or, $$\frac{1}{Z_A}=\frac{1}{Z_{ins}}-\frac{1}{Z_B}$$

$$=\frac{1}{Z_{ins}}-\frac{\sqrt{Z_{00}(Z_{in0}-Z_{ins})}}{Z_{ins}Z_{00}}$$ , taking the positive sign before the radical in (1.36)

$$=\frac{Z_{00}-\sqrt{Z_{00}(Z_{in0}-Z_{ins})}}{Z_{ins}Z_{00}}$$

Thus, $$Z_A=\frac{Z_{ins}Z_{00}}{Z_{00}-\sqrt{Z_{00}(Z_{in0}-Z_{ins})}} \qquad \ldots (1.38)$$

To find $Z_C$ we proceed as follows. Equation (1.31) can be written as

$$\frac{1}{Z_C}+\frac{1}{Z_A+Z_B}=\frac{1}{Z_{00}}$$

or, $$\frac{1}{Z_C}=\frac{1}{Z_{00}}-\frac{1}{Z_A+Z_B}$$

$$=\frac{1}{Z_{00}}-\frac{\sqrt{Z_{00}(Z_{in0}-Z_{ins})}}{Z_{ins}Z_{00}^2}(Z_{00}-\sqrt{Z_{00}(Z_{in0}-Z_{ins})})$$

$$=\frac{1}{Z_{00}}-\frac{\sqrt{Z_{in0}-Z_{ins}}}{Z_{ins}Z_{00}}(\sqrt{Z_{00}}-\sqrt{Z_{in0}-Z_{ins}})$$

$$=\frac{Z_{in0}-\sqrt{Z_{00}(Z_{in0}-Z_{ins})}}{Z_{ins}Z_{00}}$$

Hence, $$Z_C=\frac{Z_{ins}Z_{00}}{Z_{in0}-\sqrt{Z_{00}(Z_{in0}-Z_{ins})}} \qquad \ldots (1.39)$$

The ± sign in (1.36) gives rise to two possible solutions as obtained in the case of equivalent T- network. Now, $Z$ is a function of signal frequency $\omega$, in general. Thus, equivalence in terms of $Z$ is all right at all frequencies. But, equivalence in terms of circuit elements $R$, $L$, $C$ does hold good at a single frequency. As $\omega$ changes, $Z(\omega)$ also changes. But, the functional dependence of $Z(\omega)$ for the complicated circuit and the equivalent circuit are not the same for which the same equivalent circuit cannot hold good at all frequencies.

In conclusion, it is possible to find an equivalent T or a Π network at a single frequency for any passive electrical network which is linear and bilateral in character. (In bilateral network the magnitude of the current flowing through an element remains unchanged if the polarity of the supply is reversed.)

In tunnel diode, the current is a multi-valued function of the forward bias voltage. The current increases monotonically under reverse bias. The I-V characteristics is shown in Fig. 4.6(b).

The width of the depletion layer is small due to heavy doping. Here, $I_P$ = peak current, $I_V$ = valley current, $V_P$ = forward voltage corresponding to peak current, $V_V$ = forward voltage at valley current, $V_{PP}$ = injection current voltage. Let us explain the operation of the tunnel diode with the help of energy band diagram.

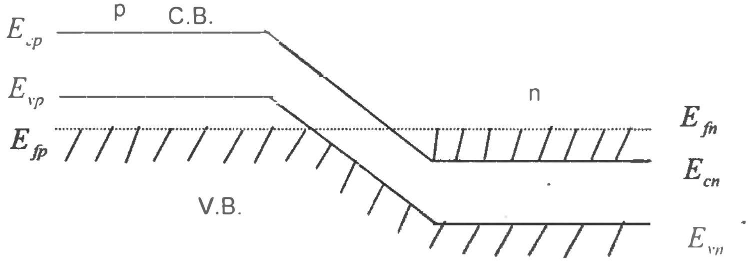


**Fig. 4.7.** Energy band diagram with no bias voltage applied.

Under no bias voltage applied, the Fermi level is continuous across the junction. The shaded region are filled states. This is shown in Fig. 4.7. $E_{cp}$ and $E_{vp}$ are the energies corresponding to the bottom of the conduction band and the top of the valence band in the p-region respectively. $E_{cn}$ and $E_{vn}$ are similar energies in the n-region. $E_{fp}$ and $E_{fn}$ are Fermi energies in the p- and n-region respectively. C.B. stands for conduction band and V.B. stands for valence band.

