4.9 Carbon Nano Tube Field Effect Transistor (CNTFETs)

Carbon nanotube field effect transistor (CNTFETs) uses semi conducting carbon nanotube as the channel. Both p-channel and n-channel devices can be made from nanotubes. The physical structure of CNTFETs is very similar to that of MOSFETs and their I-V characteristics and transfer characteristics are also very promising and they suggest that CNTFETs have the potential to be a successful replacement of MOSFETs in nanoscale electronics.

The carbon nanotube is one-dimensional, which greatly reduces the scattering probability. As a result, the device may operate in ballistic regime.

The nanotube conducts essentially on its surface where all the chemical bonds are saturated and stable. In other words, there are no dangling bonds which form interface states. Therefore, there is no need for careful passivation of the interface between the nanotube channel and the gate dielectric, i.e. there is no equivalent of the silicon/silicon dioxide interface.

The Schottkey barrier at the metal-nanotube contact is the active switching element in an intrinsic nanotube device. With these unique features CNTFET becomes a device of special interest.

Type of CNTFET

The field effect transistors made of carbon nanotubes so far can be classified into:

a) Back gate CNTFET

b) Top gate CNTFET

c) Wrap-around gate CNTFETs

d) Suspended CNTFETs

a) Back-gated CNTFET's

The earliest techniques for fabricating carbon nanotube (CNT) field-effect transistors involved pre-patterning parallel strips of metal across a silicon dioxide substrate, and then depositing the CNTs on top in a random pattern.

The semiconducting CNTs that happened to fall across two metal strips meet all the requirements necessary for a rudimentary field-effect transistor. One metal strip is the "source" contact while the other is the "drain" contact. The silicon oxide substrate can be used as the gate oxide and adding a metal contact on the back makes the semiconducting CNT gateable.

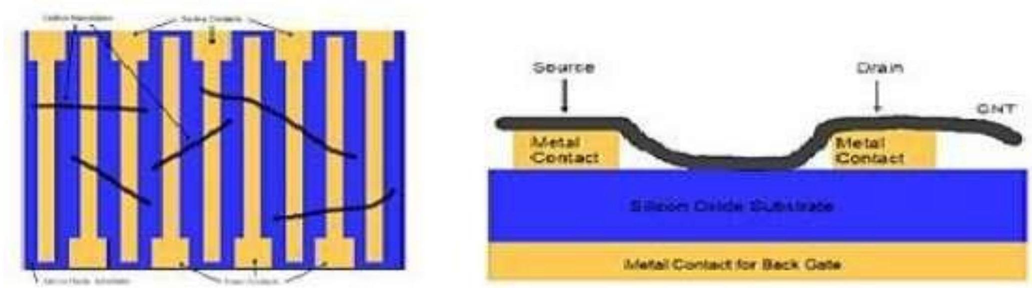

Fig 4.9.1 Top and side view of carbon nanotubes deposited on a silicon oxide substrate pre-patterned with source and drain contacts.

(source : https://core.ac.uk/download/pdf/61802786.pdf)

The types of back gate CNTFETs discussed so far have high contact resistances (≥1 MΩ), which led to a low trans conductance gm (=dI/dVG) of about 10 - 9A/V. This large contact resistance results from the weak van der Waals coupling of the devices to the noble metal electrodes in the 'side-bonding' configuration used. Here the SWNT is dispersed on top of the SiO2 film, and then source and drain electrodes made of transition metals compatible with silicon technology, such as Ti or Co, are fabricated on SWNT. Subsequent anneals at 400º C (Co) and, or at 820º C (Ti) in an inert ambient, form low resistance Co contacts or TiC contacts at the source and drain electrodes.

b) Top-gated CNTFET's

In the first step, single-walled carbon nanotubes are solution deposited onto a silicon oxide substrate. Individual nanotubes are then located via atomic force microscope or scanning electron microscope. After an individual tube is isolated, source and drain contacts are defined and patterned using high resolution electron beam lithography. A high temperature anneal step reduces the contact resistance by improving adhesion between the contacts and CNT. A thin top-gate dielectric is then deposited on top of the nanotube, either via evaporation or atomic layer deposition. Finally, the top gate contact is deposited on the gate dielectric, completing the process. Arrays of top-gated CNTFETs can be fabricated on the same wafer, since the gate contacts are electrically isolated from each other, unlike in the back-gated case. Also, due to the thinness of the gate dielectric, a larger electric field can be generated with respect to the nanotube using a lower gate voltage. These advantages mean top-gated devices are generally preferred over back-gated CNTFETs, despite their more complex fabrication process.

c) Wrap-around gate CNTFET's

Wrap-around gate CNTFETs, also known as gate-all-around CNTFETs In this device, instead of gating just the part of the CNT that is closer to the metal gate contact, the entire circumference of the nanotube is gated. This should ideally improve the electrical performance of the CNTFET, reducing leakage current and improving the device on/off ratio.

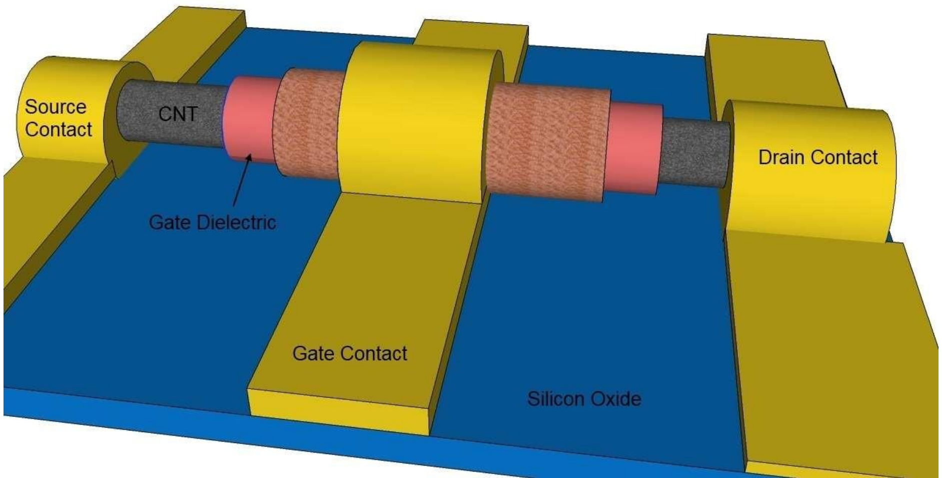

Fig 4.9.2 Wrap-around gate CNTFET

(source : https://core.ac.uk/download/pdf/61802786.pdf)

Device fabrication begins by first wrapping CNTs in a gate dielectric and gate contact via atomic layer deposition. These wrapped nanotubes are then solution-deposited on an insulating substrate, where the wrappings are partially etched off, exposing the ends of the nanotube. The source, drain, and gate contacts are then deposited onto the CNT ends and the metallic outer gate wrapping.

d) Suspended CNTFET's

CNTFET device geometry involves suspending the nanotube over a trench to reduce contact with the substrate and gate oxide. This technique has the advantage of reduced scattering at the CNT-substrate interface, improving device. There are many methods used to fabricate suspended CNTFETs, ranging from growing them over trenches using catalyst particles, transferring them onto a substrate and then under-etching the dielectric beneath , and transfer-printing onto a trenched substrate.

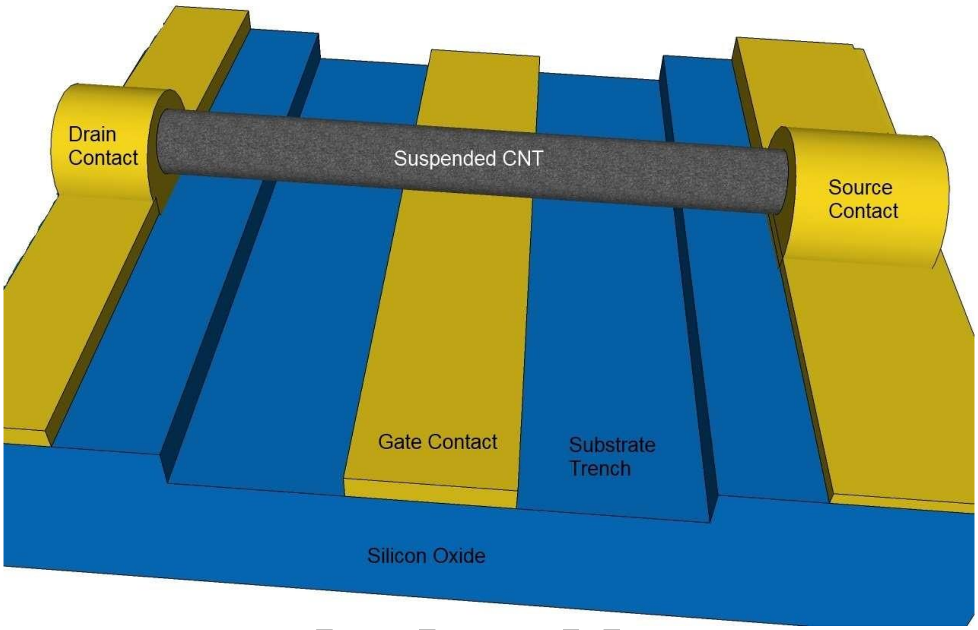

Fig 4.9.3 Suspended CNTFET device.

(source : https://core.ac.uk/download/pdf/61802786.pdf)

The main problem suffered by suspended CNTFETs is that they have very limited material options for use as a gate dielectric (generally air or vacuum), and applying a gate bias has the effect of pulling the nanotube closer to the gate, which places an upper limit on how much the nanotube can be gated. This technique will also only work for shorter nanotubes, as longer tubes will flex in the middle and droop towards the gate, possibly making touching the metal contact and shorting the device. In general, suspended CNTFETs are not practical for commercial applications, but they can be useful for studying the intrinsic properties of clean nanotubes.

Characteristics of CNTFET's

The drain I-V characteristics in 2D are shown in fig. The saturation current at VGS = 0.5 V is around 6 μA, which is not inconsistent with values emerging from recent experimental work.

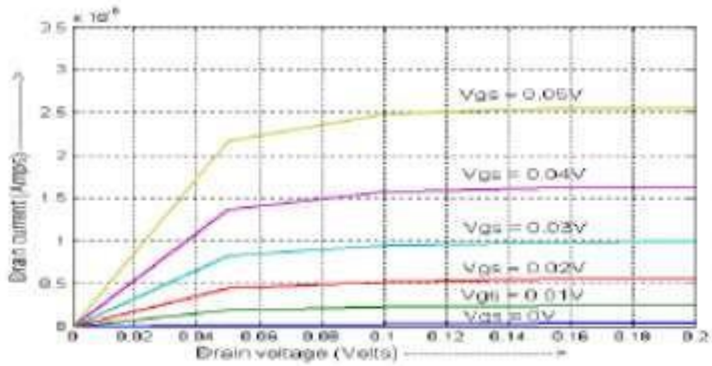

Fig 4.9.4 CNTFET sub threshold Drain characteristics.

(source : https://core.ac.uk/download/pdf/61802786.pdf)

Drain I-V characteristics exhibited dependence of saturation drain current on temperature. When CNTFET is cooled, drain saturation currents were lightly decreased.

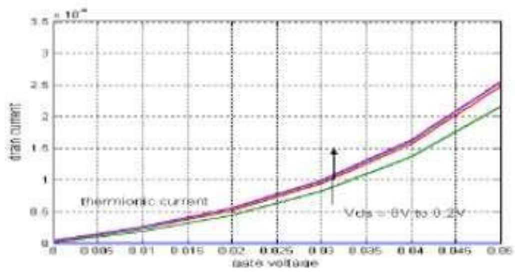

Fig 4.9.5 CNTFET sub threshold Transfer characteristics

(source : https://core.ac.uk/download/pdf/61802786.pdf)

4.7 Dual Gate MOSFET

The circuit symbol from the dual gate MOSFET expands the basic single gate MOSFET and adds a second gate into the input.

Enhancement and depletion mode as well as N channel and P channel devices can be described, although P channel devices tend not to be used much for RF applications because hole mobility is much less than electron mobility.

