LIMITING EFFICIENCIES OF NOVEL SOLAR CELL CONCEPTS IN SPACE

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ABSTRACT

In this work we study the limiting efficiency in space environmental conditions of three novel solar cell concepts (hot carrier solar cells, multiple exciton generation solar cells and intermediate band solar cells) and how this limiting efficiency is impacted by the temperature and degradation due to radiation. Comparisons are made with state of the art triple-junction solar cells whose performance is taken as reference. In the last section of the work we briefly review the status related to the experimental achievements of these cells to date.

1. NOVEL SOLAR CELL CONCEPTS OVERVIEW

In order to exceed the limiting efficiency of single gap solar cells, three novel solar cell approaches have been proposed: the hot carrier solar cell (HCSC), the multiple exciton generation solar cell (MEGSC) and the intermediate band solar cell (IBSC).

In the HCSC (Fig. 1a) photons (*hv*) create electron-hole-pairs. However, the excited electrons and holes are not allowed to interact with the semiconductor lattice so that they do not cool down and, therefore, they do not lose their energy in thermalization processes with the semiconductor lattice. It is from this property that the HCSC heritages its efficiency advantage over single gap solar cells. The extraction of these hot electrons and holes from the solar cell demands, however, the use of special contacts (named energy selective contacts) in order to make possible that electrons cool down reversibly to the contact temperature at the time they increase their electro-chemical potential. The HCSC was proposed by Ross and Nozik [1] and reviewed by Wuerfel [2, 3] who realised of the necessity of the energy selective contacts.

In the multiple exciton generation solar cell (MEGSC, Fig. 1b) high energy photons (*hv*) create high energy excited electron-hole pairs (or excitons). This pairs do not ideally lose their energy through thermalization processes but, instead, create one or more additional electron-hole pairs (e_1-h_1; e_2-h_2, e_3-h_3) depending on how many times their energy exceeds the energy of the gap. The MEGSC, proposed by Nozik [4], is an evolution of the impact ionization solar cell (IISC) proposed by Werner, Brendel and Queisser [5]. The difference relies on the fact that, while the IISC was thought to be implemented in bulk semiconductors, the MEGSC is envisaged to be implemented using quantum dots. By using quantum dots, the probability of one photon creating more than one electron-hole pair is increased because the momentum conservation selection rule is not required.

The intermediate band solar cell (IBSC) is based on the idea of implementing a semiconductor like material that, instead of exhibiting one single gap, it would exhibit two bandgaps (Fig. 1c). The two bandgaps appear when an “intermediate band” (IB) is created inside a conventional high bandgap semiconductor host. This IB allows the absorption of below bandgap energy photons that, in conventional solar cells are wasted. This absorption occurs through the successive promotion of electrons from the valence band (VB) to the IB and from the IB to the conduction band (CB). Thanks to the formation of the additional bandgap, the IBSC is capable of performing, when properly optimized, with an efficiency close to that of a triple junction solar cell [6].

The limiting efficiency of these novel concepts has been calculated in other works for operation on Earth surface and often, for operation for the sun assumed as a black body at 6000 and maximum concentration (46050 suns). However, this limiting efficiency has never been calculated systematically for AM0 [7] to our knowledge. We think this is necessary as a first step to guide the possible application of these novel concepts in space. In addition, when assuming operation on Earth, the solar cell is usually assumed to operate at 300 K. We think that, with operation in space conditions in mind, evaluating the impact of temperature on cell efficiency is also of relevance. Finally, the limiting efficiency of these novel concepts is usually calculated assuming the so-called radiative limit, a concept by which electron-hole pairs can only disappear by emitting one photon (radiative recombination). However, in space, solar cell degradation by radiation plays an important role and, in the next sections, we will also explore the impact of this degradation on the performance of these cells.

