36
P-N Junction Diode

36.1 P-N JUNCTION

When a p-type semiconductor is suitably joined to n-type semiconductor, the contact surface is called pn junction.

Most semiconductor devices contain one or more pn junction. A thorough knowledge of the properties of pn junction can enable the reader to understand the semiconductor devices.

36.2 PROPERTIES OF P-N JUNCTION

Consider one p-type and other n-type of semiconductor as shown in Fig. 36.1. In the figure, left side material is a p-type semiconductor having negative acceptor ions and positively charged holes. The right side material is n-type semiconductor having positive donor ions and free electrons.

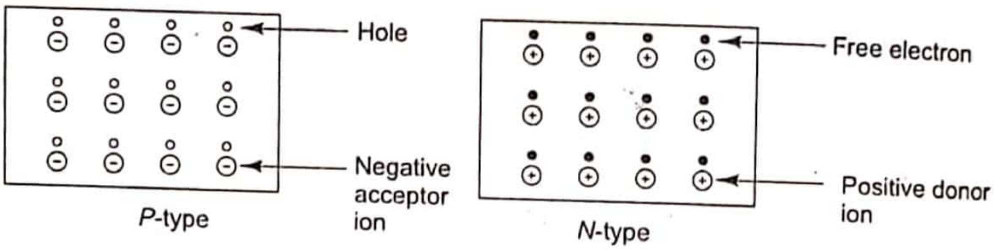

Fig. 36.1

Now, suppose the two pieces are suitably treated to form pn junction. Keep in mind that n-type material has a high concentration of free electrons while p-type material has a high concentration of holes. Therefore, at the junction, there is a tendency for electrons to diffuse over to p-side and holes to n-side. This process is called diffusion and gives rise to *conventional current* or *diffusion current.*

As holes continue to leave the p-side, some of the negative acceptor ions near the junction are left uncompensated. Similarly, some of the positive donor ions near the junction are left uncompensated as the electrons leave the n-side. Consequently, a negative space charge forms near the p-side of the junction and a positive space charge forms near the n-side (Fig. 36.2).

When a sufficient number of holes and electrons have crossed the junction, further diffusion is prevented. It is because now positive charge on n-side repels holes to cross from p-side to n-side and negative charge on p-side repels the electrons to enter from n-side to p-side. Thus, a barrier is set up against further movement of charge carriers i.e., holes and electrons. This is called *potential barrier* or *junction barrier* V_0. The potential barrier is of the order of 0.1 to 0.3 volts. The potential distribution diagram is shown in Fig. 36.2. It is clear from the diagram that a potential barrier V_0 is set up which gives rise to electric field. This field prevents the respective majority carriers from crossing the barrier region.

However, this field allows the few holes in the *n*-material to shift from *n* to *p* and the few electrons in the *p*-material to shift from *p* to *n*, both giving rise to *drift current* from *n* to *p* in a direction opposite to the *diffusion current.*

At equillibrium, drift and diffusion currents for each type of carriers (holes as well as electrons) separately cancel each other and there is no net current.

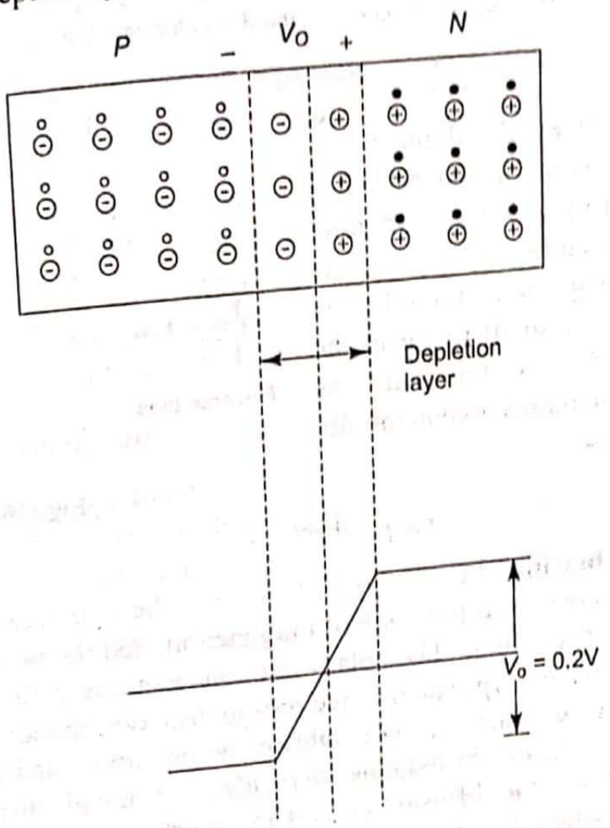

Fig. 36.2

36.3 THE P-N JUNCTION AS A RECTIFIER

The essential electrical characteristics of a *p–n* junction is that it constitutes a rectifier which permits the easy flow of charge in one direction but restrains the flow in opposite direction. The potential difference across the *pn* junction can be applied in two ways, namely; *forward biasing* and *reverse biasing.*