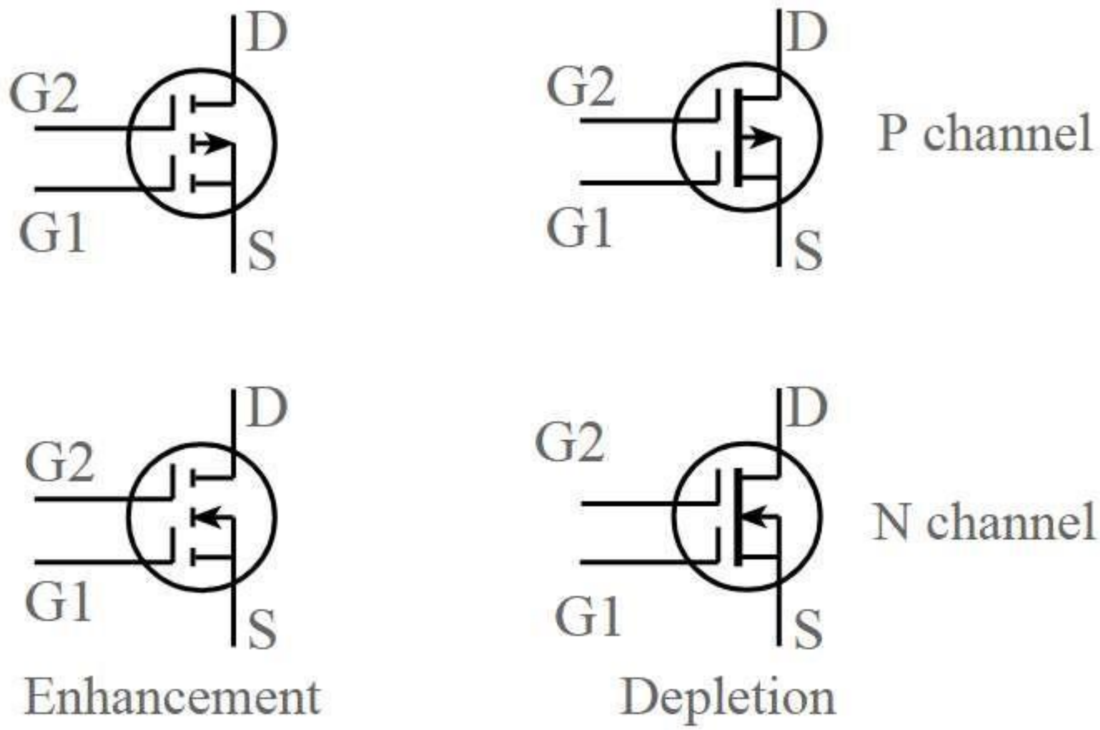

Fig:4.7.1 Symbol of Dual Gate DE, E - MOSFET

The dual gate MOSFET can be used in a number of applications including RF mixers /multipliers, RF amplifiers, amplifiers with gain control and the like.

Dual gate MOSFET structure

The dual gate MOSFET has what may be referred to as a tetrode construction where the two grids control the current through the channel.

The different gates control different sections of the channel which are in series with each other.

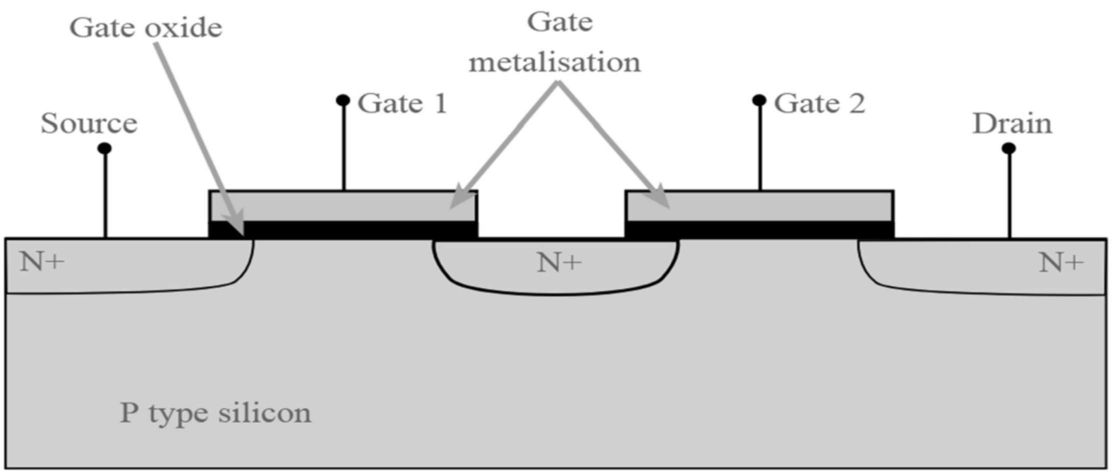

Fig:4.7.2 Dual gate MOSFET structure

Dual gate MOSFET applications

RF amplifier: The dual gate MOSFET enables a cascode two stage amplifier to be constructed using a single device.The cascade amplifier helps overcome the Miller effect where capacitance is present between the input and output stages. Although the Miller effect can relate to any impedance between the input and output, normally the most critical is capacitance. This capacitance can lead to an increase in the level of input capacitance experienced and in high frequency (e.g. VHF & UHF) amplifiers it can also lead to instability.

RF mixer / multiplier: The dual gate MOSFET is able to provide a basis for an RF mixer. The dual gate MOSFET operation enables both the local oscillator and RF signal inputs to be accommodated.The RF signal is normally applied to gate 1 and the local oscillator to gate 2.

The operation of this dual gate MOSFET circuit is relatively easy to understand. The RF signal appears at gate 1 and controls the channel current in the normal way. However the much higher level local oscillator signal is applied to gate 2 and superimposes its effect on the channel current.

Level / gain control: The output from the dual gate MOSFET is proportional to the input at both of the gates. With a constant level at gate 1, for example, varying the voltage on gate 2 will alter the output level. Accordingly the dual gate MOSFET can be used to provide linear gain control.

4.5 LASER DIODE

Laser diodes play an important role in our everyday lives. They are very cheap and small. Laser diodes are the smallest of all the known lasers. Their size is a fraction of a millimeter.

Laser diodes are also known as semiconductor lasers, junction lasers, junction diode lasers or injection lasers. Before going into laser diodes, let us first look at diode itself.

The energy level of free electrons in the conduction band is high as compared to the holes in the valence band. Therefore, the free electrons will release their extra energy(non-radiative energy) while recombining with the holes.

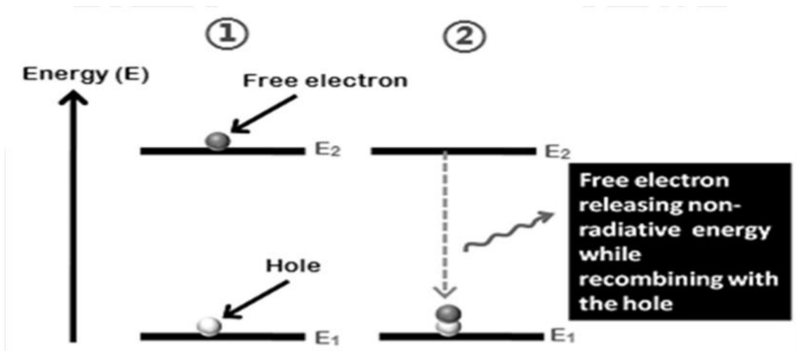

Fig:4.5.1 Electron Transition in Ordinary Diode

In the light emitting diodes (LEDs) or laser diodes, the recombination takes place in a similar manner. However, the free electrons in LED's or laser diodes release energy in the form of light while recombining with the holes.

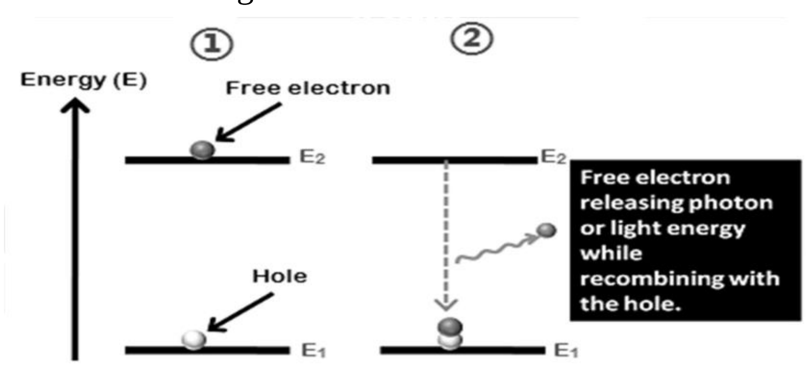

Fig:4.5.2 Electron Transition in Laser Diode

Laser Diode

A laser diode is an optoelectronic device, which converts electrical energy into light energy to produce high-intensity coherent light. In a laser diode, the p-n junction of the semiconductor diode acts as the laser medium or active medium.

The working of the laser diode is almost similar to the light emitting diode (LED). The main difference between the LED and laser diode is that the LED emits incoherent light whereas the laser diode emits coherent light.

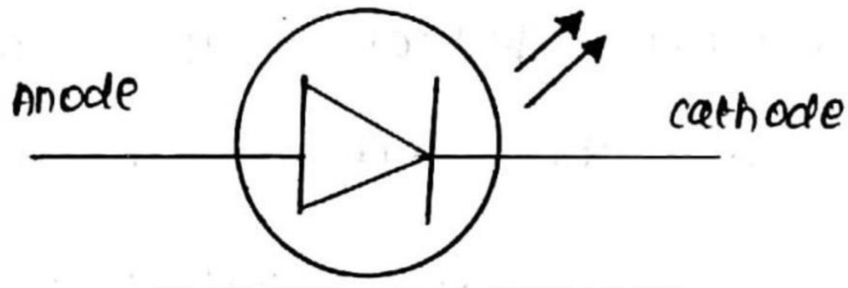

Fig:4.5.3 Symbol of Laser Diode

Laser diode construction

The laser diode is made of two doped gallium arsenide layers. One doped gallium arsenide layer will produce an n-type semiconductor whereas another doped gallium arsenide layer will produce a p-type semiconductor. In laser diodes, selenium, aluminum, and silicon are used as doping agents.

P-N junction

When a p-type layer is joined with the n-type layer, a p-n junction is formed. The point at which the p-type and n-type layers are joined is called p-n junction. The p-n junction separates the p-type and n-type semiconductors.

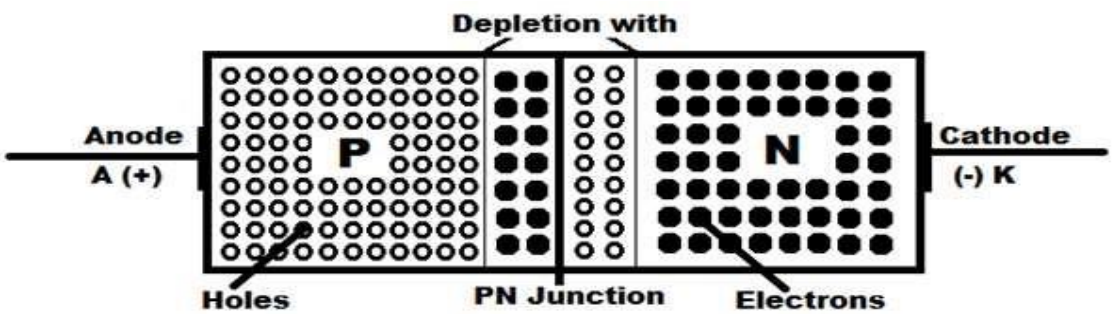

Fig:4.5.4 Construction of Normal PN Diode

For the construction of laser diodes, gallium arsenide is chosen over silicon. In silicon diodes, the energy is released during recombination. However, this release of energy is not in the form of light.

In gallium arsenide diodes, the release of energy is in the form of light or photons. Therefore, gallium arsenide is used for the construction of laser diodes.

Main steps required for producing a coherent beam of light in laser diodes

The main steps required for producing a coherent beam of light in lasers diodes are: light absorption, spontaneous emission, and stimulated emission.

Absorption of energy

Absorption of energy is the process of absorbing energy from the external energy sources. In laser diodes, electrical energy or DC voltage is used as the external energy source. When the DC voltage or electrical energy supplies enough energy to the valence electrons or valence band electrons, they break bonding with the parent atom and jumps into the higher energy level (conduction band). The electrons in the conduction band are known as free electrons.

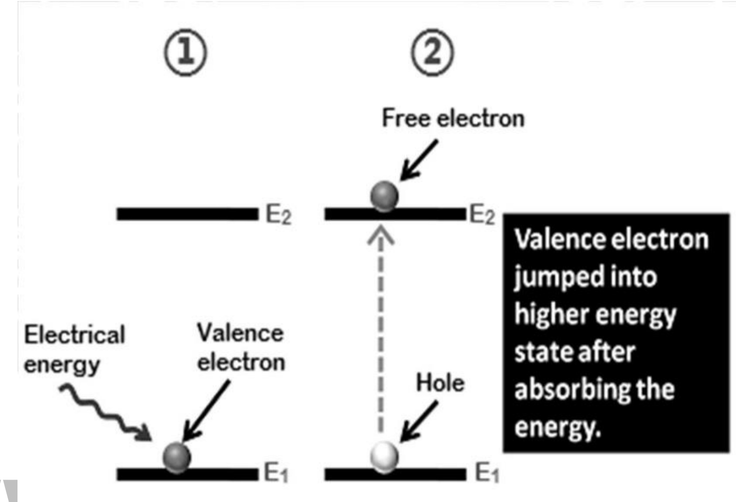

Fig:4.5.5 Absorption

When the valence electron leaves the valence shell, an empty space is created at the point from which electron left. This empty space in the valence shell is called a hole.

Thus, both free electrons and holes are generated as a pair because of the absorption of energy from the external DC source.

Spontaneous emission

Spontaneous emission is the process of emitting light or photons naturally while electrons falling to the lower energy state.

In laser diodes, the valence band electrons or valence electrons are in the lower energy state. Therefore, the holes generated after the valence electrons left are also in the lower energy state.

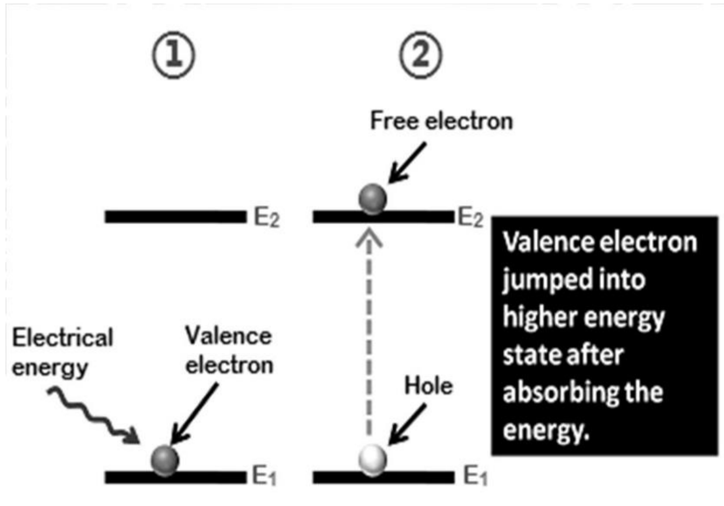

Fig:4.5.6 Spontaneous Emission

On the other hand, the conduction band electrons or free electrons are in the higher energy state. In simple words, free electrons have more energy than holes.

