The P-N Junction

3.1 Introduction

When a *p*-type and an *n*-type semiconductor are brought together in close contact, the boundary of the interface where the two types meet is called the ***p*-*n* junction**.

A useful *p*-*n* junction cannot be constructed merely by welding a piece of *p*-type material against another piece of *n*-type semiconductor as this will introduce a grain boundary i.e., a discontinuity across the junction. There are two principal techniques of fabricating a *p*-*n* junction : (i) *grown junction* and (ii) *fused junction*, into the details of which we shall not enter. The *p*-*n* junctions are created by doping one side of a single crystal semiconductor with acceptors and the other side with donors. A *p*-*n* junction is thus a two-terminal device and is known as a ***junction diode***. Most of the semiconductor devices contain one or more *p*-*n* junctions because of its effective role as a control element. So, the *p*-*n* junctions are elementary 'building blocks' of almost all the semiconductor devices like transistors, LEDs, ICs, solar cells etc.

3.2 Unbiased *p*-*n* junction

In a *p*-type semiconductor, holes are the majority carriers and in an *n*-type semiconductor electrons are the majority carriers. When a *p*-*n* junction is formed (Fig 3.1(a)), electrons from *n*-region diffuse into *p*-region and holes from *p*-region diffuse into *n*-region due to the difference in carrier concentration. During the process of diffusion, the electrons recombine with the holes in the *p*-side after crossing the junction, leaving behind the positively charged immobile donor ions in *n*-region. The hole in their turn cross the junction to recombine with the electrons in the *n*-region, leaving behind the negatively charged immobile acceptor ions in the *p*-region.

