ENERGY CONVERSION EFFICIENCY LIMIT OF SERIES CONNECTED INTERMEDIATE BAND SOLAR CELLS

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ABSTRACT: This paper presents and studies the operation of a tandem of intermediate band solar cells (IBSC). This approach is the one considered feasible in order to effectively increase the number of gaps involved in the operation of this type of solar cell in the sense of making a better use of the solar spectrum. This is so because it can preserve the fact that the intermediate band has to be half-filled with electrons in order to serve to the purpose of both receiving electrons from the valence band as to supply them to the conduction band. The limiting efficiency of the series connected tandem of two IBSC is found to be 72.5 % under maximum concentration, close to the limit of a six-junction tandem solar cell but with the potential advantage of requiring only one tunnel junction.

Keywords: Fundamentals, Devices, Modelling.

1 INTRODUCTION

The limiting efficiency of the intermediate band solar cell (IBSC) concept was found to be 63.2 % [1], the same that a tandem of three cells connected in series [2]. Increasing the number of cells in a tandem increases their limiting efficiency up to 86.8 %, a figure that is reached for a system consisting of an infinite number of solar cells [3]. The reader is supposed to be familiarised with the IBSC concept (see, for example [4, 5]) so that the operation of this cell will not be specifically reviewed here.

To follow a similar approach in an IBSC by increasing the number of gaps involved would require, for example, increasing the number of intermediate bands (Fig. 1). Under this approach [2], the limiting efficiency of the IBSC is also found to approach the efficiency limit found for the tandem case with an infinite number of solar cells. However, this approach has the drawback that in equilibrium, only one intermediate band (IB) can be half-filled with electrons and therefore, have both empty states to receive electrons form the valence band (VB) and to supply them to the conduction band (CB). To have a band half-filled with electrons is necessary condition in order this band can effectively contribute to the absorption of photons in a two step process and fulfil the principles of operation of the IBSC concept. Both completely filled bands as emptied ones cannot serve to this purpose.

It is true that, out of the equilibrium and supported by the assumption that each band has associated its own quasi-Fermi level, this situation can change so that several bands find themselves half-filled with electrons. However, this situation is considered unstable for the cell operation because the position of each of these quasi-Fermi levels would depend on the operating conditions of the cell. Note that this is not the case when only one intermediate band is used because the position of the IB quasi-Fermi level can be fixed to its equilibrium position by increasing its density of states compared with that of the CB and VB [6].

An alternative approach to increase the number of gaps in an IBSC, and the one presented and studied in this paper, consist of creating a stack of IBSCs as illustrated in Fig. 2 and whose operation will be described in the next section.

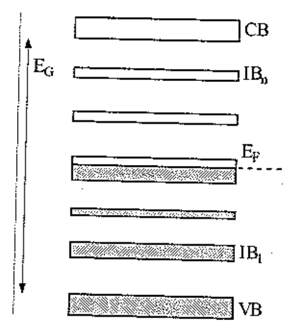

Figure 1. Multiband approach for the intermediate band solar cell concept. In equilibrium, only one band can be half-filled by electrons.

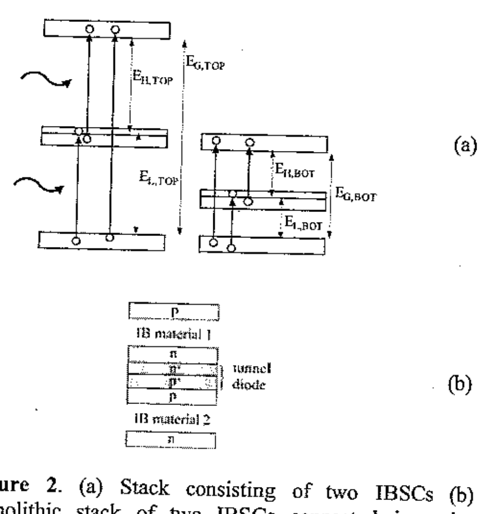

Figure 2. (a) Stack consisting of two IBSCs (b) monolithic stack of two IBSCs connected in series through a tunnel junction.

2 IBSC TANDEM MODEL

In the tandem approach using IBSCs, one IBSC is located after another. The top cell is characterised by a total bandgap $E_{G,TOP}$ that is divided in two sub-bandgaps $E_{L,TOP}$ and $E_{H,TOP}$. Similarly, the bottom cell exhibits a total bandgap $E_{G,BOT}$ divided in two subbandgaps, $E_{L,BOT}$ and $E_{H,BOT}$. When individually considered, both cells operate according to the basic principles of the IBSC [1]. This implies, among other assumptions, that the absorption coefficients related to the three electronic transitions allowed in the cell are selective, i.e., a photon that can be used in a given transition is not wasted in a less energetic transition. In this case, as in any tandem system, the top cell absorbs the photons whose energy lies in the range of its transitions, so that only those with energy below $E_{L,TOP}$ are available for the bottom cell to be converted.

