ELECTRONICS 1A

PHS 206/216

BY

DR HUMPHREY IBIFUBARA

LECTURE 1

ELECTRON EMISSION

Free Electrons

- The valence electrons of different materials possess different energies. The greater the energy of a valence electron, the lesser it is bound to the nucleus. In certain substances, particularly metals, the valence electrons possess so much energy that they are very loosely attached to the nucleus. These loosely attached valence electrons move at random within the material and are called free electrons.
- The free electrons can be easily removed or detached by applying a small amount of external
- energy. As a matter of fact, these are the free electrons which determine the electrical conductivity of a material. On this basis, conductors, insulators and semiconductors can be defined as under :

- (i) A conductor is a substance which has a large number of free electrons. When potential difference is applied across a conductor, the free electrons move towards the positive terminal of supply, constituting electric current.
- (ii) An insulator is a substance which has practically no free electrons at ordinary temperature.

Therefore, an insulator does not conduct current under the influence of potential difference.

- (iii) A semiconductor is a substance which has very few free electrons at room temperature.

Consequently, under the influence of potential difference, a semiconductor practically conducts no current.

Electron Emission

- The liberation of electrons from the surface of a substance is known as electron emission.
- For electron emission, metals are used because they have many free electrons. However, these
- electrons are free only to the extent that they may transfer from one atom to another within the metal but they cannot leave the metal surface to provide electron emission due to what is known a surface barrier.
- **A surface barrier is the force that prevents free electrons from leaving the surface of a metal.**
- **The amount of additional energy required to emit an electron from a metallic surface is known as work function of that metal.**

Types of Electron Emission

(*i*) Thermionic emission. In this method, the metal is heated to sufficient temperature (about 2500ºC) to enable the free electrons to leave the metal surface. The number of electrons emitted depends upon the temperature. The higher the temperature, the greater is the emission of electrons. This type of emission is employed in vacuum tubes.

(*ii*) Field emission. In this method, a strong electric field (*i.e.* a high positive voltage) is applied at the metal surface which pulls the free electrons out of metal because of the attraction of positive field. The stronger the electric field, the greater is the electron emission.

(*iii*) Photo-electric emission. In this method, the energy of light falling upon the metal surface is transferred to the free electrons within the metal to enable them to leave the surface. The greater the intensity (*i.e.* brightness) of light beam falling on the metal surface, the greater is the photo-electric emission.

(*iv*) Secondary emission. In this method, a high velocity beam of electrons strikes the metal surface and causes the free electrons of the metal to be knocked out from the surface.

Thermionic Emitter

- The substance used for electron emission is known as an *emitter* or *cathode.*
- A cathode should have the following properties:

(*i*) **Low work function.** The substance selected as cathode should have low work function so that electron emission takes place by applying small amount of heat energy *i.e.* at low temperatures.

(*ii*) **High melting point.** As electron emission takes place at very high temperatures (>1500ºC), therefore, the substance used as a cathode should have high melting point. For a material such as copper, which has the advantage of a low work function, it is seen that it cannot be used as a cathode because it melts at 810ºC. Consequently, it will vaporise before it begins to emit electrons.

(*iii*) **High mechanical strength.** The emitter should have high mechanical strength to withstand the bombardment of positive ions. In any vacuum tube, no matter how careful the evacuation, there are always present some gas molecules which may form ions by impact with electrons when current flows. Under the influence of electric field, the positive ions strike the cathode.If high voltages are used, the cathode is subjected to considerable bombardment and may be damaged.

Commonly Used Thermionic Emit ters

S.No.	Emitter	Work Function	Operating temperature	Emission efficiency
1	*Tungsten*	4.52 eV	2327°C	4 mA/watt
2	*Thoriated tungsten*	2.63 eV	1700°C	60 mA/watt
3	*Oxide-coated*	1.1 eV	750°C	200 mA/watt

Richardson-Dushman equation

- The equation states that the amount of thermionic emission increases rapidly as the emitter temperature is raised.
- The emission current density is given by Richardson-Dushman equation given below :
- $J_s = A T^2 e^{-\frac{b}{T}}$ -----(i)
- where *Js* = emission current density *i.e*. current per square metre of the

emitting surface

- *T* = absolute temperature of emitter in K
- *A* = constant, depending upon the type of emitter and is measured in amp/m^2/K^2
- *b* = a constant for the emitter
- *e* = natural logarithmic base

Richardson-Dushman equation

- The value of *b* is constant for a metal and is given by : $b = \frac{\phi e}{k}$
- where = work function of emitter
- *e* = electron charge = 1.602×10^{-19} coulomb
- *k* = Boltzmann's constant = 1.38×10^{-23} J/K

$$b = \frac{\phi \times 1.602 \times 10^{-19}}{1.38 \times 10^{-23}} = 11600\,\phi\,\mathrm{K}$$

- Putting the value of *b* in exp. (*i*), we get,
- $$J_s = AT^2 e^{-\frac{11600\,\phi}{\mathrm{T}}}$$ -----(ii)

- The following points may be noted from eqn. (*ii*) :

(***i***) The emission is markedly affected by temperature changes. Doubling the temperature of an emitter may increase electron emission by more than 10^7 times. For instance, emission from pure tungsten metal is about 10^{-6} ampere per sq. cm. at 1300ºC but rises to enormous value of about 100 amperes when temperature is raised to 2900ºC.

(***ii***) Small changes in the work function of the emitter can produce enormous effects on emission. Halving the work function has exactly the same effect as doubling the temperature.

Example 1

- *A tungsten filament consists of a cylindrical cathode 5 cm long and 0.01 cm in diameter. If the operating temperature is 2500 K, find the emission current. Given that A = 60.2 × 10^4 A/m2 / K2, = 4.517 eV.*

Solution. $A = 60.2 \times 10^4 \text{ amp/m}^2/\text{K}^2, \; T = 2500 \text{ K}, \; \phi = 4.517 \text{ eV}$

$\therefore \quad b = 11600\,\phi \text{ K} = 11600 \times 4.517 \text{ K} = 52400 \text{ K}$

Using Richardson-Dushman equation, emission current density is given by :

$$J_s = AT^2 e^{-\frac{b}{T}} \text{ amp/m}^2 = 60.2 \times 10^4 \times (2500)^2 \times (2.718)^{-\frac{52400}{2500}}$$

$$= 0.3 \times 10^4 \text{ amp/m}^2$$

Surface area of cathode, $a = \pi d l = 3.146 \times 0.01 \times 5 = 0.157 \text{ cm}^2 = 0.157 \times 10^{-4} \text{ m}^2$

$\therefore$ Emission current $= J_s \times a = (0.3 \times 10^4) \times (0.157 \times 10^{-4}) = \mathbf{0.047\ A}$

Example 2

- *A tungsten wire of unknown composition emits 0.1 amp/cm² at a temperature of 1900 K. Find the work function of tungsten filament. Determine whether the tungsten is pure or contaminated with substance of lower work function. Given that A = 60.2 amp/cm²/K².*

Solution. $J_s = 0.1 \text{ amp/cm}^2 ; A = 60.2 \text{ amp/cm}^2/\text{K}^2 ; T = 1900 \text{ K}$

Let ϕ electron-volt be the work function of the filament.

$\therefore \quad b = 11600\,\phi \text{ K}$

Using Richardson-Dushman equation, emission current density is given by :

$$J_s = A T^2 e^{-\frac{b}{T}} \text{ amp/cm}^2$$

or $$0.1 = 60.2 \times (1900)^2 \times e^{-\frac{11600\phi}{1900}}$$

or $$e^{-\frac{11600\phi}{1900}} = \frac{0.1}{60.2 \times (1900)^2} = 4.6 \times 10^{-10}$$

or $$e^{-6.1\phi} = 4.6 \times 10^{-10}$$

or $$-6.1\,\phi \log_e e = \log_e 4.6 - 10 \log_e 10$$

or $$-6.1\,\phi = 1.526 - 23.02$$

$\therefore$ $$\phi = \frac{1.526 - 23.02}{-6.1} = \mathbf{3.56\ eV}$$

Comment: Since the work function of pure tungsten is 4.52 eV, the sample must be contaminated. Thoriated tungsten has a work function ranging from 2.63 eV to 4.52 eV, depending upon the percentage of metallic thorium. Therefore, the sample is most likely to be thoriated tungsten.

LECTURE 2

Tube devices; structure, characteristics and applications

VACUUM TUBE

- **INTRODUCTION**

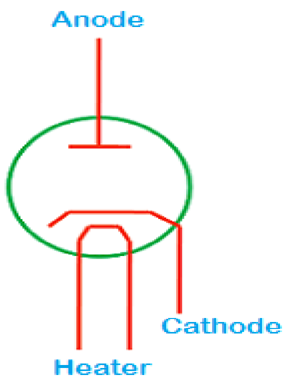
- Generally, vacuum refers to a space where charged particles such as electrons, protons, neutrons and all other matter are absent. In other words, vacuum is nothing but the empty space.

- Vacuum tube is an electronic device that controls the flow of electrons in a vacuum. It is also called as electron tube or valve.

- John Ambrose Fleming developed the first vacuum tube in 1904. Fleming’s diode allows the flow of electric current in only one direction (from cathode to anode) and blocks the electric current in another direction (from anode to cathode). In 1906, American electrical engineer Lee De Forest invented Audion vacuum tube.

- The invention of vacuum tubes has produced a new branch of engineering called electronics. In early days, vacuum tubes are used in television, radios, radar, electronic computers, and amplifiers. However, after the development of semiconductor devices, the usage of vacuum tubes in the electronic devices was reduced. Now-a-days, most of the electronic devices (computers, television, radar etc.) made from vacuum tubes are replaced by the semiconductor devices such as diodes, transistors, and integrated circuits.

- Vacuum tubes are mostly depends on the thermionic emission process to emit the free electrons. In the thermionic process, heat is used to emit the free electrons.
- A vacuum tube consists of cathode (also called as filament), anode (also called as plate), and electrode (also called as grid). Cathode is an electron emitter that emits the free electrons whereas anode is an electron collector that collects the free electrons.
- Grid or electrode controls the electric current or flow of electrons between anode and cathode. The free electrons that are emitted by the cathode are attracted towards the anode or plate. These free electrons carry the electric current while moving from cathode to anode.