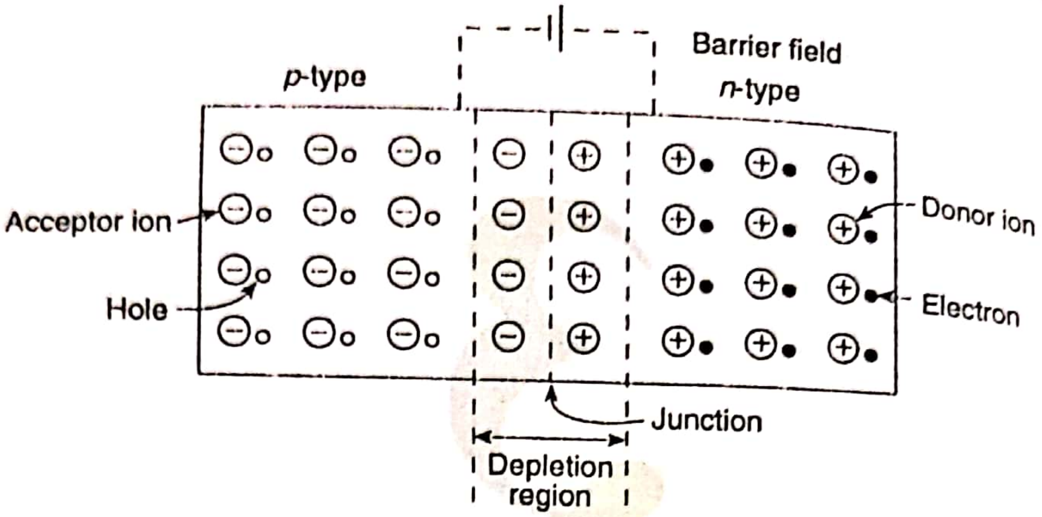


Fig. 3.1 Schematic diagram of a p-n junction

As a consequence of the diffusion and recombination, non-neutralized ions are left in the neighbourhood of the junction. Since the region near the junction becomes deprived of the mobile charge carriers (electrons or holes) and contains only the immobile ions, it is called the ***depletion region*** or *the space charge region.* It is also called *transition region.* The thickness of depletion region is $\sim 10^{-6}$ m. The non-neutralized positive and negative charges produce an electric field across the junction directed from *n*-side to the *p*-side. This field is called *potential barrier* or ***barrier field*** which opposes further diffusion of electrons and holes through the junction. In equilibrium, the internal barrier field is just sufficient to prevent diffusion of majority charge carriers. However, it is to be noted that the field helps the minority carriers to move across the junction and a very small amount of current flows. The potential barrier V_b acts as a *fictitious* battery connected respectively with its positive terminal to *n*-side and negative terminal to *p*-side. The circuit symbol of a *p-n* junction diode is shown in Fig. 3.2 where the arrowhead is in the direction of current flow when the *p*-side and the *n*-side are connected respectively to the positive and negative pole of a battery.

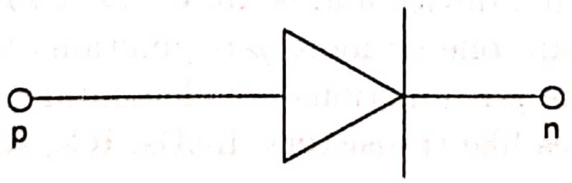


Fig. 3.2 Circuit symbol of a p-n junction diode

- It is worthnoting that the depletion region is a region over which the bulk properties of the *p* or *n*-region are *not* applicable.

on the n-side so that equilibrium is established on equating E_F in both sides such that no current flows through the junction. The energy band diagram of an unbiased p-n junction is shown in Fig. 3.3.