The limiting efficiency of this system has been determined according to the principle of detailed balance. A more extended description of the application of this principle to the IBSC can be found in [1]. The key point of this analysis is that in the ideal case, where only radiative recombination is taken into account and total absorption is assumed, the minimal (and, for thermodynamic reasons, unavoidable) loss in the photoconversion that takes place in a cell when illuminated by a hotter black-body comes from its own radiation emission due to the radiative recombination within the device. In our model, the sun has been considered as a black-body at 6000K and the cell operates at ambient temperature (300K). The level of light concentration has been set to the maximum (46050 suns) unless other magnitudes are given. This corresponds to the ideal case in which the cell receives all photons emitted by the sun.

All photon fluxes that enter and leave any of the cells are given by the generalized Planck equation:

$$\dot N(\varepsilon_m,\varepsilon_M,T,\mu)=\frac{2\Omega}{h^3c^2}\int_{\varepsilon_m}^{\varepsilon_M}\frac{\varepsilon^2 d\varepsilon}{e^{(\varepsilon-\mu)/kT}-1}, \qquad (1)$$

where the constants c, h and k have their usual meanings, ε_m and ε_M stand respectively for the lower and upper limit of the spectral range of the flux, T is the temperature of the radiation source, μ is the chemical potential of the photons and Ω is the etendue of the radiation (π at maximum concentration). In the case of absorbed photons, the temperature is that of the sun (T_s) and the chemical potential is cero, since the sun is assumed to be a black-body. For emitted radiation, the temperature of the cell (T_C) is considered and the chemical potential equals the corresponding quasi-Fermi split in the device (represented here by μ_{XY}, X and Y indicating the bands to which the quasi-Fermi levels are related: C for conduction, I for intermediate and V for valence band). As no current is extracted from the intermediate band, each of the cells has to fulfil the constrain:

$$[\dot N(\varepsilon_L,\varepsilon_H,T_S,0)-\dot N(\varepsilon_L,\varepsilon_H,T_C,\mu_{IV})] = [\dot N(\varepsilon_H,\varepsilon_G,T_S,0)-\dot N(\varepsilon_H,\varepsilon_G,T_C,\mu_{CI})], \qquad (2)$$

For a given value of external voltage, equation (2) together with

$$qV=\mu_{CI}+\mu_{IV}=\mu_{CV}, \qquad (3)$$

allow us the calculation of all chemical potentials related to each of the cells.

The total current delivered by the top cell in the tandem can be expressed as:

$$I_{TOP}/q=[\dot N(\varepsilon_{G,TOP},\infty,T_S,0)-\dot N(\varepsilon_{G,TOP},\infty,T_C,\mu_{CV,TOP})]+ [\dot N(\varepsilon_{H,TOP},\varepsilon_{G,TOP},T_S,0)-\dot N(\varepsilon_{H,TOP},\varepsilon_{G,TOP},T_C,\mu_{CI,TOP})] \qquad (4)$$

In the case of the bottom cell, $E_{L,TOP}$ limits the spectral range, so the current is given by:

$$I_{BOT}/q=[\dot N(\varepsilon_{G,BOT},\varepsilon_{L,TOP},T_S,0)- \dot N(\varepsilon_{G,BOT},\varepsilon_{L,TOP},T_C,\mu_{CV,BOT})]+[\dot N(\varepsilon_{H,BOT},\varepsilon_{G,BOT},T_S,0) -\dot N(\varepsilon_{H,BOT},\varepsilon_{G,BOT},T_C,\mu_{CI,BOT})] \qquad (5)$$

Substituting the chemical potentials obtained from equation (2) and (3) in equations (4) and (5), the IV curve of each cell can be drawn.

Two cases of study will be considered here. In the first (unconstrained case) the two cells are considered independently connected, and their power will be added after optimization. In the second (series case), the cells are considered to be connected in series so that the current through both devices is the same. This means that the results of equation (4) and (5) are matched while the optimization is performed. Fig. 2,b illustrates the latest case in a monolithic implementation. This structure contains as many energy thresholds as a conventional stack of six single gap solar cells with the difference that only one tunnel junction would be needed instead of five.