Types of vacuum tubes

Vacuum tubes are generally classified into four types:

- Vacuum diodes
- Vacuum triodes
- Vacuum tetrodes
- Vacuum pentodes

Advantages and disadvantages of vacuum tubes

- **Advantages of vacuum tubes**

1. Vacuum tubes are replaced easily.
2. Vacuum tubes can work at high temperature without any damage.
3. Vacuum tubes produce superior sound quality.

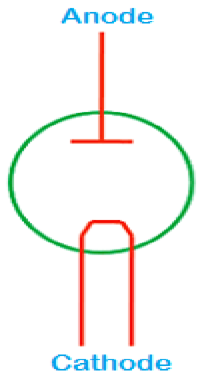
- **Disadvantages of vacuum tubes**

1. Vacuum tubes are huge compared to the semiconductor devices such as diodes, transistors, and integrated circuits.
2. Vacuum tubes generate more heat.
3. High voltages are required to operate the vacuum tubes.
4. Vacuum tubes consume more power.
5. High cost.
6. Failure rate is high.
7. Vacuum tubes occupy more space than the transistors.

Vacuum diode

- **Two electrodes of vacuum diode**

- Vacuum diode is the simplest form of vacuum tube. It consists of two electrodes, a cathode, and an anode or plate. The cathode emits the free electrons. Hence, it is called as emitter. The anode collects the free electrons. Hence, it is called as collector.



- The cathode and anode are enclosed in an empty glass envelope. The anode is a hollow cylinder made of molybdenum or nickel and cathode is a nickel cylinder coated with strontium and barium oxide. The anode surrounds the cathode. In between the cathode and anode an empty space is present, through which the free electrons or electric current flow.

Vacuum triode

- The basic vacuum tube (vacuum diode) is used to convert the alternating current into direct current. However, they cannot amplify the electric signal. In other words, they cannot amplify the voltage or power. To amplify the electrical signal, an extra electrode is required. When the extra electrode is placed between the cathode and anode, the resulting electronic device is called vacuum triode.
- Vacuum triode consists of three electrodes: anode, cathode and control grid. The anode, cathode and control grid are enclosed in an empty glass envelope. The cathode is surrounded by a control grid, which is in turn surrounded by anode. The construction of vacuum triode is similar to vacuum diode. However, vacuum triode contains an extra electrode (control grid).

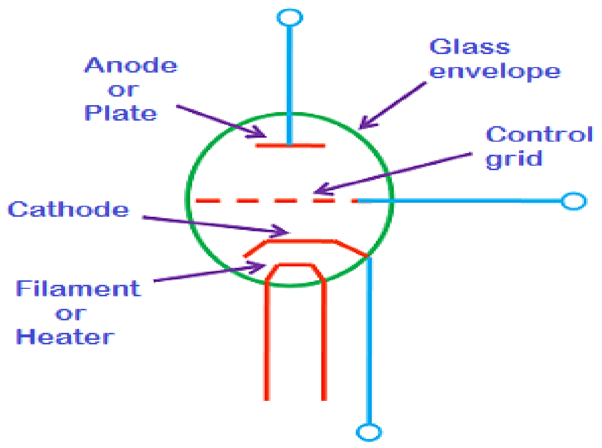
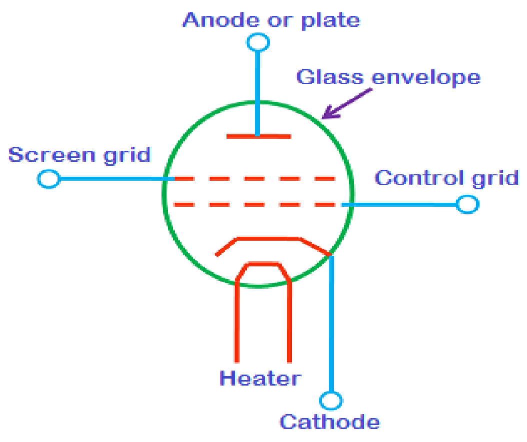


Fig: Symbol of vacuum triode

Vacuum tetrode

- Triode is used to amplify the electrical signal, but at higher frequencies, it will acts as an oscillator rather than as an amplifier. Adding the extra grid (screen grid) between the control grid and the plate or anode reduces the unwanted capacitance between plate and the control grid.

- Vacuum tetrode consists of four electrodes: cathode, anode, control grid, and screen grid. The cathode, anode, control grid, and screen grid are enclosed in an empty glass envelope. The cathode is surrounded by control grid. The control grid is surrounded by the screen grid. The screen grid is surrounded by the anode or plate.
- The construction of vacuum tetrode is similar to vacuum triode. However, vacuum tetrode contains an extra electrode called screen grid.



Vacuum pentode

- The screen grid in tetrode is used to reduce capacitance between the control grid and plate (anode). However, tetrodes have one drawback. When the screen grid voltage is greater than the plate voltage, the secondary electrons emitted from the plate are attracted to the screen grid. Because of this, the electric current flows in reverse direction (from plate to screen grid) which is undesirable.
- This drawback can be overcome by placing an extra grid called suppressor grid in between screen grid and the plate. The suppressor grid repels secondary electrons towards anode or plate.
- The pentode is made of evacuated glass envelope containing 5 electrodes. The air inside the glass envelope is removed completely. The 5 electrodes of the pentode include cathode, control grid, screen grid, suppressor grid, and plate.
- The cathode is surrounded by control grid. The control grid is surrounded by screen grid. The screen grid is surrounded by suppressor grid. The suppressor grid is surrounded by plate or anode.
- The construction of vacuum pentode is similar to vacuum tetrode. However, vacuum pentode contains an extra grid (suppressor grid).

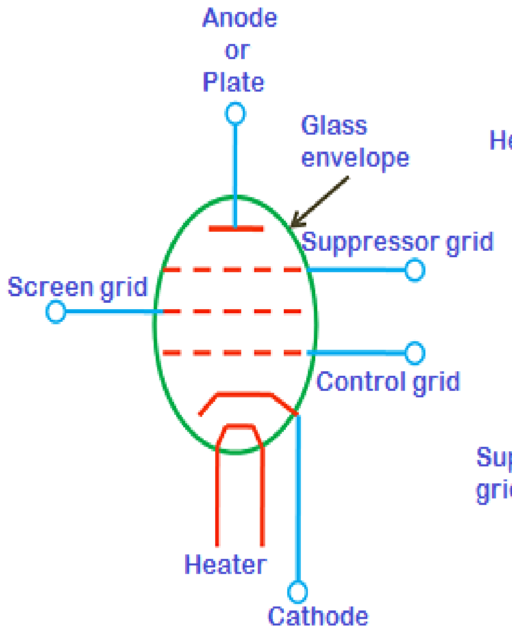
Vacuum pentode

Applications of pentode

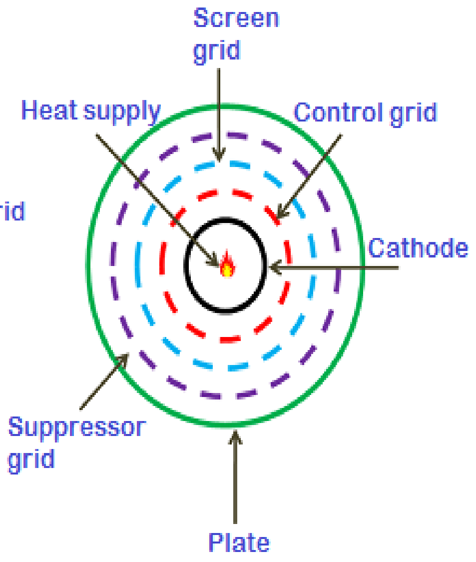
Pentodes are widely used in radios and televisions until 1960s. After 1960s they were replaced by transistors. However, they continued to be used in some applications such as electric guitar amplifiers, microphone preamplifiers, high-power radio transmitters, and professional audio applications.

Advantages of pentode

- Pentodes are able to operate at high frequencies
- Pentodes have high amplification factor than tetrodes



Symbol of pentode



Circular view of pentode

LECTURE 3

Semiconductors; doping transport phenomena in semiconductors

INTRODUCTION

- Certain substances like germanium, silicon, carbon etc. are neither good conductors like copper nor insulators like glass. In other words, the resistivity of these materials lies in between conductors and insulators. Such substances are classified as semiconductors. Semiconductors have some useful properties and are being extensively used in electronic circuits. For instance, transistor—a semiconductor device is fast replacing bulky vacuum tubes in almost all applications. Transistors are only one of the family of semiconductor devices ; many other semiconductor devices are becoming increasingly popular.

SEMICONDUCTOR

- A semiconductor is a substance which has resistivity (10^{-4} to 0.5 Ωm) in between conductors and insulators e.g. germanium, silicon, selenium, carbon etc.

S.No.	Substance	Nature	Resistivity
1	Copper	good conductor	$1.7 \times 10^{-8}\ \Omega\ m$
2	Germanium	semiconductor	$0.6\ \Omega\ m$
3	Glass	insulator	$9 \times 10^{11}\ \Omega\ m$
4	Nichrome	resistance material	$10^{-4}\ \Omega\ m$

Properties of Semiconductors

- (i) The resistivity of a semiconductor is less than an insulator but more than a conductor.
- (ii) Semiconductors have negative temperature co-efficient of resistance i.e. the resistance of a semiconductor decreases with the increase in temperature and vice-versa. For example, germanium is actually an insulator at low temperatures but it becomes a good conductor at high temperatures.
- (iii) When a suitable metallic impurity (e.g. arsenic, gallium etc.) is added to a semiconductor, its current conducting properties change appreciably. This property is most important and is discussed later in detail

TYPES OF SEMICONDUCTION

- There are two types of semiconductor

1. Intrinsic semiconductor
2. Extrinsic semiconductor

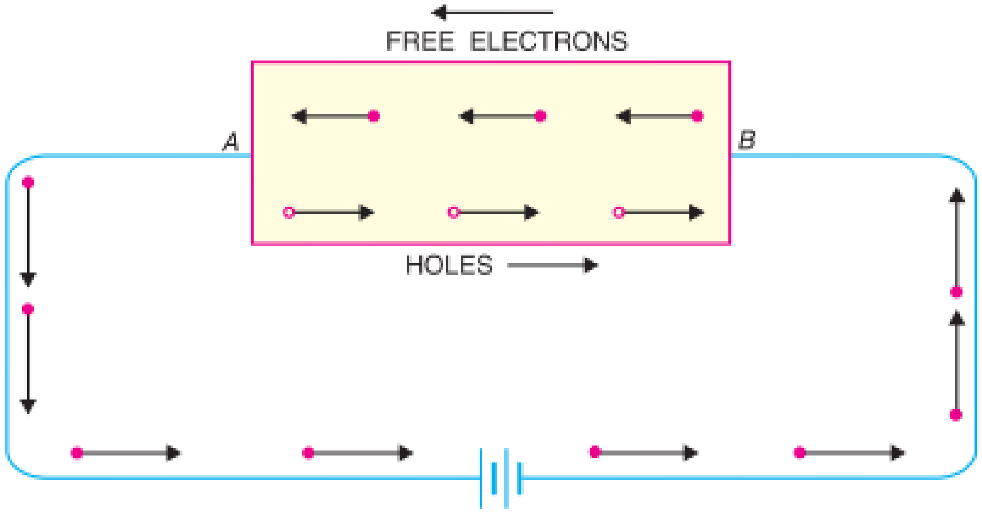
Intrinsic Semiconductor

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.

