UNIT IV – SPECIAL SEMICONDUCTOR DEVICES

INTRODUCTION

In addition to the PN – junction diode, other types are also manufactured for specific applications.

METAL – SEMICONDUCTOR JUNCTIONS

Metal – Semiconductor junctions are very common in all semiconductor devices and have very high importance. Depending upon the doping concentration, materials, and the characteristics of the interface, the metal – semiconductor junctions can act as either an ohmic contact or as a Schottky barrier. An analysis of metal – semiconductor is presented.

Structure of Metal – Semiconductor Junction

A metal – semiconductor junction, as the name indicates, consists of a metal in contact with a piece of semiconductor. The structure of a typical metal – semiconductor junction is shown. The active junction is the interface between the metal, which act as an anode, and the semiconductor. The other interface between the semiconductor and metal, which acts as a cathode, is an ohmic contact and there is no potential drop at this junction.

Energy Band Diagram

The energy band diagram helps in identifying the barrier between the metal and the semiconductor. In order to understand the energy band structure at a metal – semiconductor junction, first let us consider the energy bands in metal and semiconductor separately. The energy bands are aligned at the same vacuum level. When the metal and semiconductor are brought together, the Fermi level does align them at thermal equilibrium. The condition that exists before the thermal equilibrium is reached is depicted in the fig below.

Let us define Φ_B, the barrier height as the potential difference between the Fermi level of the metal and the band edge where the majority carriers exist. For an N – type semiconductor, the barrier height id given by the difference between the metal work function (Φ_M) and the electron affinity (χ).

$$\Phi_{BN} = \Phi_M - \chi$$

The work function Φ_M varies depending upon surface preparation. For P – type semiconductor, the barrier height is given by the difference between the valence band and the Fermi level in the metal,

$$\Phi_{BP} = \chi + \frac{E_g}{q} - \Phi_M$$

$$E_g = energy\ gap\ between\ the\ conduction\ and\ valence\ bands.$$

The sum of the barrier heights on N – type and P – type substrate is expected to be equal to the energy gap, $E_g, i.e., (\Phi_{BN} + \Phi_{BP})q = E_g$.

In a metal – semiconductor junction, a barrier is formed if the Fermi level of the metal is somewhere between the valence and conduction band edges of the semiconductor. Let us also define a built – in potential (Φ_1) as the difference between the Fermi level of the metal and the Fermi level of the semiconductor.

For an N – type semiconductor, the barrier height is given by,

$$\Phi_{BN} = \Phi_M - \chi$$

$$\Phi_{IN} = \Phi_{BN} - \frac{E_C - E_F}{q} = \Phi_M - \chi - \frac{E_C - E_F}{q}$$

For an P – type semiconductor, the Fermi level is closer to the valence band and the built – in potential is given by,

$$\Phi_{IP} = \chi + \frac{E_F - E_V}{q} - \Phi_M$$

The Fermi level in an N – type semiconductor is given by

$$E_F = E_C - kTln\frac{N_C}{N_D}$$

and the Fermi level in a P – type semiconductor is given by

$$E_F = E_V + kTln\frac{N_V}{N_A}$$

Substituting the above equations

$$\Phi_{IN} = \Phi_{BN} - \frac{E_C - E_F}{q} = \Phi_{BN} - \frac{kT}{q}ln\frac{N_C}{N_D} \ for\ N - type\ semiconductor$$

$$\Phi_{IP} = \Phi_{BP} - \frac{E_F - E_V}{q} = \Phi_{BP} - \frac{kT}{q}ln\frac{N_V}{N_A} \ for\ P - type\ Semiconductor$$

Thermal Equilibrium

After the metal and semiconductor have been brought into contacts, electrons start to flow from the semiconductor into the metal, and as a result, a depletion region of width x_d, with uncompensated donors is formed. Electrons continue to flow into the metal until the Fermi level of metal and semiconductor align with each other. In metal, the electron current forms a negative surface charge layer. This result is an electric field and the band edges are lowered in the semiconductor as shown.

