exerted in the negative Y-direction. If the semiconductor is *n-type*, so that current is carried by electrons, these electrons will be forced downward toward side 1. So side 1 becomes negatively charged with respect to side 2. Hence a potential V_H called the ***Hall Voltage*** appears between the surface 1 and 2.

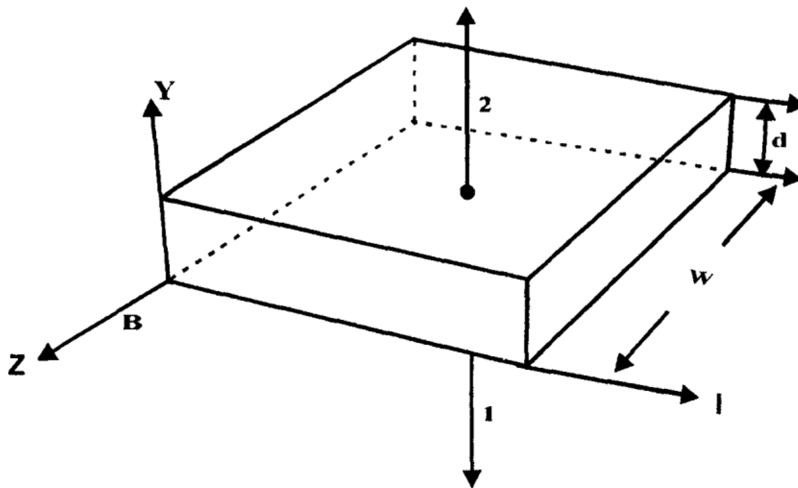


Fig 2.14 Hall effect.

In the equilibrium condition, the force due to electric field intensity 'E', because of Hall effect should be just balanced by the magnetic force or

$e\varepsilon = B\ ev$

v = Drift Velocity of carriers in m / sec

B = Magnetic Field Intensity in Tesla (wb/m^2)

or

$\varepsilon = Bv$ .... (a)

But $\varepsilon = V_H/d$

where V_H = Hall Voltage

d = Thickness of semiconductors.

J = nev or $J = \rho v$

ρ = charge density.

J = Current Density (Amp / m^2)

or $J = \dfrac{I}{\omega.d}$

ω = width of the semiconductor; ωd = cross sectional area

I = current

$\therefore$ J = Current Density = $\dfrac{I}{\omega d}$

$\varepsilon = V_H/d$

or $V_H = \varepsilon d$

But $\varepsilon = Bv$ .... From Equation (a)

$\therefore$ $V_H = B \times v \times d$ But $v = J/\rho$

$= \frac{B.J.d}{\rho}$ But $J = \frac{I}{\omega d}$

$$V_H = \frac{B.I.d}{\rho.\omega.d} = \frac{B.I}{\rho\omega}$$

$$\boxed{V_H = \frac{B.I}{\rho\omega}} \quad \text{.......... (2.28)}$$

If the semiconductor is n-type, electrons the majority carriers under the influence of electric field will move towards side 1, side 2 becomes positive and side 1 negative. If on the other hand terminal 1 becomes charged positive then the semiconductor is p-type.

$\rho = n \times e$ (For n - type semiconductor)

or $\rho = p \times e$ (for p-type semiconductor)

and ρ = Charge density.

$\because$ $V_H = \frac{B.I}{\rho\omega}$

$$\rho = \frac{B.I}{V_H.\omega}$$

$$\therefore \quad \boxed{R_H = \frac{V_H.\omega}{BI}} \quad \text{.......... (2.29)}$$

The Hall Coefficient, R_H is defined as $R_H = \frac{1}{\rho}$. Units of R_H are m^3 / coulombs

If the conductivity is due primarily to the majority carriers conductivity, $\sigma = ne\mu$ in n-type semiconductors.

$n.e = \rho$ = charge density.

$\therefore$ $\sigma = \rho \times \mu$

But $\frac{1}{\rho} = R_H$

$\therefore$ $\sigma = \frac{1}{R_H} \times \mu$

or $\mu = R_H \times \sigma = \frac{V_H.\omega}{B.I} \times \sigma$

We have assumed that the drift velocity 'v' of all the carriers is same. But actually it will not be so. Due to the thermal agitation they gain energy, their velocity increases and also collision with other atoms increases. So for all particles v will not be the same. Hence a correction has to be made and it has been found that satisfactory results will be obtained if $\frac{1}{R_H}$ is taken as $\frac{3\pi}{8\rho}$.

$$\therefore \qquad \mu = \left(\frac{8\sigma}{3\pi}\right) R_H \qquad \text{.......... (2.30)}$$

Multiply R_H by $\frac{8}{3\pi}$. Then it becomes ***Modified Hall Coefficient***. Thus mobility of carriers (electrons or holes) can be determined experimentally using Hall Effect.

The product Bev is the ***Lorentz Force***, because of the applied magnetic field B and the drift velocity v. So the majority carriers in the semiconductors, will tend to move in a direction perpendicular to B. But since there is no electric field applied in that particulars direction, there will develop a Hall voltage or field which just opposes the Lorentz field.

So with the help of Hall Effect, we can experimentally determine

1. *The mobility of Electrons or Holes.*
2. *Whether a given semiconductor is* p-type *or* n-type *(from the polarity of Hall voltage V_H)*

Problem 2.30

The Hall Effect is used to determine the mobility of holes in a p-type Silicon bar. Assume the bar resistivity is 200,000 Ω-an, the magnetic field B_z = 0.1 Wb/m^2 and d = w = 3mm. The measured values of the current and Hall voltage are 10mA and 50 mv respectively. Find μ_p mobility of holes.

Solution

$B = 0.1$ Wb / m^2 (or Tesla)

$V_H = 50$ mv.

$I = 10$ mA;

$\rho = 2 \times 10^5\ \Omega$ - cm ;

$d = w = 3\text{mm} = 3 \times 10^{-3}$ meters

$$\frac{1}{R_H} = \frac{B.I}{V_H.w} = \frac{0.1 \times 10 \times 10^{-3}}{50 \times 10^{-2} \times 3 \times 10^{-3}} = \frac{1}{150} = 0.667.$$

$$\text{Conductivity} = \frac{1}{\rho} = \frac{1}{2 \times 10^5 \times 10^{-2}} = \frac{1}{2000} \text{ mhos / meter.}$$

$$\mu = \sigma \times R_H$$

$$\mu_p = \frac{1}{0.667} \times \frac{1}{2000} = 750 \text{ cm}^2/\text{ V - sec}$$

2.16 SEMICONDUCTOR DIODE CHARACTERISTICS

If a junction is formed using *p-type* and *n-type* semiconductors, a diode is realised and it has the properties of a rectifier. In this chapter, the volt ampere characteristics of the diodes, electron-hole currents as a function of distance from the junction and junction capacitances will be studied.

2.16.1 THEORY OF p-n JUNCTION

Take an intrinsic Silicon or Germanium crystal. If donor (*n-type*) impurities are diffused from one point and acceptors impurities from the other, a p-n junction is formed. The donor atoms will donate electrons. So they loose electrons and become positively charged. Similarly, acceptor atoms accept an electron, and become negatively charged. Therefore in the p-n junction on the *p-side*, holes and negative ions are shown and on the *n-side* free electrons and positive ions are shown. To start with, there are only *p-type* carriers to the left of the junction and only *n-type* carriers to the right of the junction. But because of the concentration gradient across the junction, holes are in large number on the left side and they diffuse from left side to right side. Similarly electrons will diffuse to the right side because of concentration gradient.