- Intrinsic semiconductor

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.



- Extrinsic Semiconductor

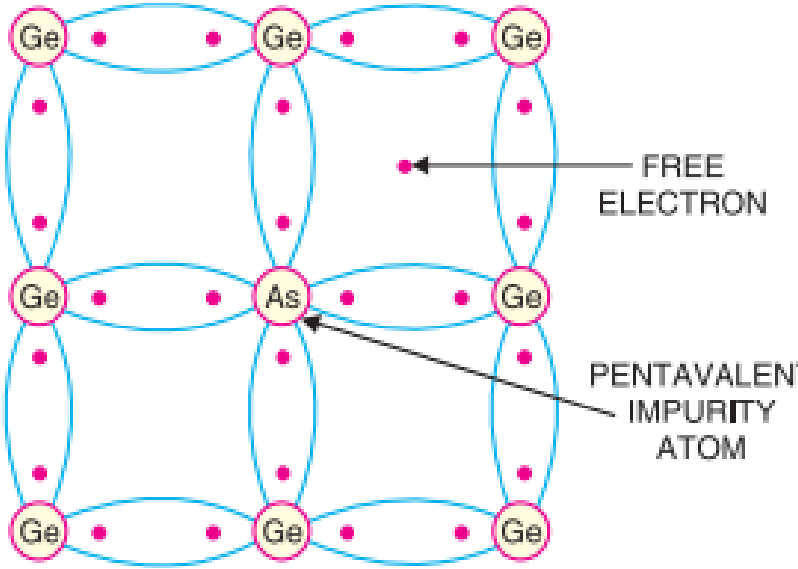
The intrinsic semiconductor has little current conduction capability at room temperature. To be useful in electronic devices, the pure semiconductor must be altered so as to significantly increase its conducting properties. This is achieved by adding a small amount of suitable impurity to a semiconductor.

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.

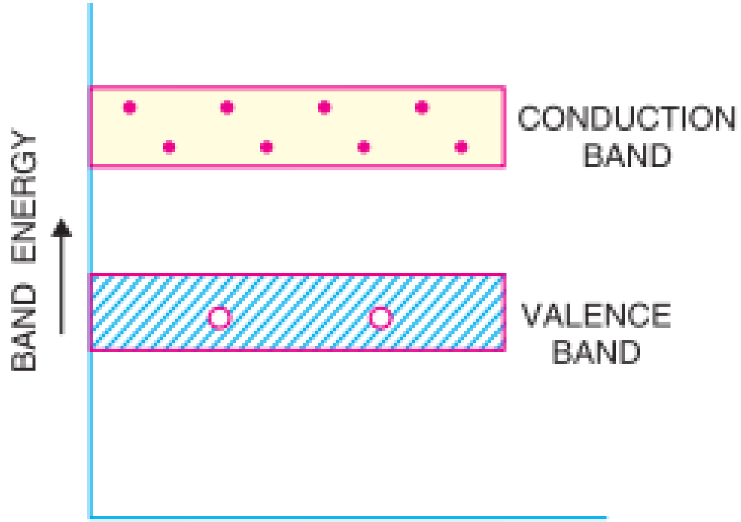
- Depending upon the type of impurity added, extrinsic semiconductors are classified into: (i) n-type semiconductor (ii) p-type semiconductor.
- The addition an impurity to a semiconductor crystal is known as doping.

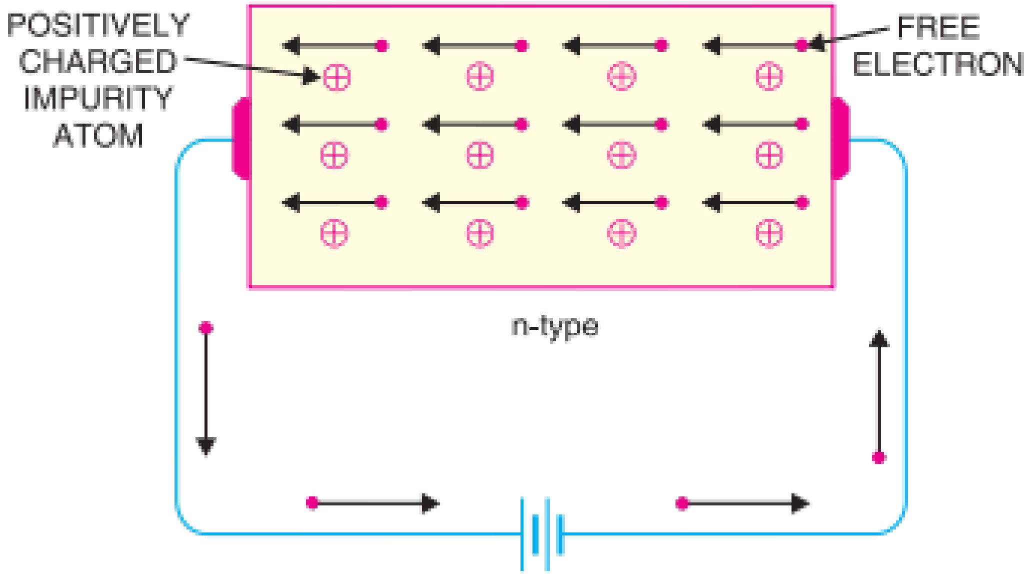
- n-type Semiconductor

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 and antimony. Such impurities which produce n-type semiconductor are known as donor impurities because they donate or provide free electrons to the semiconductor crystal.



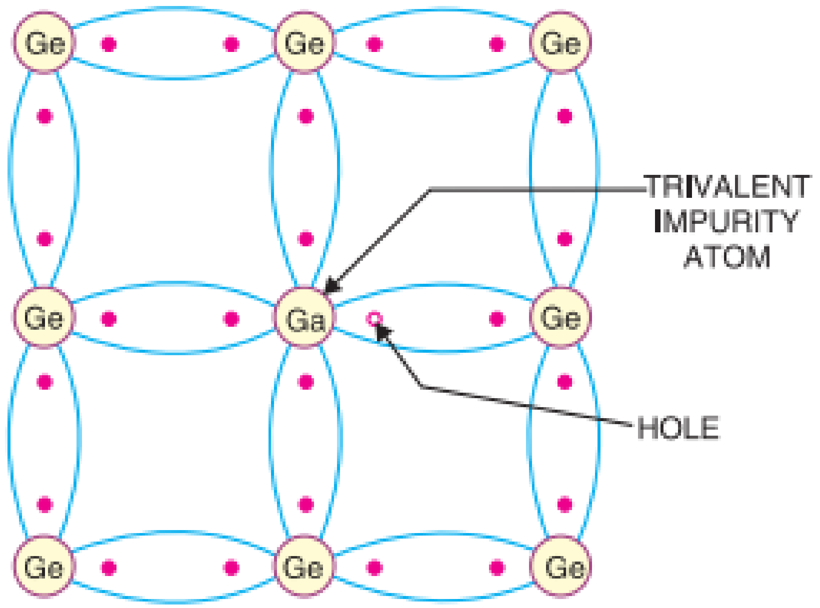
- The current conduction in an n-type semiconductor is predominantly by free electrons i.e. negative charges and is called n-type or electron type conductivity.
- When p.d. is applied across the n-type semiconductor, the free electrons (donated by impurity) in the crystal will be directed towards the positive terminal, constituting electric current.
- The addition of pentavalent impurity has produced a number of conduction band electrons i.e., free electrons.



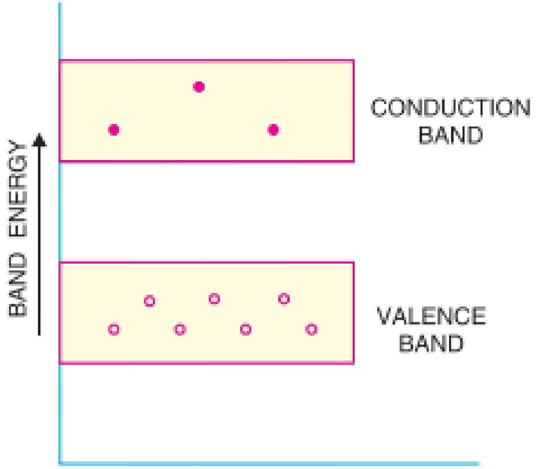


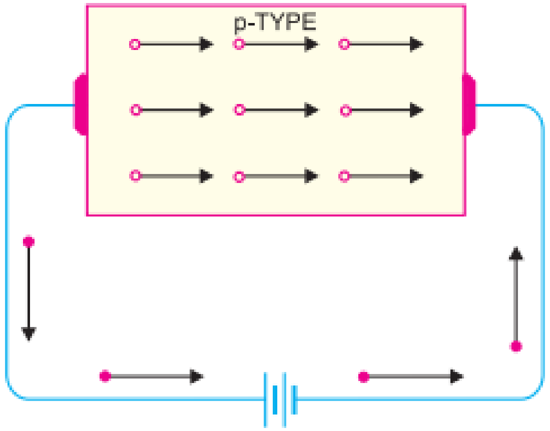
p-type Semiconductor

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 and indium. Such impurities which produce p-type semiconductor are known as acceptor impurities because the holes created can accept the electrons.



