Chapter two

Semiconductor Diode

Germanium (Ge) and Silicon (Se)

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

The atomic number of germanium is 32. Therefore, a germanium atom has four valence electrons, i.e., it is a tetravalent element. Fig. 1(ii) shows how the various germanium atoms are held through covalent bonds. As the atoms are arranged in an orderly pattern, germanium has a crystalline structure.

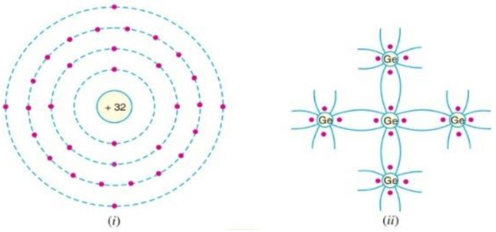

Fig.1 Germanium atomic system

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

The atomic number of silicon is 14. Silicon atom has four valence electrons, i.e., it is a tetravalent element. Fig. 2(ii) shows how various silicon atoms are held through covalent bonds. Like germanium, silicon semiconductor atoms are also arranged in an orderly manner. Therefore, silicon has a crystalline structure.

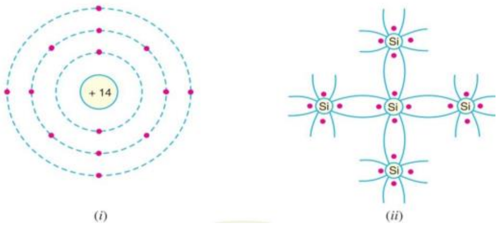

Fig.2 Silicon atomic system

Semiconductor Diode

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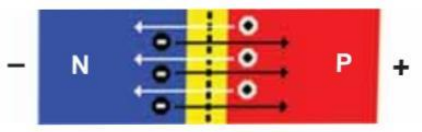
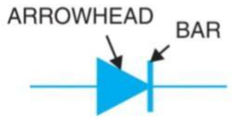
A pn junction is known as a semiconductor or crystal diode. Also, silicon and germanium diode is known as semiconductor or crystal diodes. The outstanding property of a crystal diode to conduct current in one direction only permits it to be used as a rectifier. A crystal diode is usually represented by the schematic symbol shown in Fig. The arrow in the symbol indicates the direction of easier conventional current flow.





A crystal diode has two terminals. When it is connected in a circuit, one thing to decide is whether the diode is forward- or reverse-biased. There is an easy rule to ascertain it. If the external circuit is trying to push the conventional current in the direction of the arrow, the diode is forward-biased. On the other hand, if the conventional current is trying to flow opposite to the arrowhead, the diode is reverse-biased. Putting in simple words:

(i) If the arrowhead of the diode symbol is positive with respect to the bar of the symbol, the diode is forward-biased.

(ii) If the arrowhead of the diode symbol is negative with respect to the bar, the diode is reverse-biased. Identification of crystal diode terminals. While using a crystal diode, it is often necessary to know which end is the arrowhead and which end is the bar. For this purpose, the following methods are available :

(i) Some manufacturers actually paint the symbol on the body of the diode, e.g., BY127, BY114 crystal diodes manufactured by BEL [See Fig. 3(i)].
(ii) Sometimes, red and blue marks are used on the body of the crystal diode. Red mark denotes arrow, whereas blue mark indicates bar, e.g., OA80 crystal diode [See Fig. 3 (ii)]

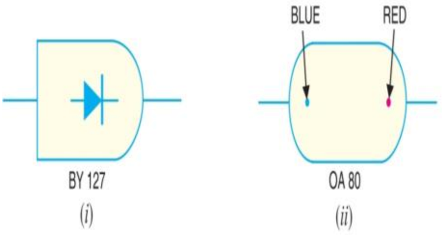


Fig.3 Diode symbols

pn Junction

When a p-type semiconductor is suitably joined to an n-type semiconductor, the contact surface is called a pn junction. Most semiconductor devices contain one or more p-n junctions. The pn junction is of great importance because it is, in effect, the control element for semiconductor devices. A thorough knowledge of the formation and properties of the pn junction can enable the reader to understand semiconductor devices.

