CHAPTER 2: Semiconductor Diode
(24 marks)

Introduction:

- The word **semiconductor** is composed of two words **Semi** and **conductor**.
- We know that conductor is the material which has an ability to conduct electricity, whereas semiconductors are the devices that conduct electricity to some extend depending on the material of the semiconductor.
- In other words, semiconductor is that material which has intermediate conductivity between a conductor and an insulator.

Types of Semiconductors:

Semiconductors are mainly categorized into 2 types-

1. **Intrinsic Semiconductors:** An intrinsic semiconductor is chemically pure and possesses poor conductivity. Here the semiconducting properties happen naturally, i.e. they are intrinsic to the material's nature. **Silicon** and **Germanium** are the most elemental semiconductors.
2. **Extrinsic Semiconductor:** It is an improved intrinsic semiconductor with a small amount of impurities added by the process, known as **Doping.** Introducing impurities into semiconductor material alters its electrical properties and improves its conductivity. The semiconducting properties of extrinsic materials are manufactured by us, to make the material behave in the manner we require. Compound semiconductors include GaAs, GaP, etc.

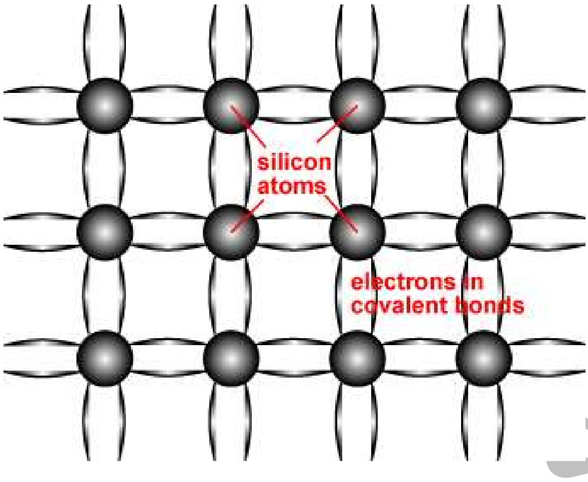
Doping process in semiconductors:

The pure or intrinsic semiconductor is neutral. It contains no free electrons in its conduction bands. Even with the application of thermal energy, only a small amount of covalent bonds are broken, giving rise to a very small current.

The most efficient method of increasing this current flow is by the process of **Doping.**

Doping is the process of **adding some impurity** atoms in the semiconductor. These impurity atoms are known as **Dopants.** After addition of these dopants some of the properties of conductors can be changed as per our need.

We know that every semiconductor atom consist of four valence electrons. Each atom shares these 4 valance electrons with the neighboring four atoms (covalent bonds) to form a stable semiconductor lattice.

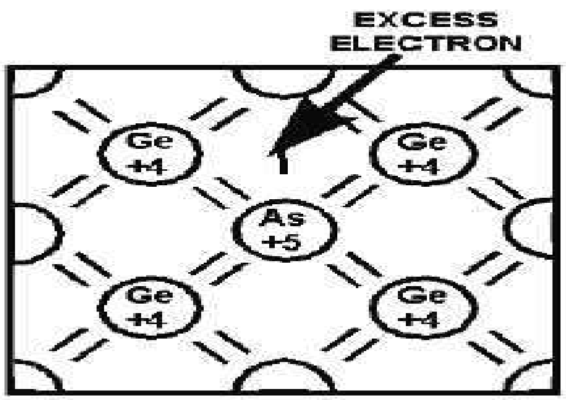


Depending on the impurity atom used in doping, extrinsic semiconductors are of two types-

1. **N-type Semiconductor:**

- The purpose of semiconductor doping is to increase the number of free charges that can be moved by external applied voltage. When the added impurity increases the number of electrons in the lattice, then the doped semiconductor is **Negative or N-type semiconductor.**
- The impurity that is added consists of **5 valence electrons** and is termed as **pentavalent impurity**. Its four electrons are shared with neighboring four electrons of doped semiconductor material and one electron is left free. These extra electrons from the atoms of pentavalent impurity are used as free charges and thus increase the conductivity of semiconductor material.

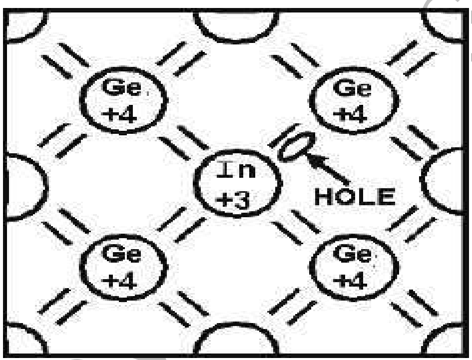
  -As shown in the figure, arsenic is used as pentavalent impurity atom and donor of one extra electron.



- **Examples of pantavalent impurities are:**
  Phosphorus (P), arsenic (As),
  antimony (Sb) bismuth (Bi).

2**. P-type semiconductor:**

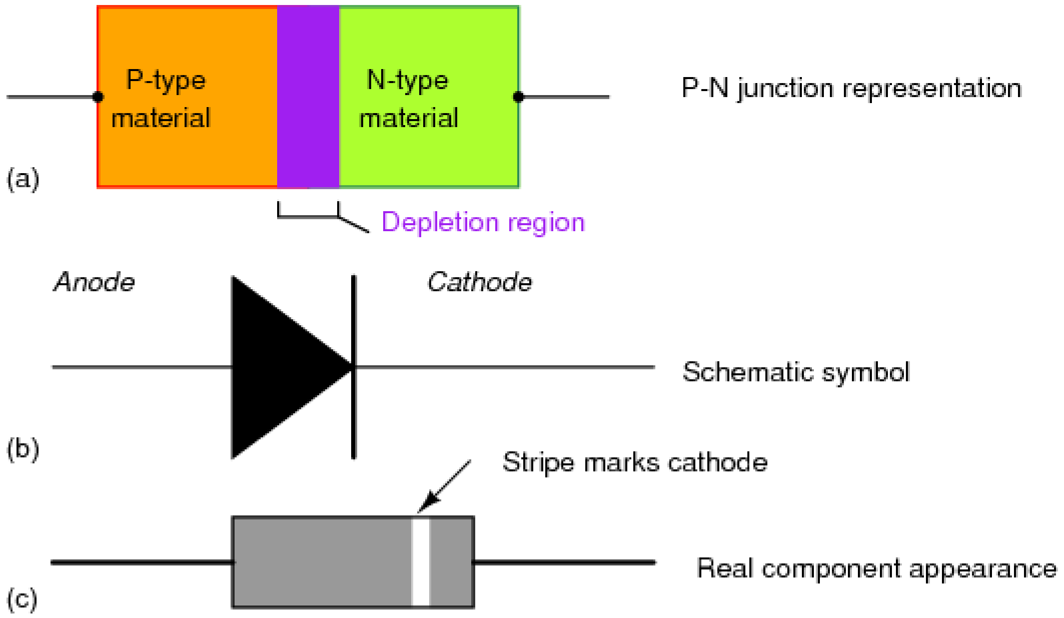
- The impurities added to this type of semiconductor consist of **3 electrons in its valance shell** and are termed as **trivalent impurity**.
- Since the impurity atom consists of only 3 valence electrons, it shares its 3 electrons with neighboring 3 electrons of semiconductor and creates one deficiency.
- In this case, the impurity is 1 electron short of the required amount of electrons needed to establish covalent bonds with 4 neighboring atoms. Thus, in a single covalent bond, there will be only 1 electron instead of 2. This arrangement leaves a hole in that covalent bond.