- The current conduction in p-type semiconductor is predominantly by holes i.e. positive charges and is called p-type or hole-type conductivity.
- 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.
- 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.

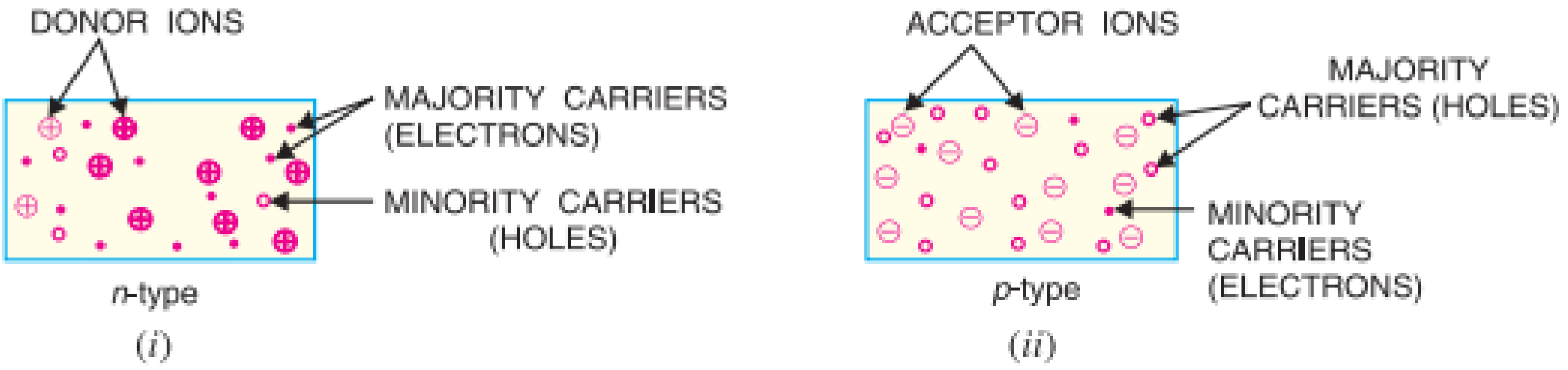




Majority and Minority Carriers

- 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.

- In n-type material the free electrons are considered majority carriers and the holes are the minority carriers.
- Similarly, in a p-type material, holes outnumber the free electrons therefore, holes are the majority carriers and free electrons are the minority carriers.



Electron and hole mobility

- Drift velocity is directly proportional to electric field. Hence, when the electric field increases drift velocity also increases. However, mobility of electrons is independent of applied electric field i.e. change in electric field does not change the mobility of electrons.
- The SI unit of electric field is V/m, and the SI unit of velocity is m/s. Thus, the SI unit of mobility is $m^2/(V.s)$.

$$I = nAvQ$$

Where,

- I is the current flowing through the conductor which is measured in amperes
- n is the number of electrons
- A is the area of the cross-section of the conductor which is measured in m^2
- v is the drift velocity of the electrons
- Q is the charge of an electron which is measured in Coulombs

Example:

- Let's consider a current of 3A that is flowing in a copper conductor with a cross-section of $1mm^2$ ($1\times10^{-6}m^2$). We know that for copper, n = 8.5×10^{28} per m^3
- *So according to the formula* $I = nAvQ$

we have,

$$3 = 8.5\times10^{28} \times 1\times10^{-6}\times v \times 1.6\times10^{-19}$$

$$v = 2.205882\times10^{-4}\ ms^{-1}$$

- Relation between Drift Velocity and Current Density

We can define current density as the total amount of current passing through a unit cross-sectional conductor in unit time.
From drift velocity, we know the formula for drift velocity as:

$$I = nAvQ$$

$$J = I/A = nVQ$$

Where,

- J is the current density measured in Amperes per square meter
- v is the drift velocity of the electrons

- Electron mobility

The ability of an electron to move through a metal or semiconductor, in the presence of applied electric field is called electron mobility.

- It is mathematically written as

$$V_n = \mu_n E$$

- Where v_n = drift velocity of electrons

  μ_n = mobility of electrons

  E = applied electric field

- Let us consider a semiconductor that consists of large number of free electrons. When there is no voltage or electric field applied across the semiconductor, the free electrons moves randomly.

- However, when the voltage or electric field is applied across the semiconductor, each free electron starts to move more quickly in particular direction. Electrons move very fast in vacuum. However, in metals or semiconductors, free electrons do not move very fast instead they move with a finite average velocity, called drift velocity.

- Hole mobility

- The ability of an hole to move through a metal or semiconductor, in the presence of applied electric field is called hole mobility.
- It is mathematically written as
- $$V_p = \mu_p E$$
- Where v_p = drift velocity of holes
  μ_p = mobility of holes
  E = applied electric field

Applications of Semiconductors

- Semiconductors are used in almost all electronic devices. Without them, our life would be much different.
- Their reliability, compactness, low cost and controlled conduction of electricity make them ideal to be used for various purposes in a wide range of components and devices. transistors, diodes, photosensors, microcontrollers, integrated chips and much more are made up of semiconductors.

- **Uses of Semiconductors in Everyday life**
- Temperature sensors are made with semiconductor devices.
- They are used in 3D printing machines
- Used in microchips and self-driving cars
- Used in calculators, solar plates, computers and other electronic devices.
- Transistor and MOSFET used as a switch in Electrical Circuits are manufactured using the semiconductors.

- **Industrial Uses of Semiconductors**
- The physical and chemical properties of semiconductors make them capable of designing technological wonders like microchips, transistors, LEDs, solar cells, etc.
- The microprocessor used for controlling the operation of space vehicles, trains, robots, etc is made up of transistors and other controlling devices which are manufactured by semiconductor materials.

- **Importance of Semiconductors**
- Here we have discussed some advantages of semiconductors which makes them highly useful everywhere.
- They are highly portable due to the smaller size
- They require less input power
- Semiconductor devices are shockproof
- They have a longer lifespan
- They are noise-free while operating

LECTURE 4

P-n junctions, p-n diode, diode characteristics.

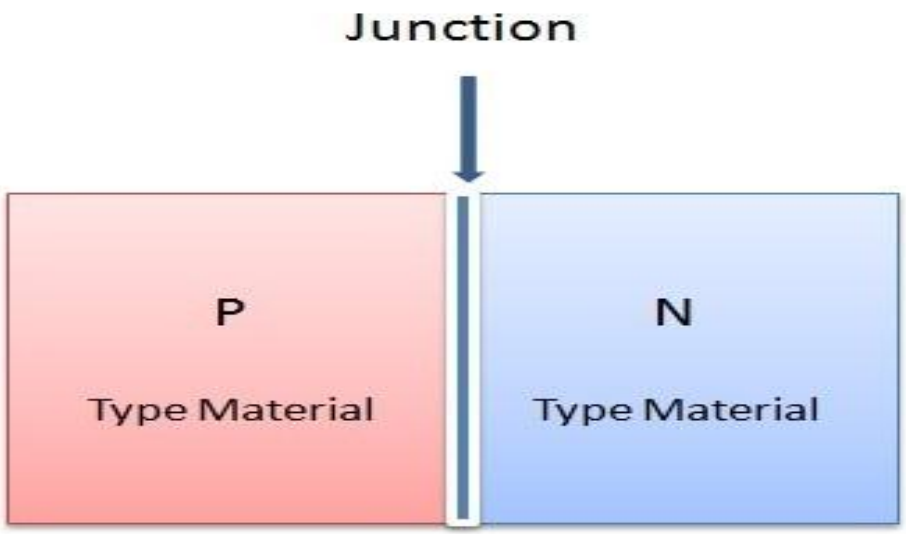
P-n junctions

- A crystal structure made of P and N materials is generally known as junction diode. It is generally regarded as a two-terminal device. As shown in the following diagram one terminal is attached to P-type material and the other to N-type material.

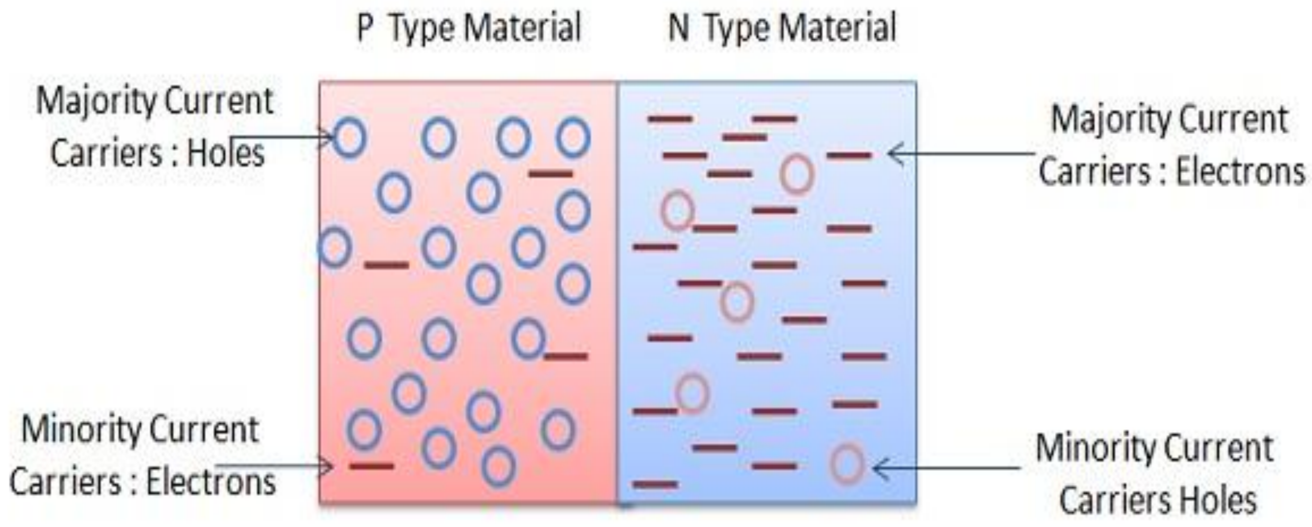
- The common bond point where these materials are connected is called a junction. A junction diode allows current carriers to flow in one direction and obstruct the flow of current in the reverse direction.