1. **Forward biasing:** An external voltage applied with the polarity such that negative terminal of the battery is connected to *n* side of the junction and the positive terminal to *p*-side, is called a *forward bias* (Fig. 36.3). For such a biasing, the height of the potential barrier at the junction will be lowered and the diffusion current due to both electrons and holes, increases rapidly. The current *I* is related to the voltage *V* by the equation.

$$I = I_s \left(e^{qV/nkT} - 1\right) \tag{36.1}$$

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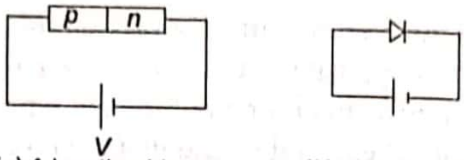
Here V is the applied voltage, q is the charge on an electron, k is the Boltzmann's constant, T is the absolute temperature, $n = 1$ for Ge and 2 for Si and I_s is the reverse saturation current.



(*a*) A junction biased in forward direction

(*b*) The diode symbol used with forward biasing

Fig. 36.3

For zero external voltage $I = 0$; as V increases, I increases. When V is positive and large, the unity in the parenthesis of eqn. (36.1) may be neglected. Accordingly, except for a small range in the neighbourhood of the origin, the current increases exponentially with voltage,

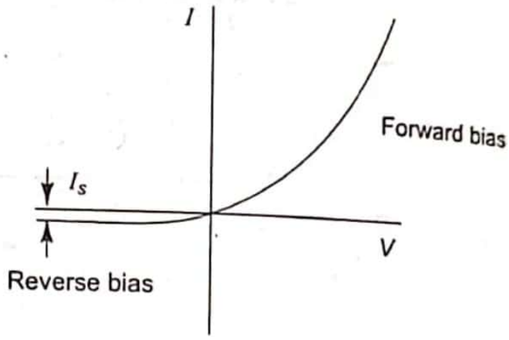
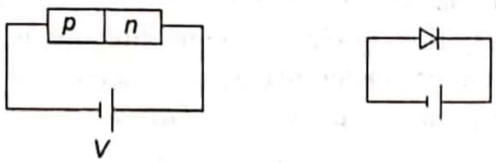


Fig. 36.4

$$I = I_s\, e^{qV/nkT} \tag{36.2}$$

2. **Reverse biasing:** In this type of biasing, the negative terminal of the battery is connected to p-side of the junction, and the positive terminal to the n-side (Fig. 36.5). The polarity of connection is such as to cause both the holes in the p type and the electrons in the n type to move away from the junction. Consequently, the height of the potential barrier increases. No electrons in the n-side and holes in p-side have enough energy to cross this barrier. Hence the diffusion current is almost negligible for reverse bias. However when the reverse applied voltage is considerably large, $I \approx -I_0$ (Eqn. 36.1). The reverse current is therefore constant, independent of the applied reverse bias. Consequently, I_s is referred to as the *reverse saturation current*.



(*a*) A junction biased in reverse direction

(*b*) The diode symbol used with reverse biasing

Fig. 36.5

Experiment 36.1: To draw the V-I characteristics of a forward and reverse biased *p-n* junction diode.

Apparatus: A junction diode, a rheostat, Power Supply (10 volts DC) and

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For Forward bias—DC voltmeter (0–2V), DC milliammeter (0–100 mA)
For Reverse bias—DC voltmeter (0–10V), DC micro-ammeter (0–100 μA)

Theory: Already discussed.