Formation of a p-n junction

In actual practice, the characteristic properties of a p-n junction will not be apparent if a p-type block is just brought in contact with an n-type block. In fact, pn junctions are fabricated by special techniques. One common method of making a pn junction is called alloying. In this method, a small block of indium (trivalent impurity) is placed on an n-type Germanium slab as shown in Fig. 4 (i). The addition of indium overcomes the excess of electrons in the n-type germanium to such an extent that it creates a p-type region.

The system is then heated to a temperature of about 500°C. The indium and some of the Germanium melt to form a small puddle of molten germanium-indium mixture as shown in Fig. 4(ii). The temperature is then lowered, and puddles begin to solidify. Under proper conditions, the atoms of indium impurity will be suitably adjusted in the Germanium slab to form a single crystal.

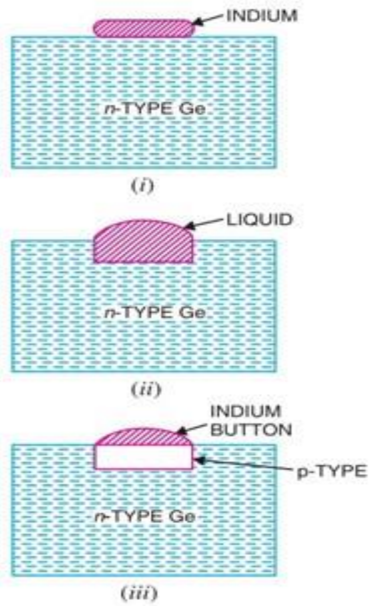


Figure: 4

As the process goes on, the remaining molten mixture becomes increasingly rich in indium. When all Germanium has been redeposited, the remaining material appears as an indium button, which is frozen onto the outer surface of the crystallized portion as shown in Fig. 4 (iii). This button serves as a suitable base for soldering on leads.

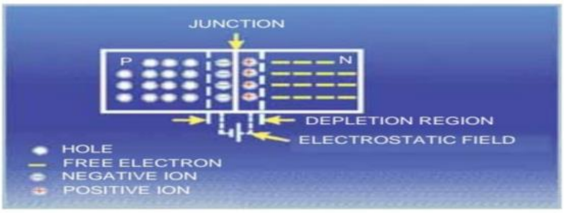


Figure: 5

Properties of a p-n Junction

At the instant of pn-junction formation, the free electrons near the junction in the n region begin to diffuse across the junction into the p region, where they combine with holes near the junction. The result is that n region loses free electrons as they diffuse into the junction. This creates a layer of positive charges (pentavalent ions) near the junction. As the electrons move across the junction, the p region loses holes as the electrons and holes combine. The result is that there is a layer of negative charges (trivalent ions) near the junction. These two layers of positive and negative charges form the depletion region (or depletion layer). The term depletion is due to the fact that near the junction, the region is depleted (i.e., emptied) of charge carriers (free electrons and holes) due to diffusion across the junction. It may be noted that the depletion layer is formed very quickly and is very thin compared to the n region and the p region. For clarity, the width of the depletion layer is shown exaggerated.

Once the pn junction is formed and the depletion layer created, the diffusion of free electrons stops. In other words, the depletion region acts as a barrier to the further movement of free electrons across the junction. The positive and negative charges set up an electric field. This is shown by a black arrow in Fig. 11 (i). The electric field is a barrier to the free electrons in the n-region. There exists a potential difference across the depletion layer, which is called the barrier potential (V_0). The barrier potential of a pn junction depends upon several factors, including the type of semiconductor material, the amount of doping, and temperature. The typical barrier potential is approximately: For silicon, $V_0 = 0.7$ V; For Germanium, $V_0 = 0.3$ V.

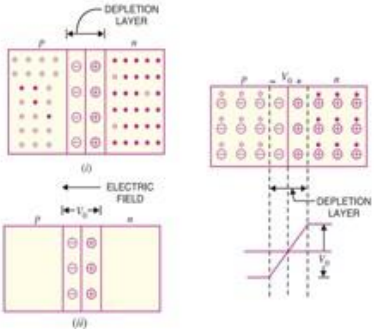


Fig. 11 shows the potential (V_0) distribution curve.