Forward and Reverse Bias

When an external bias is applied, the metal – to – semiconductor barrier remains unchanged, whereas, the semiconductor – to – metal barrier is either decreased (forward bias) or increased (reverse bias).

When the metal is connected to a positive bias with respect to the semiconductor. The Fermi energy level of the metal is lowered from its equilibrium level. The depletion region is narrowed, and the potential barrier in the semiconductor is reduced. The number of electrons that diffuse from the semiconductor to metal is now more than the number of electrons that drift from metal into the semiconductor. Thus, there will be positive current through the device.

If the metal is connected to a negative bias with respect to the semiconductor, the metal is charged even more negatively than without any bias. The Fermi energy level of the metal is raised. The electrons in the semiconductor side are repelled even more. The depletion region becomes wider and the potential barrier on semiconductor side is further increased as shown. However, the barrier on the metal side remains unchanged and limits the flow of electrons. A small current flows as a result of a few electrons in the metal acquiring enough thermal energy to overcome barrier.

Ohmic Contacts

An ohmic contact is another type of metal – semiconductor junction. It is formed by applying a metal to a heavily doped semiconductor. Here the current is conducted equally in both directions and there will be a very little voltage drop across the junction. The usage of ohmic contacts is to connect one semiconductor device to another on an IC, or to connect an IC to its external terminals.

Ohmic contacts are very common in semiconductor devices. Metal – semiconductor contacts cannot be considered to offer a resistance as low as that of two metals connected to each other. Metal – semiconductor junction can act as either a rectifying junction or an ohmic contact depending on the Fermi levels of the metal and the semiconductor used. A proper choice of metal and semiconductor can offer a low resistance ohmic contact. Alternatively, the contacts that have a thin barrier can be created by heavily doping the semiconductor through which the carriers can tunnel. Both these types of contacts are presented.

A metal – semiconductor junction can be an ohmic contact if the Schottky barrier height, $\emptyset_B$ is zero or negative. This means, for an N – type semiconductor, the metal work function, $\emptyset_M$, is either close to or smaller than the electron affinity (χ) of the semiconductor; and for a P – type semiconductor, the metal work function is either close to or greater than the sum of electron affinity and the band gap energy.

That is, $\phi_M \leq \chi\ for\ an\ N - type\ semiconductor$

Or, $\phi_M \geq \chi + E_g\ for\ an\ P - type\ semiconductor$

GALLIUM ARSENIDE DEVICES

Gallium Arsenide is a compound semiconductor made of two elements.

Gallium – three valence electrons

Arsenic – five valence electrons

SCHOTTKY BARRIER DIODE

The metal contacts are required to be ohmic and no PN junctions to be formed between the metal silicon layers. The N^+ diffusion region serves the purpose of generating ohmic contacts. On the other hand, if aluminium is deposited directly on the N – type silicon, then a metal – semiconductor diode can be said to be formed. Such a metal semiconductor diode junction exhibits the same type of V – I characteristics as that of an ordinary PN junction.

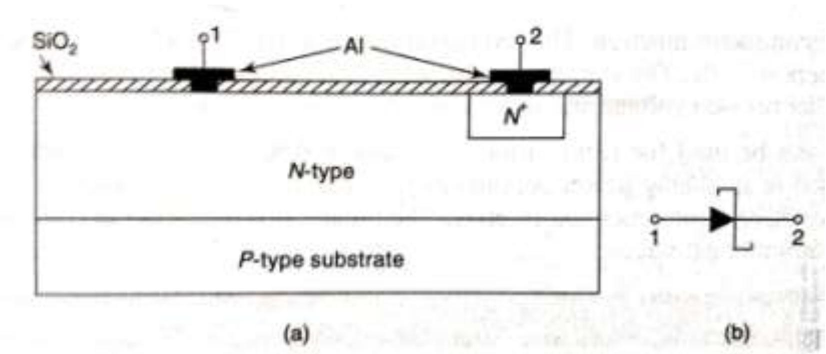


Fig: Schottky barrier diode (a) Cross Sectional View (b) Symbol

The cross – sectional view and symbol of a Schottky barrier diode are shown. Contact 1: Schottky barrier & Contact 2: Ohmic Contact. The contact potential between the semiconductor and metal generates a barrier for the flow of conducting electrons from semiconductor to metal. When the junction is forward biased, this barrier lowered and the electron flow is allowed from semiconductor to metal.