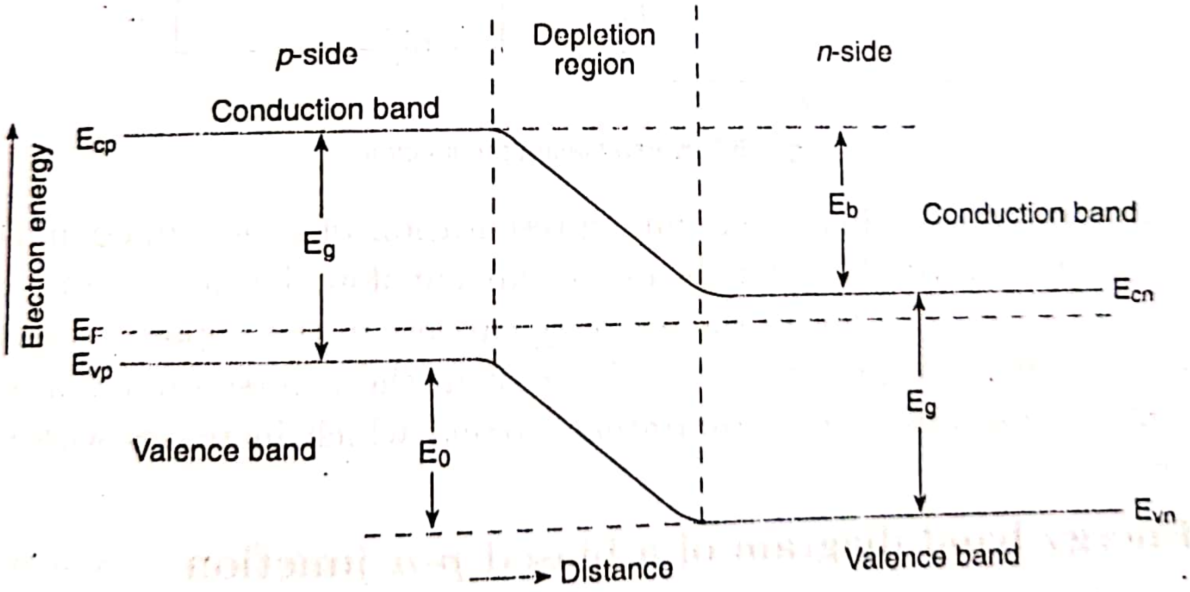


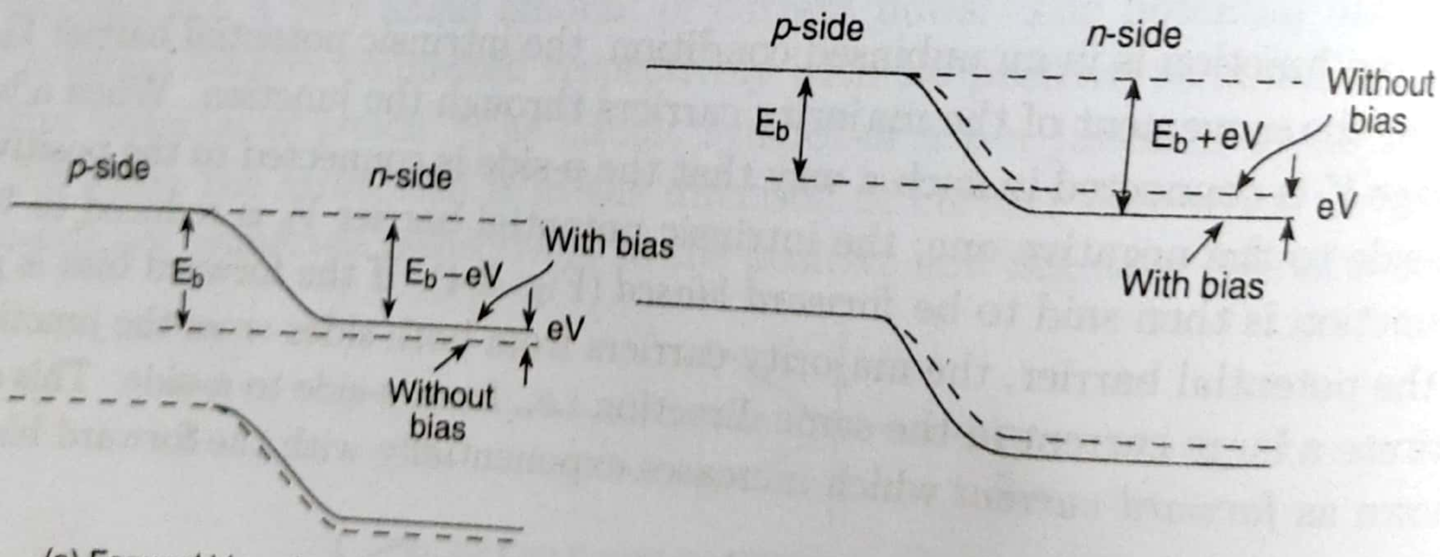
Fig. 3.3 Energy-band diagram of an unbiased p-n junction

The energy barrier E_b for electrons in crossing the junction from the n-side to the p-side is given by

$$\boxed{E_b = E_{cp} - E_{cn}} \tag{3.2.1}$$

3.3.1 Energy band diagram of a biased p-n junction

In an unbiased p-n junction under thermal equilibrium, the energy bands are separ by a barrier energy E_b as shown in Fig. 3.3. When the junction is forward biased voltage V, the energy barrier is reduced to a value $E_b - eV$ and the Fermi levels on either side are shifted by an energy eV. This causes the majority carriers on ei side to cross the reduced barrier and diffuse into other side so that a large compon of diffusion current-flow in the forward direction is obtained. The minority carr constitute a very small current due to their random thermal motion. The energy ba diagram of a forward biased p-n junction is shown in Fig. 3.6(a).



(a) Forward biased

(b) Reverse biased

Fig. 3.6 Energy diagram of a biased p-n junction

When however a p-n junction is reverse biased by

3.4 Current-voltage characteristic of a *p-n* junction

The total current I flowing through a p-n junction under the application of a voltage V across it, is given by the following equation known as ***diode equation*** :

$$I = I_s\left(e^{\frac{eV}{\eta kT}} - 1\right) \qquad (3.4.1)$$

where I_s is the reverse saturation current, e is the electronic charge, k is the Boltzmann constant, T the absolute temperature of the junction and η is a dimensionless constant known as *emission coefficient* or *ideality factor* having a value between 1 and 2, depending on the semiconductor material. For Ge, $\eta \approx 1$ and for Si, $\eta \approx 2$. The plot of current *versus* voltage across the junction is called the *I-V characteristic* of a *p-n* junction diode.