- Figure illustrates this theory by showing what happens when germanium is doped with an **indium (In)** atom. Notice, the indium atom in the figure is 1 electron short of the required amount of electrons needed to form covalent bonds with 4 neighboring atoms and, therefore, creates a hole in the structure. **Gallium and boron**, which are also trivalent impurities, exhibit these same characteristics when added to germanium.

2.1 P-N JUNCTION:

- When p-type and n-type semiconductors are appropriately joined together with special fabrication technique, then the contact surface is called as PN Junction or p-n junction diode. The term 'diode' means the device having 'two electrodes'.
- Schematic representation and symbol of p-n junction diode is shown below-



- The arrowhead in the symbol points to the direction of conventional current in device. This current will flow through the diode only if an external source voltage is connected to it with appropriate polarities.

CONCEPT OF HOLES:

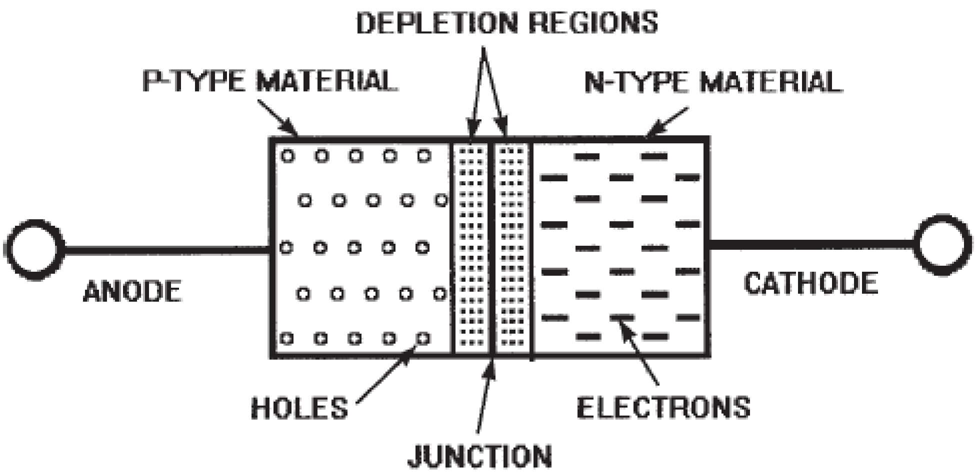
- We know that the semiconductors distinguish themselves from conductors and insulators by the fact that they contain almost empty conduction band and almost full valence band. In order to improve conductivity, these electrons must be transferred from valence band to conduction band by application of proper energy.
- While transporting these charges, we have to deal only with electrons since these are the only real particles in semiconductor. However, the concept of hole was basically introduced based on the notion that it is much easier to keep track of missing particles in almost full valence band, rather than keeping track of actual electrons in that band.
- Holes are nothing but missing electrons. They exhibit the same properties as the electrons would have occupying the same state except that holes have positive charge.
- A hole is an electric charge carrier having positive charge, equal in magnitude but opposite in polarity to the charge on the electron. Electrons and holes are the two charge carriers responsible for flow of current in semiconductor materials.

MAJORITY AND MINORITY CHARGE CARRIERS:

- We know that the charge carriers that are present in abundant quantities are termed as majority charge carriers; and the carriers that are present in minute quantities are termed as minority charge carriers.
- It must be noted that in any semiconductor material, holes are never equal to electrons. The number of holes or electrons depends on the dopant used and amount of dopant used.
- In n-type semiconductor, since we use pentavalent impurity, the majority charge carriers are electrons. Minority charge carriers in n-type semiconductor are holes.
- The situation is reversed in P-type semiconductor. In P-type semiconductor holes are the majority charge carrier.
- P-type semiconductor contains some electrons that are loosened by thermal effects, and they act as minority charge carriers.

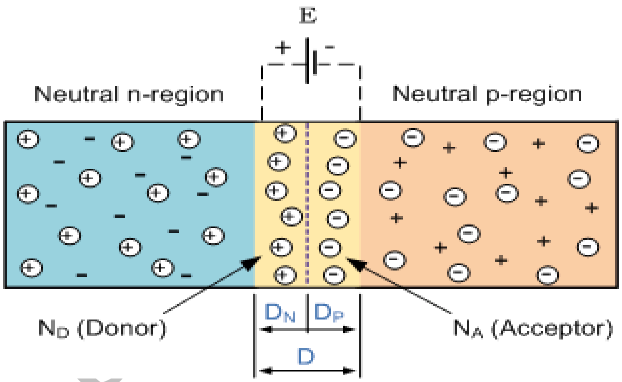
FORMATION OF DEPLETION LAYER IN P-N JUNCTION:

- Intrinsic semiconductors when doped with proper dopants produce n-type or p-type semiconductors. However, these semiconductors do very little on their own as they are electrically neutral; but when we join them together these materials behave in a very different way producing p-n junction.



- As show in fig, when p-type and n-type semiconductors are fused together, some reaction occurs that results in the formation of depletion regions.

- When fused together, electrons start diffusing from n-type region to p-type region. Since the *n*-type region has a high electron concentration and the *p*-type a high hole concentration, electrons diffuse from the *n*-type side to the *p*-type side. Similarly, holes flow by diffusion from the *p*-type side to the *n*-type side. This process is known as **diffusion.**
- The electrons from n-side will diffuse into p-side and recombine with the holes present there. Each electron that diffuses into the p-side will behind a positive immobile ion on the n-side.
- Similarly, when an electron combines with a hole on p-side, an atom that accepts this electron loses its electrical neutrality and becomes a negative immobile ion.
- Due to this recombination process, a large number of positive ions accumulate near the junction on the n-side, and large number of negative ions accumulates near the junction on the p-side.



- When sufficient negative ions get accumulated in the p-region near the junction, the electrons experience the force of repulsion while diffusing from n-region to p-region. Hence, diffusion stops.
- Similarly, the positive ions near the junction in n-region repel the holes so that the diffusion of holes too stops.
- This layer of ions is termed as **depletion layer** or **space charge region**, since it is depleted of charge carriers (electrons and holes). After the formation of these immovable ions near the junction, no more electrons and holes can cross the junction and it creates a barrier at the junction.
- The basic property of junction diode is that it conducts electric current in one direction and blocks in other direction. This property is mainly because of the formation of such a depletion layer.

BARRIER VOLTAGE:

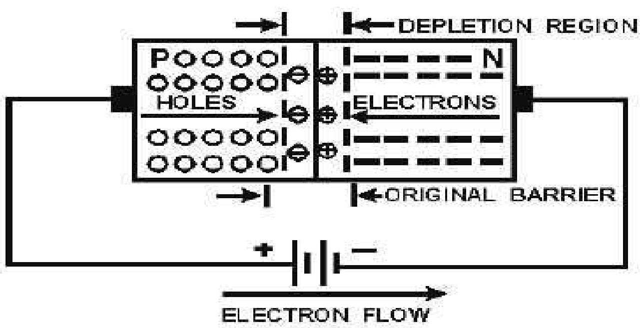
- The width of the depletion region is very small. The presence of immobile positive and negative ions on the opposite side of the junction creates a potential across the junction. This potential is known as the **Barrier potential** or **junction potential** or **cut-in voltage** or **knee voltage.**
- The barrier potential for silicon is about 0.7volts, whereas for germanium is 0.3V. The polarities of this potential are fixed.

