band gaps (multiband solar cells) has been studied in [53, 54]. Some related concepts are that of an impurity band, in which the IB is made up of impurities [55], and the use of intermediate band materials as up- and down-converters [56, 57].

Suitable materials for a metallic IB are not very common. Accurate theoretical calculations establish that some alloys of the type III_3-V_4-IVb (with four electrons in the outer shell) present the required band [58]. No experiment has been carried out so far for implementing these materials, and therefore it is not certain whether the required metallic IB is actually formed or if the corresponding alloys are thermodynamically stable or separate into phases.

Another proposal [59] for forming the required IB is the use of nanotechnology. In particular, closely spaced quantum dot arrays might produce the desired band Figure 4.16. $In_{0.58}Ga_{0.42}As$ dots (of band gap 0.87 eV) of a radius of 39 nm in a barrier material of $Al_{0.4}Ga_{0.6}As$ of band gap 1.95 eV could produce an IB centred at 0.71 eV from the CB (if strain effects could be avoided and the offset in the VB could be suppressed [60]). The half filling of the IB can be achieved by barrier material doping [61, 62]. Experiments to prove the principle of operation of this type of cell have not yet been carried out.

4.6 CONCLUSIONS

In this chapter we have provided a thermodynamic basis that allows evaluating the thermodynamic consistency of classical and newly proposed solar cells. Also, we have assessed the efficiency limit of several PV concepts.

As deduced by Shockley and Queisser, the upper limit reachable with a single-junction solar cell is 40.7% for the cell illuminated by a black body source of photons at 6000 K and assuming the cell temperature at 300 K. This value is rather low if we take into account that the Carnot limiting efficiency for a reversible engine operating between hot and cold heat reservoirs at 6000 K and 300 K, respectively, is 95%. High-efficiency devices that can ideally surpass the Shockley–Queisser efficiency have been called *third generation PV converters*. Thus, the following question arises: could we invent a solar converter that exhibits this Carnot efficiency?

The answer is negative and the reason for it lies in the definition of efficiency. In the definition of the Carnot efficiency, the term entering in the denominator is the power *consumed*, that is, the power *arriving* at the converter less the power *leaving* the converter owing to the radiation that is emitted. In the conventional definition of the efficiency for solar converters, the term entering in the denominator is the power *arriving* at the converter and because it is higher than the *consumed* power this leads to a lower efficiency. With this definition, the higher achievable efficiency is the Landsberg efficiency of 93.33%. However, this efficiency, if reachable, cannot be reached with any known ideal solar converter.

A very high efficiency of 85.4% can ideally be reached with several devices such as the TPV converter, constituted by one ideal solar cell and one absorber and the TPH converter, conceived with one ideal solar cell and one LED that also plays the role of an absorber, or even a hot carrier solar cell. To reach this efficiency they all must emit radiation with zero chemical potential (free radiation) at 2544 K. This efficiency is also the limit for solar thermal devices.