The majority carriers carry the conduction current in the Schottky diode whereas in the PN junction diode, minority carriers carry the conduction current and it incurs an appreciable delay from ON to OFF state. This is due to the fact that the minority carriers stored in the junction have to be totally removed.

Advantage:

i. Exhibits negligible

ZENER DIODE

When the reverse voltage reaches breakdown voltage in normal PN junction diode, the current through the junction the power dissipated at the junction will be high. Such an operation is destructive, and the diode gets damaged. Whereas diodes can be designed with adequate power dissipation capabilities to operate in the breakdown region. On such diode is known as Zener Diode. Zener diode is heavily doped than the ordinary diode.

V – I characteristics of the zener diode

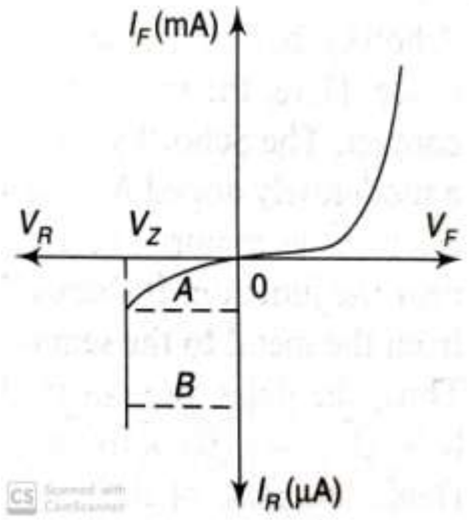


Fig: V – I Characteristics

Operation of zener diode is same as that of ordinary PN diode under forward – biased condition. Whereas under reverse biased condition, breakdown of the junction occurs. The breakdown depends upon the amount of doping. If the diode is heavily doped, the depletion layer is thin and, consequently, breakdown occur at lower reverse voltage and further, the breakdown voltage is sharp. Whereas lightly doped diode is has a higher breakdown voltage. Thus, breakdown voltage can be selected with the amount of doping.

The sharp increase in current under breakdown conditions are due to the following two mechanisms.

i. Avalanche Breakdown
ii. Zener Breakdown

Avalanche Breakdown:

As the **applied reverse bias voltage increases**, the field across the junction increases correspondingly. Thermally generated carriers while **traversing the junction acquire a large amount of kinetic energy** from this field. As a result, the **velocity of these carriers increases**. The **electrons disrupt the covalent bond** by colliding with immobile ions and **create new electron – hole pairs**. These new carriers again acquire sufficient energy from the field and collide with other immobile ions thereby generating further electron – hole pairs. This **process is cumulative** in nature and results in generation of avalanche of charge carriers within a short time. This mechanism of carrier generation is known as Avalanche multiplication. This process results in flow of large amount of current at the same value of reverse bias.

Zener Breakdown:

When the P and N regions are heavily doped, **direct rupture of covalent bonds** takes place **because of strong electric fields**, at the junction of PN diode. The new electron – hole pairs so created **increase the reverse current** in a reverse biased PN junction diode. The increase in current takes place at a constant value of reverse bias typically below 6V for heavily doped diodes.

Heavily doping of P and N regions, the depletion region becomes very **small** and for an applied voltage of 6V or less, the field across the depletion region becomes very high, of the order of 10^7 V/m, making conditions suitable for zener breakdown.

Lightly doped, zener breakdown voltage becomes high and breakdown is then predominantly by avalanche multiplication.

Though Zener breakdown occurs for lower breakdown voltage and avalanche breakdown occurs for higher breakdown voltage, such diodes normally called zener diodes.