3.4.1 Forward biased characteristics

To understand the nature of the forward bias characteristics, we use positive value of V in (3.4.1). When the forward voltage V is much greater than kT/e, equation (3.4.1) is approximated as

$$I = I_s e^{\frac{eV}{\eta kT}} \qquad (3.4.2)$$

which shows that the forward current increases exponentially with the bias voltage.

- The quantity (kT/e) is called the *thermal voltage*.

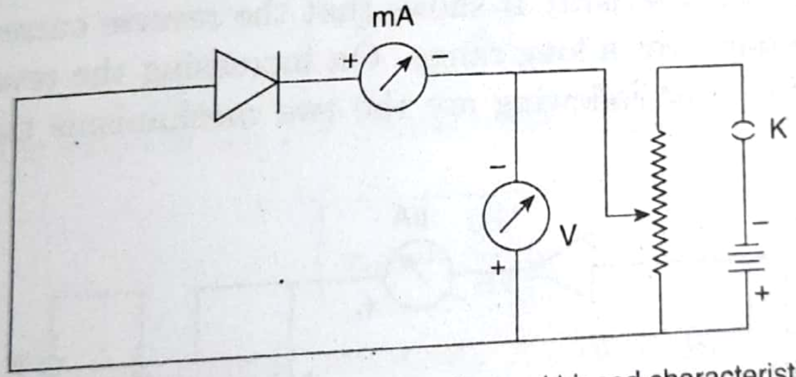


Fig. 3.7 Circuit diagram for studying forward biased characteristics

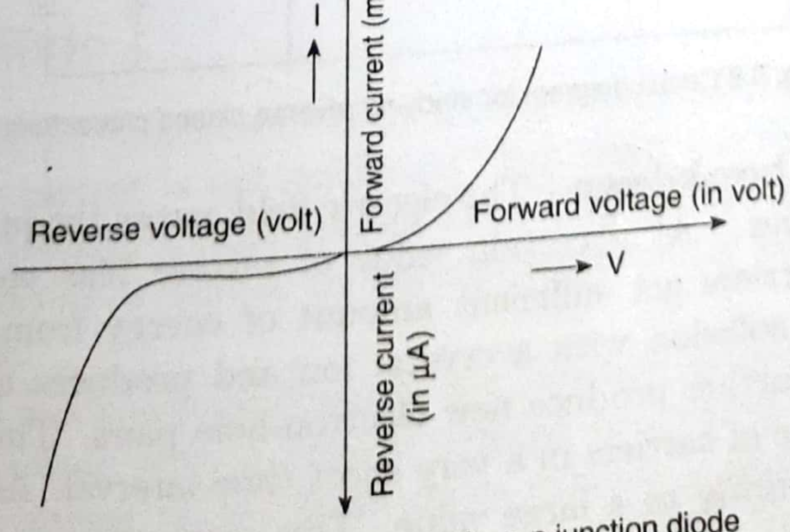


Fig. 3.8 I-V characteristics of a p-n junction diode

The circuit diagram for plotting the graph between forward bias voltage and forward current is shown in Fig. 3.7. The milliammeter and the voltmeter are used to measure respectively the forward current and the p.d. across the diode. The forward bias voltage is increased in steps and corresponding current is recorded for drawing the I-V characteristic. The curve in the first quardrant of Fig. 3.8 is the forward characteristic. It shows that when the external voltage exceeds the potential barrier, the forward current starts to flow and increases exponentially with forward bias.