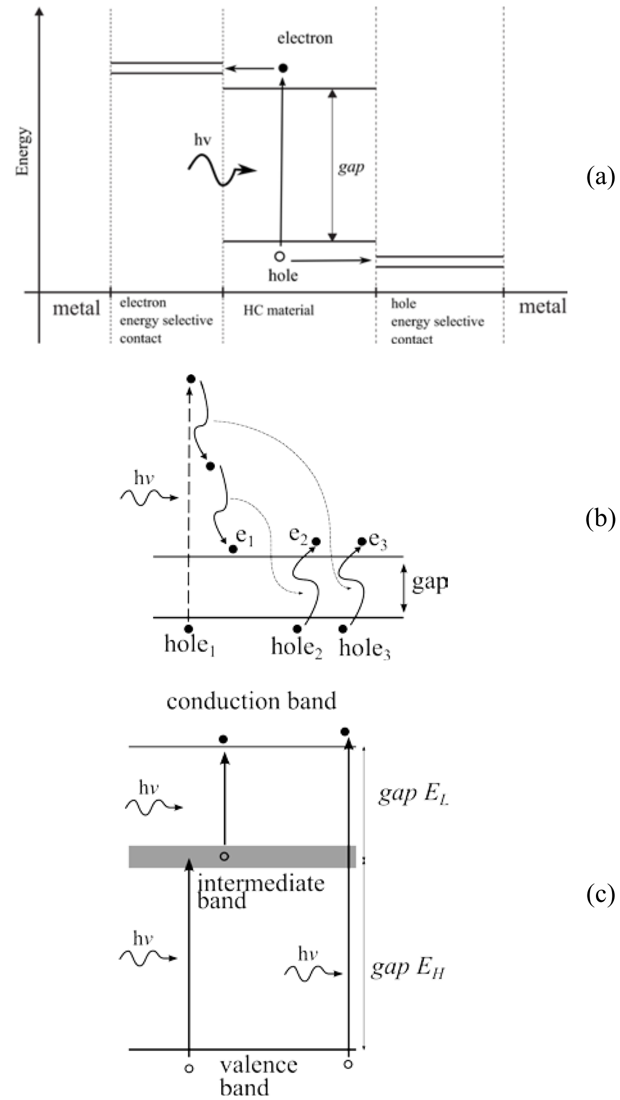

Figure 1. Illustration of the basic structure and operation of (a) a hot carrier solar cell; (b) a multiple exciton generation solar cell and (c) an intermediate band solar cell.

2. HOT CARRIER SOLAR CELL

Figure 2 plots the limiting efficiency of the HCSC for AM0 illumination as a function of the semiconductor bandgap. The physical model used to calculate this limiting efficiency is known as "energy conservation model" adapted for AM0 spectral conditions [2]. The impact of the temperature, in the range from 103 K to 413 K (minimum temperature has been considered for a standard Geostationary Orbit –GEO- mission; maximum temperature has been considered for a Low-Earth Orbit –LEO- mission) is also illustrated. As it can be seen, the optimum bandgap for operation at 300 K is located at around 0.9 eV (with a 51.8 % limiting efficiency) and shifts towards higher values (1 eV) when the temperature of operation is increased to 413 K and towards lower values (0.6 eV) when the temperature is decreased to 103 K. The limiting efficiency decreases from 51.8 % to 41.7 % when the temperature is increased to 413 K and increases to 76.8 % when the temperature is decreased from 300 K to 103 K.

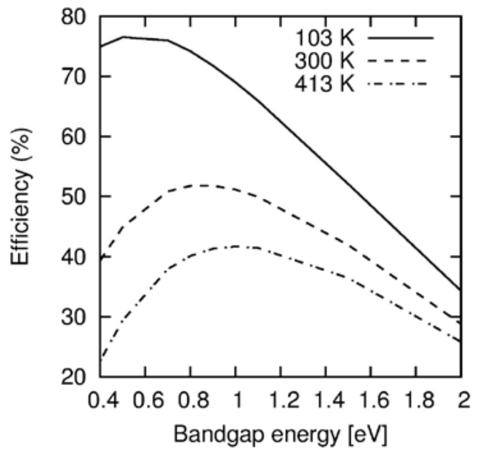

Figure 2. Limiting efficiency of the hot carrier solar cell for AM0 illumination conditions as a function of the semiconductor bandgap and the temperature of operation of the cell.