Procedure: ***Forward-bias Characteristics***

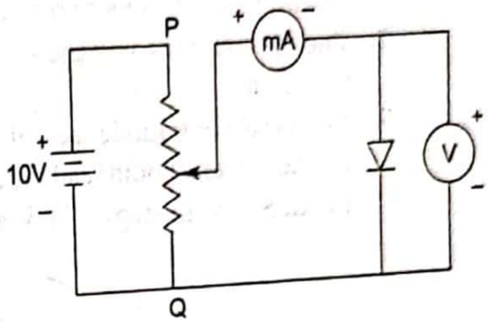

Fig. 36.5

1. Connect the junction diode in forward biased mode as shown in the circuit diagram of Fig. 36.5.
2. Keeping the sliding contact of the rheostat towards *Q*, switch on the power supply. The voltmeter will show zero.
3. Increase the voltage in steps of 0.1 V by moving the sliding contact of the rheostat and record the voltmeter and milliammeter readings. Take observations till the milliammeter reads about 100 mA.

Reverse-bias Characteristics

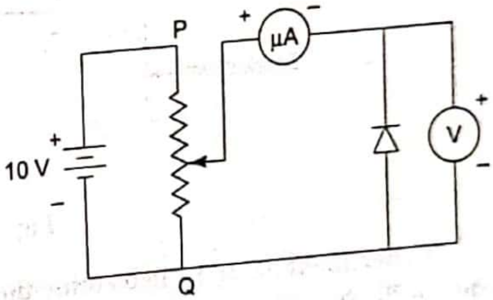

Fig. 36.6

4. Connect the junction diode in reverse bias mode as shown in the circuit diagram of Fig. 36.6.
5. Keeping the sliding contact of the rheostat towards *Q*, switch on the power supply. Increase the voltage across the diode in steps of 1 volt by moving the sliding contact of the rheostat and record the voltmeter and micro-ammeter readings.
6. Draw forward voltage and current respectively along +*x* and +*y*-axis choosing a suitable scale. Also draw on the same graph paper, the reverse voltage and current respectively along –*x* and –*y*-axes choosing another suitable scale.

Observations

S.No.	*Forward bias*		*Reverse bias*	
	Voltage (V)	*Current (mA)*	*Voltage (V)*	*Current (μA)*
1.				
2.				
3.				
.				
.				
.				

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Result: The forward bias and reverse bias characteristic curves are drawn for the given junction diode (Fig. 36.7).

Precautions and Sources of Error

1. In both forward-bias and reverse-bias, the sliding contact of the rheostat should be kept to its minimum before switching on the power supply.
2. The reverse-bias voltage should be kept below the breakdown voltage of the diode.
3. In forward bias mode the voltage should be increased in steps of 0.1 V and a milliammeter should read the current. In reverse bias mode the voltage should be increased in steps of 1 V and a microammeter should read the current.

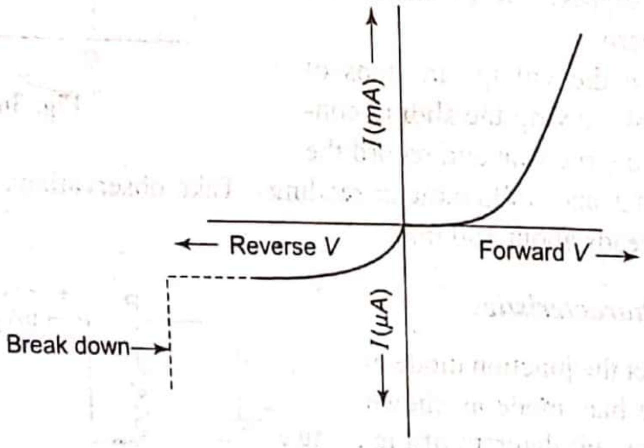

Fig. 36.7

Experiment 36.2: To determine the value of Boltzmann's constant using a semiconductor diode.

Apparatus: A p-n-junction diode, a DC power supply (5 volts), a rheostat, a milliammeter (0–20 mA), a voltmeter (0–2 volt) and connecting wires.

Theory: When a positive potential is applied to the *p*-side of a *p–n* junction diode with respect to its *n*-side, the diode is said to be forward-biased as discussed earliar. If V is the voltage across the junction, the diode current I is given by

$$I = I_s \left[\exp \frac{qV}{nkT} - 1 \right] \tag{36.8}$$

where I_s is the reverse saturation current, q is the electronic charge, k is the Boltzmann constant, T is the absolute temperature, and n is a numerical constant depending on the material of the diode. For germinium $n = 1$, and for silicon $n = 2$.

For a silicon diode at room temperature ($T = 300°K$) Eqn. (36.8) reduces to

$$I = I_s [\exp (19.3\ V) - 1] \tag{36.9}$$

where V is the voltage across the diode in volts.