Forward and Reverse Bias

In relation to a pn junction, there are the following two bias conditions:

1. Forward biasing

2. Reverse biasing.

1. Forward biasing:

When external d.c. The voltage applied to the junction is in such a direction that it cancels the potential barrier, thus permitting current flow; it is called forward biasing.

To apply forward bias, connect the positive terminal of the battery to the p-type and the negative terminal to the n-type as shown in Fig. 6. The applied forward potential establishes an electric field that acts against the field due to the potential barrier. Therefore, the resultant field is weakened and the barrier height is reduced at the junction, as shown in Fig. 6. As the potential barrier voltage is very small (0.1 to 0.3 V), a small forward voltage is sufficient to eliminate the barrier. Once the potential barrier is eliminated by the forward voltage, the junction resistance becomes almost zero, and a low-resistance path is established for the entire circuit. Therefore, current flows in the circuit. This is called forward current.

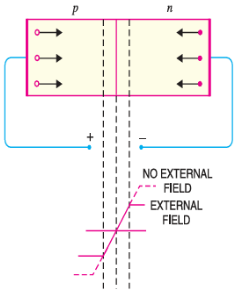


Fig. 6 Forward basing.

The following points are worth noting:

(i) The potential barrier is reduced and at some forward voltage (0.1 to 0.3 V), it is eliminated.

(ii) The junction offers low resistance (called forward resistance, R_f) to current flow.

(iii) Current flows in the circuit due to the establishment of a low-resistance path. The magnitude of the current depends upon the applied forward voltage.

2. Reverse biasing:

To apply reverse bias, connect the negative terminal of the battery to the p-type and the positive terminal to the n-type as shown in Fig. 7. Applied reverse voltage establishes an electric field which acts in the same direction as the field due to the potential barrier. Therefore, the resultant field at the junction is strengthened, and the barrier height is increased as shown in Fig. 7. The increased potential barrier prevents the flow of charge carriers across the junction. Thus, a high resistance path is established for the entire circuit, and hence the current does not flow. With reverse bias to the p-n junction, the following points are worth noting:

(i) The potential barrier is increased.

(ii) The junction offers very high resistance (called reverse resistance, Rr) to current flow.

(iii)No current flows in the circuit due to the establishment of a high-resistance path.

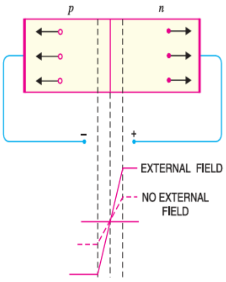
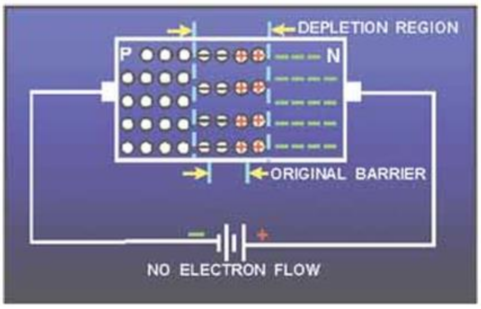


Fig.7 Reverse biasing.

Conclusion: From the above discussion, it follows that with reverse bias to the junction, a high resistance path is established, and hence no current flow occurs. On the other hand, with forward bias to the junction, a low resistance path is set up, and hence current flows in the circuit.



Volt-Ampere Characteristics of *pn* Junction

The volt-ampere or V-I characteristic of a *pn* junction (also called a crystal or semiconductor diode) is the curve between the voltage across the junction and the circuit current. Usually, voltage is taken along the x-axis and current along the y-axis. Fig. 8 shows the circuit arrangement for determining the V-I characteristics of a pn junction. The characteristics can be studied under three heads, namely: zero external voltage, forward bias, and reverse bias.