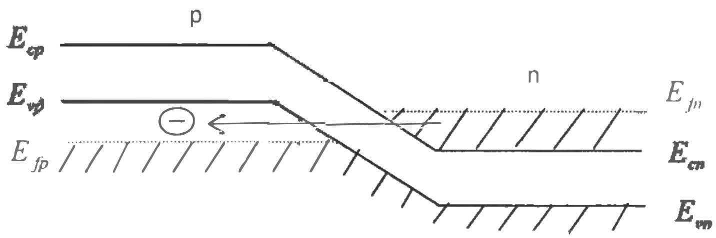


**Fig. 4.8.** Forward bias applied and tunnelling occurs.

In Fig. 4.8, a forward bias is applied. Electrons in the conduction band of the n-type semiconductor face vacant states in the valence band of the p-type semiconductor. So, tunnelling occurs and current increases. With increasing forward bias, more and more electrons face the empty states in the valence band and tunnel current increases accordingly. With increasing forward bias, a condition is reached when the overlap of the conduction band electrons and the empty states at the top of the valence band becomes maximum. The forward diode current becomes a maximum. This is shown in Fig. 4.9. If forward bias is further increased, this overlap of occupied and unoccupied states decreases and current decreases. This decrease of forward current with increase in forward voltage continues until the diode current reaches a minimum value. Under this condition, the conduction band electrons in the n-region face the band gap. So, no tunnelling occurs. The small current that flows in this condition is due to normal injection

In the short wavelength region Si ($E_g = 1.14$ eV at 300° K) photodiode is suitable while at long wavelength region InGaAs is preferred as the photodiode material. The bandgap of InGaAs (Indium Gallium Arsenide) depends upon the composition of the semiconductor – particularly, the molecular fraction of In and Ga present in InGaAs will matter. If x = 0.53 in $In_xGa_{1-x}As$ then $E_g = 0.75$ eV.

### 4.10.2 P-I-N PHOTODIODE

In p-i-n photodiode, an intrinsic semiconductor layer is fabricated in between the p and n regions. This increases the width of the depletion layer. The existence of the electric field in the whole depletion layer makes the photo-generated electrons and holes move fast through the intrinsic layer. This makes the response of the p-i-n photodiode to the incident light considerably faster. The increase in width of the depletion region due to the fabrication of the intrinsic layer leads to an increase in efficiency of the p-i-n photodiode. Since the width of the depletion layer is larger in p-i-n photodiode, the capacitance of the diode is reduced in comparison with the simple p-n junction photodiode. Reduction in device capacitance leads to a higher bandwidth of the p-i-n photodiode.

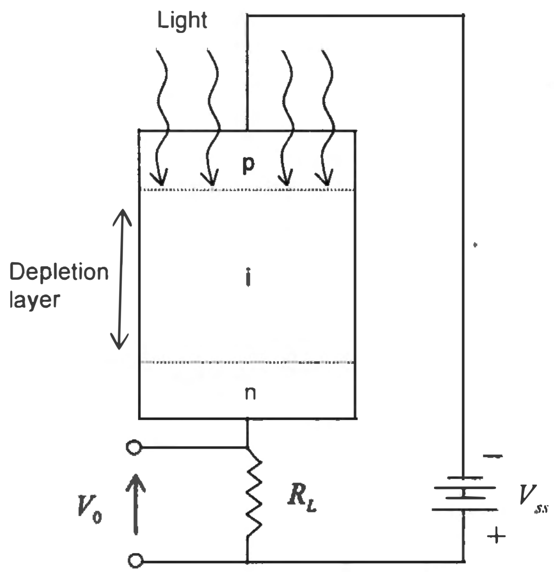


**Fig. 4.18.** A schematic diagram of the p-i-n photodiode.

In Fig. 4.18, $V_0$ is the output voltage developed across the load $R_L$. $V_{ss}$ is the bias voltage applied to the photodiode (PD). 'i' is the intrinsic layer.

The quantum efficiency of the PD is defined as the average number of electron-hole pairs produced per incident photon. If $I_L$ be the load current of the PD generated by the incident light having a power $P_i$ then the number of electron-hole pair generated per unit time is equal to where $I_{s1}$ and $I_{s2}$ are initial and final reverse saturation currents and $\Delta T$ is the rise in temperature. Here,

$$\frac{I_{s2}}{I_{s1}} = 20$$

$$\therefore \quad 20 = 2^{\Delta T/6}$$

$$\therefore \quad \Delta T = 6\frac{\ln(20)}{\ln(2)}$$

$$= 25.93^{\circ}\,\mathrm{C}$$

4.5 A Ge p-n diode conducts forward currents of 1 mA and 4 mA for forward bias voltages equal to 260 mV and 300 mV respectively. Calculate the operating temperature of the diode. Given $\eta = 1$.

**Solution**

We have, $I_1 = I_s\left(e^{qv_1/\eta kT} - 1\right)$

$$I_2 = I_s\left(e^{qv_2/\eta kT} - 1\right)$$

$$\therefore \quad \frac{I_2}{I_1} = \frac{e^{qv_2/\eta kT} - 1}{e^{qv_1/\eta kT} - 1} \approx e^{\frac{q}{\eta kT}(v_2 - v_1)}$$

$$\therefore \quad \ln\left(\frac{I_2}{I_1}\right) = \frac{q}{\eta kT}(v_2 - v_1)$$

$$\therefore \quad T = \frac{q}{\eta k}\frac{(v_2 - v_1)}{\ln\left(\frac{I_2}{I_1}\right)}$$

Here,

$$v_2 = 300\,\mathrm{mV}$$

$$v_1 = 260\,\mathrm{mV}$$

$$I_2 = 4\,\mathrm{mA}$$

$$I_1 = 1\,\mathrm{mA}$$

$$\eta = 1$$