The free electrons in the conduction band need to lose their extra energy in order to recombine with the holes in the valence band.

The free electrons in the conduction band will not stay for long period. After a short period, the free electrons recombine with the lower energy holes by releasing energy in the form of photons.

Stimulated Emission

Stimulated emission is the process by which excited electrons or free electrons are stimulated to fall into the lower energy state by releasing energy in the form of light. The stimulated emission is an artificial process.

In stimulated emission, the excited electrons or free electrons need not wait for the completion of their lifetime. Before the completion of their lifetime, the incident or external photons will force the free electrons to recombine with the holes. In stimulated emission, each incident photon will generate two photons.

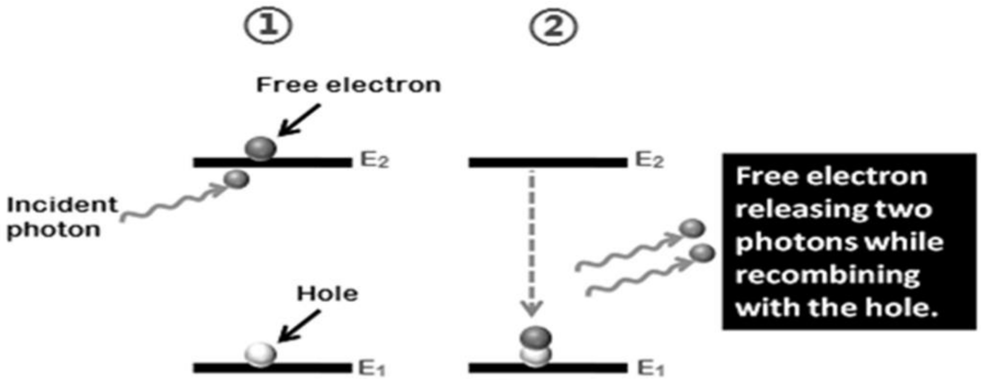

Fig:4.5.7 Stimulated Emission

All the photons generated due to the stimulated emission will travel in the same direction. As a result, a narrow beam of high-intensity laser light is produced.

Working principles of laser diode

When DC voltage is applied across the laser diode, the free electrons move across the junction region from the n-type material to the p-type material. In this process, some electrons will directly interact with the valence electrons and excites them to the higher energy level whereas some other electrons will recombine with the holes in the p-type semiconductor and releases energy in the form of light. This process of emission is called spontaneous emission.

The photons generated due to spontaneous emission will travel through the junction region and stimulate the excited electrons (free electrons). As a result, more photons are released. This process of light or photons emission is called stimulated emission. The light generated due to stimulated emission will moves parallel to the junction.

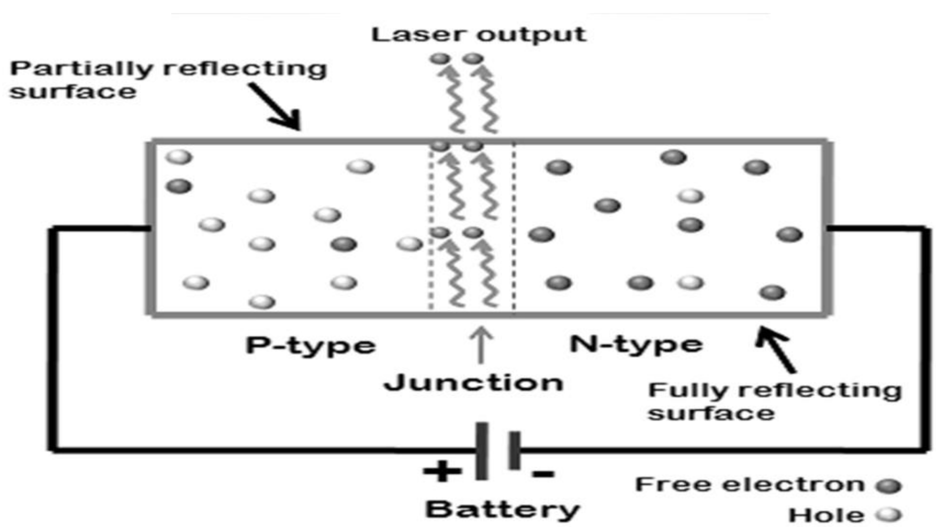

Fig:4.5.8 Working of Laser Diode

The two ends of the laser diode structure are optically reflective. One end is fully reflective whereas another end is partially reflective. The fully reflective end will reflect the light completely whereas the partially reflective end will reflect most part of the light but allows a small amount of light.

The light generated in the p-n junction will bounce back and forth (hundreds of times) between the two reflective surfaces. As a result, an enormous optical gain is achieved.

The light generated due to the stimulated emission is escaped through the partially reflective end of the laser diode to produce a narrow beam laser light.

All the photons generated due to the stimulated emission will travel in the same direction. Therefore, this light will travel to long distances without spreading in the space.

Advantages of laser diodes

1. Simple construction
2. Lightweight
3. Very cheap
4. Small size
5. Highly reliable compared to other types of lasers.
6. Longer operating life
7. High efficiency
8. Mirrors are not required in the semiconductor lasers.
9. Low power consumption

Disadvantages of laser diodes

1. Not suitable for the applications where high powers are required.
2. Semiconductor lasers are highly dependent on temperature.

Applications of laser diodes

1. Laser diodes are used in laser pointers.
2. Laser diodes are used in fiber optic communications.
3. Laser diodes are used in barcode readers.
4. Laser diodes are used in laser printing.
5. Laser diodes are used in laser scanning.
6. Laser diodes are used in range finders.
7. Laser diodes are used in laser absorption spectrometry.

4.6 LIGHT DEPENDENT RESISTOR

A Light Dependent Resistor (LDR) or a photo resistor is a device whose resistivity is a function of the incident electromagnetic radiation. Hence, they are light sensitive devices. They are also called as photo conductors, photo conductive cells or simply photocells. They are made up of semiconductor materials having high resistance. There are many different symbols used to indicate a LDR, one of the most commonly used symbol is shown in the figure below. The arrow indicates light falling on it.

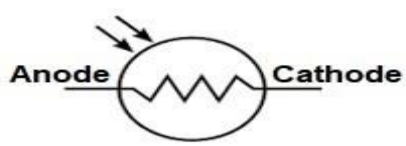

Fig:4.6.1 Symbol of LDR

Working Principle of LDR

A light dependent resistor works on the principle of photo conductivity. Photo conductivity is an optical phenomenon in which the materials conductivity is increased when light is absorbed by the material.

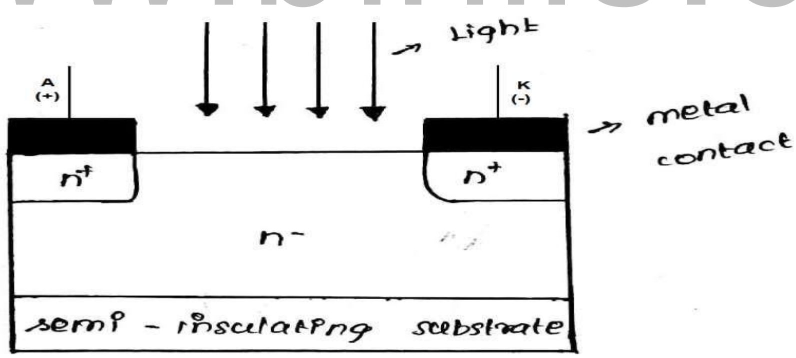

Fig:4.6.2 Working Principle of LDR

When light falls i.e. when the photons fall on the device, the electrons in the valence band of the semiconductor material are excited to the conduction band. These photons in the incident light should have energy greater than the band gap of the semiconductor material to make the electrons jump from the valence band to the conduction band. Hence when light having enough energy strikes on the device, more and more electrons are excited to the conduction band which results in large number of charge carriers. The result of this process is more and more current starts flowing through the device when the circuit is closed and hence it is said that the resistance of the device has been decreased. This is the most common working principle of LDR.

Characteristics of LDR

LDR's are light dependent devices whose resistance is decreased when light falls on them and that is increased in the dark. When a light dependent resistor is kept in dark, its resistance is very high. This resistance is called as dark resistance. It can be as high as 1012 Ω and if the device is allowed to absorb light its resistance will be decreased drastically. If a constant voltage is applied to it and intensity of light is increased the current starts increasing. Figure below shows resistance vs. illumination curve for a particular LDR.

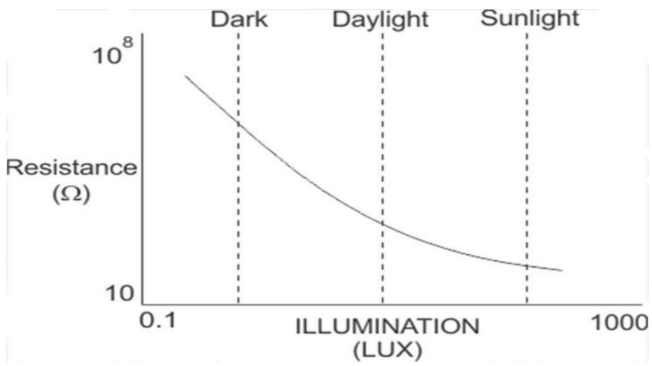

Fig:4.6.3 Characteristics of LDR

Photocells or LDR's are non linear devices. There sensitivity varies with the wavelength of light incident on them. Some photocells might not at all response to a certain range of wavelengths. Based on the material used different cells have different spectral response curves.

When light is incident on a photocell it usually takes about 8 to 12 ms for the change in resistance to take place, while it takes one or more seconds for the resistance to rise back again to its initial value after removal of light. This phenomenon is called as resistance recovery rate. This property is used in audio compressors.

Also, LDR's are less sensitive than photo diodes and phototransistor. (A photo diode and a photocell (LDR) are not the same, a photo-diode is a pn junction semiconductor device that converts light to electricity, whereas a photocell is a passive device, there is no pn junction in this nor it "converts" light to electricity).

Types of Light Dependent Resistors

Based on the materials used they are classified as:

1. Intrinsic photo resistors (Un doped semiconductor): These are made of pure semiconductor materials such as silicon or germanium. Electrons get excited from valance band to conduction band when photons of enough energy fall on it and number charge carriers is increased.

2. Extrinsic photo resistors: These are semiconductor materials doped with impurities which are called as dopants. Theses dopants create new energy bands above the valence band which are filled with electrons. Hence this reduces the band gap and less energy is required in exciting them. Extrinsic photo resistors are generally used for long wavelengths.

Construction of a Photocell

The structure of a light dependent resistor consists of a light sensitive material which is deposited on an insulating substrate such as ceramic. The material is deposited in zigzag pattern in order to obtain the desired resistance and power rating. This zigzag area separates the metal deposited areas into two regions. Then the ohmic contacts are made on the either sides of the area. The resistances of these contacts should be as less as possible to make sure that the resistance mainly changes due to the effect of light only. Materials normally used are cadmium sulphide, cadmium selenide, indium antimonide and cadmium sulphonide.

Applications of LDR

1. Light sensors,
2. Camera light meter,
3. Street lamps, Alarm clock,
4. Burglar alarm circuits,
5. Light intensity meters,
6. Counting the packages moving on a conveyor belt.

4.8 PINFET

PINFET stands for P type- intrinsic- N type Field Effect transistor. It is a integration of PIN Photodiode and FET in a single IC. PIN diode converts light energy into an electrical signal and it is designed to operate in a reverse biased condition. Field Effect Transistor is a voltage controlled device. The voltage which is given in the gate terminal as input controls the current passing through it.