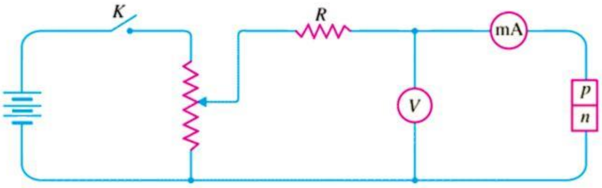


Fig.8 circuit arrangement for determining the V-I characteristics of a pn junction.

(i) Zero external voltage. When the external voltage is zero, i.e., the circuit is open at K, the potential barrier at the junction does not permit current flow. Therefore, the circuit current is zero as indicated by point O in Fig. 9.

(ii) Forward bias. With forward bias to the pn junction, i.e., p-type connected to the positive terminal and n-type connected to the negative terminal, the potential barrier is reduced. At some forward voltage (0.7 V for Si and 0.3 V for Ge), the potential barrier is altogether eliminated, and current starts flowing in the circuit. From now onwards, the current increases with the increase in forward voltage.

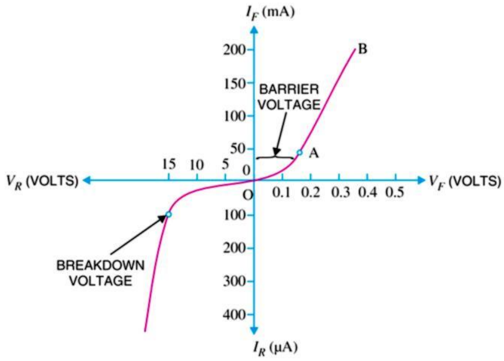


Fig.9 *I-V* characteristics of a pn junction diode.

Thus, a rising curve OB is obtained with forward bias as shown in Fig. 9. From the forward characteristic, it is seen that at first *(region OA),* the current increases very slowly and the curve is non-linear. It is because the externally applied voltage is used up in overcoming the potential barrier. However, once the external voltage exceeds the potential barrier voltage, the pn junction behaves like an ordinary conductor. Therefore, the current rises very sharply with an increase in external voltage *(region AB on the curve).*

(iii) Reverse bias. With reverse bias to the pn junction, i.e., p-type connected to the negative terminal and n-type connected to the positive terminal, the potential barrier at the junction is increased. Therefore, the junction resistance becomes very high and practically no current flows through the circuit. However, in practice, a very small current (of the order of μA) flows in the circuit with reverse bias as shown in the reverse characteristic.

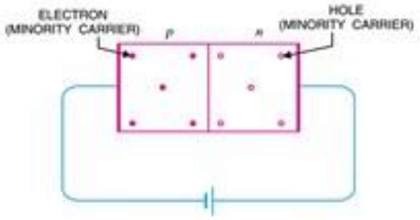
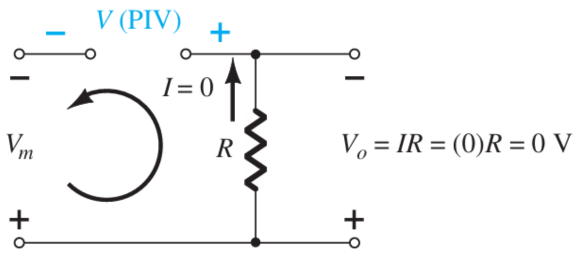


Fig. 10. The minority carriers in a p-n junction diode.

This is called *reverse saturation current (I_S)* and is due to the minority carriers. It may be recalled that there are a few free electrons in p-type material and a few holes in n-type material. These undesirable free electrons in p-type and holes in n-type are called minority carriers. As shown in Fig. 10, to these minority carriers, the applied reverse bias appears as forward bias. Therefore, a small current flows in the reverse direction. If the reverse voltage is increased continuously, the kinetic energy of electrons *(minority carriers)* may become high enough to knock out electrons from the semiconductor atoms. At this stage, *breakdown* of the junction occurs, characterized by a sudden rise of reverse current and a sudden fall of the resistance of the barrier region. This may destroy the junction permanently.

PIV Rating, Load Line & Q-point.