BIASING THE P-N JUNCTION:

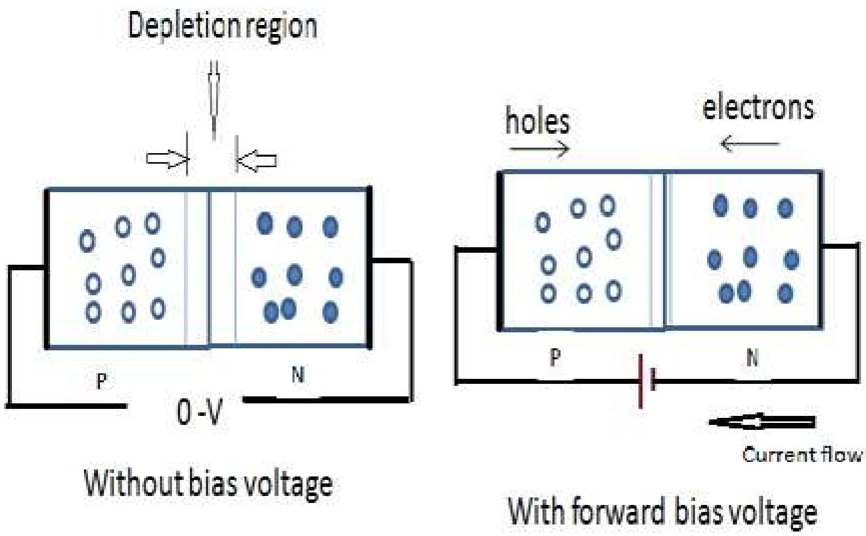
- Biasing is the process of applying external DC voltage to the semiconductor diode. When external voltage is not applied to diode, the depletion region is available at the junction. Hence, there is no current flowing through it.
- To make the current flow, it is necessary to bias the diode.
- If we make some electrical connections at both ends of p-type and n-type materials and connect an external voltage source, then there exists an additional energy source to over the barrier resulting in free charges being able to cross the depletion region.
- However, to achieve flow of current the diode can have two types of biasing: **Forward biasing and Reverse Biasing**.

1. Forward Biasing:

- The process of applying and external voltage to a junction in such a direction that it cancels the potential barrier, thus permitting the current flow is called as forward biasing.



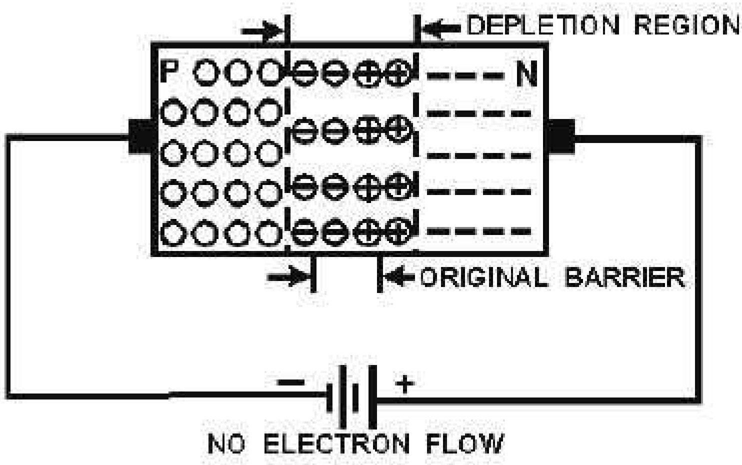
- If the p-region (anode) is connected to the positive terminal of the external source and n-side (cathode) connected to the negative terminal of the external source, then the diode is said to be forward biased. It is shown in the fig above. Conventional current flows in the direction opposite to the flow of electrons.
- The applied forward potential establishes an electric field, which acts against the field due to potential barrier. Therefore the resultant field is weakened and the barrier height is reduced at the junction. The holes are electrons are attracted to opposite polarities of the battery and start to make efforts to cross the junction.



- As potential barrier is very small, a small forward voltage is sufficient to completely eliminate the barrier.
- Once the potential barrier is eliminated by forward voltage, junction resistance almost becomes zero and a low resistance path is established for entire circuit. Therefore, current flowing in the circuit is called as forward current.

2. Reverse Biasing:

- The process of applying external voltage to a junction in such a direction that the potential barrier is increased is called **reverse biasing**.



- If the **p-region** of the diode is connected to **negative terminal** of the battery and **n-side** of the diode is connected to **positive terminal** of the battery, then the diode is said to be reversed biased.
- When the diode is reverse biased, holes in the p-region are attracted towards negative terminal of the battery and electrons in the n-side are attracted towards positive terminal of the battery.
- Due to the movement of holes and electrons away from the junction, width of the depletion region increases. This happens due to creation of more number of positive and negative immobile ions.
- Due to more number of immobile ions present on opposite sides of the junction, the barrier potential increases. This increased barrier potential prevents the flow of charges across the junction. Thus, high resistance path is established for the entire circuit and the current doesn't flow.
- However, in actual very small current flows due to movement of minority carriers, called reverse saturation current.

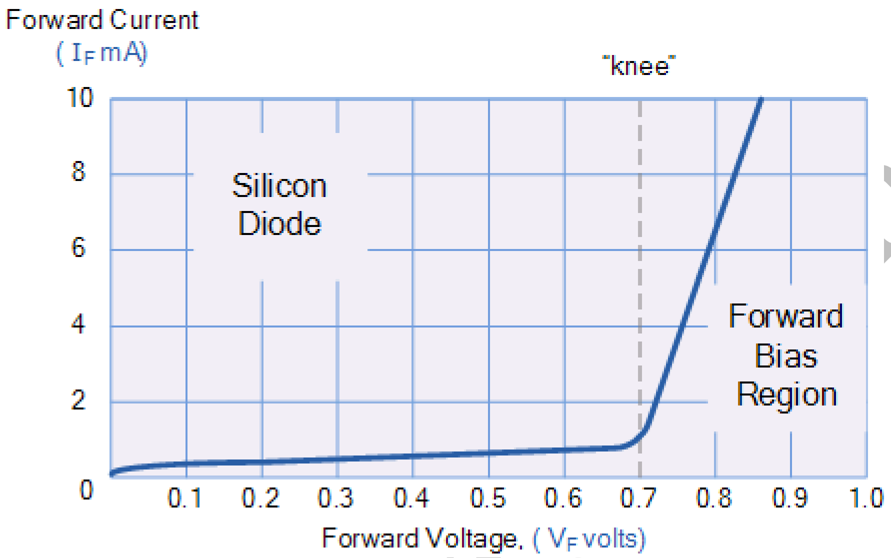
V-I CHARTERISTICS OF P-N JUNCTION:

- The volt-ampere characteristics of the diode are represented by the graph of voltage across the diode versus current flowing through it. Voltage is plotted on x-axis and current is plotted on y-axis.