3 RESULTS

The calculated efficiency limits for the unconstrained case are shown in Figure 3 in a two-dimensional plot as a function of the total bandgaps $E_{G,TOP}$ and $E_{G,BOT}$. For each pair ($E_{G,TOP}$, $E_{G,BOT}$) the position of the intermediate band in the energy diagram of each IBSC has been optimised. The dark region situated around (3.8, 1.2) eV shows efficiencies close to 73%. It is remarkable that for a wide range of bandgap combinations the efficiency limit exceeds 70%. This implies that many different known materials could be good candidates for the insertion of an IB. In this sense, for instance, silicon or gallium arsenide, which are not appropriated as basis materials for single IBSCs due to their low bandgap, could be used in high efficiency IBSC tandem devices.

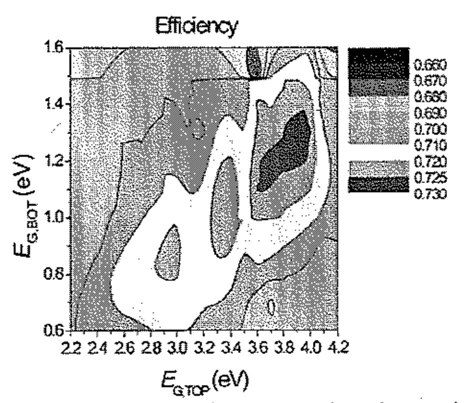

Figure 3. Contour plot representing the maximal efficiencies calculated for different combinations of ($E_{G,TOP}$, $E_{G,BOT}$) in an unconstrained IBSC tandem.

In a similar plot, Fig. 4 shows the efficiency limits for the series connected case. As a consequence of the constrain imposed to this tandem, the optimisation of the system cannot render an efficiency limit as high as the one reached in the unconstrained case (as long as the number of gaps involved is finite [7]). The maximal value is 72.5% corresponding to bandgaps $E_{G,TOP}$= 2.96 eV and $E_{G,BOT}$=0.89 eV. Table I collects these figures as well as the ones corresponding to the five- and six-cells-conventional tandems for comparison purposes. As it can be observed, the efficiency of the tandem of IBSCs lies in-between the efficiency limits of the 5 junction and 6 junction cases.

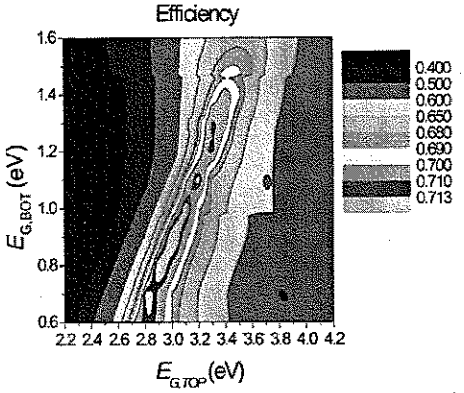

Figure 4. Contour plot representing the maximal efficiencies calculated for different combinations of ($E_{G,TOP}$, $E_{G,BOT}$) in a series constrained IBSC tandem.

Table I. Efficiencies (η) and optimum gaps obtained for a tandem of IBSCs for the unconstrained and series connected cases. The case of a conventional tandem of 5 and 6 junction solar cells is also shown (All gap figures are in eV).

IBSC tandem independently connected						
$E_{G,TOP}$	$E_{G,BOT}$	$E_{L,TOP}$	$E_{L,BOT}$			η (%)
4.00	1.25	1.73	0.44			72.6
IBSC tandem series connected						
$E_{G,TOP}$	$E_{G,BOT}$	$E_{L,TOP}$	$E_{L,BOT}$			η (%)
2.96	0.89	1.20	0.27			72.5
5 junctions tandem-independently connected						
$E_{G,1}$	$E_{G,2}$	$E_{G,3}$	$E_{G,4}$	$E_{G,5}$		η (%)
0.45	0.88	1.34	1.88	2.66		72.0
5 junctions tandem-series connected						
$E_{G,1}$	$E_{G,2}$	$E_{G,3}$	$E_{G,4}$	$E_{G,5}$		η (%)
0.44	0.81	1.16	1.58	2.18		71.1
6 junctions tandem-independently connected						
$E_{G,1}$	$E_{G,2}$	$E_{G,3}$	$E_{G,4}$	$E_{G,5}$	$E_{G,6}$	η (%)
0.40	0.78	1.17	1.60	2.12	2.87	74.4
6 junctions tandem-series connected						
$E_{G,1}$	$E_{G,2}$	$E_{G,3}$	$E_{G,4}$	$E_{G,5}$	$E_{G,6}$	η (%)
0.38	0.71	1.01	1.33	1.72	2.31	73.3