PIV: The peak inverse voltage (PIV) rating of the diode is of primary importance in the design of rectification systems. Recall that it is the voltage rating that must not be exceeded in the reverse-bias region, or the diode will enter the Zener avalanche region. The required PIV rating for the half-wave rectifier can be determined from the Figure.



Applying Kirchhoff's voltage law, it is fairly obvious that the PIV rating of the diode must equal or exceed the peak value of the applied voltage. Therefore,

$$PIV\ rating\ \geq V_m$$

Fig. 12. Determining the required PIV rating for the half-wave rectifier.

LOAD LINE ANALYSIS:

In Fig. 13, the diode characteristics are plotted on the same set of axes as a straight line defined by the network's parameters.

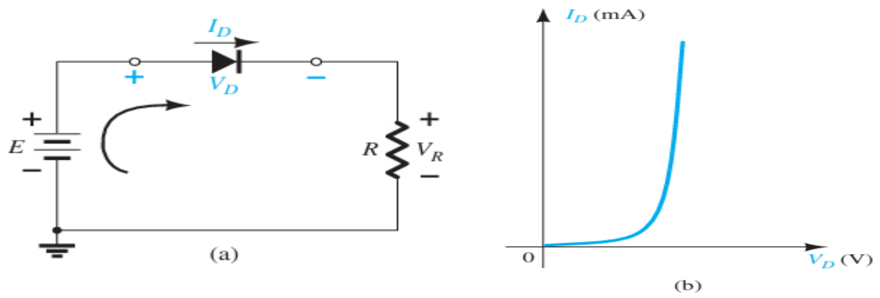


Fig. 13. Series diode configuration (a) circuit (b) characteristics

The straight line is called a load line because the intersection on the vertical axis is defined by the applied load R. The analysis that follows is therefore referred to as load-line analysis. The intersection of the two curves defines the solution for the network, determining the current and voltage levels within it.

Before reviewing the details of drawing the load line on the characteristics, we need to determine the expected response of the simple circuit of Fig. 14.

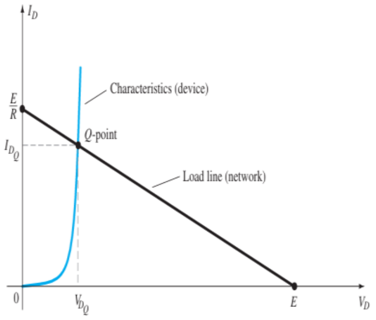


Fig. 14. Drawing the load line and finding the point of operation.

Applying KVL, we may write,

$$E = V_D + I_D R \ \ldots\ldots\ldots\ldots\ldots (2.1)$$

The two variables of Eq. (2.1), V_D and I_D, are the same as the diode axis variables of Fig. 14. This similarity permits plotting Eq. (2.1) on the same characteristic of Fig. 14.

The intersections of the load line on the characteristics can easily be determined if one simply employs the fact that, anywhere on the horizontal axis $I_D = 0$ A and anywhere on the vertical axis $V_D = 0\,V$. If we set $V_D = 0\,V$ in Eq. (2.1) and solve for I_D, we have the magnitude of I_D on the vertical axis. Therefore, with $V_D = 0\,V$, Eq. (2.1) becomes

$$E = V_D + I_D R$$

$$= 0\,V + I_D R$$

And

$$I_D = \frac{E}{R}\Big|_{\,V_D = 0V} \ \ldots\ldots\ldots\ldots\ldots\ldots (2.2)$$

As shown in Fig. 2.2. If we set I_D= 0 A in Eq. (2.1) and solve for V_D, we have the magnitude of V_D on the horizontal axis. Therefore, with $I_D = 0$ A, Eq. (2.1) becomes

$$E = V_D + I_D R$$

$$= V_D + (0\ A)R$$

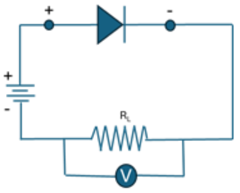
And

$$V_D = E|_{I_D = 0\ A} \quad ……….. (2.3)$$

As shown in Fig. 14, a straight line drawn between the two points defines the load line, as depicted in Fig. 14. Changing the level of R (the load) changes the intersection on the vertical axis. The result will be a change in the slope of the load line and a different point of intersection between the load line and the device characteristics.