- The characteristics can be studied under 3 heads namely: **zero external voltage, forward bias and reverse bias.**
- ZERO EXTERNAL VOLTAGE:

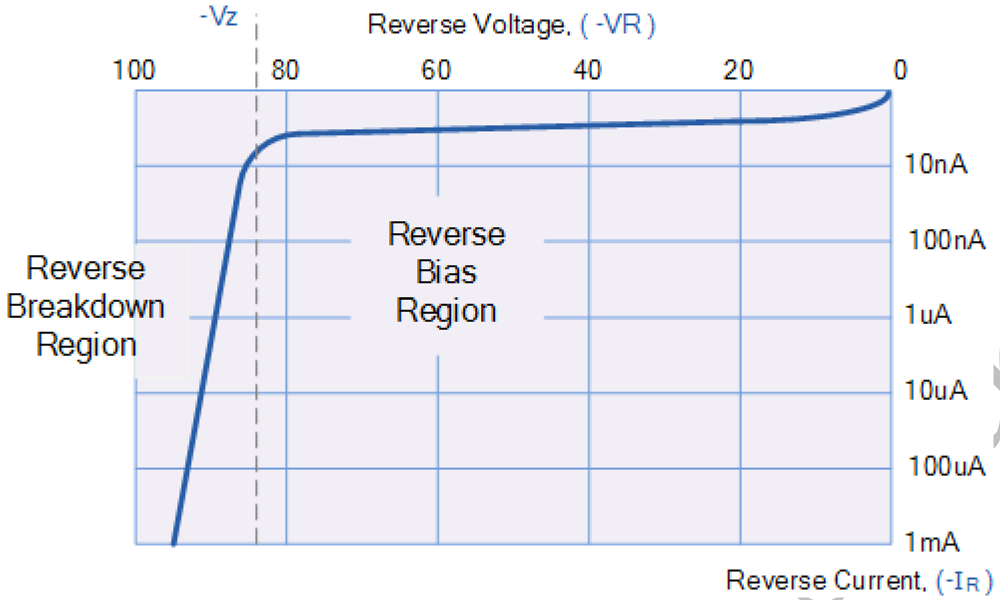
When the external potential is zero, the potential barrier at the junction does not permit the current flow. Hence, the circuit current is zero.

- FORWARD CHARACTERISTICS:



- During forward bias, the potential barrier is reduced. At some forward voltage, the potential barrier is altogether eliminated and current starts flowing in the circuit.
- The current increases with the increase in forward voltage. Thus, as shown in the graph, a rising curve is obtained with forward bias.
- From the forward characteristics it can be seen that the current increases very slowly and the curve is non-linear. It is because the external voltage is utilized in overcoming the barrier.
- However, once the external voltage exceeds the potential barrier voltage, the diode behaves like the ordinary conductor. Therefore, the current rises very sharply with the increase in external voltage, and curve is almost linear.
- The voltage at which the forward current starts increasing rapidly is known as cut-in voltage of the diode.

➢ REVERSE CHARACTERISTICS:



- During the reverse bias, the barrier potential at the junction is increased. Hence, the junction resistance becomes very high and theoretically no current flows through the circuit.
- However, in actual practice, small current flows due to movement of minority carriers, which is called as **reverse saturation current.**
- If the reverse voltage is increased continuously, the kinetic energy of the electrons (minority carriers) may become high enough to knock out electrons from semiconductor atoms. At this stage, the **breakdown** of junction occurs, characterized by sudden rise of reverse current and sudden fall of resistance of the barrier region.
- The voltage at which p-n junction breaks down with sudden rise in reverse current is called **breakdown voltage**.

STATIC AND DYNAMIC RESISTANCE OF THE DIODE:

STATIC RESISTANCE:

➢ The resistance offered by a diode to dc operating conditions is called as dc or static resistance and is denoted as R_f.

➢ When dc voltage is applied to the diode, a dc current will flow through it. The resistance at the operating point can be calculated by taking the ratio of V_f and I_f.

$$R_f = V_f / I_f$$

DYNAMIC RESISTANCE:

- The resistance offered by the diode to ac operating conditions is called as ac or dynamic resistance and is denoted by R_f.
- The operating point of the diode does not remain fixed.
- It can be defined as the ratio of change in input voltage to the change in current.

$$R_f = \triangle V_f / \triangle I_f$$

KNEE VOLTAGE:

- The forward voltage at which the current through the junction starts increasing rapidly is called as **knee voltage** or **cut-in voltage**.
- Knee voltage for **Si diode is 0.7v** & for **Ge diode is 0.3v**
- The reverse voltage at which the junction breaks down and huge current starts flowing through it is called as **breakdown voltage**.

DIODE SPECIFICATIONS:

- FORWARD VOLTAGE: It is defined as the voltage at which the potential barrier at the junction breaks and current starts flowing in the circuit.

- MAXIMUM FORWARD CURRENT: It is a maximum instantaneous forward current that a diode can conduct without damaging the junction. If the forward current is more than this value, the diode will destroy due to overheating.

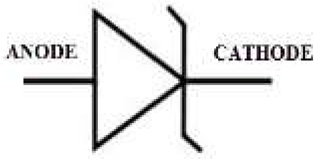
- PEAK INVERSE VOLTAGE (PIV): It is the maximum reverse voltage that can be applied to a diode without damaging the junction. If the reverse voltage across the diode exceeds this value, the reverse current increases sharply and breaks down the junction due to excessive heat.

- REVERSE SATURATION CURRENT: It is defined as the small current flows due to movement of minority carriers in reverse bias condition, is called as **reverse saturation current.**

2.2 TYPES OF DIODES:

2.2.1 ZENER DIODE:

SYMBOL:



OPERATING PRINCIPLE:

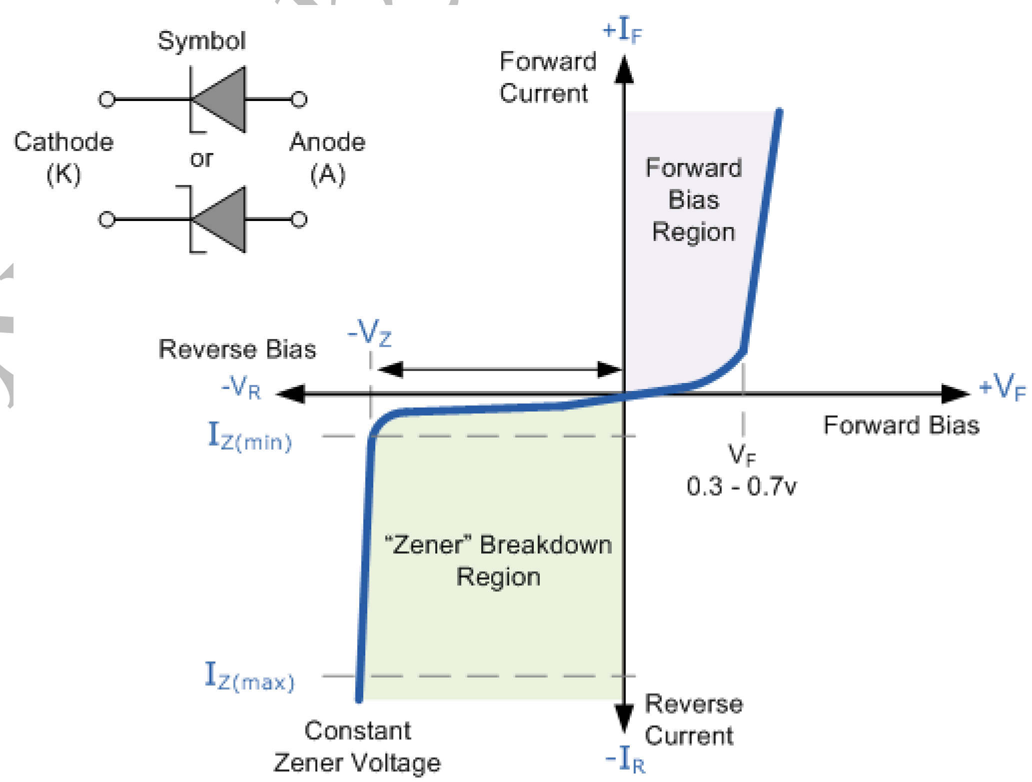
- When an ordinary diode is reverse biased the potential barrier across the junction increases. Therefore, the junction resistance becomes very high and practically no current flows through the circuit.
- But, in actual very small current flows called as **reverse saturation current.** If the reverse voltage is increased continuously, the kinetic energy of electrons may become high enough to knock out the electrons from semiconductor atoms. At this stage the breakdown of junction occurs and huge current starts flowing in the circuit.
- The p-n junction breaks down with the sudden increase in reverse current at a voltage called as breakdown voltage or zener voltage.
- The **breakdown voltage** depends on the **amount of doping.** If the diode is heavily doped, depletion layer will be thin and the breakdown of junction will occur at lower reverse voltage. On the other hand, a lightly doped diode has higher breakdown voltage.
- When an ordinary diode is properly doped so that it has very sharp breakdown voltage, it is called as **Zener diode**.
- Thus, zener diode is reverse biased properly doped p-n junction diode, which is always reverse biased and operates in the breakdown region where current is limited only by both external resistance and power dissipation of the diode.
- The conventional diode never operates in the breakdown region, but zener diode makes virtue of it and operates always in the breakdown region.