For a positive voltage of value 0.5 – 1 V, the exponential term varies from 1.55×10^4 to 2.41×10^8. Hence in this voltage range or above it, we can easily neglect '1' in Eqn. (36.8) as compared to the exponential term and can write,

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$$I = I_s \exp\left(\frac{qV}{nkT}\right)$$

or

$$\log_{10} I = \log_{10} I_s + \frac{qV}{2.303\,nkT}$$

So a plot of $\log_{10} I$ versus V gives $\frac{q}{2.303\,nkT}$ as the slope from which the Boltzmann constant k can be evaluated easily.

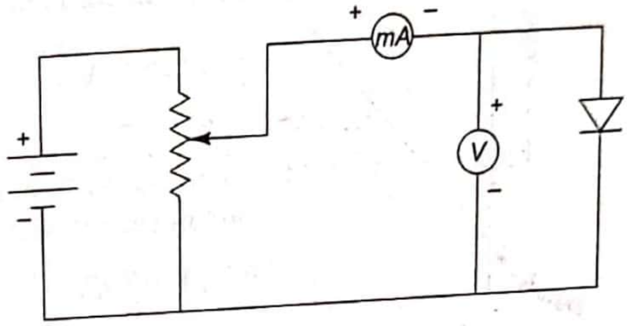

Fig. 36.8

Procedure

1. Make the connections as shown in Fig. (36.8) with p–n diode in the forward bias mode. (A variable dc-supply can also be used in place of the fixed supply and the rheostat)
2. Slowly increase the input voltage from zero in convenient steps, and note the voltage V across the diode and the current I through it. Take readings till the current is about 20 mA. To get a large number of readings voltmeter and milliammeter should be of low least counts. A digital multimeter can also be used for the purpose.
3. Plot a graph between V along x-axis and $\log_{10} I$ along y-axis.

Observations

Temperature T = ... °K

S. No.	*Voltage, V (volts)*	*Current (mA)*	*Current I, (in Ampere)*	*$\log_{10} I$*
1.				
2.				
3.				
.				
.				
.				

Calculations:

The graph between V and $\log_{10} I$ is a straight line as shown in Fig. (36.9). Calculate its slope.

[Note: The $\log_{10} I$ are negative values. So the graph is actually in the fourth quadrant but the slope remains positive. (Fig. 36.9)].

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Bolzmann's constant k is calculated from the formula

$$k = \frac{q}{2.303\,nT} \times \frac{1}{\text{slope}}$$

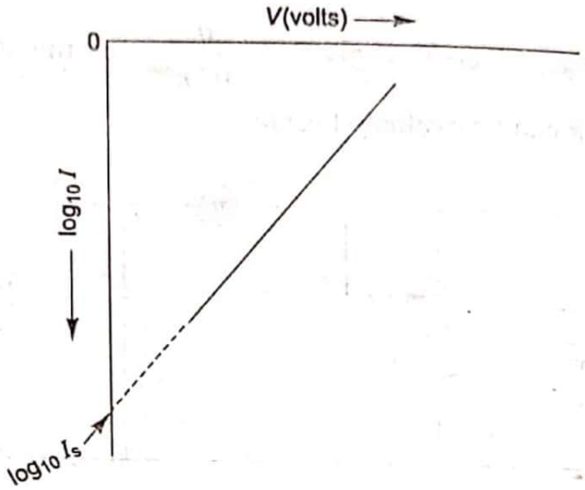

Fig. 36.9

Thus for a silicon diode at 300 K

$$k = \frac{11.59 \times 10^{-23}}{\text{slope}}$$

$$= \ldots\ JK^{-1}$$

Result: The experimentally obtained value of Boltzmann's constant

$= \ldots\ JK^{-1}$

Standard value = ... $1.38 \times 10^{-23}\ JK^{-1}$

% Error = ... %

Precautions and Sources of Error

1. Ensure that p-side is made positive w.r.t the n-side.
2. Increase the supply voltage slowly from zero. Take care that the input voltage does not increase excessively; the safe value for BY 127 is about 2 V. Otherwise, the diode current will be harmfully large.
3. The temperature T should be noted down in Kelvin.
4. It should be remembered that in Eqn. (36.8) $n = 1$ for germanium diode and 2 for silicon diode.

Note: We can determine the reverse saturation current I_s at room temperature as the y-intercept in Fig. 36.9 gives $\log_{10} I_s$ from which I_s can be found.

36.4 REVERSE SATURATION CURRENT

The reverse saturation current is due to minority carriers which have to climb down the potential barrier and hence is independent of the applied voltage V. The magnitude of the reverse saturation current I_s depends only on the rate of generation