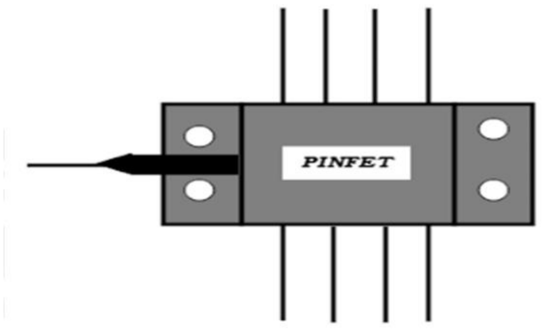

Fig:4.8.1 PINFET

(source: https://www.learnelectronicswithme.com/2020/09/pinfet-construction-working-and.html)

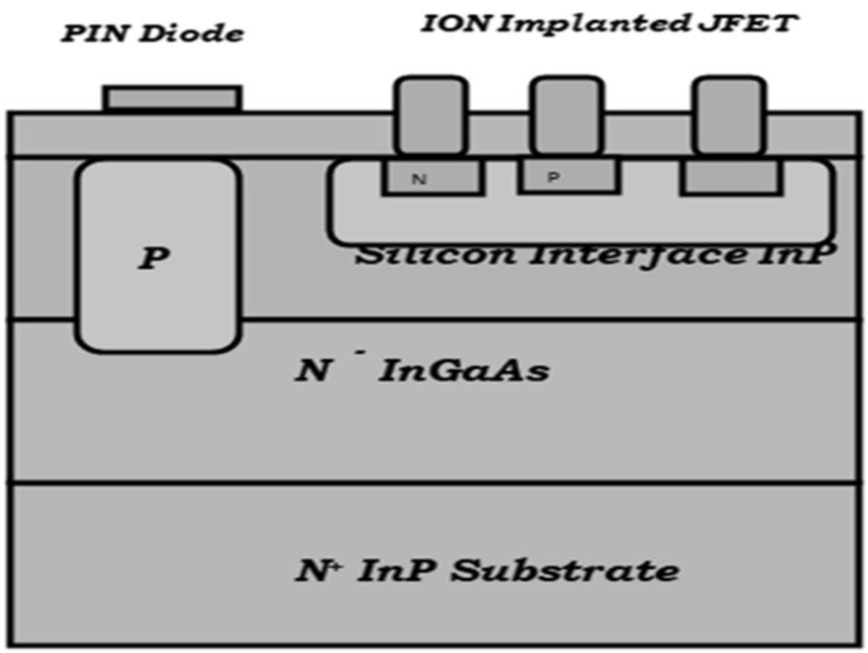

Fig:4.8.2 Construction of PINFET

(source: https://www.learnelectronicswithme.com/2020/09/pinfet-construction-working-and.html)

Construction of PINFET

PINFET is the combination of InGaAs PIN Photodiode and InGaAs FET. The construction process includes the following

1) Metal Organic chemical vapour deposition(MOCVD):

By using this method PINFET is fabricated over semi insulating InGaAs substrate.

2) Chloride Vapour Phase epitaxy(VPE):

By this process InGaAs layer of low concentration of electrons is grown above the substrate.

3) Atmospheric pressure metal organic chemical vapour deposition technique:

By this method silicon interface layer is grown over the InGaAs layer.

4) Ion Implantation: By this process which is done in series the FET is formed.

5) Deposition and diffusion: By this process PIN diode is formed.

Working of PINFET

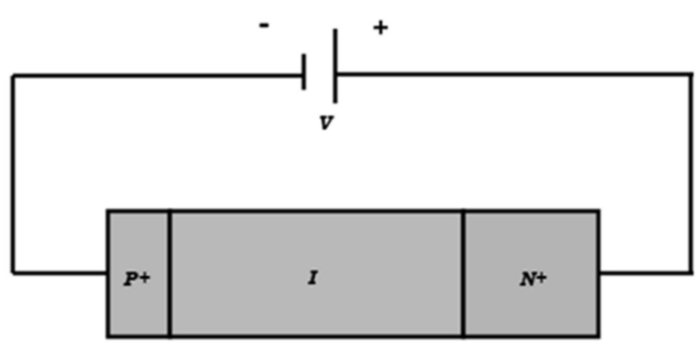

Fig:4.8.3 Working of PINFET

(source: https://www.learnelectronicswithme.com/2020/09/pinfet-construction-working-and.html)

It consists of three regions P region, I region and N region. P region and N region are heavily doped regions and they are used as Ohmic contacts. A wider intrinsic silicon layer is sandwiched between two heavily doped layers and it absorbs the light photons which forms the electron hole pairs. The intrinsic layer is highly resistive and it increases the width of the depletion region. In normal diode only voltage is used to form the current but in PINFET both voltage and light is used to form the current.

When reversed biased the majority carriers in highly doped P type and N type does not conduct current so the charge carriers move away from the junction and the intrinsic layer is undoped which does not have majority charge carriers. So the width of the depletion region increases. When the light is incident on the PINFET the wider intrinsic layer absorbs the light energy and forms large number of electron hole pairs.

The free electrons which are generated in the intrinsic region move towards the N region and the free holes move towards the P region and these charge carriers are attracted towards the positive and negative terminals. Thus current is formed due to the movement of these charge carriers.

The intrinsic layer acts as a dielectric layer and highly doped P and N layer acts as electrodes in the capacitor. Since the distance between the electrodes are very large, the capacitance is very low and thus the noise is very low.

Advantages of PINFET

- Wide bandwidth
- Low noise
- High sensitivity to light
- Low sensitivity to temperature
- Low cost
- Small size
- Long lifetime

Disadvantages of PINFET

- It always operates in reverse biased condition
- It is a light sensitive device
- Should not exceed the working temperature limit specified by the manufacturer.

Applications

- PINFET is mainly used as a photo receiver in optical communication because of its low noise and high speed.
- Used in optical Sensor systems.
- Used as repeaters in telecommunication

4.4 SCHOTTKY DIODE

Schottky diode can switch on and off much faster than the p-n junction diode. Also, the schottky diode produces less unwanted noise than p-n junction diode. These two characteristics of the schottky diode make it very useful in high-speed switching power circuits.

When sufficient voltage is applied to the schottky diode, current starts flowing in the forward direction. Because of this current flow, a small voltage loss occurs across the terminals of the schottky diode. This voltage loss is known as voltage drop.

A silicon diode has a voltage drop of 0.6 to 0.7 volts, while a schottky diode has a voltage drop of 0.2 to 0.3 volts. Voltage loss or voltage drop is the amount of voltage wasted to turn on a diode.

In silicon diode, 0.6 to 0.7 volts is wasted to turn on the diode, whereas in schottky diode, 0.2 to 0.3 volts is wasted to turn on the diode. Therefore, the schottky diode consumes less voltage to turn on.

The voltage needed to turn on the schottky diode is same as that of a germanium diode. But germanium diodes are rarely used because the switching speed of germanium diodes is very low as compared to the schottky diodes.

Symbol of Schottky Diode

The symbol of schottky diode is shown in the below figure. In schottky diode, the metal acts as the anode and n-type semiconductor acts as the cathode.

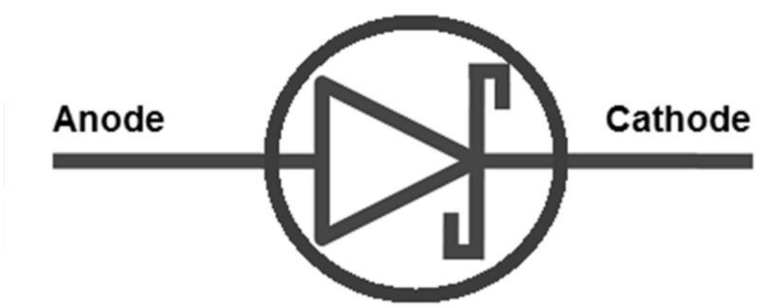

Fig:4.4.1 Symbol of Schottky Diode

Metal-semiconductor (M-S) junction

Metal-semiconductor (M-S) junction is a type of junction formed between a metal and an n-type semiconductor when the metal is joined with the n-type semiconductor. Metal-semiconductor junction is also sometimes referred to as M-S junction.

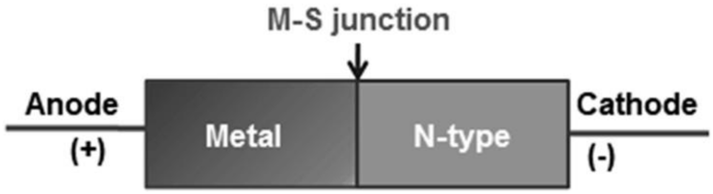

Fig:4.4.2 Metal-Semiconductor (M-S) Junction

The metal-semiconductor junction can be either non-rectifying or rectifying. The non-rectifying metal-semiconductor junction is called ohmic contact. The rectifying metal-semiconductor junction is called non-ohmic contact.

schottky barrier

Schottky barrier is a depletion layer formed at the junction of a metal and n-type semiconductor. In simple words, schottky barrier is the potential energy barrier formed at the metal-semiconductor junction. The electrons have to overcome this potential energy barrier to flow across the diode.

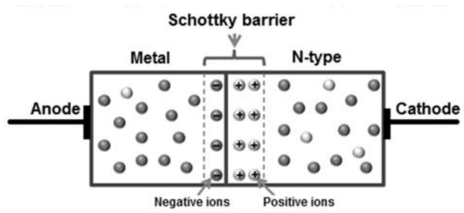

Fig:4.4.3 Construction of Schottky Diode

The rectifying metal-semiconductor junction forms a rectifying schottky barrier. This rectifying schottky barrier is used for making a device known as schottky diode. The non-rectifying metal-semiconductor junction forms a non-rectifying schottky barrier.

One of the most important characteristics of a schottky barrier is the schottky barrier height. The value of this barrier height depends on the combination of semiconductor and metal.

The schottky barrier height of ohmic contact (non-rectifying barrier) is very low whereas the schottky barrier height of non-ohmic contact (rectifying barrier) is high.

In non-rectifying schottky barrier, the barrier height is not high enough to form a depletion region. So depletion region is negligible or absent in the ohmic contact diode.

On the other hand, in rectifying schottky barrier, the barrier height is high enough to form a depletion region. So the depletion region is present in the non-ohmic contact diode.

The non-rectifying metal-semiconductor junction (ohmic contact) offers very low resistance to the electric current whereas the rectifying metal-semiconductor junction offers high resistance to the electric current as compared to the ohmic contact.

The rectifying schottky barrier is formed when a metal is in contact with the lightly doped semiconductor, whereas the non-rectifying barrier is formed when a metal is in contact with the heavily doped semiconductor.

The ohmic contact has a linear current-voltage (I-V) curve whereas the non-ohmic contact has a non-linear current-voltage (I-V) curve.

Energy band diagram of schottky diode

The energy band diagram of the N-type semiconductor and metal is shown in the below figure.

The vacuum level is defined as the energy level of electrons that are outside the material.

The work function is defined as the energy required to move an electron from Fermi level (EF) to vacuum level (E0).

The work function is different for metal and semiconductor. The work function of a metal is greater than the work function of a semiconductor. Therefore, the electrons in the n-type semiconductor have high potential energy than the electrons in the metal.

The energy levels of the metal and semiconductor are different. The Fermi level at N-type semiconductor side lies above the metal side.

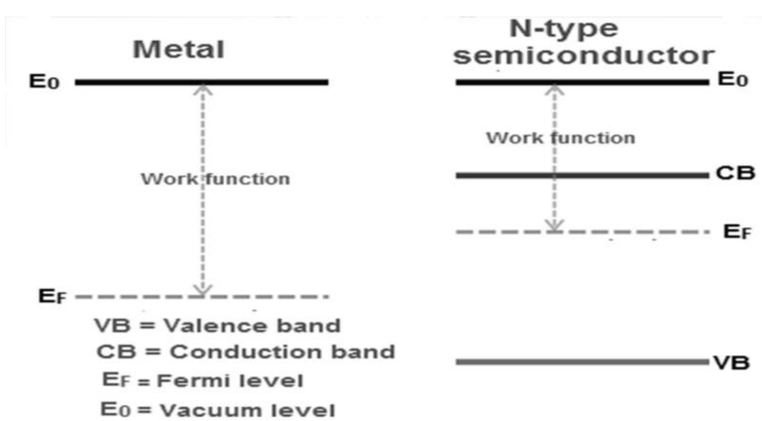

Fig:4.4.4 Energy Band Diagram of Schottky Diode

The electrons in the higher energy level have more potential energy than the electrons in the lower energy level. So the electrons in the N-type semiconductor have more potential energy than the electrons in the metal.

When the metal is joined with the n-type semiconductor, a device is created known as schottky diode. The built-in-voltage (Vbi) for schottky diode is given by the difference between the work functions of a metal and n-type semiconductor.

Working of schottky diode

When the metal is joined with the n-type semiconductor, the conduction band electrons (free electrons) in the n-type semiconductor will move from n-type semiconductor to metal to establish an equilibrium state.

When a neutral atom loses an electron it becomes a positive ion similarly when a neutral atom gains an extra electron it becomes a negative ion.
The conduction band electrons or free electrons that are crossing the junction will provide extra electrons to the atoms in the metal. As a result, the atoms at the metal junction gains extra electrons and the atoms at the n-side junction lose electrons.

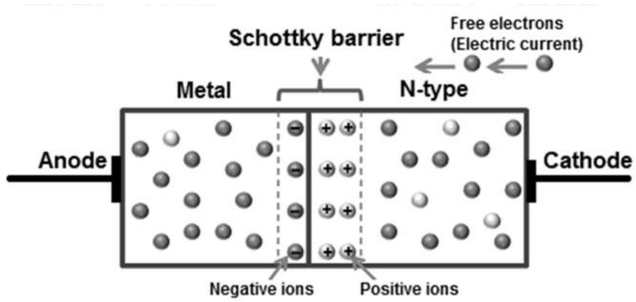

Fig:4.4.5 Unbiased Schottky Diode

The atoms that lose electrons at the n-side junction will become positive ions whereas the atoms that gain extra electrons at the metal junction will become negative ions. Thus, positive ions are created the n-side junction and negative ions are created at the metal junction. These positive and negative ions are nothing but the depletion region.
Since the metal has a sea of free electrons, the width over which these electrons move into the metal is negligibly thin as compared to the width inside the n-type semiconductor. So the built-in-potential or built-in-voltage is primarily present inside the n-type

semiconductor. The built-in-voltage is the barrier seen by the conduction band electrons of the n-type semiconductor when trying to move into the metal.