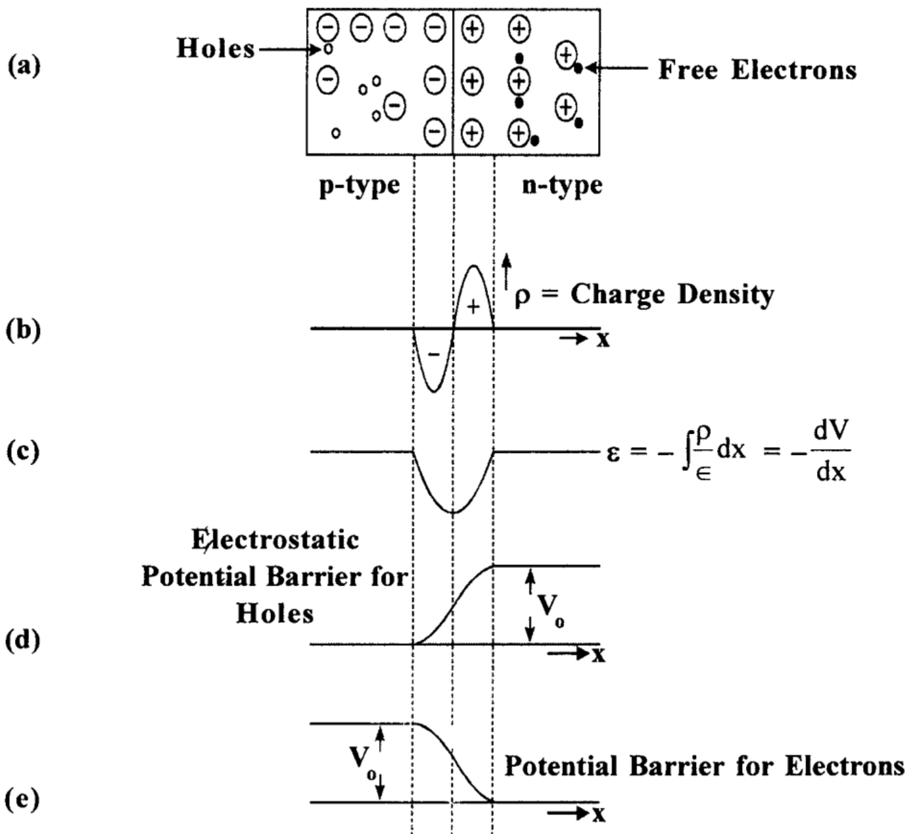


Fig 2.15. Potential distribution in p-n junction diode.

Because of the displacement of these charges, electric field will appear across the junction. Since *p-side* looses holes, negative field exists near the junction towards left. Since *n-side* looses electrons, positive electric field exists on the n side. But at a particular stage the negative field on *p-side* becomes large enough to prevent the flow of electrons from *n-side*. Positive charge on *n-side* becomes large enough to prevent the movement of holes from the *p-side*. The charge distribution is as shown in Fig. 2.15 (b). The charge density far away from the junction is zero, since before all the holes from *p-side* move to *n-side*, the barrier potential is developed. Acceptor atoms near the junction have lost the holes. But for this they would have been electrically neutral. Now these holes have combined with free electrons and disappeared leaving the acceptor atom negative. Donor atoms on *n-side* have lost free electrons. These free electrons have combined with holes and disappeared. So *the region near the junction is depleted of mobile charges. This is called depletion region, space charge region or transition region.* The thickness of this region will be of the order of few microns

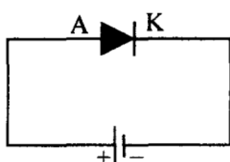
$$1 \text{ micron} = 10^{-6} \text{ m} = 10^{-4}\text{cm}.$$

The electric field intensity near the junction is shown in Fig. 2.15 (c). This curve is the integral of the density function ρ. The electro static potential variation in the depletion region is shown in Fig. 2.15 (d). $\varepsilon = -\int \frac{dv}{dx}$. This variation constitutes a potential energy barrier against further diffusion of holes across the barrier.

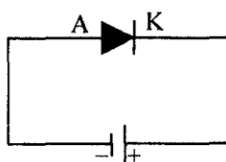
When the diode is open circuited, that is not connected in any circuit, the hole current must be zero. Because of the concentration gradient, holes from the *p-side* move towards *n-side*. So, all the holes from *p-side* should move towards *n-side*. This should result in large hole current flowing even when diode is not connected in the circuit. But this will not happen. So to counteract the diffusion current, concentration gradient should be nullified by drift current due to potential barrier. Because of the movement of holes from *p-side* to *n-side*, that region (p-region) becomes negative. A *potential gradient* is set up across the junction such that *drift current flows* in opposite direction to the *diffusion current*. So the net hole current is zero when the diode is open circuited. The potential which exists to cause drift is called *contact potential* or *diffusion potential*. Its magnitude is a few tenths of a volt (0.01V).

2.16.2 p-n JUNCTION AS A DIODE

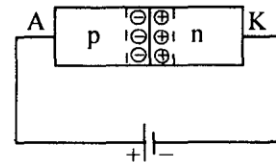
The p-n Junction shown here forms a semiconductor device called **DIODE**. Its symbol is A ─▶|─K. **A** is anode. **K** is the cathode. It has two leads or electrodes and hence the name Diode. If the anode is connected to positive voltage terminal of a battery with respect to cathode, it is called ***Forward Bias***, (Fig. 2.16 (a)). If the anode is connected to negative voltage terminal of a battery with respect to cathode, it is called ***Reverse Bias***, (Fig. 2.16 (b)).



(a) ***Forward bias***



(b) ***Reverse bias***



(c) ***p-n junction forward bias***

Fig 2.16

2.16.3 Ohmic Contact

In the above circuits, external battery is connected to the diode. But directly external supply cannot be given to a semiconductor. So metal contacts are to be provided for *p-region* and *n-region*. A Metal-Semiconductor Junction is introduced on both sides of p-n junction. So these must be contact potentials across the metal-semiconductor junctions. But this is minimized by fabrication techniques and the contact resistance is almost zero. Such a contact is called ohmic contact. So the entire voltage appears across the junction of the diode.

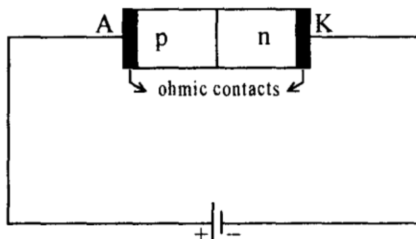


Fig 2.17 Ohmic contacts.

2.17 THE P-N JUNCTION DIODE IN REVERSE BIAS

Because of the battery connected as shown, holes in (Fig. 2.16 (b)) *p-type* and electrons in *n-type* will move away from the junction. As the holes near the junction in *p-region* they will move away from the junction and negative charge spreads towards the left of the junction. Positive charge density spreads towards right. But this process cannot continue indefinitely, because to have continuous flow of holes from right to left, the holes must come from the *n-side*. But *n-side* has few holes. So very less current results. But some electron hole pairs are generated because of thermal agitation. The newly generated holes on the *n-side* will move towards junction. Electrons created on the *p-side* will move towards the junction. So there results some small current called ***Reverse Saturation Current***. It is denoted by I_0. I_0 will increase with the temperature. So the *reverse resistance* or *back resistance decreases with temperature*. I_0 is of the order of a few μA. *The reverse resistance of a diode will be of the order of MΩ. For ideal diode, reverse resistance is ∞.*

The same thing can be explained in a different way. When the diode is open circuited, there exists a barrier potential. If the diode is reverse biased, the barrier potential height increases by a magnitude depending upon the reverse bias voltage. So the flow of holes from *p-side* to *n-side* and electrons from *n-side* to *p-side* is restricted. But this barrier doesn't apply to the minority carriers on the *p-sides* and *n-sides*. The flow of the minority carriers across the junction results in some current.