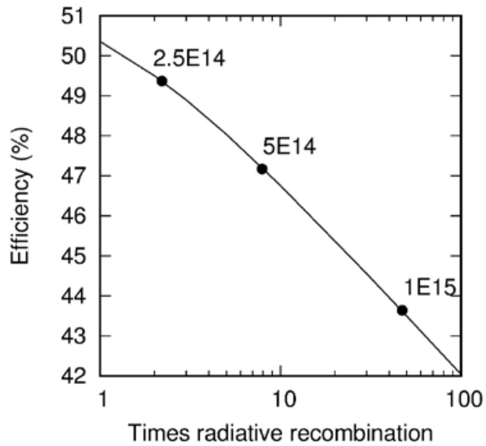

Figure 3. Impact of non-radiative recombination (measured as times the radiative recombination) on the limiting efficiency of the hot carrier solar cell. The temperature for the case illustrated has been assumed 300 K and the bandgap of the cell 0.9 eV which corresponds to the optimum gap for operation at this temperature.

Figure 3 illustrates the impact of the degradation of the cell due to the appearance of non-radiative recombination measured in times the radiative recombination. In this respect, a factor 5, for example, implies that radiation has introduced non-radiative recombination in the cell that is equivalent to 5 times the radiative recombination that is calculated according to detailed balance arguments. As it can be observed, efficiency degrades from 51.8 % to 42.0 % when non-radiative recombination is 100 times the radiative recombination. In order to have a useful meaning in space environment, these factors should be correlated with radiation fluence. However, this is impossible to do, at least while the HCSC remains mostly a theoretical concept since, for example, the materials to implement the concept with have not been clearly identified yet. In this respect, the references to fluence that appear in the Figure refer to fluences that have been estimated to introduce the indicated non-radiative recombination in conventional triple junction solar cells according to the explanations that will be given in Section 5.

3. MULTIPLE EXCITON GENERATION SOLAR CELL

Figure 4 plots the limiting efficiency of the MEGSC for AM0 illumination as a function of the semiconductor bandgap. The physical model used to calculate this limiting efficiency is the one described in [5] adapted for the AM0 spectral conditions. The optimum bandgap for operation at 300 K is found to be 0.73 eV (with a 43.1 % limiting efficiency), 0.89 eV for 413 K (with a 33.9%) and 0.32 eV for 103 K (and a limiting efficiency of 68.1 %).

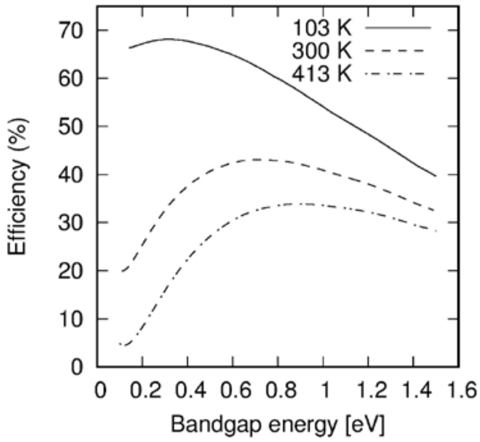

Figure 4. Limiting efficiency of the multiple exciton generation solar cell for AM0 illumination conditions as a function of the semiconductor bandgap and the temperature of operation of the cell.

As we did for the HCSC, Figure 5 illustrates now the impact of the appearance of non-radiative recombination in the efficiency of the cell. Fluences producing the same non-radiative recombination in 3J-MJSC are indicated for reference. As it can be observed, non-radiative recombination seems to have a greater impact on the MEGSC than in the HCSC since, for example, its efficiency degrades below 38 % for a non-radiative recombination 10 times the radiative one while the limiting efficiency of the HCSC remains above 46 % for the same non-radiative recombination.