- The following figure shows the crystal structure of a junction diode. Take a look at the location of the P type and N type materials with respect to the junction. The structure of crystal is continuous from one end to the other. The junction acts only as a separating point that represents the end of one material and the beginning of the other. Such structure allows electrons to move thoroughly in the entire structure.

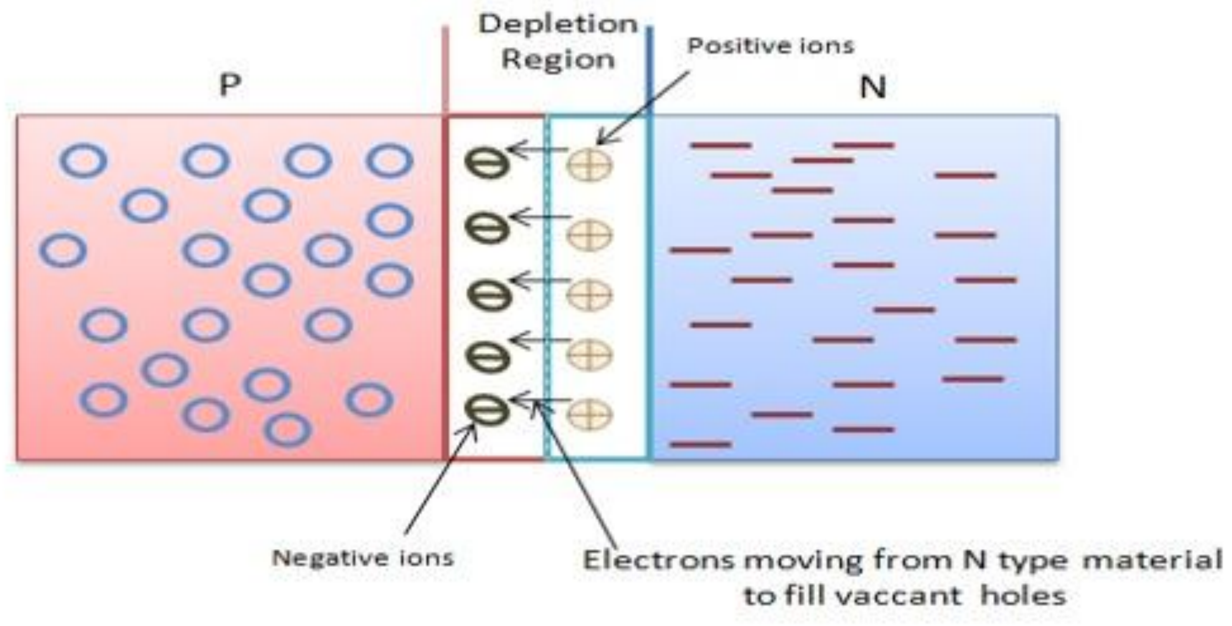
The following diagram shows two portions of semiconductor substance before they are shaped into a P-N junction. As specified, each part of material
has **majority** and **minority current carriers**.



The quantity of carrier symbols shown in each material indicates the minority or majority function. As we know electrons are the majority carriers in the N type material and holes are the minority carriers. In P type material, holes are the majority carriers and electrons are in the minority.



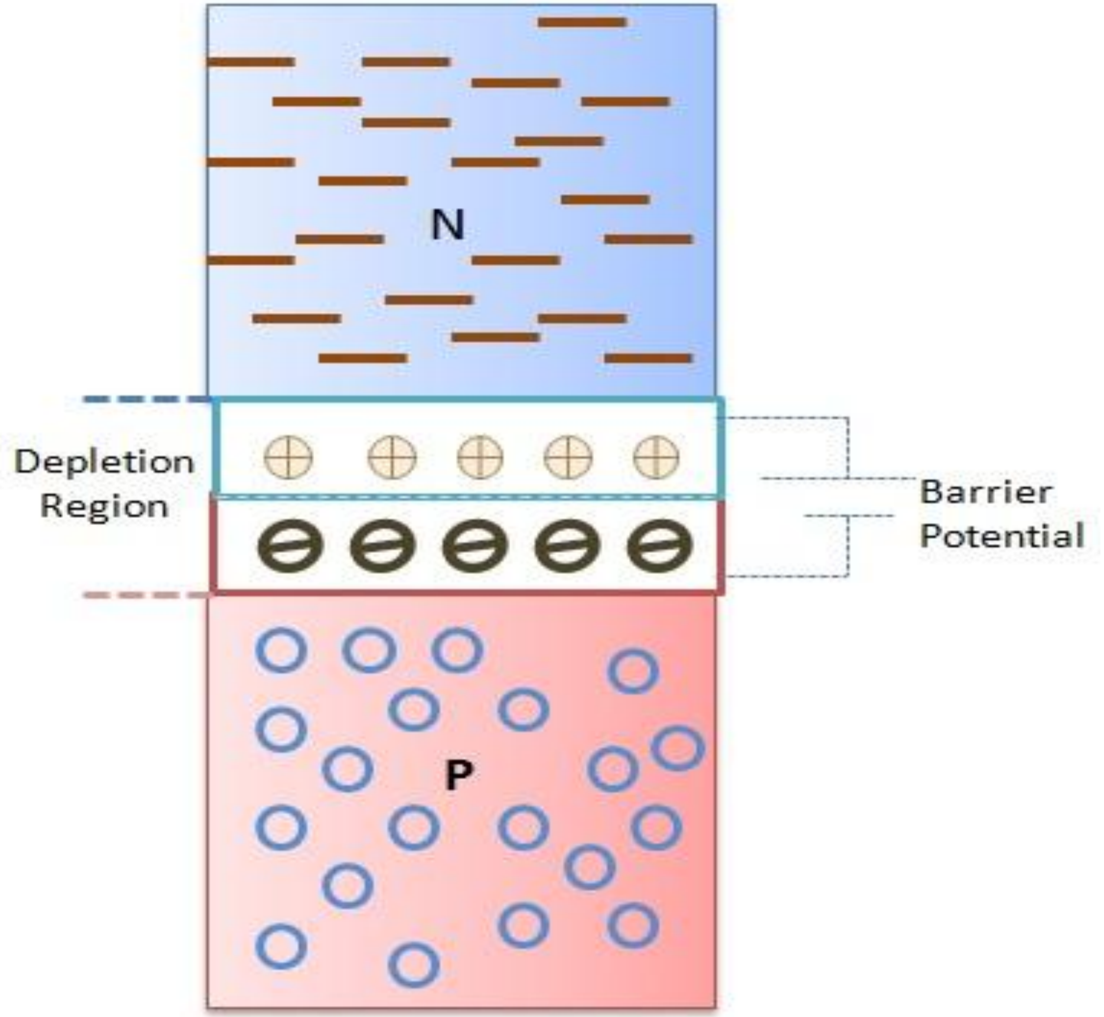
- Initially, when a junction diode is formed, there is a unique interaction between current carriers. In N type material, the electrons move readily across the junction to fill holes in the P material. This act is commonly called diffusion. Diffusion is the result of high accumulation of carriers in one material and a lower gathering in the other.
- Generally, the current carriers which are near to the junction only takes part in the process of diffusion. Electrons departing the N material cause positive ions to be generated in their place. While entering the P material to fill holes, negative ions are created by these electrons. As a result, each side of the junction contains a large number of positive and negative ions.



- The area where these holes and electrons become depleted is generally known by the term depletion region. It is an area where there is lack of majority current carriers. Normally, a depletion region is developed when P-N junction is formed. The following figure shows the depletion region of a junction diode.
- N-type and P-type material are considered as electrically neutral before they are joined together at a common junction. However, after joining diffusion takes place instantaneously, as electrons cross the junction to fill holes causing negative ions to emerge in the P material, this action causes the nearby area of the junction to take on a negative charge. Electrons departing the N material causes it to generate positive ions.
- All this process, in turn, causes the N side of the junction to take on a net positive charge. This particular charge creation tends to force the remaining electrons and holes away from the junction. This action makes it somewhat hard for other charge carriers to diffuse across the junction. As a result, the charge is built up or barrier potential emerges across the junction.

- As shown in the following figure. The resultant barrier potential has a small battery connected across the P-N junction. In the given figure observe the polarity of this potential barrier with respect to P and N material. This voltage or potential will exist when the crystal is not connected to an external source of energy.

The barrier potential of germanium is approximately 0.3 V, and of silicon is 0.7 V. These values cannot be measured directly and appears across the space charge region of the junction. In order to produce current conduction, the barrier potential of a P-N junction must be overcome by an external voltage source.



Biasing

- The term bias refers to the application of DC voltage to set up certain operating conditions. Or when an external source of energy is applied to a P-N junction it is called a bias voltage or simply biasing. This method either increases or decreases the barrier potential of the junction. As a result, the reduction of the barrier potential causes current carriers to return to the depletion region. Following two bias conditions are applied w.r.t. PN junctions.

- **Forward Biasing** − An external voltage is added of the same polarity to the barrier potential, which causes an increase in the width of the depletion region.

- **Reverse Biasing** − A PN junction is biased in such a way that the application of external voltage action prevents current carriers from entering the depletion region.