2.18 THE P-N JUNCTION DIODE IN FORWARD BIAS

When a diode is forward biased, the potential barrier that exists when the diode is open circuited, is reduced. Majority carriers from *p-side* and *n-side* flow across the junction. So a large current results. *For ideal diode, the forward resistance* $R_f = 0$. The forward current I_F, will be of the order of mA (milli-amperes).

Fig 2.18 Diode in forward bias.

2.18.1 FORWARD CURRENT

If a large forward voltage is applied (Fig. 2.19), the current must increase. If the barrier potential across the junction is made zero, infinite amount of current should flow. But this is not practically possible since the bulk resistance of the crystal and the contact resistance together will limit the current. We may see in the other sections that when the diode is conducting, the voltage across it remains constant at V_γ *cut in voltage*. If the applied voltage is too large junction breakdown will occur.

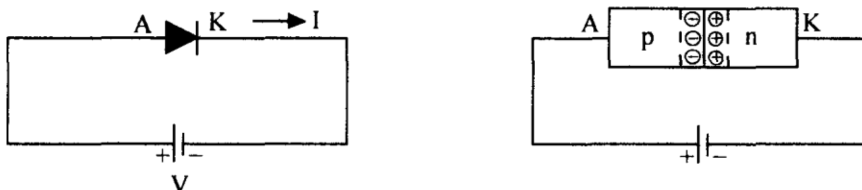


Fig 2.19 Forward biasing.

2.19 BAND STRUCTURE OF AN OPEN CIRCUIT p-n JUNCTION

When *p-type* and *n-type* semiconductors are brought into intimate contact *p-n junction* is formed. Then the fermilevel must be constant throughout the specimen. If it is not so, electrons on one side will have higher energy than on the other side. So the transfer of energy from higher energy electrons to lower energy electrons will take place till fermilevel on both sides comes to the same level. But we have already seen that in *n-type* semiconductors, E_F is close to conduction band E_{cn} and it is close to valence band edge E_{vp} on *p-side*. So the conduction band edge of *n-type* semiconductor cannot be at the same level as that of *p-type* semiconductor Hence, as shown, the energy band diagram for a *p-n junction* is where a shift in energy levels E_0 is indicated.

E_G = Energy gap in eV

E_F = Fermi energy level

E_O = Contact difference of potential

E_{cn} = Conduction Band energy level on the *n-side.*

E_{cp} = Conduction Band energy level on the *p-side.*

E_{vn} = Valence Band energy level on the *n-side.*

E_{vp} = Valence Band energy level on the *p-side.*

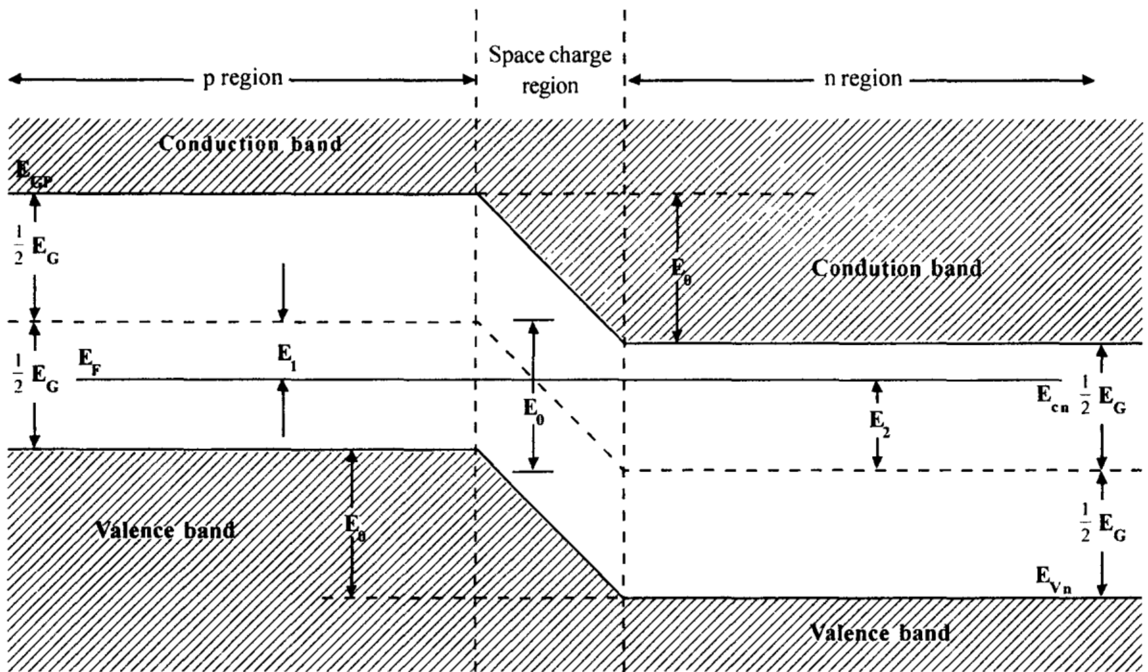


Fig 2.20 Band structure of open circuited diode.

If a central line $\frac{E_G}{2}$ is taken, the shift in energy levels is the difference between the two central lines $\frac{E_G}{2}$ of the two semiconductors.

$$E_0 = E_{cp} - E_{cn} = E_{vp} - E_{vn}.$$

$$E_1 = \frac{E_G}{2} - (E_F - E_{vp})$$

$$E_2 = \frac{E_G}{2} - (E_{cn} - E_F)$$

$$E_1 + E_2 = E_G - E_F + E_{vp} - E_{cn} + E_F$$

But $\quad E_G = E_{cp} - E_{vp}$

$\therefore \quad E_1 + E_2 = E_{cp} - E_{vp} - E_{cn} + E_{vp}.$

But $\quad E_{cp} - E_{cn} = E_O$

$$E_1 + E_2 = E_O.$$

This energy E_0 represents the potential energy barrier for electrons. The contact difference of potential

$$E_F - E_{vp} = ½ (E_G) - E_1 = \left(\frac{E_G}{2}\right) - E_1 \qquad \text{..........(1)}$$

and $$E_{cn} - E_F = \tfrac{1}{2}(E_G) - E_2 = \left(\frac{E_G}{2}\right) - E_2 \qquad \text{..........(2)}$$

Adding (1) and (2),

$$(E_F - E_{vp}) + (E_{cn} - E_F) = E_G - E_1 - E_2$$

or $$(E_1 + E_2) = E_G - (E_{cn} - E_F) - (E_F - E_{vp})$$

$$(E_1 + E_2) = E_O$$

$$(E_{cn} - E_F) = KT\ \ln\left(\frac{N_C}{N_D}\right)$$

N_D = Donor Atom Concentration N_o/m^3.