Zener Resistances

Zener Static or DC Resistance R_z

It is the ratio of total zener diode voltage to total diode current measured at the given operating point.

$$\boldsymbol{R_Z = \frac{V_{ZQ}}{I_{ZQ}}}$$

Zener Dynamic or AC Resistance $r_{Z\,Max}$

It is defined as voltage difference divided by current difference at the given operating point.

$$\boldsymbol{r_Z = \frac{\Delta V_Z}{\Delta I_Z}}$$

Zener Diode Ratings

i. Minimum Zener Current $I_{Z\,min}$

Minimum reverse current where the breakdown becomes stable. If a zener has to remain in the breakdown region the current through it has to be more than $I_{Z\,min}$

ii. Maximum Zener Current $I_{Z\,max}$

$$I_{Z\,max} = \frac{P_{Z\,max}}{V_Z}$$

This parameter gives the maximum current a zener diode can handle without exceeding its power rating.

iii. Maximum Power of a Zener Diode P_Z

The power dissipation of a Zener diode equals the product of its zener voltage and current.

$$P_Z = V_Z . I_Z$$

Effect of temperature on Zener Diode

The Zener Voltage changes with the temperature. The percentage change in zener voltage V_Z for every ^{o}C change in temperature is called temperature coefficient (TC) of a Zener diode. It is denoted as TC and expressed as %/^{o}C.

Mathematically it can be defined as

$$TC = \frac{\Delta V_Z}{V_Z(T_1 - T_O)} * 100\ \%/^{0}\text{C}$$

$$T_1 - Final\ temperature\ of\ junction$$

$$T_o - Generally\ 25^{o}C\ at\ which\ zener\ voltage\ is\ specified$$

$$\Delta V_Z - Resulting\ change\ in\ Zener\ Voltage\ due\ to\ increase\ in\ temperature$$

Positive Value of Temperature Coefficient:

- Increase in V_Z due to increases in temperature
- Decrease in V_Z due to decrease in temperature

Negative Value of Temperature Coefficient:

- Increase in V_Z due to decrease in temperature
- Decrease in V_Z due to increase in temperature

$$\Delta V_Z = \frac{V_Z TC(T_1 - T_O)}{100} = \frac{V_Z TC\Delta T}{100}$$

$$\Delta T - Change\ in\ Temperature$$

Applications

Diode can be used as a Voltage Regulator

- It is required to provide constant voltage across the load resistance R_L, whereas the input voltage may be varying over a range.

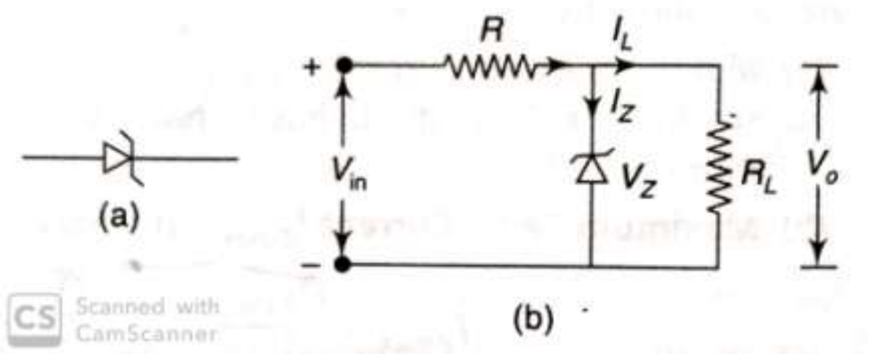


Fig: Zener Diode (a) Circuit Symbol (b) As a Voltage Regulator

Voltage Regulators

In a regulated power supply, the output voltage changes whenever the input voltage or load changes. An ideal regulated power supply is an electronic circuit designed to provide a predetermined DC voltage V_o which is independent of the load current and variations in the input voltage. A Voltage regulator is an electronic circuit that provides a stable DC voltage independent of the load current, temperature and AC line voltage variations.