Forward Biasing

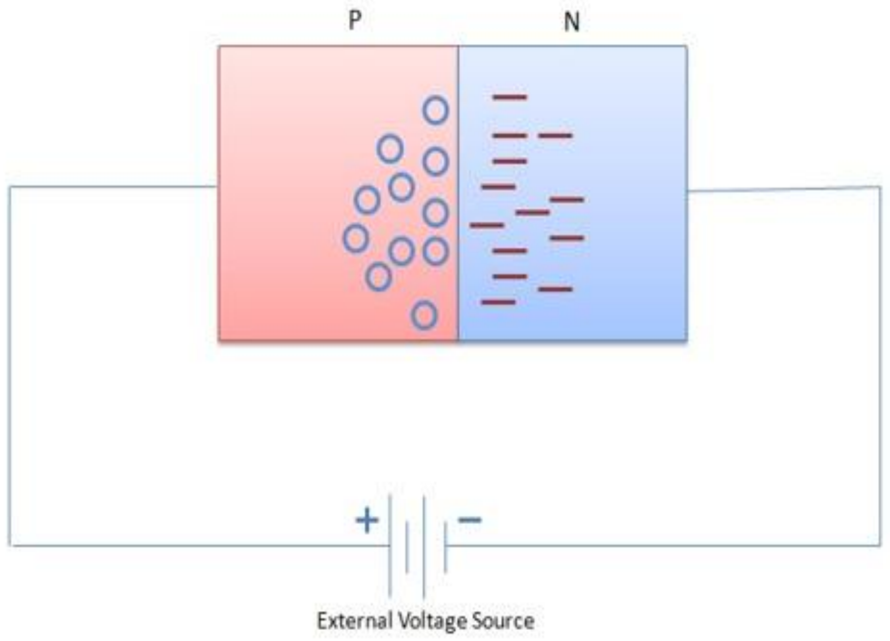
- The following figure shows a forward biased PN junction diode with external voltage applied. You can see that the positive terminal of the battery is connected to the P material and the negative terminal of the battery is connected to the N material.

Following are the observations −

•This bias voltage repels the majority current carriers of each P and N type material. As a result, large number of holes and electrons start appearing at the junction.

•At the N-side of the junction, electrons move in to neutralize the positive ions in the depletion region.

•On the P-side material, electrons are dragged from negative ions, which cause them to become neutral again. This means that forward biasing collapses the depletion region and hence the barrier potential too. It means that when P-N junction is forward biased, it will allow a continuous current flow.

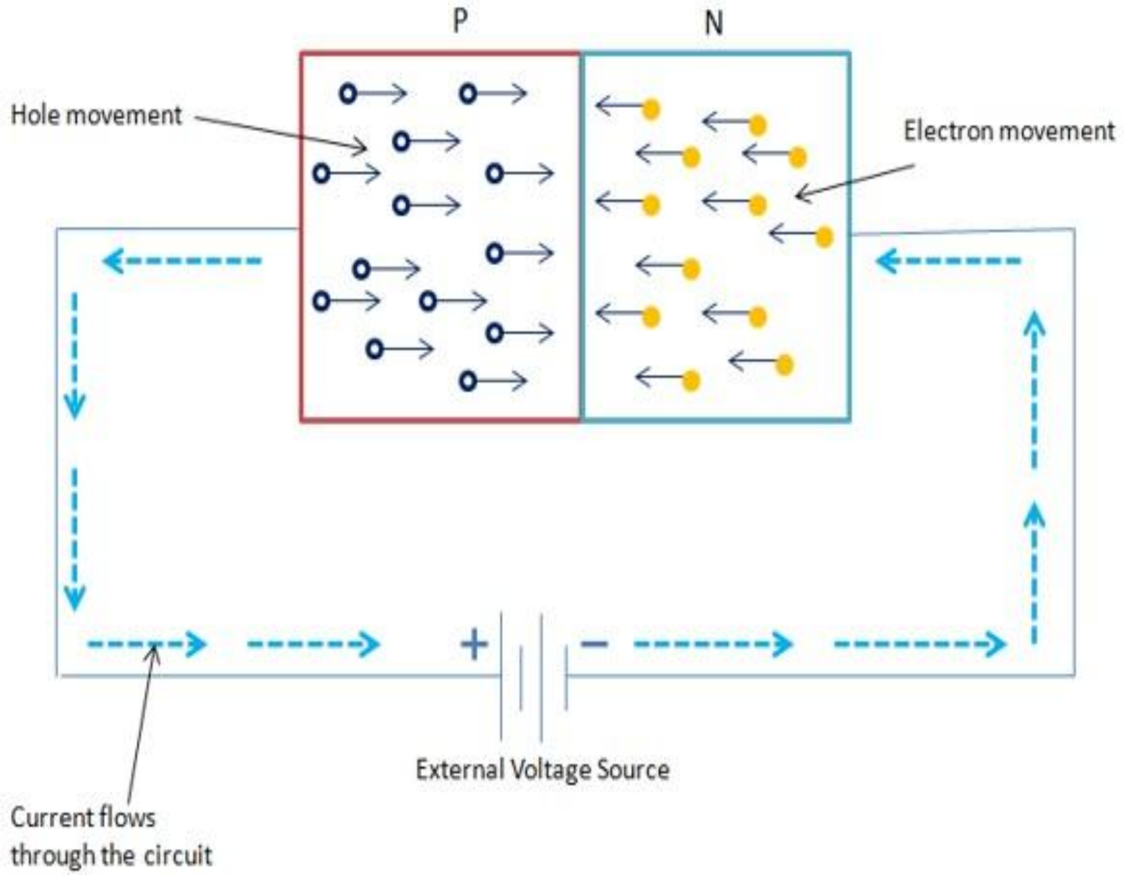


- The following figure shows the flow of current carriers of a forward-biased diode. A constant supply of electrons is available due to an external voltage source connected to the diode. The flow and direction of the current is shown by large arrows outside the diode in the diagram. Note that the electron flow and the current flow refers to the same thing.

Following are the observations −

- Suppose electrons flow through a wire from the negative battery terminal to the N material. Upon entering this material, they flow immediately to the junction.

- Similarly, on the other side an equal number of electrons are pulled from P side and are returned to the positive battery terminal. This action creates new holes and causes them to move toward the junction.



Following are the observations −

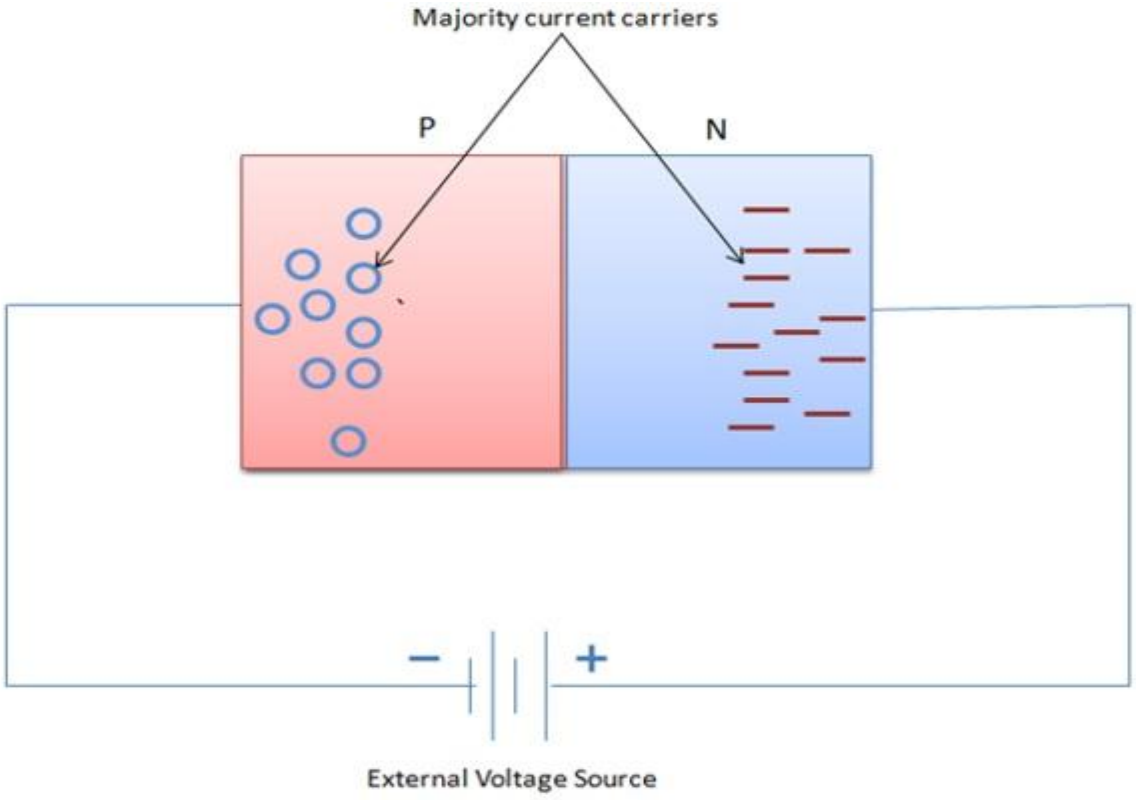
- When these holes and electrons reach the junction they join together and effectively disappear. As a result, new holes and electrons emerge at the outer ends of the diode. These majority carriers are created on a continuous basis. This action continues as long as the external voltage source is applied.

- When diode is forward biased it can be noticed that electrons flow through the entire structure of diode. This is common in N type material, whereas in the P material holes are the moving current carriers. Notice that the hole movement in one direction must begin by electron movement in the opposite direction. Therefore, the total current flow is the addition of holes and electrons flow through a diode.