Figs. 5(a) and (b) provide additional insight about the sensitivity of the optimum efficiency to variations in the position of the intermediate band as the total bandgaps $E_{G,TOP}$ and $E_{G,BOT}$ are kept constant. These variations are counted for as changes in the $E_{L,TOP}$ and $E_{L,BOT}$. It is concluded from the first graph that if the displacement of the bottom cell IB is not higher than 50 meV, the efficiency is kept over 68%. The displacement of the IB of the top cell has slightly stronger influence in the total efficiency of the tandem. This result is not surprising since the displacement of the top cell IB affects not only to the power that this cell can deliver, but also changes the upper limit of the light spectrum that the bottom cell is receiving. As it can be seen in the second graph, a displacement of 50 meV in the IB of the top cell lowers the efficiency of the tandem to approximately 65%.

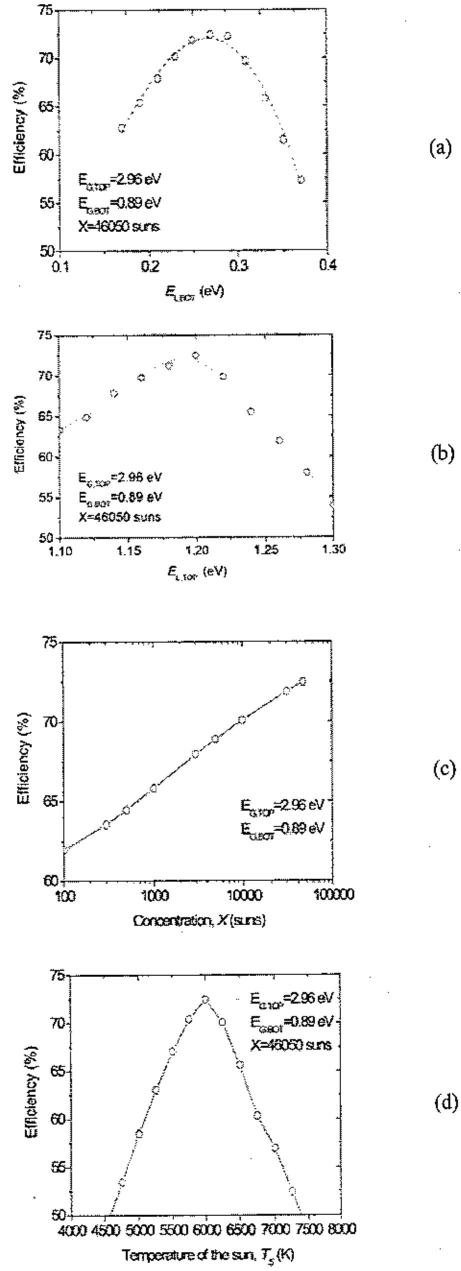

Figure 5. Dependence of the efficiency of the optimal series connected IBSC tandem with: (a) position of the IB in energy diagram of the bottom cell IB material, (b) the same for the top cell IB material, (c) concentration level and (d) solar spectrum.

The effect of variations in the concentration level has also been calculated for the optimal series connected IBSC tandem. The results are shown in Fig. 5(c). The efficiency suffers an approximately exponential decay when the concentration level is decreased, reaching a value of 63.5 % at 100 suns. Note that this kind of calculation is made to test the tolerance of the optimised structure to changes in the working conditions. The results are not indicating the efficiency limit that corresponds to each concentration level. These values could be higher, since the structure would be optimised specifically for that situation. Similarly, the results in Fig. 5(d) illustrate the dependence of the efficiency of the optimal structure with the spectrum of the light that it is absorbing. The spectrum has been changed by choosing different temperatures for the sun. The change in efficiency with the spectrum is found to be stronger than the dependence that was found in [8] for the case of a single IBSC assisted by impact ionization mechanisms.

5 CONCLUSIONS

It has been proven that the efficiency limit of a tandem of two IBSCs is close to that of a six-cells-tandem, both for the unconstrained- and series-connected systems. In the second case, under maximum concentration, a maximal conversion efficiency of 72.5 % has been found for a top cell with highest and lowest bandgap of 2.86 and 1.20 eV respectively, and a bottom cell with highest gap of 0.89 and lowest of 0.27 eV. This value has to be compared with the 73.4 % efficiency limit of the series connected six junction tandem. The IBSC-tandem approach shows the advantage that for a monolithic implementation of the cell, only one tunnel junction is needed, whereas the single cell tandem approach would require five.

Efficiency limits higher than 70% can be achieved for a wide range of combinations of total bandgaps of the two IBSCs if the IBs are optimally positioned in the band diagram of the materials.

The sensitivity of the optimum efficiency to variations in its internal parameters and working conditions has also been briefly discussed.

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