FEW POINTS:

- The zener diode is an ordinary diode except that it is properly doped so that it has sharp breakdown voltage.
- The zener diode is always reverse biased. In forward bias it will acts as an ordinary diode.
- The zener diode is not immediately burnt out just because it has entered the breakdown region. As long as the external circuit connected to the diode limits the diode current to less than burnt-out value, the diode will not burn out.
- When the reverse voltage across the zener diode is equal to or more than the breakdown voltage, the current increases very sharply and voltage across the diode remains constant even though the current through it changes. Therefore, in breakdown region, an ideal zener diode can be represented by a battery of constant voltage Vz. Under such case, the zener diode is said to be in ON state.
- When the reverse voltage across the zener diode is less than Vz but greater than zero, the diode is in OFF state.

V-I CHARACTERISTICS OF THE DIODE:

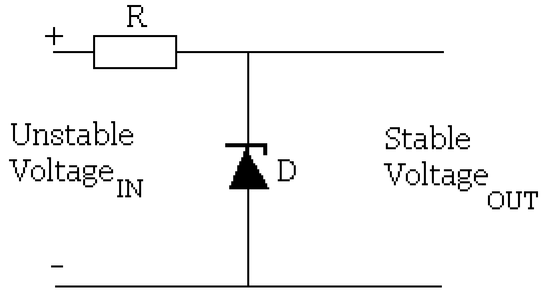
- The V-I characteristics of the zener diode are shown in the fig below.



- As shown in the graph, the current increases with the increase in reverse voltage till some point. After that, the current keeps on increasing sharply at constant voltage Vz.

ZENER DIODE AS VOLTAGE REGULATOR:

- A zener diode can be used as voltage regulator to provide a constant voltage from a source whose voltage may vary over sufficient range.
- The circuit diagram for zener diode as voltage stabilizer-



- In the fig, the zener diode of zener voltage V_z is reverse connected across the load R_L, across which the constant output s desired. The series resistance R absorbs the output voltage fluctuations so as to maintain constant voltage across the load.
- The zener will maintain constant voltage V_z across the load as long as the input voltage does not fall below V_z.
- When the circuit is properly designed, the load voltage V_o remains essentially constant (equal to V_z) even though the input voltage and the load resistance may vary over a wide range.
- The total current I passing through the series resistance R equals the sum of diode current and load current, i.e. $I= I_d+ I_L$.

  It can be seen that under all conditions, $V_o=V_z$

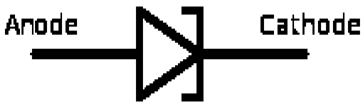
  Hence, $V_i=IR+V_z$

  CASE 1: suppose R is kept constant but supply voltage V_i is increased slightly. It will increase I. This increase in I will be absorbed by zener diode without affecting I_L. The increase in V_i will be dropped across R thereby keeping V_o constant.

  CASE 2: In this case, V_i is fixed but I_L is changed. When I_L increases, diode current I_d decreases, thereby keeping I drop and IR drop constant. If I_L decreases I_d increases, thereby keeping I drop and IR drop constant. Thus, V_o remains unaffected.

2.2.2 Tunnel Diode:

A tunnel diode is a type of semiconductor diode that is capable of very fast operation, well into the microwave frequency region, by using the quantum mechanical effect called tunneling.



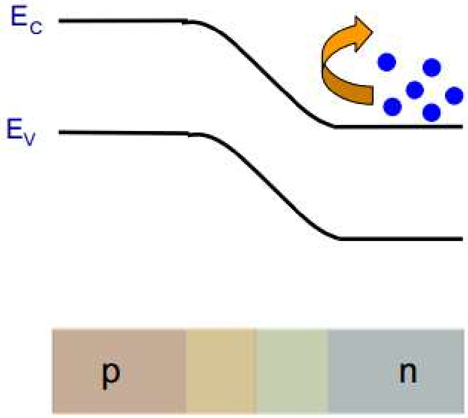
WHAT IS TUNNELING

Classically, carrier must have energy at least equal to potential-barrier height to cross the junction.

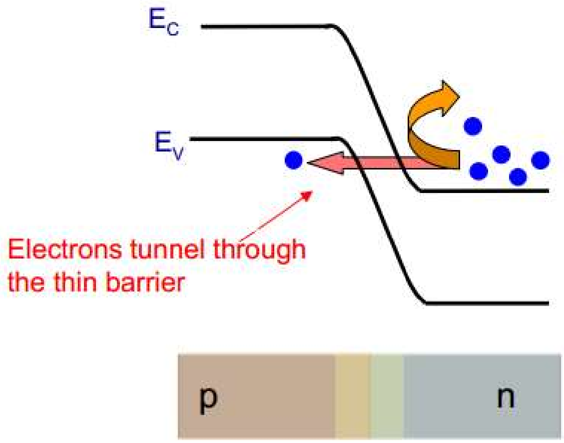
But according to **Quantum mechanics, i.e.** when the p and n region are highly doped, the depletion region becomes very thin (~10nm), there is finite probability that it can penetrate through the barrier for a thin width.

This phenomenon is called **tunneling**

Thick Depletion Layer



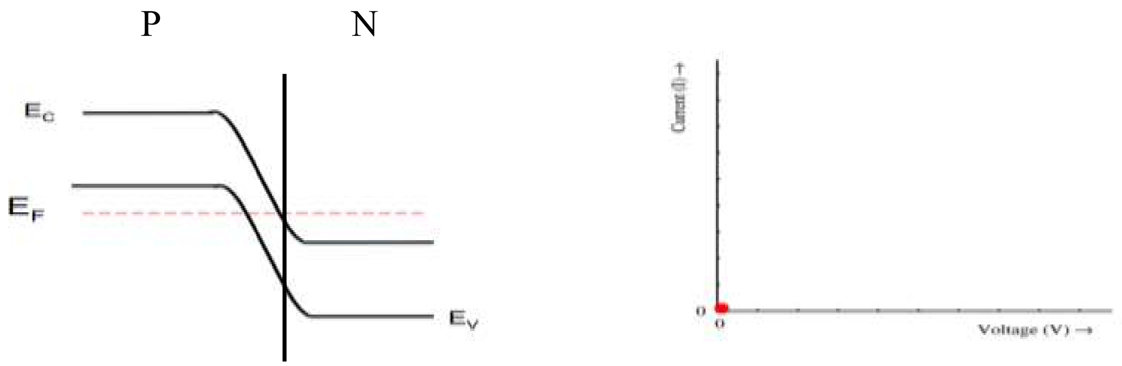
Thin Depletion Layer
(High Doping)