To overcome this barrier, the free electrons need energy greater than the built-in-voltage. In unbiased schottky diode, only a small number of electrons will flow from n-type semiconductor to metal. The built-in-voltage prevents further electron flow from the semiconductor conduction band into the metal.

The transfer of free electrons from the n-type semiconductor into metal results in energy band bending near the contact.

Forward biased schottky diode

If the positive terminal of the battery is connected to the metal and the negative terminal of the battery is connected to the n-type semiconductor, the schottky diode is said to be forward biased.

When a forward bias voltage is applied to the schottky diode, a large number of free electrons are generated in the n-type semiconductor and metal. However, the free electrons in n-type semiconductor and metal cannot cross the junction unless the applied voltage is greater than 0.2 volts.

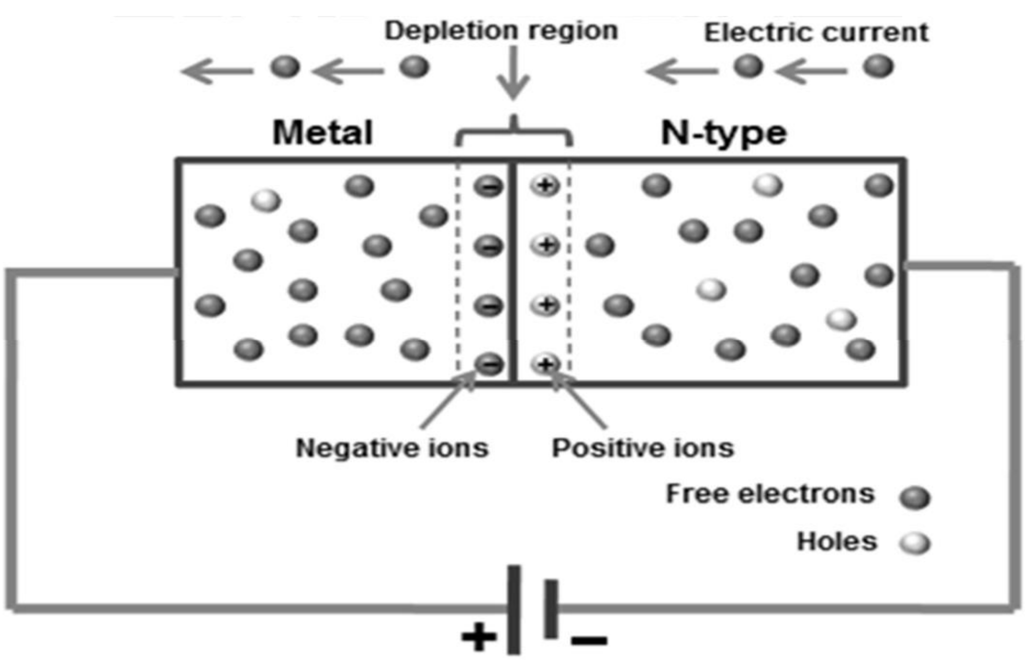

Fig:4.4.6 Forward Biased Schottky Diode

If the applied voltage is greater than 0.2 volts, the free electrons gain enough energy and overcomes the built-in-voltage of the depletion region. As a result, electric current starts flowing through the schottky diode.

If the applied voltage is continuously increased, the depletion region becomes very thin and finally disappears.

Reverse bias schottky diode

If the negative terminal of the battery is connected to the metal and the positive terminal of the battery is connected to the n-type semiconductor, the schottky diode is said to be reverse biased.

When a reverse bias voltage is applied to the schottky diode, the depletion width increases. As a result, the electric current stops flowing. However, a small leakage current flows due to the thermally excited electrons in the metal.

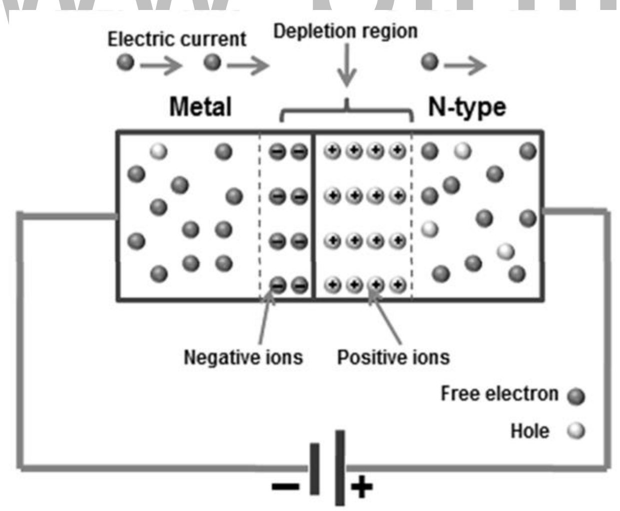

Fig:4.4.7 Reverse Biased Schottky Diode

If the reverse bias voltage is continuously increased, the electric current gradually increases due to the weak barrier.

If the reverse bias voltage is largely increased, a sudden rise in electric current takes place. This sudden rise in electric current causes depletion region to break down which may permanently damage the device.

V-I characteristics of schottky diode

The V-I (Voltage-Current) characteristics of schottky diode is shown in the below figure. The vertical line in the below figure represents the current flow in the schottky diode and the horizontal line represents the voltage applied across the schottky diode.

The V-I characteristics of schottky diode is almost similar to the P-N junction diode. However, the forward voltage drop of schottky diode is very low as compared to the P-N junction diode.

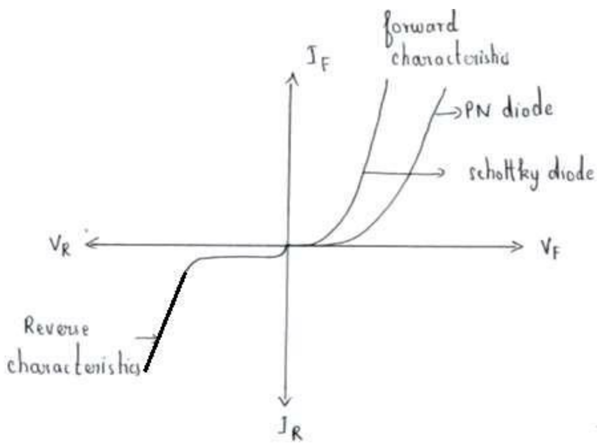

Fig:4.4.8 V-I Characteristics of Schottky Diode

The forward voltage drop of schottky diode is 0.2 to 0.3 volts whereas the forward voltage drop of silicon P-N junction diode is 0.6 to 0.7 volts.

If the forward bias voltage is greater than 0.2 or 0.3 volts, electric current starts flowing through the schottky diode.

In schottky diode, the reverse saturation current occurs at a very low voltage as compared to the silicon diode.

Difference between schottky diode and P-N junction diode

The main difference between schottky diode and p-n junction diode is as follows:

In schottky diode, the free electrons carry most of the electric current. Holes carry negligible electric current. So schottky diode is a unipolar device. In P-N junction diode, both free electrons and holes carry electric current. So P-N junction diode is a bipolar device.

The reverse breakdown voltage of a schottky diode is very small as compared to the p-n junction diode.

In schottky diode, the depletion region is absent or negligible, whereas in p-n junction diode the depletion region is present.

The turn-on voltage for a schottky diode is very low as compared to the p-n junction diode.

In schottky diode, electrons are the majority carriers in both metal and semiconductor. In P-N junction diode, electrons are the majority carriers in n-region and holes are the majority carriers in p-region.

Advantages of schottky diode

- Low junction capacitance

Capacitance is the ability to store an electric charge. In a P-N junction diode, the depletion region consists of stored charges. So there exists a capacitance. This capacitance is present at the junction of the diode. So it is known as junction capacitance.

In schottky diode, stored charges or depletion region is negligible. So a schottky diode has a very low capacitance.

- Fast reverse recovery time

The amount of time it takes for a diode to switch from ON state to OFF state is called reverse recovery time.

In order to switch from ON (conducting) state to OFF (non-conducting) state, the stored charges in the depletion region must be first discharged or removed before the diode switch to OFF (non-conducting) state.

The P-N junction diode do not immediately switch from ON state to OFF state because it takes some time to discharge or remove stored charges at the depletion region. However, in schottky diode, the depletion region is negligible. So the schottky diode will immediately switch from ON to OFF state.

- High current density

The depletion region is negligible in schottky diode. So applying is small voltage is enough to produce large current.

- Low forward voltage drop or low turn on voltage

The turn on voltage for schottky diode is very small as compared to the P-N junction diode. The turn on voltage for schottky diode is 0.2 to 0.3 volts whereas for P-N junction diode is 0.6 to 0.7 volts. So applying a small voltage is enough to produce electric current in the schottky diode.

- High efficiency
- Schottky diodes operate at high frequencies.
- Schottky diode produces less unwanted noise than P-N junction diode.

Application of Schottky diode

- Rectifier
- Voltage clamping
- TTL in digital devices
- Fast switching
- Digital computers.

4.2 TUNNEL DIODE

A Tunnel diode is a heavily doped p-n junction diode in which the electric current decreases as the voltage increases. In tunnel diode, electric current is caused by "Tunneling". The tunnel diode is used as a very fast switching device in computers. It is also used in high-frequency oscillators and amplifiers.

Symbol of Tunnel Diode

The circuit symbol of tunnel diode is shown in the below figure. In tunnel diode, the p-type semiconductor act as an anode and the n-type semiconductor act as a cathode.

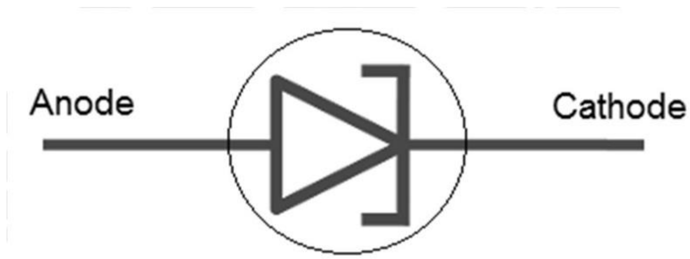

Fig:4.2.1 Symbol of Tunnel Diode

The anode is a positively charged electrode which attracts electrons whereas cathode is a negatively charged electrode which emits electrons. In tunnel diode, n-type semiconductor emits or produces electrons so it is referred to as the cathode. On the other hand, p-type semiconductor attracts electrons emitted from the n-type semiconductor so p-type semiconductor is referred to as the anode.

Leo Esaki observed that if a semiconductor diode is heavily doped with impurities, it will exhibit negative resistance. Negative resistance means the current across the tunnel diode decreases when the voltage increases. In 1973 Leo Esaki received the Nobel Prize in physics for discovering the electron tunneling effect used in these diodes.

A tunnel diode is also known as Esaki diode which is named after Leo Esaki for his work on the tunneling effect. The operation of tunnel diode depends on the quantum mechanics principle known as "Tunneling". In electronics, tunneling means a direct flow of electrons across the small depletion region from n-side conduction band into the p-side valence band.

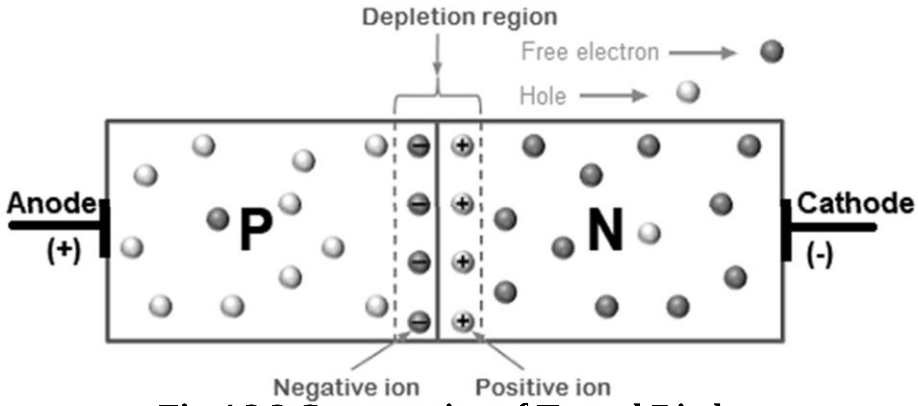

Fig:4.2.2 Construction of Tunnel Diode

The germanium material is commonly used to make the tunnel diodes. They are also made from other types of materials such as gallium arsenide, gallium antimonide, and silicon.

Width of the depletion region in tunnel diode

The depletion region is a region in a p-n junction diode where mobile charge carriers (free electrons and holes) are absent. Depletion region acts like a barrier that opposes the flow of electrons from the n-type semiconductor and holes from the p-type semiconductor.

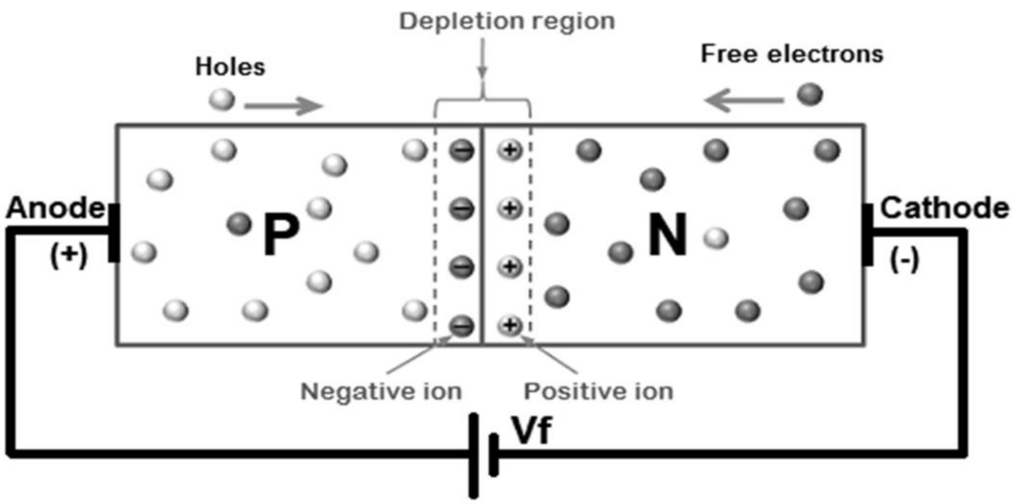

Fig:4.2.3 Working of Tunnel Diode

The width of a depletion region depends on the number of impurities added. Impurities are the atoms introduced into the p-type and n-type semiconductor to increase electrical conductivity.