N_A = Acceptor Atom Concentration N_o/m^3.

$$(E_F - E_{vp}) = KT\ \ln\left(\frac{N_V}{N_A}\right)$$

$$E_G = KT\ \ln\left(\frac{N_C.N_V}{n_i^2}\right)$$

$\therefore$ $$E_0 = KT\left(\ln\left(\frac{N_C.N_V}{n_i^2}\right) - \ln\left(\frac{N_C}{N_D}\right) - \ln\left(\frac{N_V}{N_A}\right)\right)$$

$$E_0 = KT\ \ln\left(\frac{N_C.N_V}{n_i^2} \times \frac{N_D}{N_C} \times \frac{N_A}{N_V}\right) = KT\ \ln\left(\frac{N_A.N_D}{n_i^2}\right) \qquad \text{.......... (2.32)}$$

The energy is expressed in electron volts eV.

K is Botlzman's Constant in eV / °K = 8.62 × 10^{-5} eV / °K

Therefore, E_0 is in eV and V_0 is the contact difference potential in volts V_0 is numerically equal to E_0. In the case of *n-type* semiconductors, $n_n = N_D$. (Subscript 'n' indicates electron concentration in *n-type* semiconductor)

$$n_i^2 = n_n \times p_n = N_D \times p_n$$

$\because$ $n_n = N_D$

n_i = Intrinsic Concentration

n_p = Electron Concentration in *p-type* semiconductor

n_n = Electron Concentration in *n-type* semiconductor

p_p = Hole Concentration in *p-type* semiconductor

p_n = Hole Concentration in *n-type* semiconductor

$$p_n = \frac{n_i^2}{N_D} \quad \text{and} \quad N_D = \frac{n_i^2}{p_n}$$

$$n_p = \frac{n_i^2}{N_A} \quad \text{and} \quad N_A = \frac{n_i^2}{n_p}$$

$$n_i^2 = n_n \times p_n$$

Substituting all these value in

$$E_0 = KT \ln\left(\frac{N_A.N_D}{n_i^2}\right)$$

$$E_0 = KT \ln\left(\frac{n_i^2}{p_n}\times\frac{n_i^2}{n_p}\times\frac{1}{n_i^2}\right)$$

$$= KT \ln\left(\frac{n_i^2}{p_n.n_p}\right)$$

$$= KT \ln\left(\frac{n_n.p_n}{p_n.n_p}\right) = KT \ln\left(\frac{n_n}{n_p}\right)$$

$$E_0 = KT \ln\left(\frac{n_{n0}}{n_{p0}}\right) = KT \ln\left(\frac{p_{pn}}{p_{n0}}\right)$$

Taking reasonable values of $n_{n0} = 10^{16} / cm^3$

$n_{p0} = 10^4 / cm^3$

$KT = 0.026$ eV

$$E_0 = 0.026 \times \ln\frac{10^{16}}{10^4} = 0.718 \text{ eV.}$$

2.20 THE CURRENT COMPONENTS IN A p-n JUNCTION DIODE

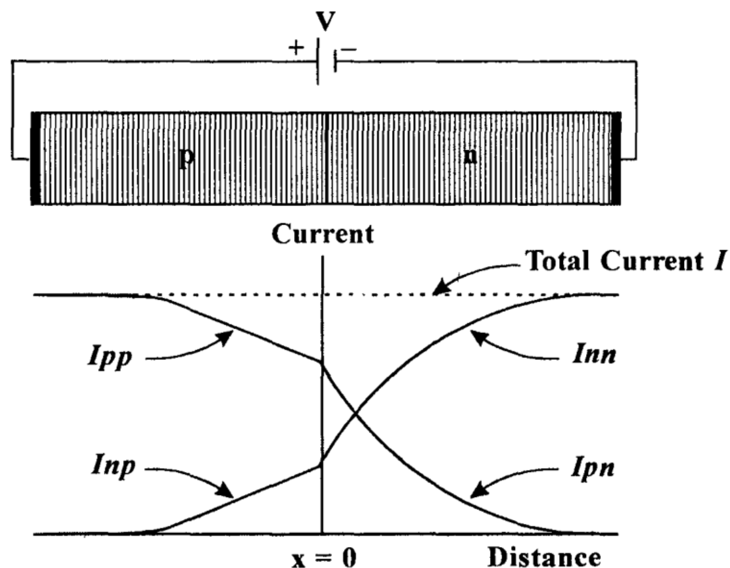


Fig 2.21 Current components in a p-n junction.

When a forward bias is applied to the diode, holes are injected into the *n-side* and electrons to the *p-side*. The number of this injected carriers decreases exponentially with distance from the junction. Since the diffusion current of minority carriers is proportional to the number of carriers, the minority carriers current decreases exponentially, with distance. There are two minority currents, one due to electrons in the *p-region* ***Inp***, and due to holes in the *n-region* ***Ipn***. As these currents vary with distance, they are represented as ***Ipn(x)***.

Electrons crossing from *n* to *p* will constitute current in the same direction as holes crossing from *p* to *n*. Therefore, the total current at the junction where x = 0 is

$$I = Ipn(0) + Inp(0)$$

The total current remains the same. The decrease in ***Ipn*** is compensated by increase in ***Inp*** on the *p-side*.

Now deep into the *p-region* (where x is large) the current is because of the electric field (since bias is applied) and it is drift current ***Ipp*** of holes. As the holes approach the junction, some of them recombine with electrons crossing the junction from *n* to *p*. So ***Ipp*** decreases near the junction and is just equal in magnitude to the diffusion current ***Inp***. What remains of ***Ipp*** at the junction enters the *n-side* and becomes hole diffusion current ***Ipn*** in the *n-region*. Since holes are minority carriers in the *n-side*, ***Ipn*** is small and as hole concentration decreases in the *n-region*, ***Ipn*** also exponentially decreases with distance.

In a forward biased *p-n junction* diode, at the edge of the diode on *p-side*, the current is hole current (majority carriers are holes). This current decreases at the junction as the junction approaches and at a point away from the junction, on the *n-side*, hole current is practically zero. But at the other edge of the diode, on the *n-side*, the current is electron current since electrons are the majority carriers. Thus in a *p-n junction* diode, the current enters as hole current and leaves as electron current.

2.21 LAW OF THE JUNCTION

p_{po} = Thermal Equilibrium Hole Concentration on *p-side*

p_{no} = Thermal equilibrium hole concentration on n side

$$p_{po} = p_{no}\, e^{V_O/V_T} \quad \text{..........(1)}$$

where V_O is the Electrostatics Barrier Potential that exists on both sides of the junction. But the thermal equilibrium hole concentration on the *p-side*

$$p_{po} = p_n(0)\, e^{(V_O - V)/V_T} \quad \text{..........(2)}$$

where $p_n(0)$ = Hole concentration on *n-side* near the junction

V = Applied forward bias voltage.

This relationship is called Boltzman's Relationship.

∴ Equating (1) and (2).

$$p_n(0)\, e^{(V_O - V)/V_T} = p_{no} \times e^{V_O/V_T}$$

or

$$p_n(0) = p_{no} \times e^{\frac{V_O}{V_T} - \frac{V_O}{V_T} + \frac{V}{V_T}}$$

$$p_n(o) = p_{no} \times e^{V/V_T}$$

Therefore, the total hole concentration in 'n' region at the junction varies with applied forward bias voltage V as given by the above expression.

