$$P_{\text{opt}}\big|_{\min} = \frac{2h\nu}{\eta}\sqrt{\frac{(S/N)I_{eq}B}{q}} \tag{22}$$

where

$$I_{eq} = I_B + I_D + \frac{2kT}{qR_{eq}}. \tag{23}$$

The noise-equivalent power (NEP) is given by ($S/N = 1$, $B = 1$ Hz)

$$\begin{aligned} \text{NEP} &= \text{rms optical power } P_{\text{opt}}\big|_{\min} \\ &= \left(\frac{h\nu}{\eta}\right)\sqrt{\frac{2I_{eq}}{q}} \quad \text{W/cm}^2\text{-Hz}^{1/2}. \end{aligned} \tag{24}$$

To improve the sensitivity of a photodiode, both η and R_{eq} should be increased while I_B and I_D should be minimized. The NEP decreases with R_{eq} until it saturates to a constant value limited by dark-current or background-current shot noise.

13.3.2 *p-i-n* and *p-n* Photodiodes

The *p-i-n* photodiode is a special case of the *p-n* junction photodiodes, and is one of the most-common photodetectors, because the depletion-region thickness (the intrinsic layer) can be tailored to optimize the quantum efficiency and frequency response. Figure 6 shows schematic representation of a *p-i-n* diode and its energy-band diagram under reverse-bias conditions, together with optical absorption characteristics. We shall discuss the operation of *p-i-n* photodiode in some detail with the help of Fig. 6. This discussion applies also to *p-n* junction photodiodes. Light absorption in the semiconductor produces electron-hole pairs. Pairs produced in the depletion region or within a diffusion length of it will eventually be separated by the electric field, leading to current flow in the external circuit as carriers drift across the depletion layer.

Quantum Efficiency. Under steady-state conditions the total photocurrent density through the reverse-biased depletion layer is given by[10]

$$J_{\text{tot}} = J_{dr} + J_{\text{diff}} \tag{25}$$

where J_{dr} is the drift current due to carriers generated within the depletion region and J_{diff} is the diffusion current due to carriers generated outside the depletion layer in the bulk of the semiconductor and diffusing into the reverse-biased junction. We shall now derive the total current under the assumptions that the thermal generation current can be neglected and that the surface *p*-layer is much thinner than $1/\alpha$. Referring to Fig. 6c, the electron-hole generation rate is given by

$$G_e(x) = \Phi_0 \alpha \exp(-\alpha x) \tag{26}$$

where Φ_0 is the incident photon flux per unit area given by $P_{\text{opt}}(1-R)/Ah\nu$, R is the reflection coefficient, and A is the device area. The drift current J_{dr} is thus given by