If a small number of impurities are added to the p-n junction diode (p-type and n-type semiconductor), a wide depletion region is formed. On the other hand, if large number of impurities are added to the p-n junction diode, a narrow depletion region is formed.

In tunnel diode, the p-type and n-type semiconductor is heavily doped which means a large number of impurities are introduced into the p-type and n-type semiconductor. This heavy doping process produces an extremely narrow depletion region. The concentration of impurities in tunnel diode is 1000 times greater than the normal p-n junction diode.

In normal p-n junction diode, the depletion width is large as compared to the tunnel diode. This wide depletion layer or depletion region in normal diode opposes the flow of current. Hence, depletion layer acts as a barrier. To overcome this barrier, need to apply sufficient voltage. When sufficient voltage is applied, electric current starts flowing through the normal p-n junction diode.

Unlike the normal p-n junction diode, the width of a depletion layer in tunnel diode is extremely narrow. So applying a small voltage is enough to produce electric current in tunnel diode.

Tunnel diodes are capable of remaining stable for a long duration of time than the ordinary p-n junction diodes. They are also capable of high-speed operations.

Tunneling

The depletion region or depletion layer in a p-n junction diode is made up of positive ions and negative ions. Because of these positive and negative ions, there exists a built-in-potential orelectric field in the depletion region. This electric field in the depletion region exerts electric force in a direction opposite to that of the external electric field (voltage). Another thing need to remember is that the valence band and conduction band energy levels in the n-type semiconductor are slightly lower than the valence band and conduction band energy levels in the p-type semiconductor. This difference in energy levels is due to the differences in the energy levels of the dopant atoms (donor or acceptor atoms) used to form the n-type and p-type semiconductor.

Electric current in tunnel diode

In tunnel diode, the valence band and conduction band energy levels in the n-type semiconductor are lower than the valence band and conduction band energy levels in the p-type semiconductor. Unlike the ordinary p-n junction diode, the difference in energy levels is very high in tunnel diode. Because of this high difference in energy levels, the conduction band of the n-type material overlaps with the valence band of the p-type material.

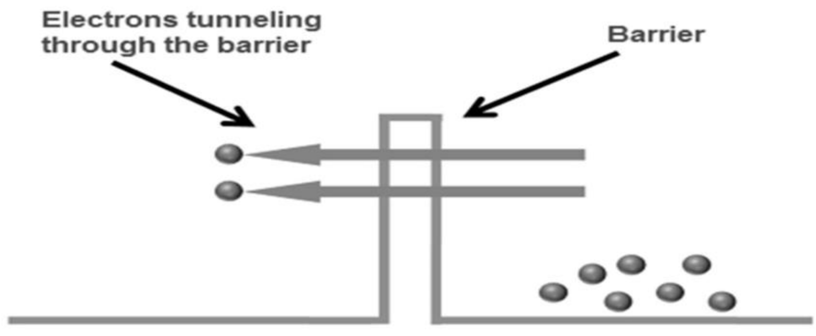

Fig:4.2.4 Tunneling

Quantum mechanics says that the electrons will directly penetrate through the depletion layer or barrier if the depletion width is very small.

The depletion layer of tunnel diode is very small. It is in nanometers. So the electrons can directly tunnel across the small depletion region from n-side conduction band into the p-side valence band.

In ordinary diodes, current is produced when the applied voltage is greater than the built-in voltage of the depletion region. But in tunnel diodes, a small voltage which is less than the built-in voltage of depletion region is enough to produce electric current.

In tunnel diodes, the electrons need not overcome the opposing force from the depletion layer to produce electric current. The electrons can directly tunnel from the conduction band of n-region into the valence band of p-region. Thus, electric current is produced in tunnel diode.

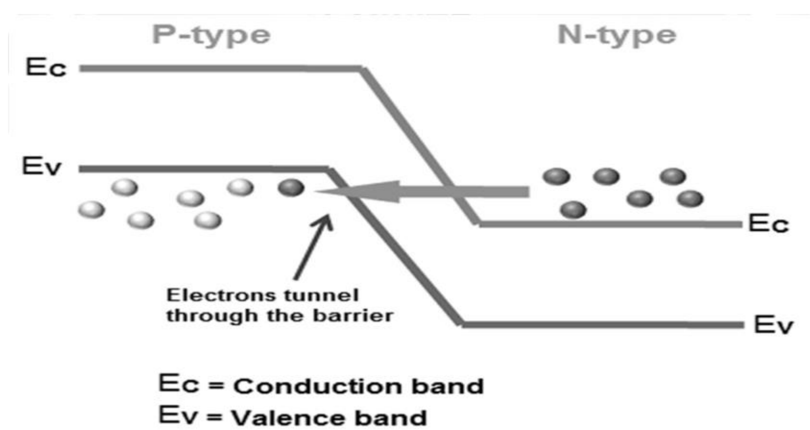

Fig:4.2.5 Energy Band Diagram of Tunnel Diode

Step 1: Unbiased tunnel diode

When no voltage is applied to the tunnel diode, it is said to be an unbiased tunnel diode. In tunnel diode, the conduction band of the n-type material overlaps with the valence band of the p-type material because of the heavy doping.

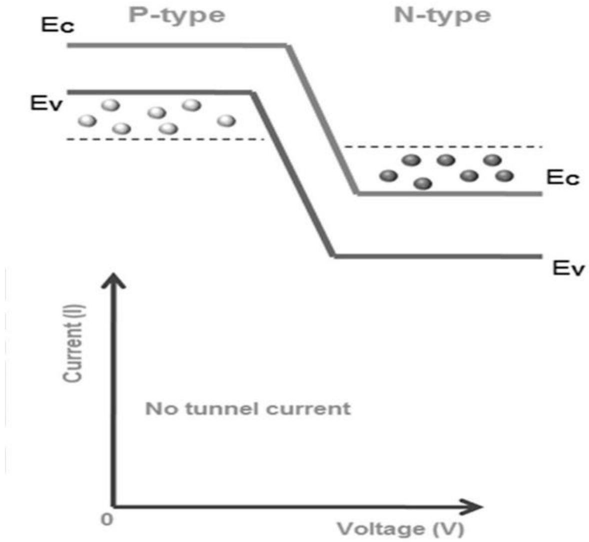

Fig:4.2.6 Unbiased Tunnel Diode

Because of this overlapping, the conduction band electrons at n-side and valence band holes at p-side are nearly at the same energy level. So when the temperature increases, some electrons tunnel from the conduction band of n-region to the valence band of p-region. In a similar way, holes tunnel from the valence band of p-region to the conduction band of n-region.

However, the net current flow will be zero because an equal number of charge carriers (free electrons and holes) flow in opposite directions.

Step 2: Small voltage applied to the tunnel diode

When a small voltage is applied to the tunnel diode which is less than the built-in voltage of the depletion layer, no forward current flows through the junction.

However, a small number of 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 small forward bias tunnel current. Thus, tunnel current starts flowing with a small application of voltage.

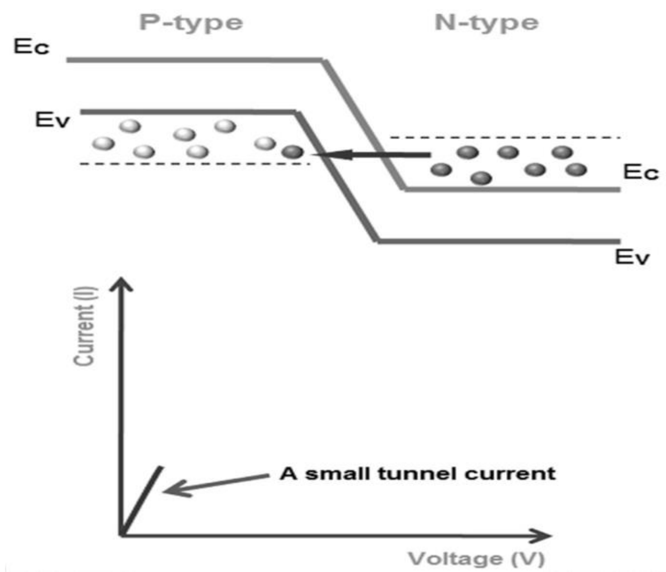

Fig:4.2.7 Small Forward Voltage

Step 3: Applied voltage is slightly increased

When the voltage applied to the tunnel diode is slightly increased, a large number of free electrons at n-side and holes at p-side are generated. Because of the increase in voltage, the overlapping of the conduction band and valence band is increased.

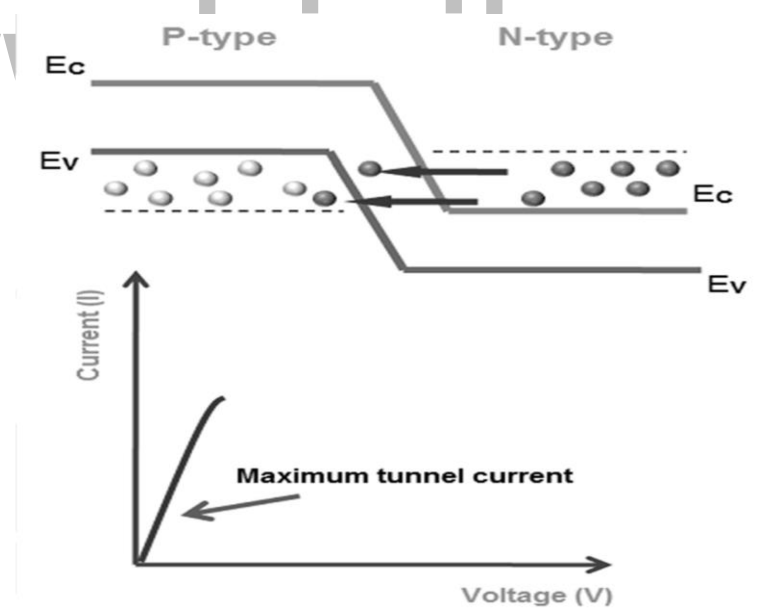

Fig:4.2.8 Maximum Forward Voltage

In simple words, the energy level of an n-side conduction band becomes exactly equal to the energy level of a p-side valence band. As a result, maximum tunnel current flows.

Step 4: Applied voltage is further increased

If the applied voltage is further increased, a slight misalign of the conduction band and valence band takes place.

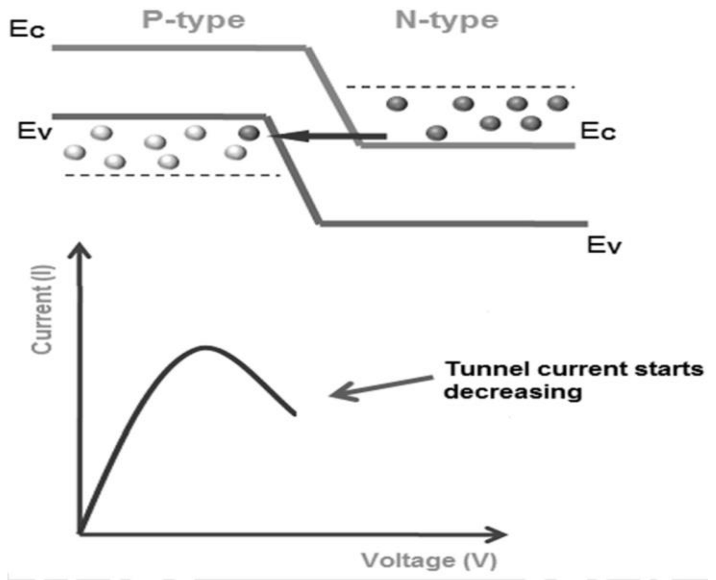

Fig:4.2.9 Applied voltage is further increased

Since the conduction band of the n-type material and the valence band of the p-type material sill overlap. The electrons tunnel from the conduction band of n-region to the valence band of p-region and cause a small current flow. Thus, the tunneling current starts decreasing.

Step 5: Applied voltage is largely increased

If the applied voltage is largely increased, the tunneling current drops to zero. At this point, the conduction band and valence band no longer overlap and the tunnel diode operates in the same manner as a normal p-n junction diode.