This is called the **Law of the Junction.**

$$p_n(0) = p_n(0) - p_{no}$$

$$= p_{no}\, e^{V/V_T} - p_{no}$$

$$\boxed{p_n(0) = p_{no}\left(e^{V/V_T} - 1\right)} \quad \text{.......... (2.32)}$$

2.22 DIODE CURRENT EQUATION

The hole current in the *n-side* ***Ipn(x)*** is given as

$$Ipn(x) = \frac{Ae \times Dp}{L_p}\, p_n(0)\, e^{-x/L_p}$$

But

$$p_n(0) = p_{no}\left(e^{V/V_T} - 1\right)$$

$$Ipn(0) = \frac{Ae \times Dp}{L_p} \times p_{no}\left(e^{V/V_T} - 1\right)$$

D_p = Diffusion coefficient of holes

D_n = Diffusion coefficient of electrons.

$\therefore$ e^{-x/L_p} at $x = 0$ is 1.

Similarly the electron current due to the diffusion of electrons from *n-side* to *p-side* is obtained from the above equation itself, by interchanging n and p.

$$\therefore \quad Inp(0) = \frac{Ae \times Dn}{L_n} \times n_{po}\left(e^{V/V_T} - 1\right)$$

The total diode current is the sum of ***Ipn (0)*** and ***Inp(0)***

or

$$\boxed{I = I_o\left(e^{V/V_T} - 1\right)} \quad \text{.......... (2.33)}$$

where

$$I_0 = \frac{AeDp}{Lp} \times p_{no} + \frac{AeDn}{L_n} \times n_{po}$$

In this analysis we have neglected charge generation and recombination. Only the current that results as a result of the diffusion of the carriers owing to the applied voltage is considered.

Reverse Saturation Current

$$I = I_0 \times \left(e^{V/V_T} - 1\right)$$

This is the expression for current I when the diode is forward biased. If the diode is reverse biased, V is replaced by –V. V_T value at room temperature is ~ 26 mV. If the reverse bias voltage is very large, $e^{\frac{-V}{V_T}}$ is very small. So it can be neglected.

$$\therefore \quad I = -I_0$$

I_0 will have a small value and I_0 is called the ***Reverse Saturation Current.***

$$I_0 = \frac{AeD_p p_{no}}{L_p} + \frac{AeD_n n_{po}}{L_n}.$$

In *n-type* semiconductor,

$$n_n = N_D$$

But $$n_n \times p_n = n_i^2 \qquad \therefore\ p_n = \frac{n_i^2}{N_D}$$

In *p-type* semiconductor,

$$p_p = N_A \qquad \therefore\ n_p = \frac{n_i^2}{N_A}$$

Substituting these values in the expression for I_0,

$$I_0 = Ae\left(\frac{D_p}{L_p N_D} + \frac{D_n}{L_n . N_A}\right) \times n_i^2$$

where $$n_i^2 = A_0\, T^3\, e^{-E_G/KT}$$

E_G is in electron volts = e.V_G, where V_G is in Volts.

$$\therefore \qquad n_i^2 = A_0\, T^3\, e^{-\frac{E_{GO}}{KT}}$$

$$E_{GO} = V_G \,.\, e$$

But $$\frac{KT}{e} = \text{Volt equivalent of Temperature } V_T.$$

For Germanium, D_p and D_n decrease with temperature and n_i^2 increases with T. Therefore, temperature dependance of I_0 can be written as,

$$I_0 = K_1 T^2\, e^{-V_G/V_T}$$

For Germanium, the current due to thermal generation of carriers and recombination can be neglected. But for Silicon it cannot be neglected. So the expression for current is modified as

$$I = I_0\left(e^{\frac{V}{\eta V_T}} - 1\right)$$

where n = 2 for small currents and n = 1 forM large currents.

2.23 VOLT-AMPERE CHARACTERISTICS OF A P-N JUNCTION DIODE

The general expression for current in the *p-n junction* diode is given by

$$I = I_0\left(e^{\frac{V}{\eta V_T}} - 1\right).$$

η = 1 for Germanium and 1 or 2 for Silicon. For Silicon, I will be less than that for Germanium.

$$V_T = 26 \text{ mV}.$$

If V is much larger than V_T, 1 can be neglected. So I increases exponentially with forward bias voltage V. In the case of reverse bias, if the reverse voltage $-V >> V_T$, then e^{-V/V_T} can be neglected and so reverse current is $-I_0$ and remains constant independent of V. So the characteristics are as shown in Fig. 2.22 and not like theoretical characteristics. The difference is that the practical characteristics are plotted at different scales. If plotted to the same scale, (reverse and forward) they may be similar to the theoretical curves. Another point is, in deriving the equations the breakdown mechanism is not considered. As V increases **Avalanche multiplication** sets in. So the actual current is more than the theoretical current.

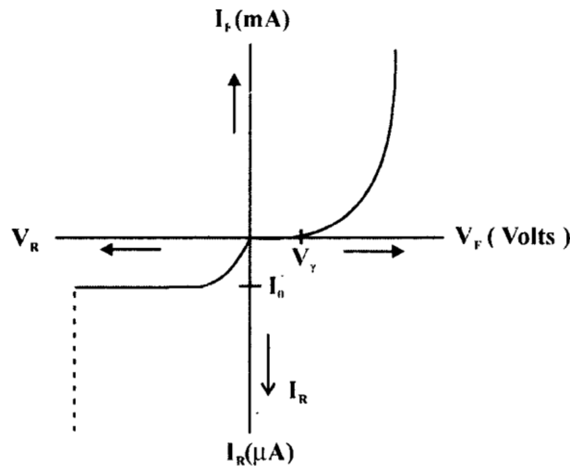


Fig 2.22 V-I Characteristics of p-n junction diode.

CUT IN VOLTAGE V_γ

In the case of Silicon and Germanium, diodes there is a ***Cut In*** or ***Threshold*** or ***Off Set*** or ***Break Point Voltage***, below which the current is negligible. It's magnitude is 0.2V for Germanium and 0.6V for Silicon (Fig. 2.23).

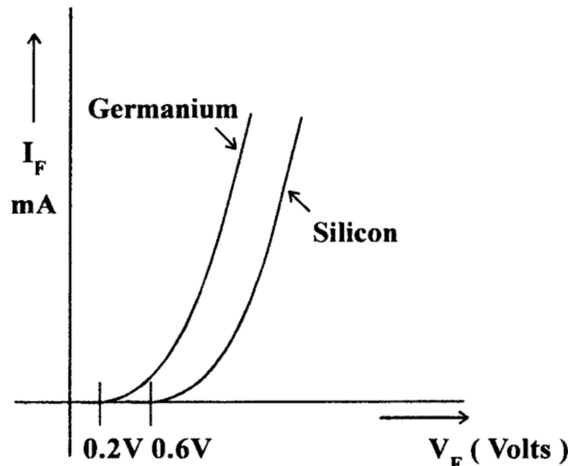


Fig 2.23 Forward characteristics of a diode.

2.23.1 DIODE RESISTANCE

The static resistance (R) of a diode is defined as the ratio of $\frac{V}{I}$ of the diode. Static resistance varies widely with V and I. The dynamic resistance or incremental resistance is defined as the reciprocal of the slope of the Volt-Ampere Characteristic $\frac{dV}{dI}$. This is also not a constant but depends upon V and I.