Reverse Biasing

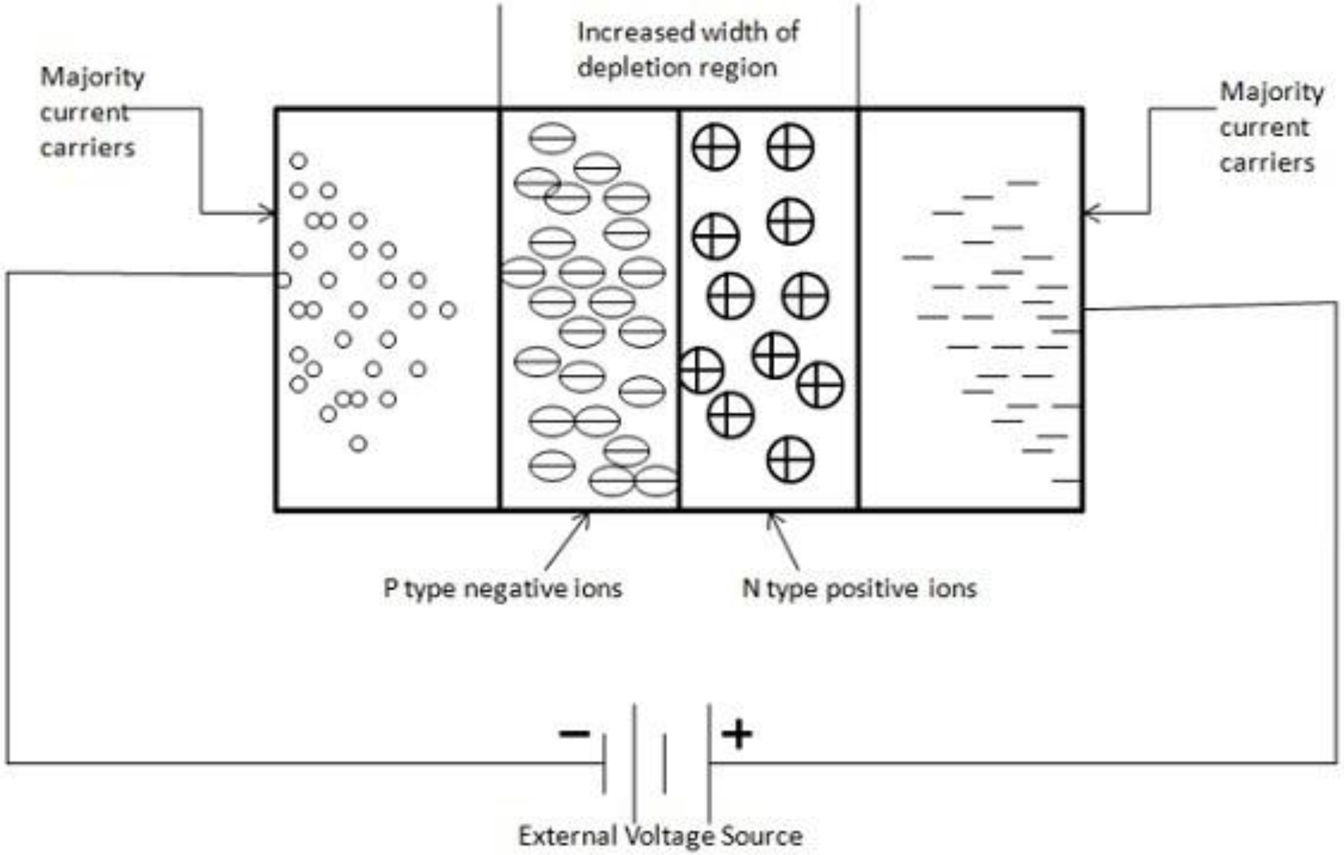
- The following figure shows reverse biased PN junction diode with external voltage applied. You can see that the positive terminal of the battery is connected to the N material and the negative terminal of the battery is connected to the P material. Note that in such an arrangement, battery polarity is to oppose the material polarity of the diode so that dissimilar charges attract. Hence, majority charge carriers of each material are dragged away from the junction. Reverse biasing causes the diode to be nonconductive.
-

The following figure shows the arrangement of the majority current carriers in a reverse biased diode.



Following are the observations −

- Due to circuit action electrons of the N material are pulled toward the positive battery terminal.
- Each electron that moves or departs the diode causes a positive ion to emerge in its place. As a result, this causes an equivalent increase in the width of the depletion region on the N side of the junction.

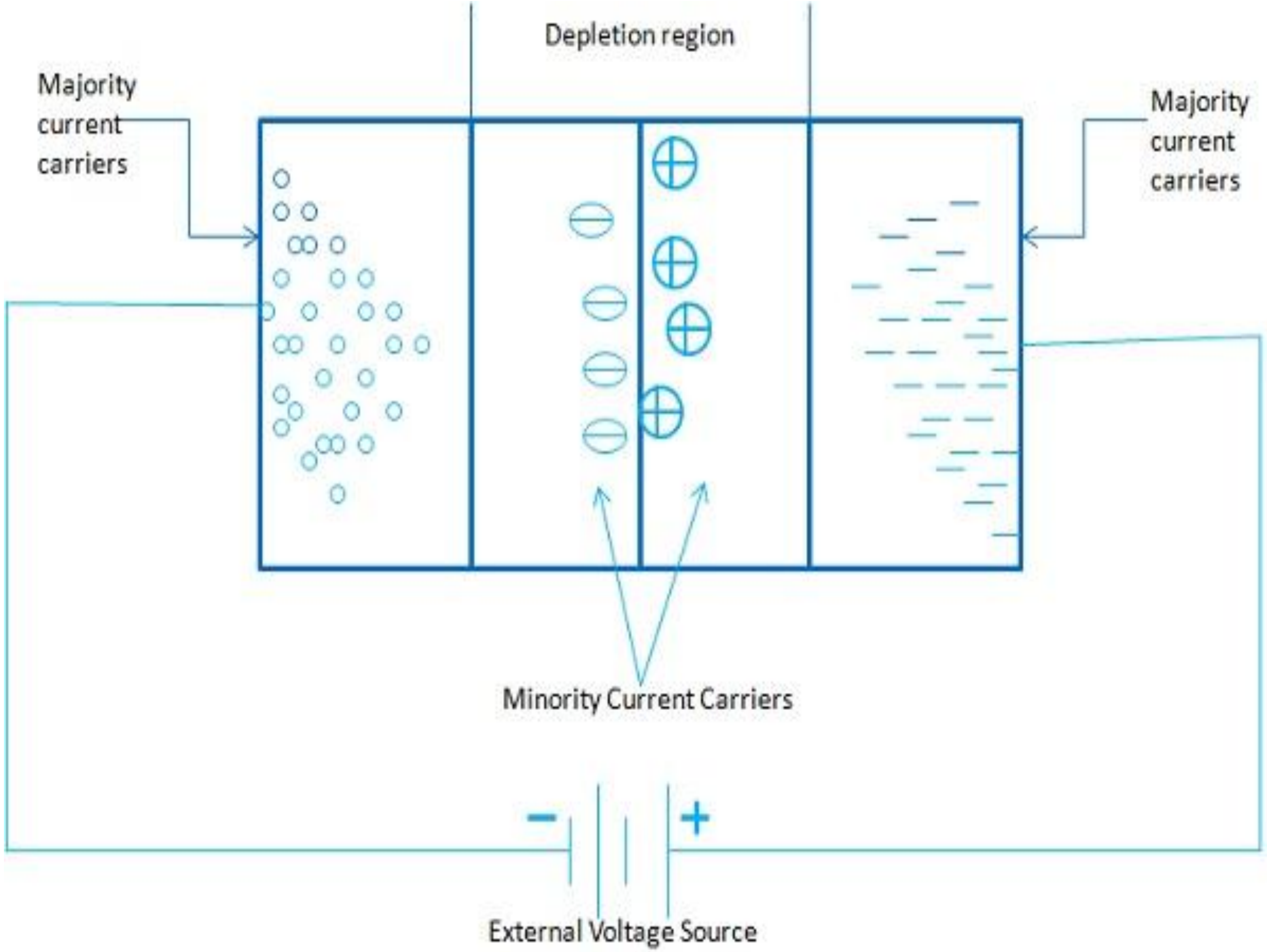


- Following are the observations −
- The P side of the diode has a similar effect alike the N side. In this action, a number of electrons leave the negative battery terminal and enter the P type material.
- These electrons then straight away move in and fill a number of holes. Each occupied hole then becomes a negative ion. These ions in turn are then repelled by the negative battery terminal and driven toward the junction. Due to this, there is an increase in the width of the depletion region on the P side of the junction.
- The overall width of the depletion region directly depends on an external voltage source of a reverse-biased diode. In this case, the diode cannot efficiently support the current flow through the wide depletion region. As a result, the potential charge starts developing across the junction and increases until the barrier potential equals the external bias voltage. After this, the diode behaves as a nonconductor.

- An important conduction limitation of PN junction diode is **leakage current**. When a diode is reverse biased, the width of the depletion region increases. Generally, this condition is required to restrict the current carrier accumulation near the junction. Majority current carriers are primarily negated in the depletion region and hence the depletion region acts as an insulator. Normally, current carriers do not pass through an insulator.
- It is seen that in a reverse-biased diode, some current flows through the depletion region. This current is called leakage current. Leakage current is dependent on minority current carriers. As we know that the minority carriers are electrons in the P type material and holes in the N type material.

- The following figure shows how current carriers react when a diode is reverse biased.

Following are the observations –



- Minority carriers of each material are pushed through the depletion zone to the junction. This action causes a very small leakage current to occur. Generally, leakage current is so small that it can be considered as negligible.

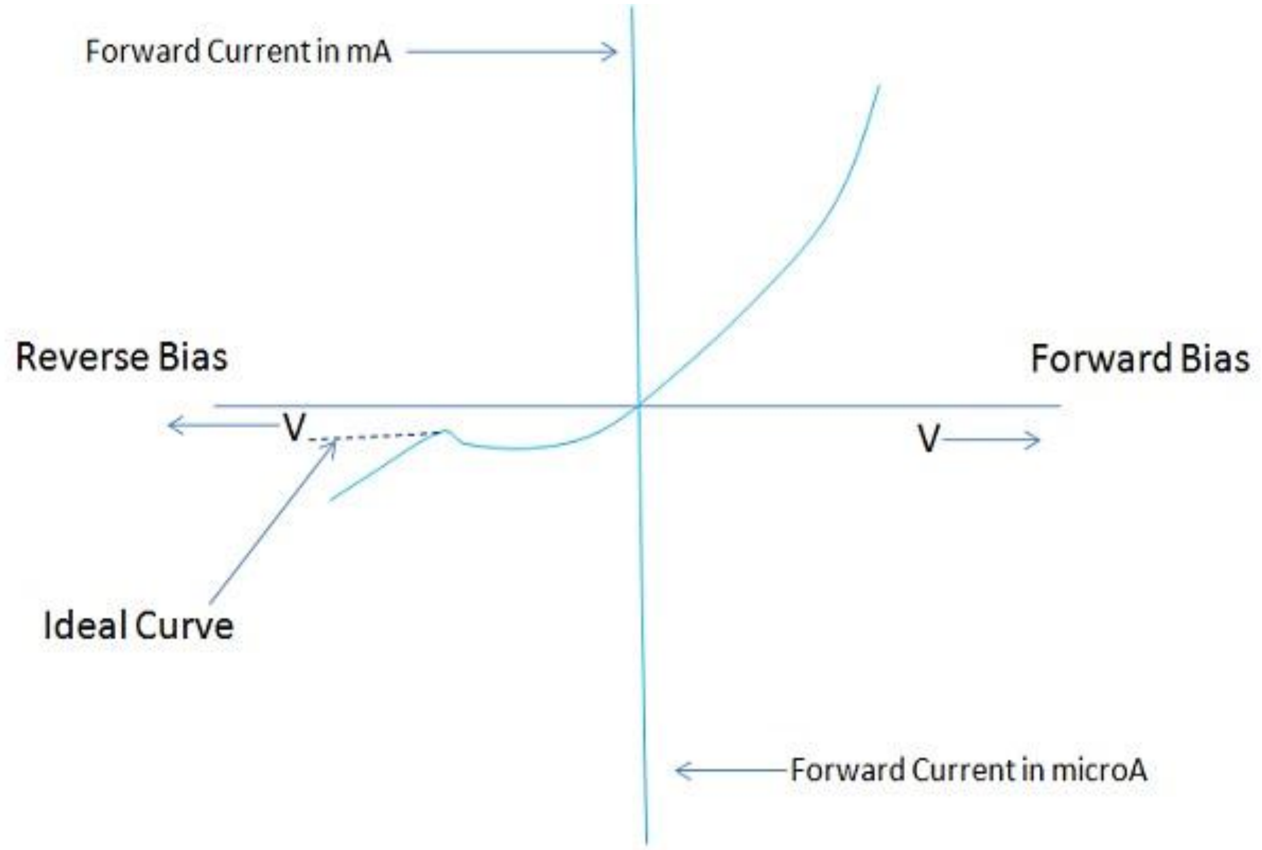
- Here, in case of leakage current, temperature plays an important role. The minority current carriers are mostly temperature dependent.

