and the power extracted from the cell can be finally computed as

$$\dot{W} = IV = [\dot{E}(T_s, 0, \varepsilon_g, \infty, H_s) - \dot{E}(T_{hc}, 0, \varepsilon_g, \infty, H_r)]\left(1 - \frac{T_a}{T_{hc}}\right) \tag{4.79}$$

which is independent of the carrier-extracting energies of the contacts. In other words, a large separation of the extracting energies leads to high voltage and low current and *vice versa*. Note that T_{hc} is a parameter for equation (4.79) and for equation (4.77). By elimination, we obtain the $W(V)$ and from it the derived IV curve. The cell efficiency is obtained from the maximum of $W(V)$ or $W(T_{hc})$.

For $\varepsilon_g \to 0$ the limit efficiency becomes

$$\eta = \left(1 - \frac{T_{hc}^4}{T_s^4}\right)\left(1 - \frac{T_a}{T_{hc}}\right) \tag{4.80}$$

just as in the TPV converters, leading to a limiting efficiency of 85.4%.

The monoenergetic membrane for electron and hole transfer to the contacting metals might perhaps be an insulator with an impurity band, but the nature of the phonon-insulated absorber is totally unknown. Ross and Nozik [48, 49] who have developed concepts close to those expressed here are investigating the poorer coupling of the electrons with the photons in materials with quantum dots with the idea of favouring this hot electron type of cell or the impact ionisation one that we have described in the preceding section.

4.5.6 Intermediate Band Solar Cell

One of the causes of efficiency reduction in single-junction solar cells is the transparency of the semiconductor to sub–band gap photons [50]. The inclusion of an intermediate band (IB) may greatly increase the efficiency. We show in Figure 4.13 a band diagram of the photon absorption and emission in this intermediate band material. Photons are absorbed not only by pumping electrons from the VB to the CB as in a traditional solar cell (photons with energy $h\nu_3$) but also by transitions from the VB to the IB (photons with energy $h\nu_2$) and from the IB to the CB (photons with energy $h\nu_1$). In total, two low-energy photons are used to pump an electron from the valence band to the conduction band, passing through the intermediate band. This certainly increases the cell current.

The three absorption mechanisms detailed above are effective if the IB is a band partially filled with electrons. In this way, there are empty states in it to accommodate the electrons from the VB and there are electrons to sustain a strong pumping to the CB. The detailed balance imposes photon emissions that are opposite to each one of the three absorption mechanisms.

The cell is contacted as shown in Figure 4.14. The electrons are extracted from the VB and returned to the CB using two layers of n and p ordinary semiconductors. A high voltage is produced as the sum of the two semiconductor junction voltages occurring at both sides of the IB material.