2.24 TEMPERATURE DEPENDANCE OF P-N JUNCTION DIODE CHARACTERISTICS

The expression for reverse saturation current I_0

$$I_0 = Ae\left(\frac{D_p}{L_pN_D} + \frac{D_n}{L_n.N_A}\right) \times n_i^2$$

$$n_i^2 \ \alpha \ T^3$$

$$\therefore \quad n_i^2 = A_0T^3 \, e^{-E_{G0}/KT}$$

D_p decreases with temperature.

$$\therefore \quad I_0 \ \alpha \ T^2$$

or $$I_0 = KT^m \, e^{-V_{G0}/\eta V_T}$$

where V_G is the energy gap in volts. (E_G in eV)

For Germanium, $\eta = 1, m = 2$

For Silicon, $\eta = 2, m = 1.5$

$$I_0 = KT^m \, e^{-V_{G0}/\eta V_T}$$

Taking ln, (Natural Logarithms) on both sides,

$$\ln I_0 = \ln(K) + m \times ln (T) \frac{-V_{G0}}{\eta V_T}$$

Differentiating with respect to Temperature,

$$\frac{1}{I_0} \times \frac{dI_0}{dT} = 0 + \frac{m}{T} - \left(-\frac{V_{G0}}{\eta V_T} \times \frac{1}{T}\right)$$

$$\frac{1}{I_0} \times \frac{dI_0}{dT} = \frac{m}{T} + \frac{V_{G0}}{\eta TV_T}$$

$\frac{m}{T}$ value is negligible 7

$$\therefore \quad \boxed{\frac{1}{I_0} \times \frac{dI_0}{dT} \simeq \frac{V_{G0}}{\eta TV_T}}$$

Experimentally it is found that reverse saturation current increases $\simeq$ 7% / °C for both Silicon and Germanium or for every 10°C rise in temperature, I_0 gets doubled. The reverse saturation current increases if expanded during the increasing portion.

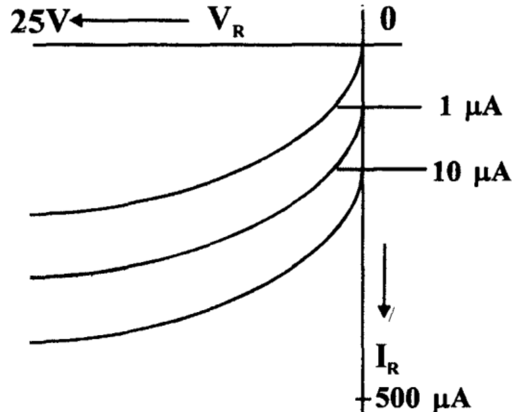


Fig 2.24 Reverse characteristics of a p-n junction diode.

Reverse Saturation Current increases 7% /°C rise in temperature for both Silicon and Germanium. For a rise of 1°C in temperature, the new value of I_0 is,

$$I_0 = \left(1 + \frac{7}{100}\right) I_0$$
$$= 1.07\ I_0.$$

For another degree rise in temperature, the increase is 7% of $(1.07\ I_0)$.

Therefore for 10 °C rise in temperature, the increase is $(1.07)^{10} = 2$.

Thus for every 10 °C rise in temp I_0 for Silicon and Germanium gets doubled.

2.25 SPACE CHARGE OR TRANSITION CAPACITANCE C_T

When a reverse bias is applied to a *p-n junction* diode, electrons from the *p-side* will move to the *n-side* and vice versa. When electrons cross the junction into the *n-region*, and hole away from the junction, negative charge is developed on the *p-side* and similarly positive charge on the *n-side*. Before reverse bias is applied, because of concentration gradient, there is some space charge region. Its thickness increases with reverse bias. So space charge Q increases as reverse bias voltage increases.

But $$C = \frac{Q}{V}$$

Therefore, Incremental Capacitance,

$$C_T = \left|\frac{dQ}{dV}\right|$$

where $|dQ|$ is the magnitude of charge increase due to voltage dV. It is to be noted that there is negative charge on the *p-side* and positive charge on *n-side*. But we must consider only its magnitude.

$$\text{Current } I = \frac{dQ}{dt}$$

Therefore, if the voltage dV is changing in time dt, then a current will result, given by

$$I = C_T \times \frac{dV}{dt}$$

This current exists for A.C. only. For D.C. Voltage is not changing with time. For D.C. capacitance is open circuit.

The knowledge of C_T is important in considering diode as a circuit element. *C_T is called Transition region capacitance or space charge capacitance or barrier capacitance, or depletion region capacitance.* This capacitance is not constant but depends upon the reverse bias voltage V. If the diode is forward biased, since space charge ≈ 0,(this doesn't exist). It will be negligible. C_T is of the order of 50 pf etc.

Alloy Junction

Indium is trivalent. If this is placed against *n-type* Germanium, and heated to a high temperature, indium diffuses into the Germanium crystal, a pn junction will be formed and for such a junction there will be abrupt change from acceptor ions on one side to donor ions on the other side. Such a junction is called ***Alloy Junction*** or ***Diffusion Junction***. In the figure, the acceptor ion concentration N_A and donor atom concentration, N_D is shown in Fig. 2.25. There is sudden change in concentration levels. To satisfy the condition of charge neutrality,

$$e \times N_A \times W_P = e \times N_D \times W_n.$$

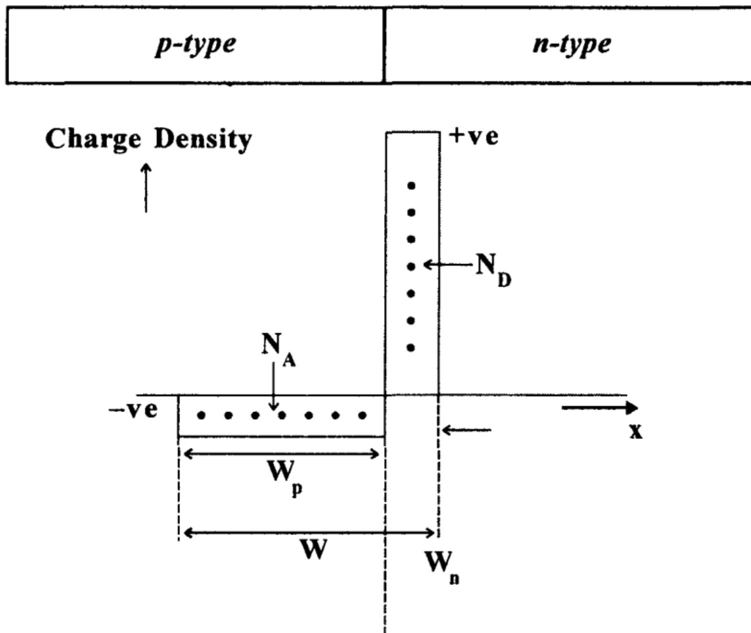


Fig 2.25 Abrupt p-n junction.

If $N_A << N_D$, then $W_p >> W_n$. In practice the width of the region, W_n will be very small. So it can be neglected. So we can assume that the entire barrier potential appears across the *p-region* just near the junction.

Poisson's Equation gives the relation between the charge density and potential.

It is $$\frac{d^2V}{dx^2} = \frac{eN_A}{\epsilon}$$

where ϵ is the permitivity of the semiconductor

$$\frac{dV}{dx} = \frac{eN_A}{\epsilon} x$$

$$V = \frac{e.N_A}{\epsilon} \times \frac{x^2}{2}.$$

At $x = w_p$, $V = V_B$ the barrier potential. $W_p = W$.

$$\therefore \quad \boxed{V_B = \frac{e.N_A}{2\epsilon} \times W^2} \qquad \text{.......... (2.34)}$$

The value of W depends upon the applied reverse bias V. If V_0 is the contact potential, $V_B = V_o - V$ where V is the reverse bias voltage with negative sign.

