Advances in the research of the Intermediate Band (IB) Solar cells

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Abstract. We describe the present state of the intermediate band (IB) solar cell, a cell concept with very high efficiency potential.

Introduction to IB solar cells

An IB solar cell is formed [1] of an IB material situated between two ordinary semiconductors —n- and p-type respectively— that play the role of selective contacts to conduction band (CB) and valence band (VB) electrons. The IB material has a band of states inside the band gap between the CB and the VB. In this way, as shown in Fig. 1, photons with less energy than the one necessary to pump an electron form the VB to the CB can be absorbed by transitions that pump an electron form the VB to the IB and form the IB to the CB. Thus a full VB→CB electron transition (or electron-hole pair generation) can be completed by means of two photons of energy below the band gap. This mechanism should increase the solar cell current.

However, any increase of cell current is usually accompanied by a reduction of the voltage. To avoid this, it is necessary that three separate quasi-Fermi levels (electrochemical potentials) appear in the IB material, two of them associated to the VB and to the CB, as in ordinary solar cells, and the third one associated to the IB. The voltage extracted from the cell is precisely the difference of the CB and VB quasi-Fermi levels at the n- and p-contacts respectively (changed of sign and divided by the charge of the electron). However photons of lower energy than this voltage can contribute to the current thanks to the IB, what is not the case in ordinary solar cells.

Limit efficiency of this concept for maximum concentration (the one providing isotropic illumination on the cell with the radiance of the sun's photosphere) is 63% to compare with the Shockley-Queisser limit of 40% for an ordinary cell in the same conditions [2].

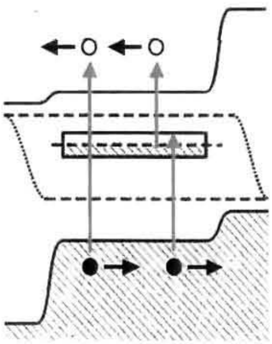

Fig. 1 Band diagram of an IB solar cell showing the 2-photon generation of one electron hole pair. The three quasi Fermi levels (dashed lines) are also shown

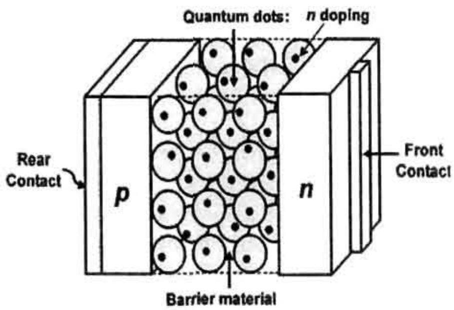

Fig. 2 Diagram of a quantum dot IB solar cell showing the IB material in the centre and the ordinary p- and n-semiconductor contacting layers.

Quantum dot IB solar cells

IB GaAs solar cells have been fabricated based on this concept using InAs quantum dots (QD) to form the IB (see Fig. 2). A small increase of the short circuit current has been measured and by using two sources of photons of different energy, evidence of the electron-hole formation through the described two-photon mechanism has been produced [3]. In addition, a separation of the quasi-Fermi levels has been experimentally found for cells forward biased [4]. However the efficiency is not higher than the one of the cells without quantum dots mainly because of the low current enhancement due to the weak absorption in the QD, resulting from their inherent low density (<1017 cm-3) and low IB material thickness (0.1 μm). However reducing stresses has increased dramatically the sub-band-gap current [5, 6]. The improvement of the light to the quantum dots by using diffraction methods[7, 8] could also enhance the sub-band-gap light absorption.

Also an important loss of open circuit voltage has also been produced, against the motivation of the concept itself. Studies have been carried out to explain the loss of voltage. In reality it is mainly due to the reduction of the effective bandgap of the barrier material (GaAs) when the quantum dots (InAs) are formed in it. This reduction of produced by the offset in the valence band and also by the appearance of the wetting layer when the QD are grown by the Stransky Krastanov technique. This can be amended by tuning the bandgap with a ternary in the barrier material (e.g. Al in GaAs).

But in any case the IB always introduces a path for easier recombination that tends naturally to lower the voltage. However this can be reduced to negligible values when the cell voltage is very high, in which case the CB → VB recombination becomes dominant. This high voltage operation can be achieved when the cell works in concentration[9].
In summary several groups have fabricated QD-IB solar cells but no record efficiency has yet been produced.

Alloyed IB solar cells

Much higher density (>1019 cm-3) of sub-band-gap absorbing centres can be found in IB solar cells seem based on alloys. Ab initio quantum band calculations were done [10] to look for materials presenting an intermediate band. that proved that Ti might form an intermediate band well separated form the valence band and the conduction band in matrices of GaAs and GaP but they are relatively unstable [11]. More stability is to be expected form chalcopyrites due to its octahedral (and not tetrahedral) coordination[12, 13] and indium thiospinels [14] where the calculated sub-ban-gap absorption has been measured. The occurrence of a separated IB becomes easier with dilution[15]. Walukiewicz and co-workers at LBNL have used the concept of band anti-crossing [16, 17] to look for materials exhibiting IB. They have found their existence by in several compounds by photo-reflectance measurements [18, 19]. From another point of view, levels situated in the mid of the gap, also called deep levels, are know to be introduced by certain impurities and to act as effective centres of SRH recombination. In this respect it is important to make a clear distinction between deep levels and an IB. The difference lies in the density of the impurities. When it is high enough as to suffer a Mott transition the electrons become delocalised, the deep level becomes an impurity band and the SRH recombination is thought to disappear[20]. Some experimental evidence is still pending of publication.
In summary several ways are sought to look for alloy IB solar cells. Several groups have prepared IB materials but to our knowledge no cell results have been published.

IB solar cells in MJ stacks

IB solar cells may be used in multi-junction stacks of solar cells (MJ solar cells), ordinary, advanced (multiple exciton generation or hot carriers) and IB, to cover the range of efficiencies above 55%, probably out of the practical reach of ordinary MJ cells. Calculations show that a tandem of 2 IB solar cells could give the same efficiency than a 6 junction solar cell [21].

Conclusions

In summary, several high-efficiency cells have been proposed that aim to lead to efficiencies above 55%, most probably, in tandem stacks. The basic principles of the IB solar cell have been proved but no record efficiency IB solar cell has yet been produced.

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