The assumption $\dot{N}_r = \dot{N}(T_a, qV, \varepsilon_g, \infty, \pi)$ states that the temperature associated with the emitted photons is the room temperature T_a. This is natural because the cell is at this temperature. However, it also states that the chemical potential of the radiation emitted, μ_{ph}, is not zero but

$$\mu_{\text{ph}} = \varepsilon_{Fc} - \varepsilon_{Fv} = qV \tag{4.20}$$

This is so because the radiation is due to the recombination of electron–hole pairs, each one with a different electrochemical potential or quasi-Fermi level. A plausibility argument for admitting $\mu_{\text{ph}} = \varepsilon_{Fc} - \varepsilon_{Fv}$ is to consider that photons and electron–hole pairs are produced through the reversible (i.e. not producing entropy) equation electron + hole $\leftrightarrow$ photon. Equation (4.20) would then result as a consequence of equalling the chemical potentials before and after the reaction. Equation (4.20) can be also proven by solving the continuity equation for photons within the cell bulk [16, 17].

When the exponential of the Bose–Einstein function is much higher than one, the recombination term in equation (4.19) for full concentration can be written as

$$\begin{aligned}\dot{N}_r &= \frac{2\pi}{h^3\mathbf{c}^2}\int_{\varepsilon_g}^{\infty} \varepsilon^2 \exp\left(\frac{\varepsilon - qV}{kT_a}\right) \mathrm{d}\varepsilon \\ &= \frac{2\pi kT}{h^3\mathbf{c}^2}[4(kT)^2 + 2\varepsilon_g kT + \varepsilon_g^2]\exp\left(\frac{qV - \varepsilon_g}{kT_a}\right)\end{aligned} \tag{4.21}$$

This equation is therefore valid for $\varepsilon_g - qV \gg kT_a$. Within this approximation, the current–voltage characteristic of the solar cell takes its conventional *single* exponential appearance. In fact, this equation, with the appropriate factor $\sin^2\theta_s$, is accurate in all the ranges of interest of the current–voltage characteristic of ideal cells under unconcentrated sunlight.

The SQ solar cell can reach an efficiency limit given by

$$\eta = \frac{\{qV[\dot{N}_s - \dot{N}_r(qV)]\}_{\max}}{\sigma_{\text{SB}}T_s^4} \tag{4.22}$$

where the maximum is calculated by optimising V. This efficiency limit was first obtained by Shockley and Queisser [2] (for unconcentrated light) and is plotted in Figure 4.3 for several illumination spectra as a function of the band gap.

Outside the atmosphere the sun is seen quite accurately as a black body whose spectrum corresponds to a temperature of 5758 K [19]. To stress the idealistic approach of this chapter, we do not take this value in most of our calculations but rather 6000 K for the sun temperature and 300 K for the room temperature.

It must be pointed out that the limiting efficiency obtained for full concentration can be obtained also at lower concentrations if the étendue of the escaping photons is made equal to that of the incoming photons [16]. This can be achieved by locating the cell in a cavity [20] that limits the angle of the escaping photons.