Factors determining the stability

The output DC voltage $\mathbf{V_o}$ depends on the input unregulated DC voltage V_{in}, load current I_L and temperature T. Hence, the change in output voltage of power supply can be expressed as follows:

$$\Delta V_O = \frac{\partial V_O}{\partial V_{in}}\Delta V_{in} + \frac{\partial V_o}{\partial I_L}\Delta I_L + \frac{\partial V_o}{\partial T}\Delta T$$

$$\Delta V_o = S_v \Delta V_{in} + R_o \Delta I_L + S_T \Delta T$$

Where the three coefficients are defined as

Input regulation factor, $S_v = \frac{\Delta V_o}{\Delta V_{in}} \mid \Delta I_L = 0;\ \Delta T = 0$

Output Resistance, $R_o = \frac{\Delta V_o}{\Delta I_L} \mid \Delta V_{in} = 0; \Delta T = 0$

Temperature Coefficient, $S_T = \frac{\Delta V_o}{\Delta T} \mid \Delta V_{in} = 0; \Delta I_L = 0$

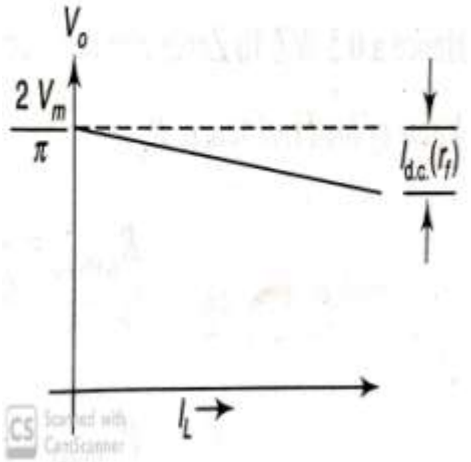
Line Regulation

It is defined as the change in output voltage for a change in line supply voltage, keeping the load current and temperature constant. Line regulation is given by

$$Line\ Regulation = \frac{change\ in\ output\ voltage}{chnage\ in\ input\ voltage} = \frac{\Delta V_o}{\Delta V_{in}}$$

Load Regulation

It is defined as a change in regulated output voltage as the load current changes from no load to full load. It is expressed as a percentage of no load voltage or full load voltage



$$\%\ Load\ Regulation = \frac{V_{no\ load} - V_{full\ load}}{V_{no\ load}} * 100$$

Or

$$\%\ Load\ Regulation = \frac{V_{no\ load} - V_{full\ load}}{V_{full\ load}} * 100$$

V_o − Output Voltage at zero load current

$V_{full\ load}$ − output voltage at rated load current

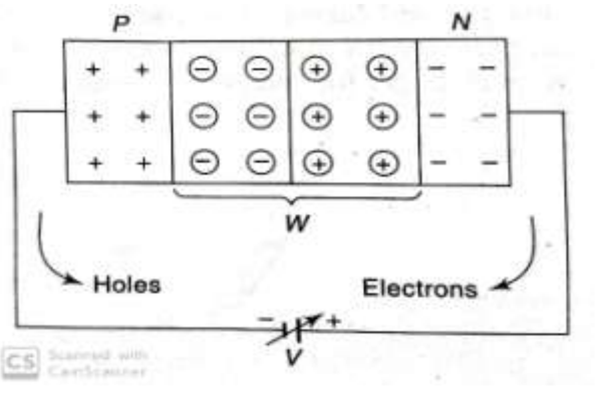
Fig: Load Regulation Characteristics

VARACTOR DIODE

The varactor, also called a **varicap**, **tuning or voltage variable capacitor diode**, is a junction diode with a small impurity dose at its junction, which has the useful property that its junction or transition capacitance is easily varied electronically.

When any diode is reverse biased, a depletion region is formed.

- **Larger the reverse bias** across the diode, the width of the depletion layer “W” become wider.
- **Decreasing the reverse bias** voltage, the depletion width “W” becomes narrower.