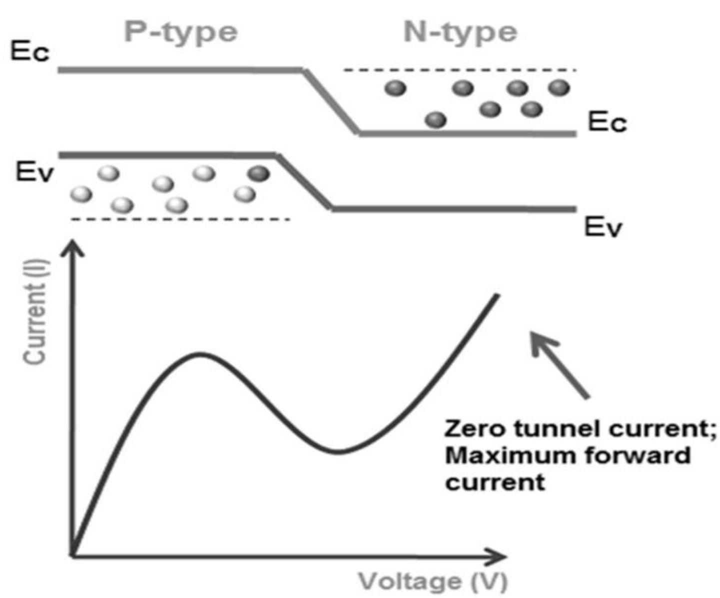

Fig:4.2.8 Applied voltage is largely increased

If this applied voltage is greater than the built-in potential of the depletion layer, the regular forward current starts flowing through the tunnel diode.

The portion of the curve in which current decreases as the voltage increases is the negative resistance region of the tunnel diode. The negative resistance region is the most important and most widely used characteristic of the tunnel diode.

A tunnel diode operating in the negative resistance region can be used as an amplifier or an oscillator.

Advantages of tunnel diodes

- Long life
- High-speed operation
- Low noise
- Low power consumption

Disadvantages of tunnel diodes

- Tunnel diodes cannot be fabricated in large numbers
- Being a two terminal device, the input and output are not isolated from one another.

Applications of tunnel diodes

- Tunnel diodes are used as logic memory storage devices.
- Tunnel diodes are used in relaxation oscillator circuits.
- Tunnel diode is used as an ultra high-speed switch.
- Tunnel diodes are used in FM receivers.

4.3 VARACTOR DIODE

Varactor diode is a p-n junction diode whose capacitance is varied by varying the reversevoltage. Varactor diode operates only in reverse bias. The varactor diode acts like a variable capacitor under reverse bias.

Varactor diode is also sometimes referred to as varicap diode, tuning diode, variable reactance diode, or variable capacitance diode.

Varactor diode symbol

The symbol of a varactor diode is shown in the below figure. The circuit symbol of the varactor diode is almost similar to the normal p-n junction diode.

Fig:4.3.1 Symbol of Varactor Diode

Two parallel lines at the cathode side represents two conductive plates and the space between these two parallel lines represents dielectric.

Construction of varactor diode

The n-type semiconductor, a large number of free electrons are present and in the p-type semiconductor, a large number of holes are present. The free electrons and holes always try to move from a higher concentration region to a lower concentration region.

For free electrons, n-region is the higher concentration region and p-region is the lower concentration region. For holes, p-region is the higher concentration region and n-region is the lower concentration region.

Therefore, the free electrons always try to move from n-region to p-region similarly holes always try to move from p-region to n-region.

When no voltage is applied, a large number of free electrons in the n-region get repelled from each other and move towards the p-region.

When the free electrons reach p-n junction, they experience an attractive force from the holes in the p-region. As a result, the free electrons cross the p-n junction. In the similar way, holes also cross the p-n junction. Because of the flow of these charge carriers, a tiny current flows across diode for some period.

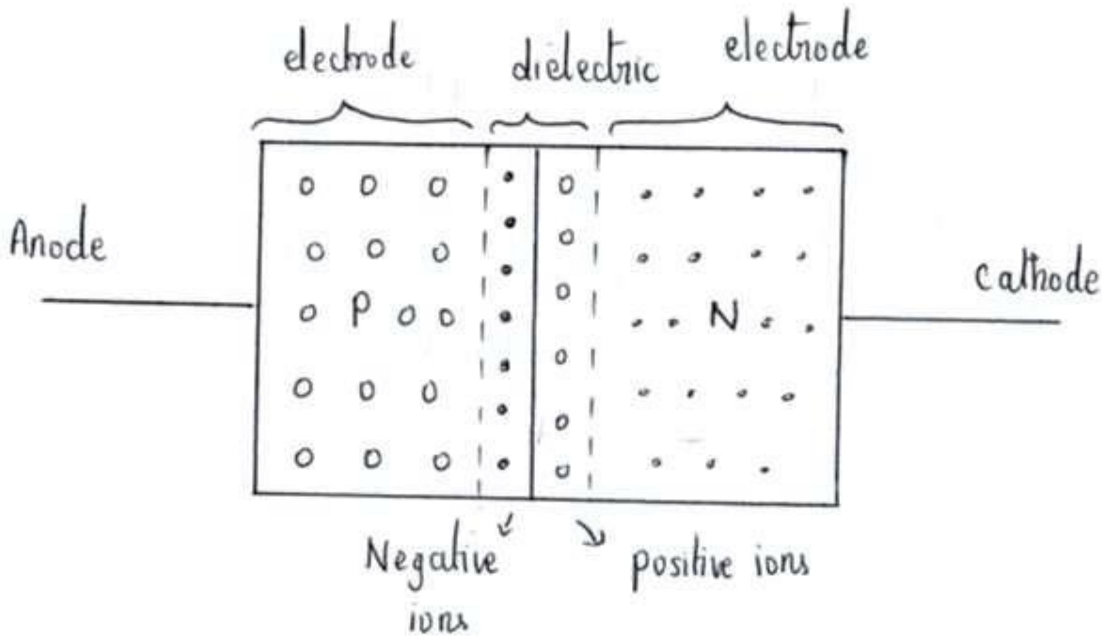

Fig:4.3.2 Construction of Varactor Diode

During this process, some neutral atoms near the junction at n-side loses electrons and become positively charged atoms (positive ions) similarly some neutral atoms near the junction at p-side gains extra electrons and become negatively charged atoms (negative ions). These positive and negative ions created at the p-n junction is nothing but depletion region. This depletion region prevents further current flow across the p-n junction.

The width of depletion region depends on the number of impurities added (amount of doping).

A heavily doped varactor diode has a thin depletion layer whereas a lightly doped varactor diode has a wide depletion layer.

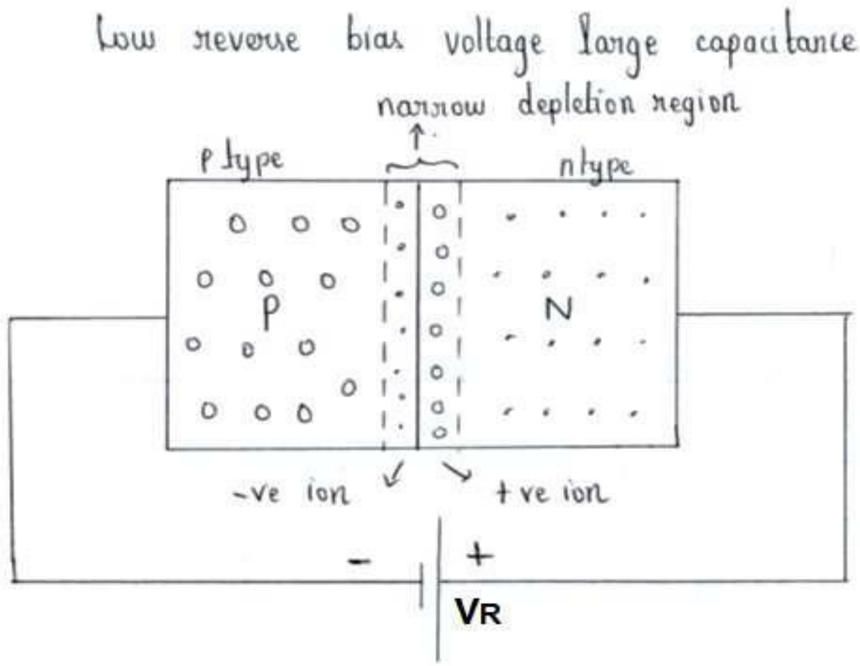

Fig:4.3.3 Low Reverse Bias of Varactor Diode

An insulator or a dielectric does not allow electric current through it. The depletion region also does not allow electric current through it. So the depletion region acts like a dielectric of a capacitor.

Electrodes or conductive plates easily allow electric current through them. The p-type and n-type semiconductor also easily allow electric current through them. So the p-type and n-type semiconductor acts like the electrodes or conductive plates of the capacitor. Thus, varactor diode behaves like a normal capacitor.

In an unbiased varactor diode, the depletion width is very small. So the capacitance (charge storage) is very large.

The varactor diode should always be operated in reverse bias. Because in reverse bias, the electric current does not flow. When a forward bias voltage is applied, the electric current flows through the diode. As a result, the depletion region becomes negligible. Depletion region consists of stored charges. So stored charges becomes negligible which is undesirable.

A varactor diode is designed to store electric charge not to conduct electric current. So varactor diode should always be operated in reverse bias.

When a reverse bias voltage is applied, the electrons from n-region and holes from p-region moves away from the junction. As a result, the width of depletion region increases and the capacitance decreases.

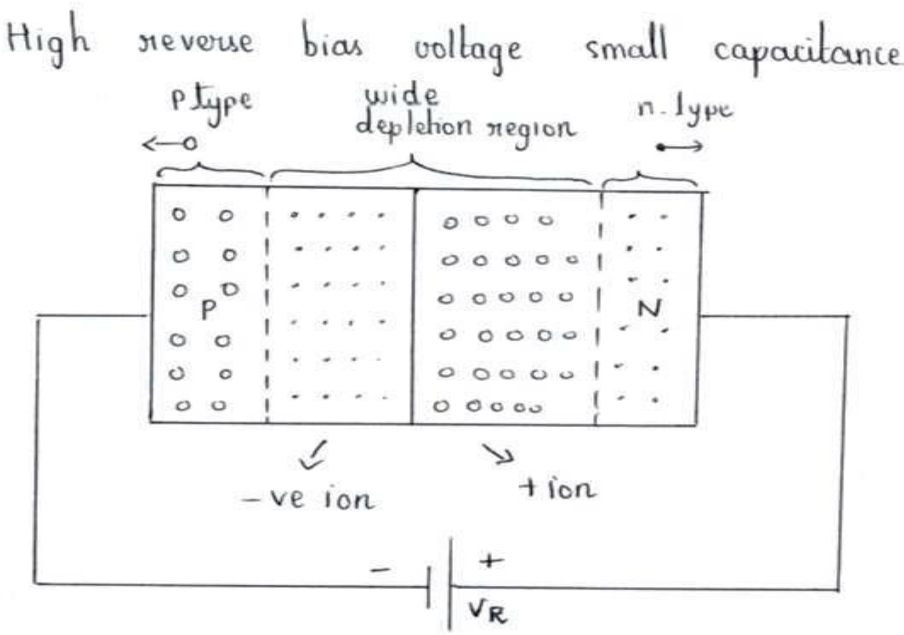

Fig:4.3.4 High Reverse Bias of Varactor Diode

However, if the applied reverse bias voltage is very low the capacitance will be very large.

The capacitance is inversely proportional to the width of the depletion region and directly proportional to the surface area of the p-region and n-region. So the capacitance decreases as the as the width of depletion region increases.

If the reverse bias voltage is increased, the width of depletion region further increases and the capacitance further decreases.

On the other hand, if the reverse bias voltage is reduced, the width of depletion region decreases and the capacitance increases.

Thus, an increase in reverse bias voltage increases the width of the depletion region and decreases the capacitance of a varactor diode.

The decrease in capacitance means the decrease in storage charge. So the reverse bias voltage should be kept at a minimum to achieve large storage charge. Thus, capacitance or transition capacitance can be varied by varying the voltage.

In a fixed capacitor, the capacitance will not be varied whereas, in variable capacitor, the capacitance is varied.

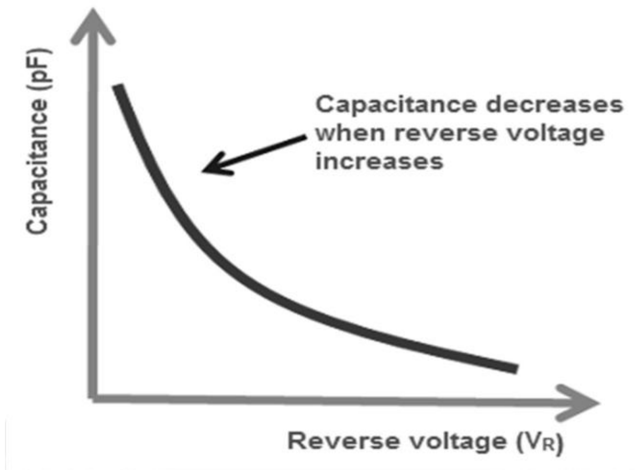

Fig:4.3.5 Characteristics of Varactor Diode

In a varactor diode, the capacitance is varied when the voltage is varied. So the varactor diode is a variable capacitor. The capacitance of a varactor diode is measured in picofarads (pF).

Applications of varactor diode

- Varactor diode is used in frequency multipliers.
- Varactor diode is used in parametric amplifiers.
- Varactor diode is used in voltage-controlled oscillators.

UNIT IV SPECIAL SEMICONDUCTOR DEVICES

4.1 ZENER DIODE

A normal p-n junction diode allows electric current only in forward biased condition. When forward biased voltage is applied to the p-n junction diode, it allows large amount of electric current and blocks only a small amount of electric current. Hence, a forward biased p-n junction diode offer only a small resistance to the electric current.