3.4.2 Reverse biased characteristics

For a reverse biased p-n junction, V is negative. When its magnitude is much greater than kT/e, then we obtain from equation (3.4.1),

$$I = -I_s \qquad (3.4.3)$$

So, the current becomes the reverse saturation current which is *independent* of the reverse voltage but *dependent* on temperature. I_s is a few mA for Ge-diode and a few nA for Si-diode.

The circuit diagram for plotting the graph between the reverse bias and the reverse current is shown in Fig. 3.9. The voltmeter V and the microammeter μA are used to measure in steps the reverse voltage and the corresponding current respectively for drawing the reverse biased characteristic. The curve in the third quadrant of Fig. 3.8 is the *reverse biased characteristic.* It shows that the reverse current is very small and remains almost constant over a long range. On increasing the reverse bias, a junction diode may *breakdown.* The following are the two mechanisms that might cause this breakdown.

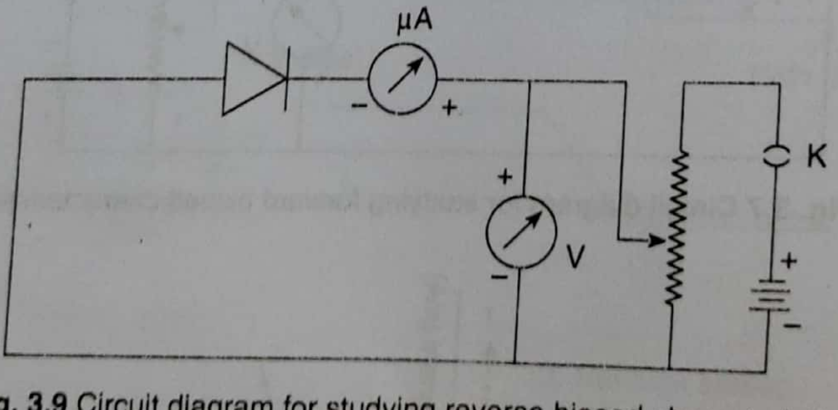


Fig. 3.9 Circuit diagram for studying reverse biased characteristics

that the Zener collision of carriers with the crystal ions.

3.5 Diode resistance

The I-V characteristic of a p-n junction shows that the junction does not obey Ohm's law. So, the resistance offered by a junction diode is not a constant but varies with the applied voltage.

The ***static*** or the ***dc resistance*** r_{dc} of a diode is defined as the ratio of the voltage V across the junction to the current I flowing through the junction.

$$\therefore \quad \boxed{r_{dc} = \frac{V}{I}} \tag{3.5.1}$$

The ***dynamic*** or ***ac resistance*** r_{ac} of a diode is defined as the ratio of the small change in voltage to the small change in diode current. Thus

$$\boxed{r_{ac} = \frac{\Delta V}{\Delta I}} \tag{3.5.2}$$

The inverse of the slope of the I-V characteristic of a p-n junction diode may also define r_{ac} as

$$\boxed{r_{ac} = \frac{dV}{dI}} \tag{3.5.3}$$

Plainly, therefore, the dynamic resistance r_{ac} of a diode is determined by the operating voltage.

(A) Avalanche breakdown—The electric field across the junction increases wit increasing reverse bias. At a certain value of reverse bias voltage, the thermall generated charge carriers get sufficient amount of energy from the field to disrupt a covalent bond by collision with a crystal ion and produces an electron-hole pair. These carriers may further produce new electron-hole pairs. This cumulative process develops an avalanche of carriers in a very short time-interval. As a result, the reverse current increases abruptly to a large value. This mechanism is known as ***avalanche multiplication*** and the diode is then said to work in the avalanche breakdown region.

(B) Zener breakdown—When the reverse bias voltage across a *p-n* junction is so high that the electric field imparts sufficient amount force to the bound electron to tear it out from the covalent bond, the Zener breakdown takes place. So, Zener breakdown is the *process of direct rupture of the covalent bond and thus produces a large number of electron-hole pairs and increases the reverse current abruptly.* It may however be noted that the Zener breakdown does not involve any collision of carriers with the crystal ions.