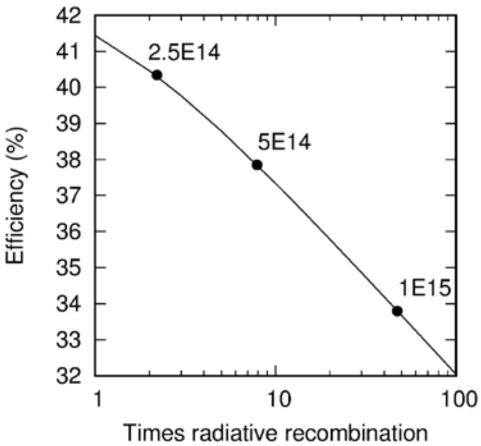

Figure 5. Impact of non-radiative recombination (measured as times the radiative recombination) on the limiting efficiency of the multiple exciton generation cell. The temperature for the case is illustrated has been assumed 300 K and the bandgap of the cell 0.73 eV which corresponds to the optimum for operation at this temperature.

4. INTERMEDIATE BAND SOLAR CELL

As introduced in section 1, the IBSC is characterized by two bandgaps E_L and E_H. Figure 6 plots the limiting efficiency of the IBSC for AM0 illumination as a function of the lowest bandgap E_L at the time the value of E_H is optimized. The physical model used to calculate this limiting efficiency is the one described in [6] adapted for the AM0 spectral conditions. The optimum bandgap for operation at 300 K is found to be E_L=0.85 eV (with a 45.8 % limiting efficiency and E_H=1.38 eV). The limiting efficiency degrades to 39 % when the cell operates at 413 K and increases to 61 % when the temperature decreases down to 103 K.

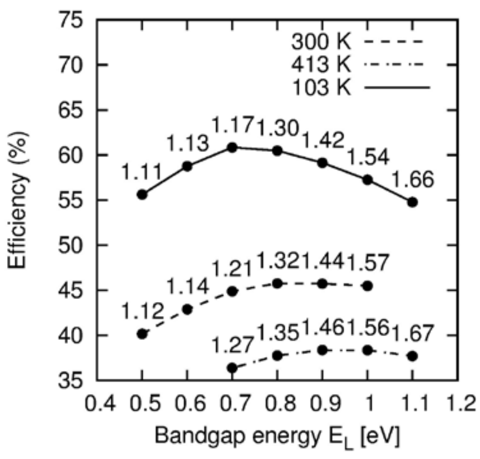

Figure 6. Limiting efficiency of the intermediate band solar for AM0 illumination conditions as a function of the semiconductor bandgap E_L and the temperature of operation of the cell. Labels indicate the optimum value for E_H.

Figure 7 shows the impact on the efficiency of the optimum cell (E_L=0.85 eV and E_H=1.38 eV) for operation at 300 K of non-radiative recombination. As it can be seen, efficiency would degrade down to 38.5 % when non-radiative recombination becomes one hundred times the radiative one. We indicate in the figure, for reference, the fluences that in the 3J-MJSC are estimated to introduce the same non-radiative recombination

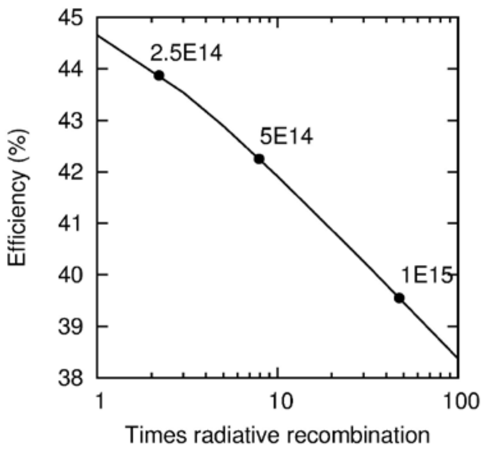

Figure 7. Impact of non-radiative recombination (measured as times the radiative recombination) on the limiting efficiency of the intermediate band solar cell. The temperature for the case is illustrated has been assumed 300 K for the bandgaps E_L=0.85 eV and E_H=1.38 eV which corresponds to the optimum gaps for operation at this temperature.

5. 3J-MULTIJUNCTION SOLAR CELL

It will be illustrative to undertake, for the solar cell commonly used today in space (the GaInP/InGaAs/Ge lattice matched tandem solar cell), the same study we have carried out in the previous sections for the novel solar cell concepts.