When reverse biased voltage is applied to the p-n junction diode, it blocks large amount of electric current and allows only a small amount of electric current. Hence, a reverse biased p-n junction diode offer large resistance to the electric current.

If reverse biased voltage applied to the p-n junction diode is highly increased, a sudden rise in current occurs. At this point, a small increase in voltage will rapidly increases the electric current. This sudden rise in electric current causes a junction breakdown called zener or avalanche breakdown.

The voltage at which zener breakdown occurs is called zener voltage and the sudden increase in current is called zener current.

A normal p-n junction diode does not operate in breakdown region because the excess current permanently damages the diode. Normal p-n junction diodes are not designed to operate in reverse breakdown region. Therefore, a normal p-n junction diode does not operate in reverse breakdown region.

A zener diode is a special type of device designed to operate in the zener breakdown region. Zener diodesacts like normal p-n junction diodes under forward biased condition. When forward biased voltage is applied to the zener diode it allows large amount of electric current and blocks only a small amount of electric current.

Zener diode is heavily doped than the normal p-n junction diode. Hence, it has very thindepletion region. Therefore, zener diodes allow more electric current than the normal p-n junction diodes.

Zener diode allows electric current in forward direction like a normal diode but also allows electric current in the reverse direction if the applied reverse voltage is greater than the zener voltage. Zener diode is always connected in reverse direction because it is specifically designed to work in reverse direction.

Zener Diode Definition

A zener diode is a p-n junction semiconductor device designed to operate in the reverse breakdown region. The breakdown voltage of a zener diode is carefully set by controlling the doping level during manufacture.

The name zener diode was named after the American physicist Clarance Melvin Zener who discovered the zener effect. Zener diodes are the basic building blocks of electronic circuits. They are widely used in all kinds of electronic equipments. Zener diodes are mainly used to protect electronic circuits from over voltage.

Breakdown in zener diode

There are two types of reverse breakdown regions in a zener diode: avalanche breakdown and zener breakdown.

Avalanche breakdown

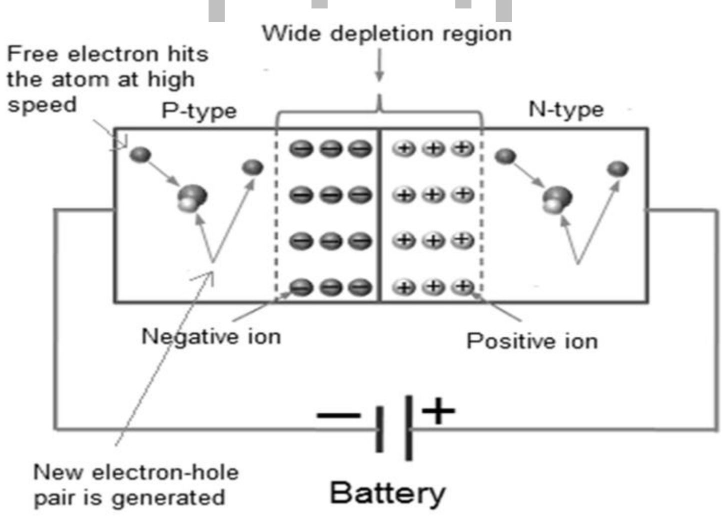

Fig:4.1.1 Avalanche breakdown

The avalanche breakdown occurs in both normal diodes and zener diodes at high reverse voltage. When high reverse voltage is applied to the p-n junction diode, the free electrons(minority carriers) gains large amount of energy and accelerated to greater velocities.

The free electrons moving at high speed will collides with the atoms and knock off more electrons. These electrons are again accelerated and collide with other atoms. Because of this continuous collision with the atoms, a large number of free electrons are generated. As a result, electric current in the diode increases rapidly. This sudden increase in electric current may permanently destroys the normal diode. However, avalanche diodes may not be destroyed because they are carefully designed to operate in avalanche breakdown region. Avalanche breakdown occurs in zener diodes with zener voltage (Vz) greater than 6V.

Zener breakdown

The zener breakdown occurs in heavily doped p-n junction diodes because of their narrow depletion region. When reverse biased voltage applied to the diode is increased, the narrow depletion region generates strong electric field.

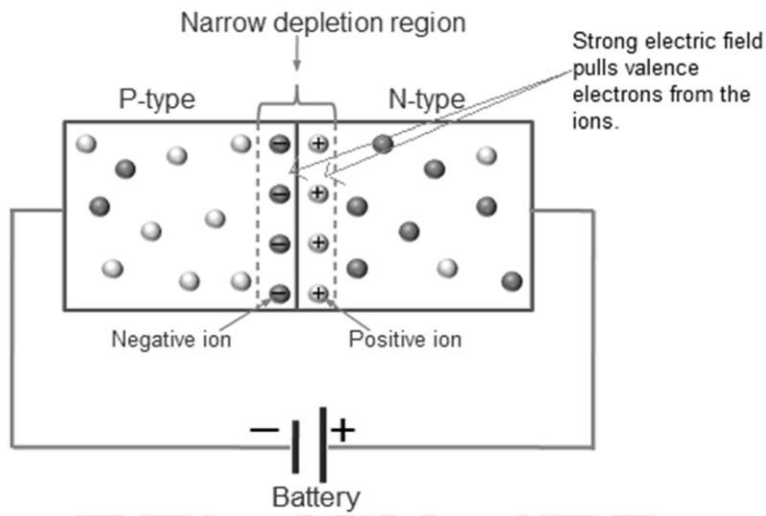

Fig:4.1.2 Zener breakdown

When reverse biased voltage applied to the diode reaches close to zener voltage, the electric field in the depletion region is strong enough to pull electrons from their valence band. The valence electrons which gains sufficient energy from the strong electric field of depletion region will breaks bonding with the parent atom. The valance electrons which break bonding with parent atom will become free electrons. This free electron carry electric current from one place to another place. At zener breakdown region, a small increase in voltage will rapidly increases the electric current.

- Zener breakdown occurs at low reverse voltage whereas avalanche breakdown occurs at high reverse voltage.
- Zener breakdown occurs in zener diodes because they have very thin depletion region.
- Breakdown region is the normal operating region for a zener diode.
- Zener breakdown occurs in zener diodes with zener voltage (Vz) less than 6V.

Symbol of Zener Diode

The symbol of zener diode is shown in below figure. Zener diode consists of two terminals: cathode and anode.

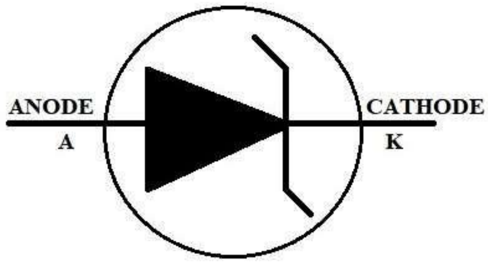

Fig:4.1.3 Symbol of Zener Diode

In zener diode, electric current flows from both anode to cathode and cathode to anode. The symbol of zener diode is similar to the normal p-n junction diode, but with bend edges on the vertical bar.

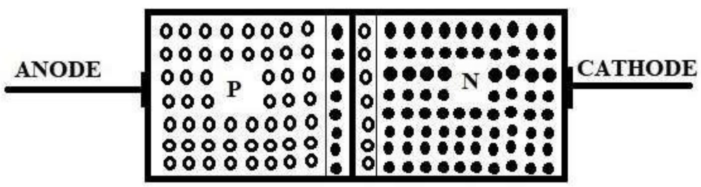

Fig:4.1.4 Construction of Zener Diode

Working of zener diode

When forward biased voltage is applied to the zener diode, it works like a normal diode.

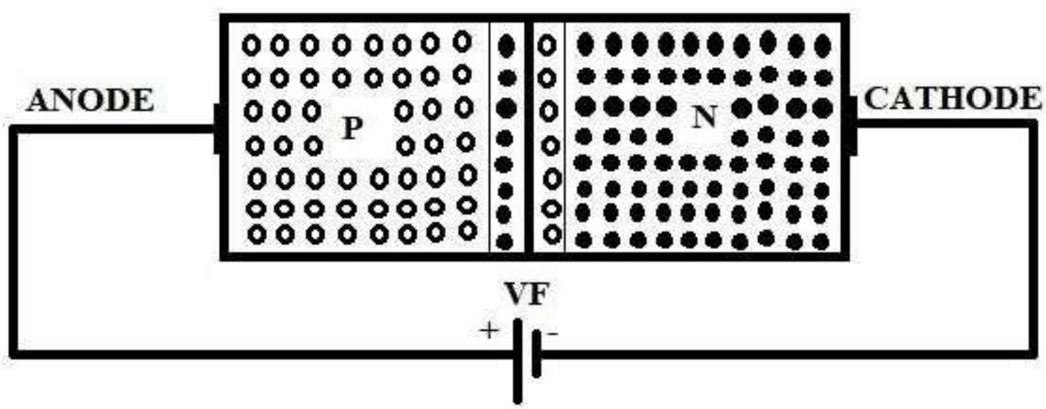

Fig:4.1.5 Forward Biasing of Zener Diode

However, when reverse biased voltage is applied to the zener diode, it works in different manner.

When reverse biased voltage is applied to a zener diode, it allows only a small amount of leakage current until the voltage is less than zener voltage. When reverse biased voltage applied to the zener diode reaches zener voltage, it starts allowing large amount of electric current. At this point, a small increase in reverse voltage will rapidly increases the electric current. Because of this sudden rise in electric current, breakdown occurs called zener breakdown. However, zener diode exhibits a controlled breakdown that does damage the device.

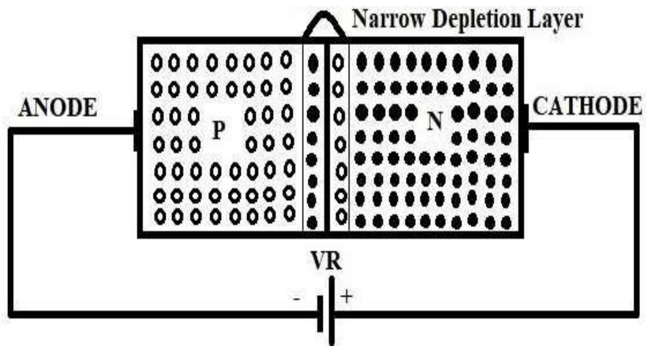

Fig:4.1.6 Reverse Biasing of Zener Diode

The zener breakdown voltage of the zener diode is depends on the amount of doping applied. If the diode is heavily doped, zener breakdown occurs at low reverse voltages. On the other hand, if the diode is lightly doped, the zener breakdown occurs at high reverse voltages. Zener diodes are available with zener voltages in the range of 1.8V to 400V.

VI characteristics of a zener diode

The VI characteristics of a zener diode is shown in the below figure.

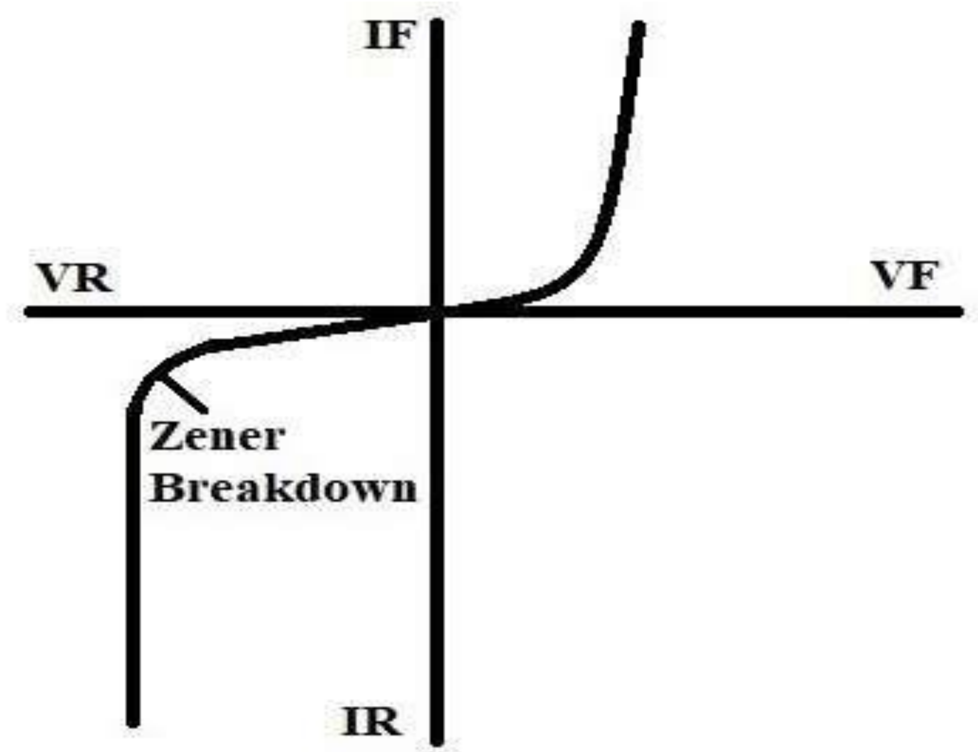

Fig:4.1.7 VI characteristics of Zener Diode

Advantages of zener diode

- Power dissipation capacity is very high
- High accuracy
- Small size
- Low cost

Applications of zener diode

- It is normally used as voltage reference
- Zener diodes are used in voltage stabilizers or shunt regulators.
- Zener diodes are used in switching operations
- Zener diodes are used in clipping and clamping circuits.
- Zener diodes are used in various protection circuits