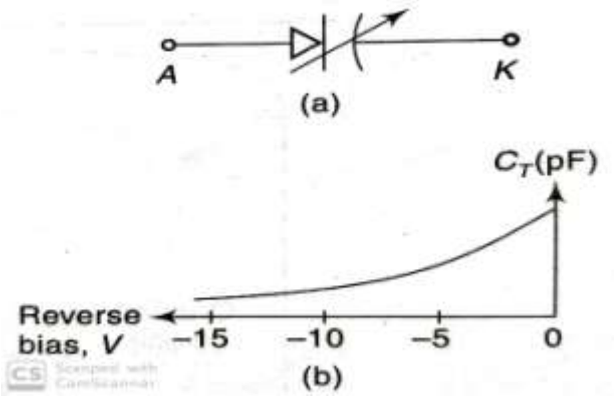


Fig: Depletion region in a reverse biased PN junction *(a) Circuit Symbol (b) Characteristics*

This depletion region is devoid of majority carriers and acts like an insulator preventing conduction between the P and N regions of the diode, just like a dielectric, which separates the two plates of a capacitor. The varactor diode with its symbol is shown in the fig.

As the capacitance is inversely proportional to the distance between the plates ($C_T \propto 1/W$), ***the transition capacitance C_T varies inversely with the reverse voltage***. Consequently, an increase in reverse bias voltage will result in an increase in the depletion region width and a subsequent decrease in transition capacitance C_T.

Applications

- FM Radio
- TV Receivers
- AFC Circuits
- Self Adjusting Bridge Circuits
- Adjustable Bandpass Filters

TUNNEL DIODE

Thin – junction diode which exhibits negative resistance under low forward bias conditions.

An ordinary PN junction diode has an impurity concentration of about 1 part in 10^8. With this amount of doping, the width of the depletion layer is of the order of 5 microns. This potential barrier restrains the flow of carriers from the majority carrier side to the minority carrier side. If the concentration of impurity atom is greatly increased to the level of 1 part in 10^3, the device characteristics are completely changed. The width of the junction barrier varies inversely as the square root of the impurity concentration and therefore, is reduced from 5 microns to less than 100 Å (10^{-8} m).

For such thin potential energy barriers, the electrons will penetrate through the junction rather than surmounting them. This quantum mechanical behaviour is referred to as **tunneling** and hence, these high – impurity density PN junction devices are called tunnel diodes.

V – I Characteristics for Germanium Tunnel Diode:

Forward Current rises sharply as applied voltage is increased, where it would have risen slowly for an ordinary PN junction diode. Also, reverse current is much larger for comparable back bias than in other diodes due to the thinness of the junction.

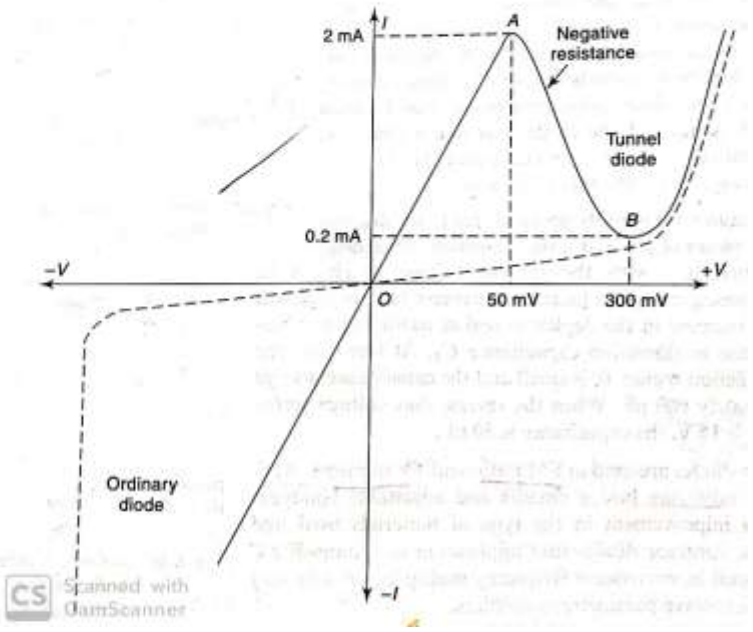


Fig: V – I characteristics of Tunnel Diode

The interesting point of the characteristics starts at **point A** on the curve, i.e., the **peak voltage**. As the forward bias is increased beyond this point, the forward current drops and continues to drop until point B is reached. This is the **valley voltage.** At **B**, the current starts to increase once again and does so very rapidly as bias is increased further. Beyond this point, characteristics resembles that of an ordinary diode. Apart from the peak voltage and valley voltage, the other two parameters normally used to specify the diode behaviour are the peak current and the peak – to – valley current ratio, which are 2mA and 10 respectively.