In this respect, Figure 8 plots the limiting efficiency of this 3J-MJSC as a function of the temperature. The limiting efficiency has been calculated using detailed balance arguments [8, 9] assuming 1.88 eV, 1,41 eV and 0,66 eV gaps for the GaInP, InGaAs and Ge respectively. Since due to the lattice matching constrains these gaps are not the ideal ones for a tandem configuration of three solar cells connected in series, a better current matching and efficiency is obtained if the GaInP cell is assumed not to absorb all the sunlight above its bandgap but, instead, 86 % of it while it allows the remaining light to reach the InGaAs middle cell. In contrast, total light absorption has been assumed for the InGaAs and Ge solar cells. No radiative coupling between the cells has been assumed in these calculations.

In the same figure we also plot, for comparison, the dependence of the limiting efficiency with the temperature of the HCSC, MEGSC and IBSC which efficiency was optimum at 300 K. This dependence shows to be linear with the temperature and Table 1 collects this slope for each of the cells. In this respect, the 3J-MJSC shows the lowest dependence (0.055 efficiency points of decrease per degree) while the HCSC shows the highest (almost 0.1 points of efficiency per degree).

Table 1 Decrease in efficiency points per K degree for the HCSC, MEGSC and IBSC which operation is optimum at 300 K.

	3J-MJSC	HCSC	MEGSC	IBSC
K^{-1}	-0.055	-0.099	-0.093	-0.069

With respect to the degradation induced by non-radiative recombination, Figure 9 plots the limiting efficiency of the 3J-MJSC as a function of the non-radiative recombination. The correlation between "fluence" and the "times radiative recombination" factor advanced in previous sections has been estimated as follows. From public data published by AzurSpace [10] for their commercial triple junction solar cell 3G30C-Advanced it has been possible to correlate that 1 MeV [e/cm2] fluences of 2.5×10^{14}, 5×10^{14} and 10^{15} degrade the cell beginning of life (BOL) efficiency by 3.1, 5.8 and 10.2 % respectively. Assuming this degradation percentages in the limiting efficiency of the ideal GaInP/InGaAs/Ge solar cell (Figure 9) leads to non-radiative factors of 2.2, 7.9 and 47.3 respectively.

These are the factors that we also indicated for reference in the efficiency plots of Figures 3, 5 and 7.

Table 2 summarises the impact on the limiting efficiency of the different novel concepts studied in this work of this levels of non-radiative recombination. As it can be observed, the MEGSC seems to exhibit the highest dependence to non-radiative recombination followed by the HCSC and IBSC.

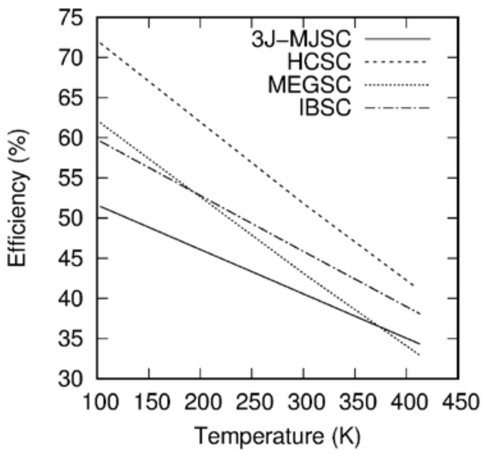

Figure 8. Impact of temperature on the limiting efficiency of the 3J-MJSC (InGaP/InGaAs/Ge lattice matched tandem solar cell), HCSC (0.9 eV), MEGSC (0,73 eV) and IBSC (E_L=0.8 eV and E_H=1.32 eV). The value of the indicated gaps were found to be optimum for photovoltaic conversion of these cells at 300 K.