So as V increases, W also increases and V_B increases

$$W \ \alpha \ \sqrt{V_B}$$

If A is the area of the junction, the charge in the width W is

$$Q = e \times N_A \times W \times A$$

where $W \times A = \text{Volume}$

$e \times N_A = \text{Total charge density}$

$$C_T = \left|\frac{dQ}{dV}\right| = e \times N_A \times A \times \left|\frac{dW}{dV}\right|$$

$$Q = \sqrt{e \times N_A}\sqrt{2\epsilon V_B \times A}$$

But $$V_B = \frac{e.N_A}{2\epsilon} \times W^2$$

or $$W = \sqrt{\frac{2\epsilon V_B}{e \times N_A}}$$

$$\frac{dW}{dV} = \frac{1}{2}\sqrt{\frac{2\epsilon}{e \times N_A}}\, V_B^{-1/2}$$

But $$\sqrt{V_B} = W\sqrt{\frac{e \times N_A}{2\epsilon}}$$

$$\frac{dW}{dV} = \frac{1}{2}\sqrt{\frac{2\in}{e \times N_A}} \times \frac{\sqrt{2\in}}{\sqrt{e \times N_A \times W}}$$

$$= \frac{\in}{e \times N_A} \times \frac{1}{W}$$

$$= \frac{\in}{e \times N_A \times W}$$

$$\therefore \quad \boxed{C_T = \frac{\in \times A}{W}} \qquad \text{.......... (2.35)}$$

This expression is similar to that of the Parallel Plate Capacitor.

2.26 DIFFUSION CAPACITANCE, C_D

When a *p-n junction* diode is forward biased, the junction capacitance will be much larger than the transition capacitance C_T. When the diode is forward biased, the barrier potential is reduced. Holes from *p-side* are injected into the *n-side* and electrons into the *p-side*. Holes which are the minority carriers in the *n-side* are injected into the *n-side* from the *p-region*. The concentration of holes in the *n-side* decrease exponentially from the junction. So we can say that a positive charge is injected into the *n-side* from *p-side*. This injected charge is proportional to the applied forward bias voltage 'V'. So the rate of change of injected charge 'Q' with voltage 'V' is called the Diffusion Capacitance C_D. Because of C_D total capacitance will be much larger than C_T in the case of forward bias, (C_D is few mF (2mF.)) C_T value will be a few pico farads.

DERIVATION FOR C_D

Assume that, the *p-side* is heavily doped compared to *n-side*. When the diode is forward biased, the holes that are injected into the *n-side* are much larger than the electrons injected into the *p-side*. So we can say that the total diode current is mainly due to holes only. So the excess charge due to minority carriers will exist only on *n-side*. The total charge Q is equal to the area under the curve multiplied by the charge of electrons and the cross sectional area A of the diode. $P_n(0)$ is the Concentration of holes/cm^3. Area is in cm^2, x in cm,

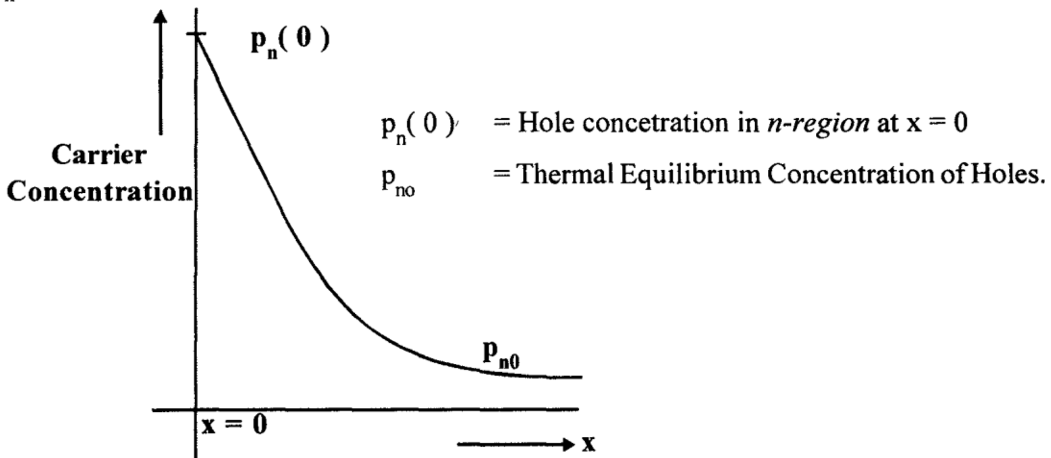


Fig 2.26 Carrier concentration variation.

$$\therefore \quad Q = \int_0^{\infty} AeP_n(0)e^{-x/Lp}\,dx$$

$$= Ae\ P_n(0) \int_0^{\infty} e^{-x/Lp}.dx$$

$$Q = AeP_n(0)\ [-Lp\ [0\text{-}1]\ ]$$

$$= AeL_p p_n(0)$$

$$C_D = \frac{dQ}{dv} = AeL_p \times \frac{dp_n(0)}{dv} \quad \text{..........(1)}$$

We know that

$$Ipn(x) = + \frac{e \times A \times Dp \times p_n(0) \times e^{-x/Lp}}{Lp}$$

or

$$Ipn(0) = I = \frac{AeD_p p_n(0)}{L_p}$$

$$p_n(0) = L_p \times I / AeD_p$$

$$\frac{dp_n(0)}{dv} = \frac{L_p}{AeD_p} \times \frac{dI}{dv}$$

$$= \frac{L_p}{AeD_p} \times g \quad \text{..........(2)}$$

where g is the conductance of the diode.

Substitute equation (2) in (1).

$$\therefore \quad C_D = Ae \times L_p \times \left(\frac{L_p}{AeD_p}\right) \times g$$

$$= \frac{L_p^2}{D_p} \times g$$

The lifetime for holes $\tau_p = \tau$ is given by the eq.

$$\tau = \frac{L_p^2}{D_p}$$

where D_p = Diffusion coefficient for holes.

L_p = Diffusion length for holes.

D_p = cm^2/sec

$\therefore \quad C_D = \tau \times g.$

But diode resistance

$$r \simeq \frac{\eta . V_T}{I}$$

where $\eta = 1$ for Germanium

$\eta = 2$ for Silicon

$$\therefore \quad g = \frac{I}{\eta . V_T}$$

$$\therefore \quad C_D = \frac{I . \tau}{\eta . V_T} \quad \text{.......... (3)}$$

C_D is proportional to I. In the above analysis we have assumed that the current is due to holes only. So it can be represented as C_{DP}. If the current due to electron is also to be considered then we get corresponding value of C_{Dn}. The total diffusion capacitance = $C_{DP} + C_{Dn}$. Its value will be ***around 20µF***.

$$C_D = \tau \times g$$

or $r \times C_D = \tau$

$r \times C_D$ is called the time constant of the given diode. It is of importance in circuit applications. Its value ranges from nano-secs to hundreds of micro-seconds.

Charge control description of a diode :

$$Q = A \times e \times L_p \times p_n(0)$$

$$I = \frac{AeD_p p_n(0)}{L_p}$$

$$\therefore \quad \frac{Q}{L_p} = A \times e \times p_n(0)$$

$$I = Q \times D_p / L_p^2$$

But $L_p^2/Dp = \tau$

$$\therefore \quad I = \frac{Q}{\tau}$$

2.27 DIODE SWITCHING TIMES

When the bias of a diode is changed from forward to reverse or viceversa. the current takes definite time to reach a steady state value.