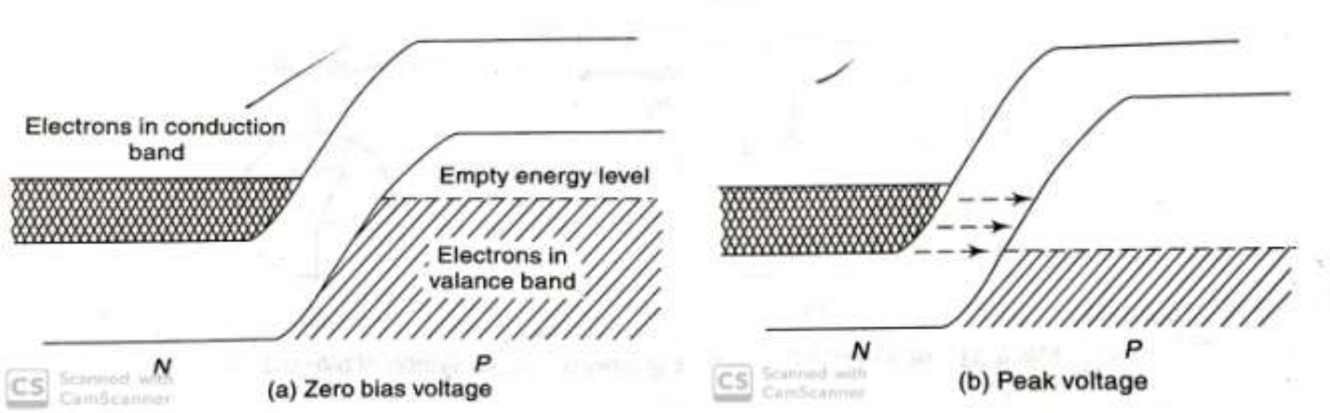
Exhibits dynamic resistance between A and B.

Energy Level:

Shaded areas - The energy states occupied by electrons in the valence band

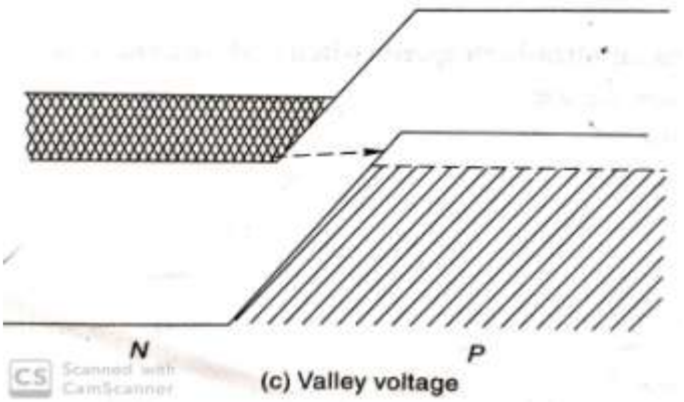
Cross hatched – Represent energy states in the conduction band occupied by the electrons.

Dotted lines – Levels to which the electrons are occupied by electrons on either side of the junctions



(a) Zero bias voltage

(b) Peak voltage



(c) Valley voltage

Fig: Energy Level diagrams of tunnel diode

When the **bias is zero** – lines are at the same height. Unless energy is imparted to the electrons from some external source, the energy possessed by the electrons on the N – side of the junction is insufficient to permit to climb over the junction barrier to reach the P – side. However, **quantum mechanics** show that there is a finite probability for the electrons to tunnel through the junction to reach the other side, provided there are allowed empty energy states in the P – side of the junction at the same energy level. Hence, the forward current is zero.

When a small **forward bias is applied** to the junction, the **energy level of the P – side is lower as compared with the N – side**. As shown the electrons in the conduction band of the N – side see empty energy level on the P – side. Hence**, tunneling from N – side to P – side takes place**. Tunneling in other direction is not possible because the valence band electrons on the P – side are now opposite to the forbidden energy gap on the N – side.