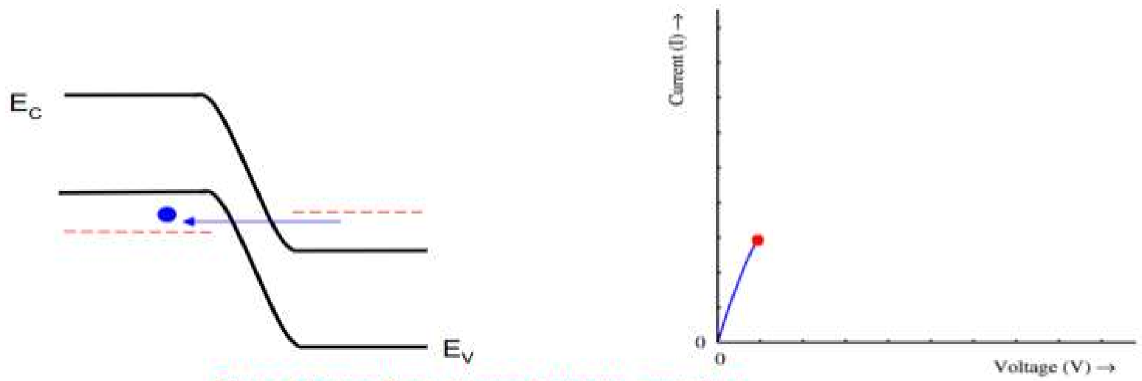
When the semiconductor is very highly doped (the doping is greater than No) the Fermi level goes above the conduction band for n-type and below valence band for p-type material.

Under Forward Bias:

1. At zero bias, there is no current – thermal equilibrium state of Tunnel Diode

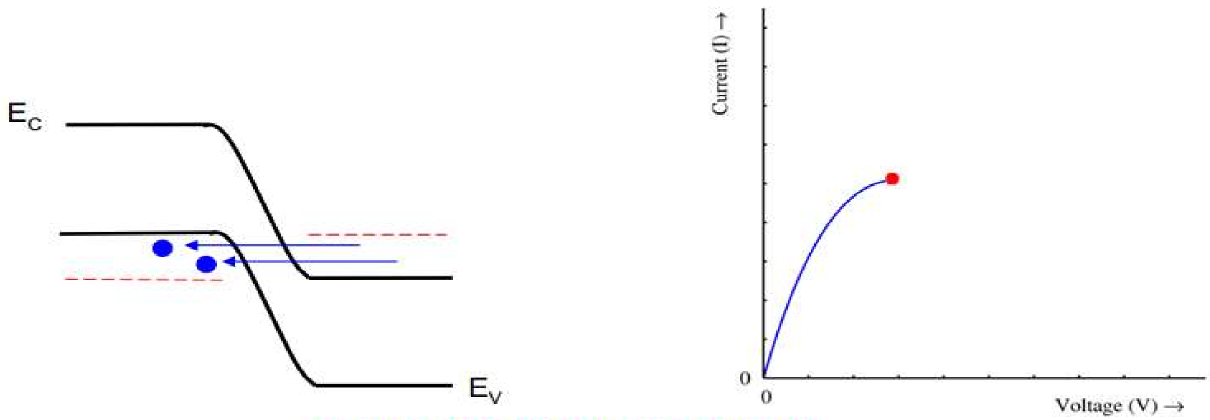


2. A small forward bias is applied. Potential barrier is still very high – no noticeable injection and forward current through the junction.
However, electrons in the conduction band of the n region will tunnel to the empty states of the valence band in p region. This will create a forward bias tunnel current.



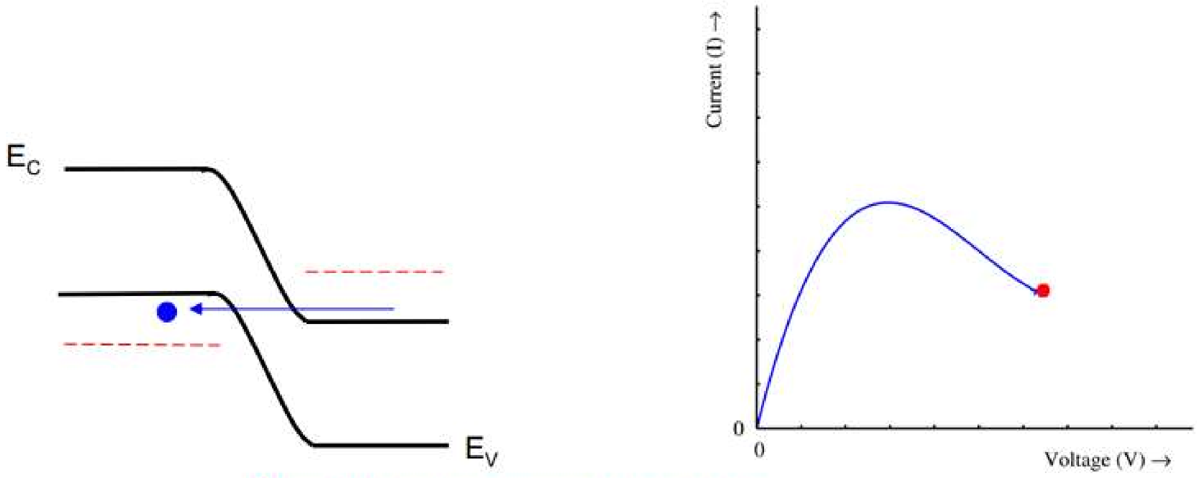
Direct tunneling current starts growing

3. With a larger voltage the energy of the majority of electrons in the n-region is equal to that of the empty states (holes) in the valence band of p-region; this will produce maximum tunneling current.



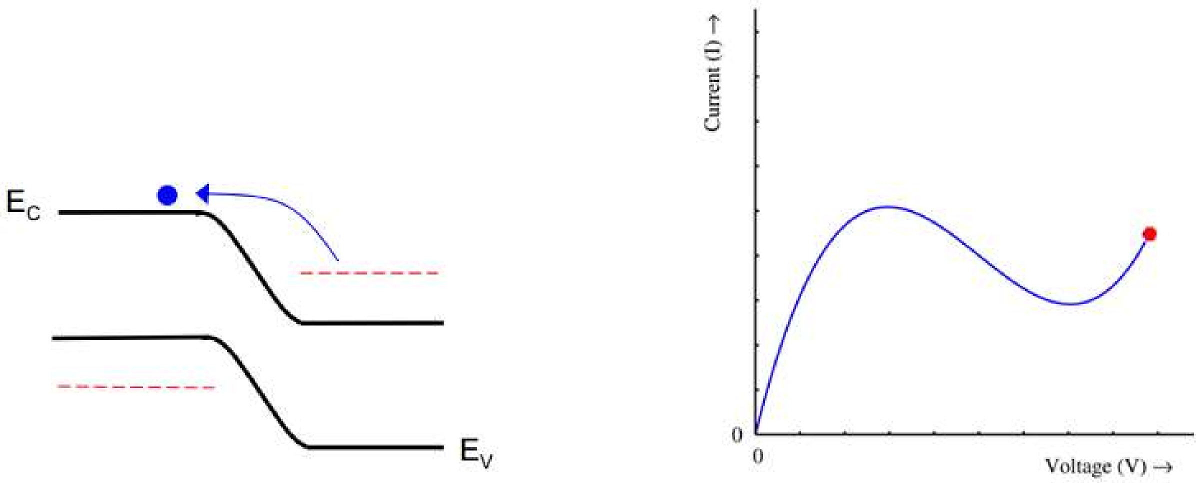
Maximum Direct tunneling current

4. As the forward bias continues to increase, the number of electrons in the n side that are directly opposite to the empty states in the valence band (in terms of their energy) decreases. Therefore decrease in the tunneling current will start.