The point of intersection between the two is the point of operation for this circuit. The point of operation is usually called the quiescent point (abbreviated "Q point") to reflect its "still, unmoving" qualities as defined by a DC network.

Maximum Current and Power Dissipation Rating

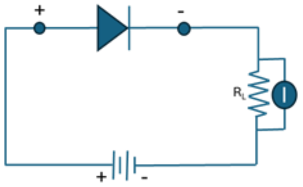


Maximum Current: The maximum current of a diode, typically referred to as the maximum forward current, is the highest continuous current that the diode can safely conduct in the forward-bias condition without being damaged or overheated. Finally, we can say that the maximum current in a diode means the highest amount of current that can safely flow through the diode in the forward direction without damaging it. $\mathbf{I_F}$

Power dissipation rating: The power dissipation of a diode is the amount of heat generated in the diode due to the current flowing through it and the voltage drop across it.

$$P_{\textbf{dissipation}} = V_F * I_F$$

$$P_D = V_D * I_D$$

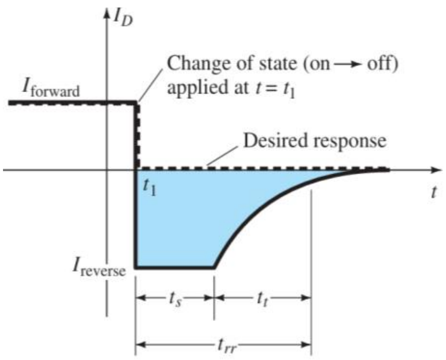


The power rating is the maximum power the diode can safely dissipate without shortening its life or degrading its properties.

$$P_{max} = I_{max} * I_{max}$$

The Reverse Recovery Time

There are certain pieces of data that are normally provided on diode specification sheets provided by manufacturers. One such quantity that has not been considered yet is **the reverse recovery time,** denoted by t_{rr}. In the forward-bias state, it was shown earlier that there are a large number of electrons from the n-type material progressing through the p-type material and a large number of holes in the n-type material — a requirement for conduction.



The electrons in the p-type material and holes progressing through the n-type material establish a large number of minority carriers in each material. If the applied voltage should be reversed to establish a reverse-bias situation, we would ideally like to see the diode change instantaneously from the conduction state to the non-conduction state. However, because of the large number of minority carriers in each material, the diode current will simply reverse as shown in the figure and stay at this measurable level for the Period of time $\boldsymbol{t_s}$ **(storage time)** required for the minority carriers to return to their majority-carrier state in the opposite material. In essence, the diode will remain in the short-circuit state with a current $\boldsymbol{I_{reverse}}$ determined by the network parameters.

Eventually, when this storage phase has passed, the current will be reduced in level to that associated with the non-conduction state. This second period is denoted by $\boldsymbol{t_t}$ **(transition interval).** The reverse recovery time is the sum of these intervals: $\boldsymbol{t_{rr} = t_s + t_t}$ .This is an important consideration in high-speed switching applications. Most commercially available switching diodes have a t_{rr} in the range of a few nanoseconds to $1\mu s$. Units are available, however, with a t_{rr} of only a few hundred picoseconds (10^{-12}s).

Zener Diode

It has already been discussed that when the reverse bias on a crystal diode is increased, a critical voltage, called the breakdown voltage, is reached, where the reverse current increases sharply to a high value. The breakdown region is the knee of the reverse characteristic as shown in Fig. 15. The satisfactory explanation of this breakdown of the junction was first given by the American scientist C. Zener. Therefore, the breakdown voltage is sometimes called the zener voltage, and the sudden increase in current is known as the zener current. The breakdown or zener voltage depends upon the amount of doping. If the diode is heavily doped, the depletion layer will be thin, and consequently, the breakdown of the junction will occur at a lower reverse voltage. On the other hand, a lightly doped diode has a higher breakdown voltage. When an ordinary crystal diode is properly doped so that it has a sharp breakdown voltage, it is called a zener diode.