When the **forward bias is raised beyond this point**, tunneling will decrease as shown. The **energy of the P – side is now depressed** further, with the result that fewer conduction band electrons on the N – side are opposite to the unoccupied P – side energy levels. As the bias is raised, **forward current drops**. This corresponds to the **negative resistance region of the diode characteristics**. As forward bias is raised further, tunneling stopped altogether and it behaves as a normal PN junction diode.

Applications

- Tunnel diode is used as an ultra – high speed switch with switching speed of the order of ns or ps.
- As logic memory storage device
- As microwave oscillator
- In relaxation oscillator circuit
- As an amplifier

Advantages

- Low noise
- Ease of operation
- High Speed
- Low power

Disadvantages

- Voltage range over which it can be operated is less than 1V.
- Being a two-terminal device, there is no isolation between the input and output circuit.

LASER DIODE

Lasers are used to **convert the electrical signals to light signal**. In direct band gap materials where high recombination velocities exist, optical gain can be achieved by creating population inversion of carriers through high – level current injection and by forming a resonant cavity. This cavity is usually produced by the high Fresnel reflectivity obtained from cleaving the material along faces perpendicular to the junction plane.

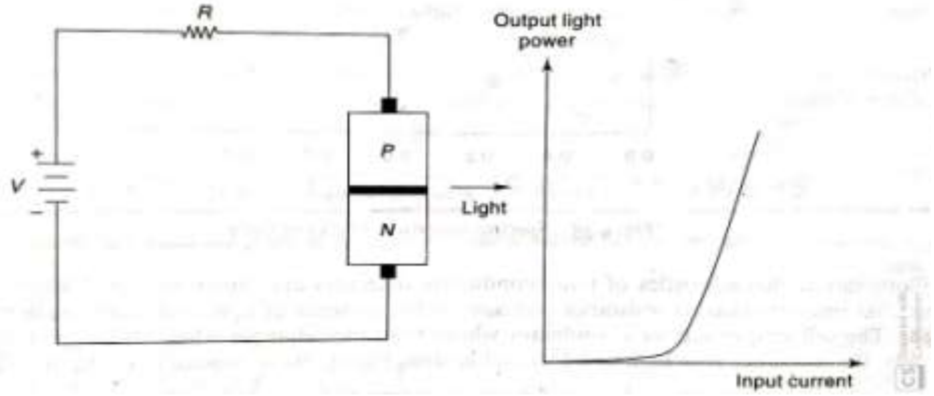


Fig: Structure and Characteristics of Laser diode

In this diode, opposite ends of the junction are polished to get mirror like surfaces. When free electrons recombine with holes, the emitted photons reflect and forth between the mirror surfaces. The region between the mirror ends acts like a cavity that filters the light and purifies its colour. As the photons bounce back and forth, they induce an Avalanche effect that causes all newly created photons to be emitted with the same phase. One of the mirror surfaces is semi-transparent. From this surface a fine thread like a beam of photons emerge out. All the photons of laser light have same frequency and phase and hence coherent.

It has well defined current threshold as seen from the power output vs drive current characteristics. Below this threshold the device exhibits low level spontaneous emission. At the limiting current density, stimulated emission occurs and the emitted radiation increases linearly with drive current.

LIGHT DEPENDENT RESISTOR

The bulk type photoresistor, photoconductive cell (PC) or photodetector is a two terminal device which is used as a Light Dependent Resistor (LDR). It is made of a thin layer of semiconductor material such as cadmium sulphide (CdS), lead sulphide (PbS), or cadmium selenide (CdSe) whose spectral responses are shown. The photo conducting device with the widest applications in the CdS cell, because it has high dissipation capability, with excellent sensitivity in the visible spectrum and low resistance when stimulated by light. The main drawback of CdS cell is its slower speed of response. PbS has the fastest speed of response.

The illumination characteristics of photoconductive detectors are shown in fig. It exhibits the peculiar property that its resistance decreases in the presence of light and increases in the absence of light. The cell simply act as conductor whose resistance changes when illuminated.