- At room temperatures of 25°C or 78°F, there is negligible amount of minority carriers present in a reverse bias diode.
- When the surrounding temperature rises, it causes significant increase in minority carrier creation and as a result it causes a corresponding increase in leakage current.

In all reverse-biased diodes, occurrence of leakage current is normal to some extent. In Germanium and Silicon diodes, leakage current is only of few microamperes and nanoamperes, respectively. Germanium is much more susceptible to temperature than silicon. For this reason, mostly Silicon is used in modern semiconductor devices.

- There are diverse current scales for forward bias and reverse bias operations. The forward portion of the curve indicates that the diode conducts simply when the P-region is made positive and the N-region negative.
- The diode conducts almost no current in the high resistance direction, i.e. when the Pregion is made negative and the N-region is made positive. Now the holes and electrons are drained away from the junction, causing the barrier potential to increase. This condition is indicated by the reverse current portion of the curve.

- The dotted section of the curve indicates the **ideal curve**, which would result if it were not for avalanche breakdown. The following figure shows the static characteristic of a junction diode.



DIODE IV Characteristics

- The forward and reverse current voltage (IV) characteristics of a diode are generally compared on a single characteristic curve. The figure depicted under the section Forward Characteristic shows that Forward Voltage and Reverse Voltage are usually plotted on the horizontal line of the graph.
- Forward and reverse current values are shown on the vertical axis of the graph. Forward Voltage represented to the right and Reverse Voltage to the left. The point of beginning or zero value is at the center of the graph. Forward Current lengthens above the horizontal axis with Reverse Current extending downward.
- The combined Forward Voltage and Forward Current values are located in the upper right part of the graph and Reverse Voltage and Reverse Current in the lower left corner. Different scales are normally used to display forward and reverse values.

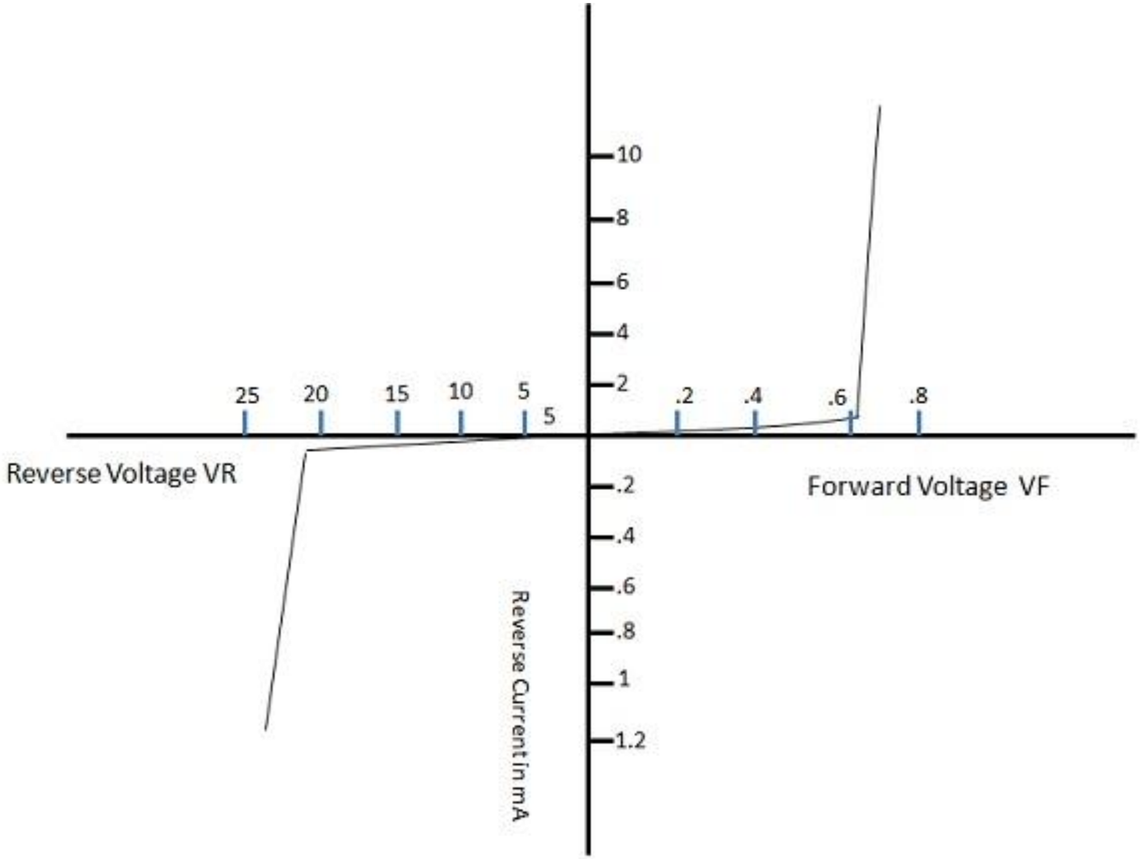
Forward Characteristic

- When a diode is forward biased it conducts current (IF) in forward direction. The value of IF is directly dependent on the amount of forward voltage. The relationship of forward voltage and forward current is called the ampere-volt, or IV characteristic of a diode. A typical diode forward IV characteristic is shown in the following figure.

Following are the observations −

•Forward Voltage is measured across the diode and Forward Current is a measure of current through the diode.

•When the forward voltage across the diode equals 0V, forward current (IF) equals 0 mA.



- When the value starts from the starting point (0) of the graph, if VF is progressively increased in 0.1-V steps, IF begins to rise.
- When the value of VF is large enough to overcome the barrier potential of the P-N junction, a considerable increase in IF occurs. The point at which this occurs is often called the knee voltage $\mathbf{V_K}$. For germanium diodes, $\mathbf{V_K}$ is approximately 0.3 V, and 0.7 V for silicon.
- If the value of IF increases much beyond $\mathbf{V_K}$, the forward current becomes quite large.
- This operation causes excessive heat to develop across the junction and can destroy a diode. To avoid this situation, a protective resistor is connected in series with the diode. This resistor limits the forward current to its maximum rated value. Normally, a current limiting resistor is used when diodes are operated in the forward direction.

Reverse Characteristic

- When a diode is reverse biased, it conducts Reverse current that is usually quite small. A typical diode reverse IV characteristic is shown in the above figure.

- The vertical reverse current line in this graph has current values expressed in microamperes. The amount of minority current carriers that take part in conduction of reverse current is quite small. In general, this means that reverse current remains constant over a large part of reverse voltage. When the reverse voltage of a diode is increased from the start, there is a very slight change in the reverse current. At the breakdown voltage (VBR) point, current increases very rapidly. The voltage across the diode remains reasonably constant at this time.

- This constant-voltage characteristic leads to a number of applications of diode under reverse bias condition. The processes which are responsible for current conduction in a reverse-biased diode are called as **Avalanche breakdown** and **Zener breakdown**.

Diode Specifications

- Like any other selection, selection of a diode for a specific application must be considered. Manufacturer generally provides this type of information. Specifications like maximum voltage and current ratings, usual operating conditions, mechanical facts, lead identification, mounting procedures, etc.
- Following are some of the important specifications −
- **Maximum forward current (IFM)** − The absolute maximum repetitive forward current that can pass through a diode.
- **Maximum reverse voltage (VRM)** − The absolute maximum or peak reverse bias voltage that can be applied to a diode.
- **Reverse breakdown voltage (VBR)** − The minimum steady-state reverse voltage at which breakdown will occur.
- **Maximum forward surge current (IFM-surge)** − The maximum current that can be tolerated for a short interval of time. This current value is much greater than IFM.
- **Maximum reverse current (IR)** − The absolute maximum reverse current that can be tolerated at device operating temperature.
- **Forward voltage (VF)** − Maximum forward voltage drop for a given forward current at device operating temperature.
- **Power dissipation (PD)** − The maximum power that the device can safely absorb on a continuous basis in free air at 25° C.
- **Reverse recovery time (Trr)** − The maximum time that it takes the device to switch from on to off stat.

- Important Terms
- **Breakdown Voltage** − It is the minimum reverse bias voltage at which PN junction breaks down with sudden rise in reverse current.
- **Knee Voltage** − It is the forward voltage at which the current through the junction starts to increase rapidly.
- **Peak Inverse Voltage** − It is the maximum reverse voltage that can be applied to the PN junction, without damaging it.
- **Maximum Forward Rating** − It is the highest instantaneous forward current that a PN junction can pass, without damaging it.
- **Maximum Power Rating** − It is the maximum power that can be dissipated from the junction, without damaging the junction.