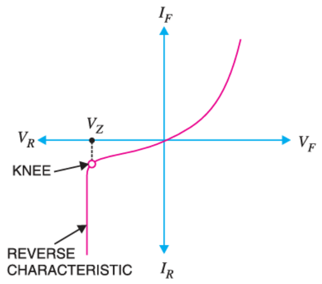


Fig. 15 The breakdown region is the knee of the reverse characteristic

A properly doped crystal diode that has a sharp breakdown voltage is known as a zener diode.

Figure 1 shows the symbol of a zener diode. It may be seen that it is just like an ordinary diode except that the bar is turned into a Z-shape. The following points may be noted about the Zener diode:

(i) A zener diode is like an ordinary diode except that it is properly doped so as to have a sharp breakdown voltage. Fig. 15.

(ii) A zener diode is always reverse connected i.e., it is always reverse biased.

(iv) A zener diode has a sharp breakdown voltage, called zener voltage V_Z.

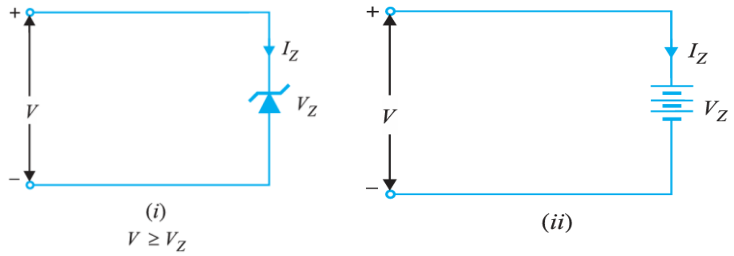
(v) When forward-biased, its characteristics are just those of an ordinary diode.

(vi) The zener diode is not immediately burnt just because it has entered the *breakdown region. As long as the external circuit connected to the diode limits the diode current to less than the burnout value, the diode will not burn out.

Equivalent Circuit of Zener Diode

The analysis of circuits using zener diodes can be made quite easily by replacing the zener diode with its equivalent circuit.

(i) "On" state. When reverse voltage across a zener diode is equal to or more than the breakdown voltage V_Z, the current increases very sharply. In this region, the curve is almost vertical. It means that the voltage across the zener diode is constant at V_Z even though the current through it changes. Therefore, in the breakdown region, an ideal zener diode can be represented by a battery of voltage V_Z as shown in Fig. 16 (ii). Under such conditions, the zener diode is said to be in the "ON" state.

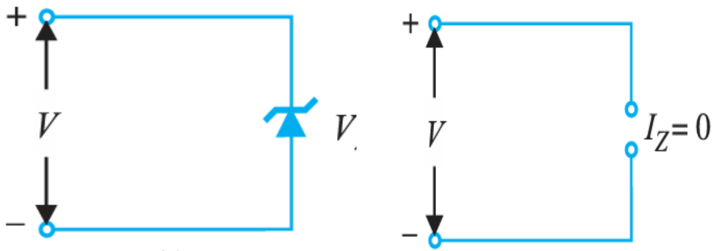


(i)
$V \geq V_Z$

(ii)
Equivalent circuit of zener for "on" state

Fig. 16

(ii) "OFF" state. When the reverse voltage across the zener diode is less than V_Z but greater than 0 V, the zener diode is in the "OFF" state. Under such conditions, the zener diode can be represented by an open circuit as shown in Fig. 17 (ii).



(i)
$V_Z > V > 0$

(ii)
Equivalent circuit of the zener for the "off" state

Fig. 17

Zener Diode as Voltage Stabilizer

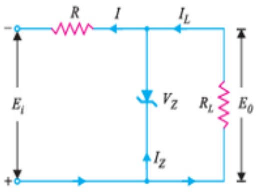


Fig. 18 (i)

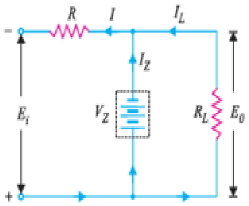


Fig. 18(ii)

A zener diode can be used as a voltage regulator to provide a constant voltage from a source whose voltage may vary over a sufficient range. The circuit arrangement is shown in Fig. 18 (*i*). The zener diode of zener voltage V_Z is reverse connected across the load R_L, across which a constant output is desired.