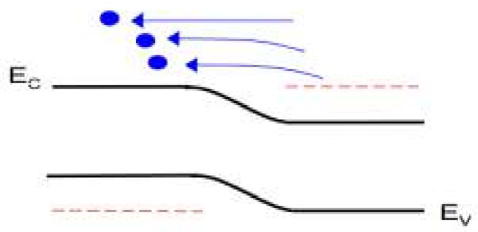
Direct tunneling current decreases

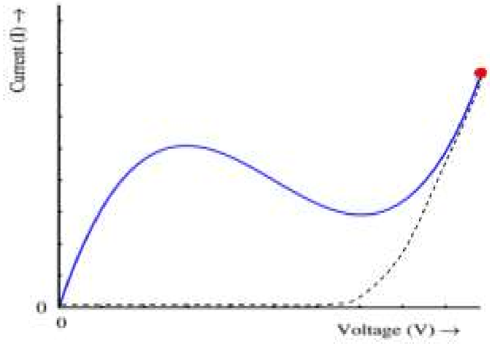
5. As more forward voltage is applied, the tunneling current drops to zero. But the regular diode forward current due to electron – hole injection increases due to lower potential barrier.



No tunneling current; diffusion current starts growing

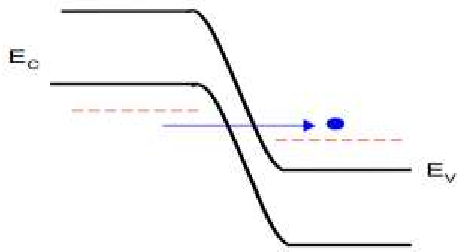
6. With further voltage increase, the tunnel diode I-V characteristic is similar to that of a regular p-n diode.

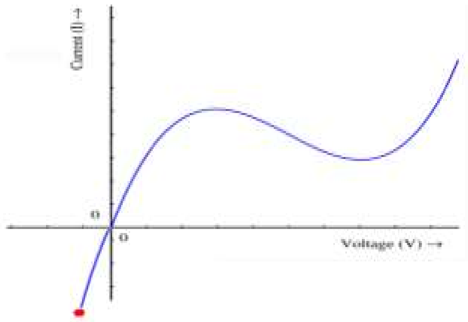




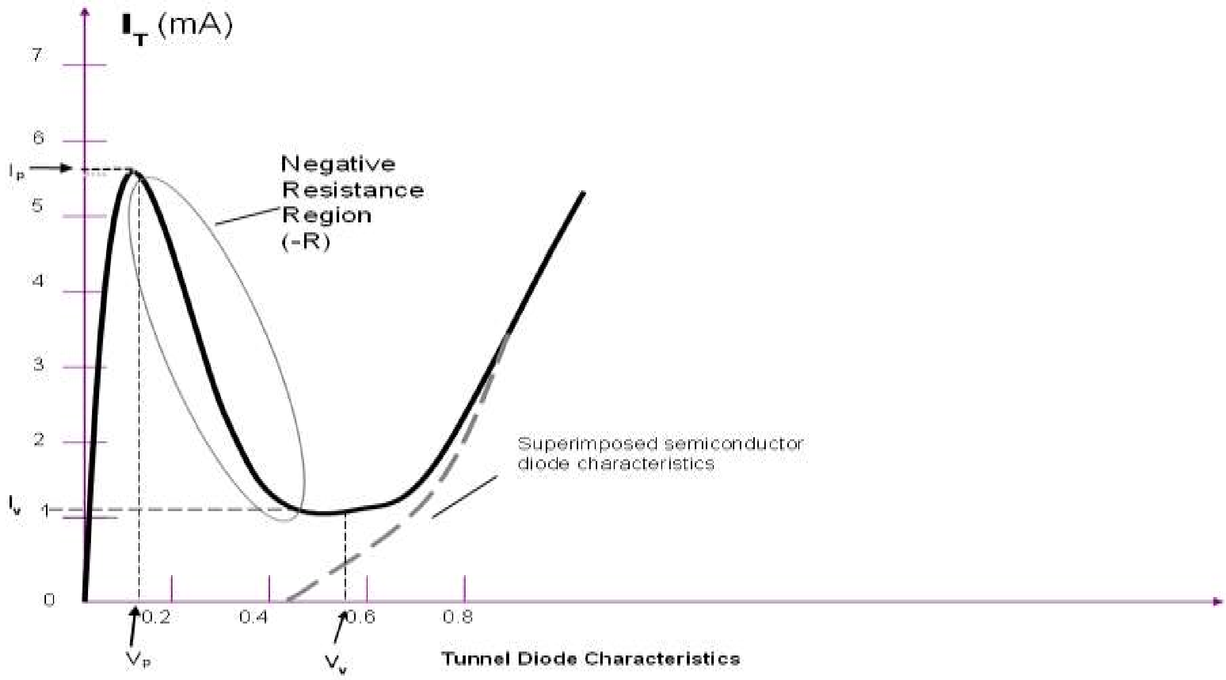
Under Reverse Bias

In this case the, electrons in the valence band of the p side tunnel directly towards the empty states present in the conduction band of the n side creating large tunneling current which increases with the application of reverse voltage. The TD reverse I-V is similar to the Zener diode with nearly zero breakdown voltage.





V-I Characteristics:

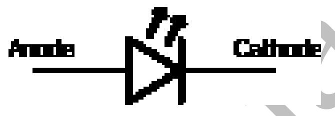


Applications:

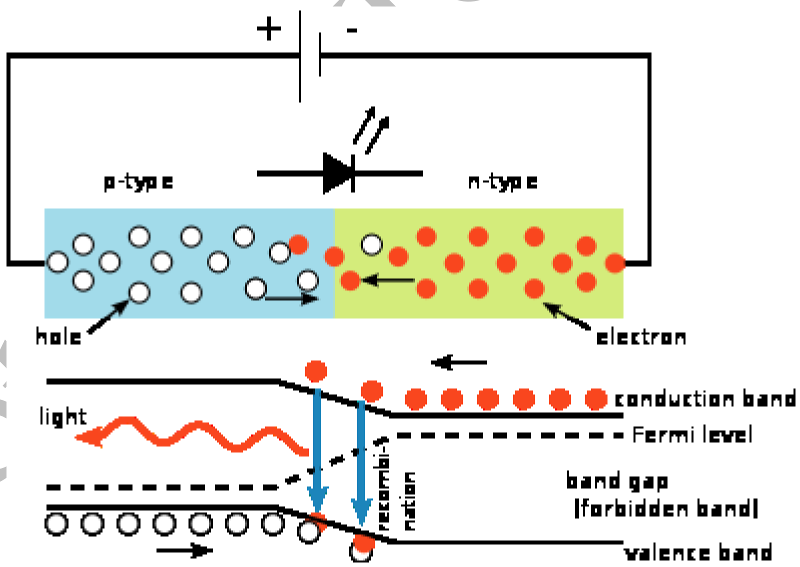
- Tunnel Diode can be used as an Oscillator at high frequency.
- Tunnel Diode can be used as an amplifier.
- Used in high speed switching circuit.
- Used as pulse generator.
- Used for storage of binary information.
- Used for the construction of shift register.
- Sensor modulator for telemetry of temperature in human beings and animals.
- Used in electron tunneling microscope.