2.27.1 Forward Recovery Time (T_{FR})

Suppose a voltage of 5V is being applied to the diode. Time taken by the diode to reach from 10% to the 90% of the applied voltage is called as the forward recovery time t_{fr}. But usually this is very small and so is not of much importance. This is shown in Fig. 2.26.

2.27.2 Diode Reverse Recovery Time (t_{rr})

When a diode is forward biased, holes are injected into the '*n*' side. The variation of concentration of holes and electrons on *n-side* and *p-side* is as shown in Fig. 2.27. P_{no} is the thermal equilibrium concentration of holes on *n-side*. P_n is the total concentration of holes on '*n*'-side.

$$r_{AC} = \frac{1}{g_{ac}} = \frac{dI}{dv}$$

$$\frac{dI}{dv} = \frac{I_0\left(e^{\frac{V}{V_T}}\right)}{V_T} = 38.1 \times 10^{-3}\ \mho$$

$$r_{AC} = 26.3\Omega$$

Problem 2.33

Find the width of the depletion layer in a germanium junction diode which has the following specifications Area A = 0.001 cm^2, σ_n = 1mhos / cm, σ_p = 100 mhos / cm, μ_n = 3800 cm^2/sec μ_p = 1800 cm^2/sec.

Solution

Permitivity of Germanium,

$$\in = 16 \times 8.85 \times 10^{-14}\ \text{F/cm}$$

$$n_i^2 = 6.25 \times 10^{26}$$

$$T = 300^oK.$$

Applied reverse bias voltage = 1V.

$$W = \sqrt{\frac{2\in.V_B}{e.N_A}}$$

In this formula, in the denominators, N_A is used since in the expression we have assumed that *p-side* of the p-n junction is heavily doped. If *n-side* is heavily doped, it would be N_D.

V_B = Total barrier potential = Applied reverse bias voltage + the contact difference of potential (V_o).

$$V_B = V_R + V$$

So first V_0 should be calculated.

$$V_0 = KT\ \ln.\ \frac{n_n.p_p}{n_i^2}$$

$$KT = 0.026\ \text{eV}$$

$$N_D = n_n = \frac{\sigma_n}{e\mu_n} = \frac{1}{1.6\times10^{-19}\times3800} = 1.64 \times 10^{15}/\text{cm}^3$$

$$N_A = p_p = \frac{\sigma_p}{e\mu_p} = \frac{100}{1.6\times10^{-19}\times1800} = 3.5 \times 10^{17}/\text{cm}^3$$

$$\therefore \quad V_0 = 0.026\ \ln.\ \frac{3.5\times10^{17}\times1.64\times10^{15}}{6.25\times10^{26}} = 0.357\text{V}$$

$$W = \sqrt{\frac{2\times16\times8.85\times10^{-14}\times(0.35+1)}{1.6\times10^{-19}\times3.5\times10^{17}}} = 0.083 \times 10^{-4}\text{cm}$$

Problem 2.34

Calculate the dynamic forward and reverse resistance of a p - n junction diode, when the applied voltage is 0.25V for Germanium Diode. $I_o = 1\mu A$ and T = 300°K.

Solution

$$I_0 = 1\mu A$$
$$T = 300°K$$
$$V_f = 0.25V$$
$$V_r = 0.25V$$
$$I = I_0\left(e^{V/V_T} - 1\right)$$

For Germanium, $\eta = 1$

Dynamic Forward Resistance :

V is positive

$$\frac{1}{r_f} = \frac{dI}{dV} = \frac{I_0}{V_T}\, e^{\frac{V}{V_T}} - 0$$
$$= \frac{1\times10^{-6}}{0.026} \cdot e^{\frac{0.25}{0.026}}$$
$$\frac{1}{r_f} = 0.578 \text{ mhos}$$
$$r_f = 1.734\ \Omega$$

Dynamic Reverse Resistance :

$$I = I_0\left(e^{\frac{-V}{V_T}} - 1\right)$$
$$\frac{1}{r_r} = \frac{dI}{dV} = \cdot \frac{I_0}{V_T} \cdot e^{-V/V_T}$$
$$= \frac{1\times10^{-6}}{0.026}\, e^{\frac{-0.25}{0.026}}$$
$$\frac{1}{r_r} = 2.57\times10^{-9} \text{ mhos}$$
$$r_r = \frac{1}{2.57\times10^{-9}} = 389.7\ M\Omega$$

In practice r_r is much smaller due to surface leakage current.

2.28 BREAK DOWN MECHANISM

There are three types of breakdown mechanisms in semiconductor devices.

1. Avalanche Breakdown 2. Zener Breakdown 3. Thermal Breakdown

2.28.1 Avalanche Breakdown

When there is no bias applied to the diode, there are certain number of thermally generated carriers. When bias is applied, electrons and holes acquire sufficient energy from the applied potential to produce new carriers by removing valence electrons from their bonds. These thermally generated carriers acquire additional energy from the applied bias. They strike the lattice and impart some energy to the valence electrons. So the valence electrons will break away from their parent atom and become free carriers. These newly generated additional carriers acquire more energy from the potential (since bias is applied). So they again strike the lattice and create more number of free electrons and holes. This process goes on as long as bias is increased and the number of free carriers gets multiplied. This is known as ***avalanche multiplication***, Since the number of carriers is large, the current flowing through the diode which is proportional to free carriers also increases and when this current is large, avalanche breakdown will occur.

2.28.2 Zener Breakdown

Now if the electric field is very strong to disrupt or break the covalent bonds, there will be sudden increase in the number of free carriers and hence large current and consequent breakdown. Even if thermally generated carriers do not have sufficient energy to break the covalent bonds, the electric field is very high, then covalent bonds are directly broken. This is ***Zener Breakdown***. A junction having narrow depletion layer and hence high field intensity will have zener breakdown effect. ($\simeq 10^6$ V/m). If the doping concentration is high, the depletion region is narrow and will have high field intensity, to cause Zener breakdown.

2.28.3 Thermal Breakdown

If a diode is biased and the bias voltage is well within the breakdown voltage at room temperature, there will be certain amount of current which is less than the breakdown current. Now keeping the bias voltage as it is, if the temperature is increased, due to the thermal energy, more number of carriers will be produced and finally breakdown will occur. This is ***Thermal Breakdown***.

In zener breakdown, the covalent bonds are ruptured. But the covalent bonds of all the atoms will not be ruptured. Only those atoms, which have weak covalent bonds such as an atom at the surface which is not surrounded on all sides by atoms will be broken. But if the field strength is not greater than the critical field, when the applied voltage is removed, normal covalent bond structure will be more or less restored. This is Avalanche Breakdown. But if the field strength is very high, so that the covalent bonds of all the atoms are broken, then normal structure will not be achieved, and there will be large number of free electrons. This is ***Zener Breakdown***.

In Avalanche Breakdown, only the excess electron, loosely bound to the parent atom will become free electron because of the transfer of energy from the electrons possessing higher energy.

2.29 ZENER DIODE

This is a *p-n junction* device, in which zener breakdown mechanism dominates. ***Zener diode is always used in Reverse Bias***.

Its constructional features are:

1. *Doping concetration is heavy on* p *and* n *regions of the diode, compared to normal* p-n junction *diode.*
2. *Due to heavy doping, depletion region width is narrow.*