The series resistance *R* absorbs the output voltage fluctuations so as to maintain a constant voltage across the load. It may be noted that the zener will maintain a constant voltage V_Z $(= E_0)$ across the load so long as the input voltage does not fall below V_Z. When the circuit is properly designed, the load voltage E_0

remains essentially constant (equal to V_Z) even though the input voltage E_i and resistance R_L may vary over a wide range.

(i) Suppose the input voltage increases. Since the zener is in the breakdown region, the zener diode is equivalent to a battery V_Z as shown in Fig. 18 (ii). It is clear that the output voltage remains constant at V_Z $(= E_0)$. The excess voltage is dropped across the series resistance R. This will cause an increase in the value of total current I. The zener will conduct the increase of current in I while the load current remains constant. Hence, output voltage E_0 remains constant irrespective of the changes in the input voltage Ei.

(ii) Now, suppose that the input voltage is constant but the load resistance R_L decreases. This will cause an increase in load current. The extra current cannot come from the source because a drop in R (and hence source current I) will not change as the zener is within its regulating range. The additional load current will come from a decrease in zener current I_Z. Consequently, the output voltage stays at a constant value.

Voltage drops across $R = Ei - E_0$

Current through R, $I = I_Z + I_L$

Applying Ohm's law, we have,

$$R = \frac{E_i - E_0}{I_Z + I_L}$$

Light Emitting Diode (LED)

A **light-emitting diode (LED)** is a diode that gives off visible light when forward-biased. Light-emitting diodes are not made from silicon or germanium but are made by using elements like gallium, phosphorus, and arsenic. By varying the quantities of these elements, it is possible to produce light of different wavelengths with colors that include red, green, yellow, and blue. For example, when an LED is manufactured using gallium arsenide, it will produce a red light. If the LED is made with gallium phosphide, it will produce a green light.

Figure 19. Light Emitting Diode

Theory: When a light-emitting diode (LED) is forward biased, as shown in **Fig. 19**, the electrons from the n-type material cross the p-n junction and recombine with holes in the p-type material. Recall that these free electrons are in the conduction band and at a higher energy level than the holes in the valence band.

When recombination takes place, the recombining electrons release energy in the form of heat and light. In germanium and silicon diodes, almost the entire energy is given up in the form of heat, and the emitted light is insignificant. However, in materials like gallium arsenide, the number of photons of light energy is sufficient to produce quite intense visible light.

Fig. 20 shows the schematic symbol for an LED. The arrows are shown as pointing away from the diode, indicating that light is being emitted by the device when forward-bias. Although LEDs are available in several colours (red, green, yellow, and orange are the most common), the schematic symbol is the same for all LEDs. There is nothing in the symbol to indicate the colour of a particular LED.

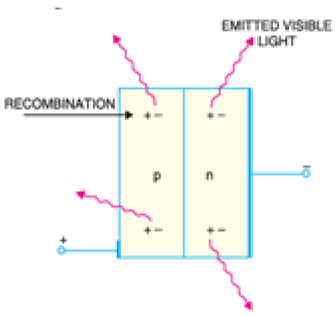


Figure 20 (i)

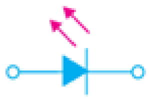


Fig. 20(ii)

Fig. 21 shows the graph between radiated light and the forward current of the LED. It is clear from the graph that the intensity of radiated light is directly proportional to the forward current of the LED

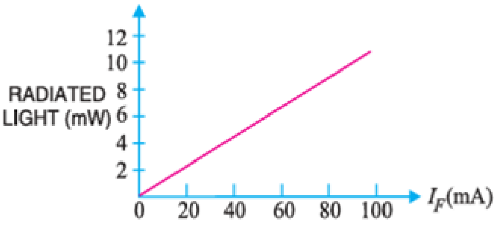


Figure 21

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