2.2.3 LIGHT EMITTING DIODE:

SYMBOL:



OPERATION:

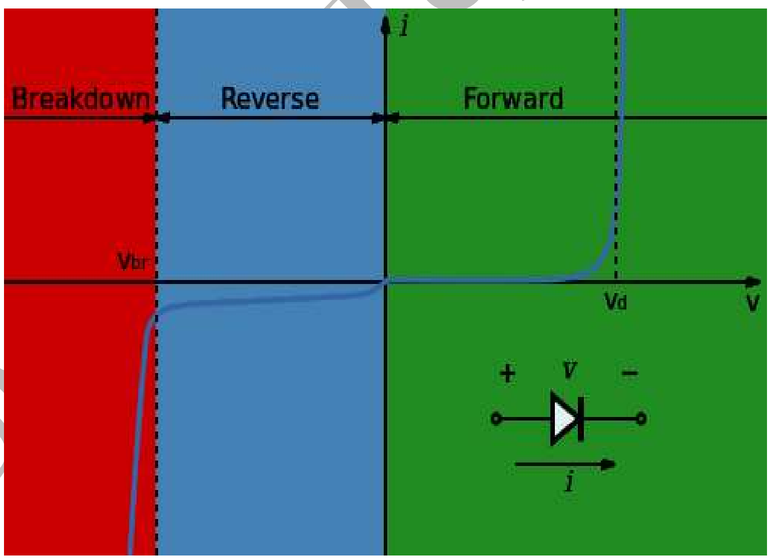


- A **light-emitting diode** (**LED**) is a semiconductor light source. LEDs are used as indicator lamps in many devices and are increasingly used for other lighting.
- The LED consists of a chip of semiconducting material doped with impurities to create a *p-n junction*. As in other diodes, current flows easily from the p-side, or anode, to the n-side, or cathode, but not in the

reverse direction. Charge-carriers—electrons and holes—flow into the junction from electrodes with different voltages. When an electron meets a hole, it falls into a lower energy level, and releases energy in the form of a photon.

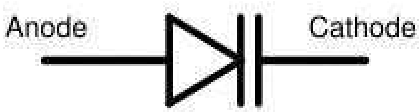
- The wavelength of the light emitted, and thus its color depends on the band gap energy of the materials forming the *p-n junction*. In silicon or germanium diodes, the electrons and holes recombine by a *non-radiative transition*, which produces no optical emission, because these are indirect band gap materials.
- The materials used for the LED have a direct band gap with energies corresponding to near-infrared, visible, or near-ultraviolet light.
- LED development began with infrared and red devices made with gallium arsenide. Advances
- LEDs are usually built on an n-type substrate, with an electrode attached to the p-type layer deposited on its surface. P-type substrates, while less common, occur as well. Many commercial LEDs, especially GaN/InGaN, also use sapphire substrate.

V-I CHARACTERISTICS:



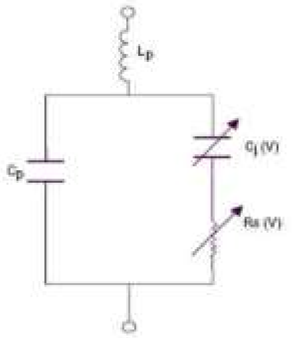
2.2.4 VARACTOR DIODE:

SYMBOL:



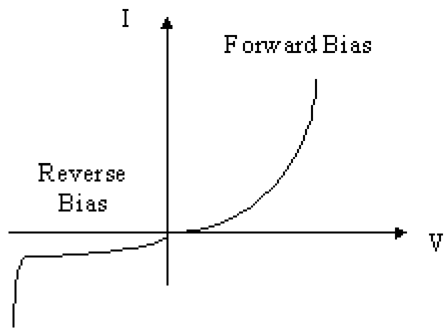
OPERATING PRINCIPLE:

- A varactor diode is a P-N junction diode that changes its capacitance and the series resistance as the bias applied to the diode is varied. The property of capacitance change is utilized to achieve a change in the frequency and/or the phase of an electrical circuit. A simple model of a packaged varactor diode is shown below:



- In the above figure, CJ (V) is the variable junction capacitance of the diode die and RS (V) is the variable series resistance of the diode die.
- CP is the fixed parasitic capacitance arising from the installation of the die in a package. Contributors to the parasitic capacitance are the package material, geometry and the bonding wires or ribbons.
- These factors also contribute to the parasitic inductance LP. The contribution to the series resistance from the packaging is very small and may be ignored. Similarly, the inductance associated with the die itself is very small and may be ignored.
- The capacitance of a varactor decreases when the reverse-voltage gets larger.
- They are usually placed in parallel with an inductor in order to form a resonant frequency circuit. When the reverse voltage changes, so does the resonant frequency, which is why varactors may be substituted for mechanically tuned capacitors.

V-I CHARACTERISTICS:



APPLICATIONS:

- Used in tuning circuits.
- Used in switching applications.

2.2.5 SCHOTTKY DIODE:

SYMBOL:

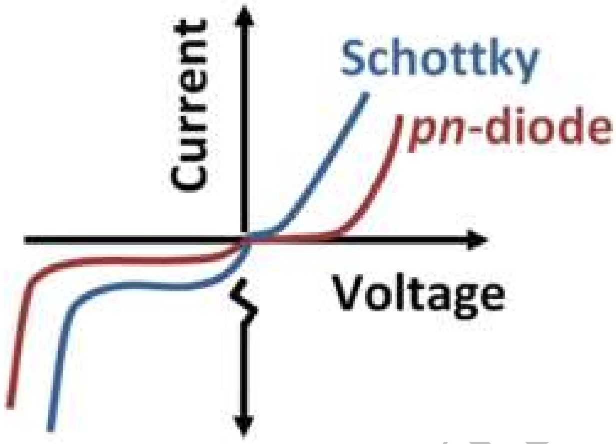
[redacted]

OPERATING PRINCIPLE:

- Schottky diodes are very efficient diodes that lose a very small amount of electricity when the electricity travels from terminal to terminal.
- Normally, diodes use a p-n junction. But the metal junction of the Schottky leads to a greater preservation of electricity.
- This controlled voltage also protects circuits from damage.
- These diodes are also easier to build and can create higher frequencies.
- There are a number of points of interest from the fabrication process. The most critical element in the manufacturing process is to ensure a clean surface for an intimate contact of the metal with the semiconductor surface, and this is achieved chemically.
- The metal is normally deposited in a vacuum either by the use of evaporation or sputtering techniques.
- However in some instances chemical deposition is gaining some favor, and actual plating has been used although it is not generally controllable to the degree required.
- When silicides are to be used instead of a pure metal contact, this is normally achieved by depositing the metal and then heat treating to give the silicide. This process has the advantage that the reaction uses the surface silicon, and the actual junction propagates below the surface, where the silicon will not have been exposed to any contaminants.

- A further advantage of the whole Schottky structure is that it can be fabricated using relatively low temperature techniques, and does not generally need the high temperature steps needed in impurity diffusion.

V-I CHARACTERISTICS:



APPLICATIONS:

Schottky diode can be used in following applications.

- RF mixer and detector diode
- Power rectifier
- Solar cell applications