Table 2. Limiting efficiency of several novel concepts for several that 1 MeV [e/cm2] fluences. For the calculation we have assumed that the given fluence introduced in the novel concept the same average non-radiative recombination that it would introduce in a 3J-MJSC. For the 3J-MJSC we have assumed a InGaP/InGaAs/Ge lattice matched solar cell. The increment Δ refer to the variation of the efficiency between the 1×10^{15} fluence and the BOL efficiency,

	BOL	2.5×10^{14}	5×10^{14}	1×10^{15}	Δ
HCSC	51.8	49.4	71.2	43.6	-15.8 %
MEGSC	43.1	40.3	37.9	33.8	-21.6 %
IBSC	45.8	43.9	42.3	39.6	-13.5 %
3J-MJSC	41.8	40.5	39.4	37.5	-10.3 %

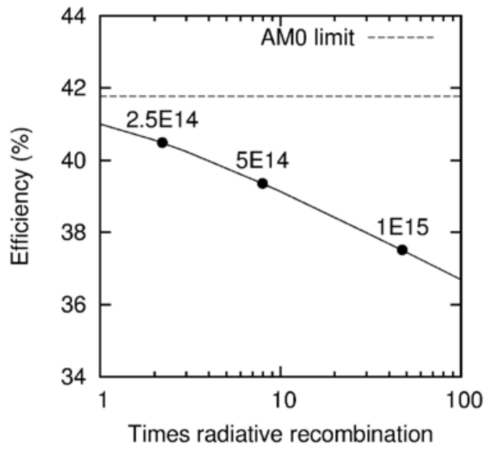

Figure 9. Impact of non-radiative recombination in the limiting efficiency of a 3J-MJSC InGaP/InGaAs/Ge lattice matched tandem solar cell. Dots indicate the 1 MeV [e/cm2] fluence that is estimated to induce the corresponding non-radiative recombination. (3 gaps in series: 0.7 eV, 1.1 eV and 1.7 eV).

6. BRIEF REVIEW OF THE STATUS OF EMPIRICAL RESEARCH ON NOVEL CONCEPTS

The results above show the limiting efficiency of the HCSC, MEGSC and IBSC for space operation conditions as well as the impact of the temperature and degradation by non-radiative recombination. However, looking forward the real use of these cells, it must be taken into account that, so far, none of these cells have demonstrated the promised efficiencies although, to more or less extent the physical principles involved in their operation have been demonstrated.

Hence, for the case of the IBSC, the absorption of two below bandgap energy photons to create one electron-hole pair has been demonstrated, for example, in several implementations that use III-V semiconductor quantum dots [11-15]. In addition, it has also been proved that the presence of the intermediate band does not limit the output voltage of the cell [16, 17].

In the MEGSC context, Semonin et al. [18] have demonstrated a solar cell based on colloidal quantum dots that exhibited an external quantum efficiency higher than one.

Research on HCSC focuses, on one side, on finding a suitable hot carrier material and, on the other side, on finding suitable energy selective contacts. As for the hot carrier material concerns, Conibeer et al. have proposed

[19] materials such as InN, HfN and SnSi. Yao and Köning have proposed BSb [20]. As for the energy selective contacts, the most studied option is based on the exploitation of different variations of the resonant tunnelling using nanostructures [21]. Dimmock et al. [22] have proposed and investigated a HCSC implemented on a metal-semiconductor junction.

7. CONCLUSIONS

HCSC, MEGSC and IBSC promise efficiencies of 51.8 %, 43.1% and 45.8 % in ideal conditions for AM0 illumination and 300 K. Regarding the dependence of these limiting efficiencies with temperature, the HCSC has revealed the highest dependence and the IBSC the lowest (see Table I).

As for the impact of non-radiative recombination in this efficiency, assuming this would introduce the same non-radiative recombination factor than in a 3J-MJSC, the MEGSC has exhibited the highest sensibility to non-radiative recombination while the IBSC has exhibited the lowest (see Table II).

In the laboratory, however, no cell has demonstrated efficiencies exceeding the efficiency of single gap solar cells. Therefore, their practical application in space will still need to wait a few years more. In spite of this, all the concepts have provided strong experimental support demonstrating that the physical principles they are based on are correct. It is also noticeable that the three concepts demand the use of nanostructures, in a way or another, for their practical implementation.

8. ACKNOWLEDGMENTS

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