

THEORETICAL INVESTIGATIONS OF III-V MULTI-JUNCTION CONCENTRATOR CELLS UNDER REALISTIC SPECTRAL CONDITIONS

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ABSTRACT: Based on theoretical considerations bandgap combinations for multi-junction concentrator cells (one to six subcells) are calculated. The structures of these cells are adapted to either the AM1.5d reference spectrum or the new proposed reference spectrum with a lower aerosol optical depth. These bandgap combinations were used to calculate the energy production on one real day. Therefore outdoor spectra were measured. It is shown that the increase in efficiency can be cancelled out by losses due to higher spectral sensitivity when the number of junctions is increased over a certain value. Thus, this paper gives a contribution to the ongoing discussion concerning the optimal number of junctions under real working conditions with daily and yearly changing spectra.

Keywords: Simulation, Concentrator Solar Cells, Multijunction Solar Cells

1 INTRODUCTION

Very high efficiencies of 36–37% [1,2] have been reached experimentally with monolithic III-V triple-junction concentrator solar cells for terrestrial applications. In order to improve the efficiency further, the number of subcells can be increased, thereby minimising the thermalisation losses. Several simulations have been performed showing the gain in efficiency achieved by increasing the number of bandgaps [3-5]. However, these calculations are always performed assuming a single, fixed sun spectrum. In fact the earth's spectral condition changes during the day, which in turn leads to varying optimum bandgap combinations during a day. Thus, the assumption of a fixed spectrum is not satisfactory.

Nevertheless, the PV community defines a reference spectrum that can be considered as an average of different spectra during the day and over the whole year. The definition of a reference spectrum is important because the design of the optimum multi-junction (MJ) solar cell structure strongly depends on the spectral conditions and it is the basis for comparing cell efficiencies internationally. Currently, for concentrator PV, two different spectra are under discussion: the "old" AM1.5d [6] spectrum and the "new" AM1.5d spectrum with a lower aerosol optical depth value (in the following "AOD 085"). The new spectrum is intended to match the real conditions better on average than the old reference spectrum [7-9].

Due to the fact, that monolithic MJ cells are series connected, the worst performing subcell limits the current of the whole device. Thus, monolithic MJ cells are designed in such a way that all subcells produce the same current under the reference spectrum. This condition is called "current matched" [10-12]. However, during a day or year a MJ cell does not always operate at its current matching point due to varying spectral conditions.

In this paper optimum cell structures from one to six junctions were calculated for the two above mentioned reference spectra. Using these bandgap combinations power yields of one randomly selected real day were calculated.

2 MODELLING

The efficiencies of MJ cells are calculated with the program "etaOpt" which has been developed at the Fraunhofer ISE [13]. The model used in the calculation is based on the detailed balance method first introduced by Shockley and Queisser [14], i.e. only radiative recombination is considered. All subcells have an external quantum efficiency (EQE) equal to one and it is assumed that photocurrent from upper subcells can be transferred to lower ones to achieve current matching conditions. In reality this is achieved by thinning the absorbing layers.

To evaluate the daily power output under varying spectral conditions, outdoor spectra were measured in Freiburg on several days. One clear day was chosen from this data base. Some of the almost 100 spectra measured on this day and the integrated power vs. time are shown in Fig. 1.

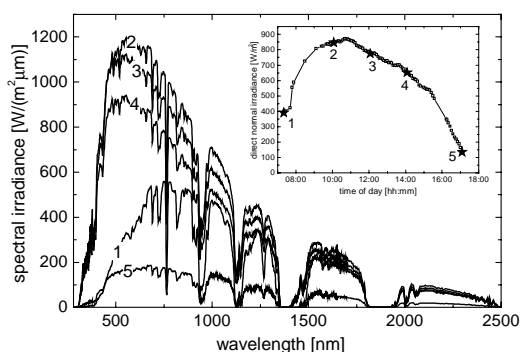


Figure 1: Spectra measured in Freiburg on the 17th of March 2004. The inserted graph shows the absolute irradiance vs. time on that day. The numbers give the local time of day of the measurements.

The measurements of the spectra were performed with a spectroradiometer from Instrument Systems. The detectors (Si and GaInAs) of the spectroradiometer are only sensitive in the range between 380 and 1650 nm. To extend the spectra to other wavelength regions, the AOD 085 spectrum, which runs from 280 to 4000 nm, was scaled to agree with the measurements. Applying this procedure lead to only minor errors verified by simulations performed with the computer code

SMARTS2 [15]. SMARTS2 can be used for modelling outdoor spectra. The simulations show that the measured wavelength range is sufficient to define the total spectrum. Thus, using a scaled AOD 085 spectrum in the regions that were not measured is a good approximation for all measured spectra.

All calculations were performed assuming a sun concentration factor of 1000 and a cell temperature of 300 K. MJ cells with three or more subcells usually need a bandgap of no more than 1 eV as the lowest junction. Since Germanium (Ge) is the only low bandgap material suitable as a substrate, the bandgap of the lowest junction was restricted to being equal to or higher than 0.66 eV – the bandgap of Ge. It will be shown that this assumption is no serious restriction. Maximum efficiencies of MJ cells using Ge are only slightly lower than MJ cells using an arbitrary lowest bandgap.

3 RESULTS

First of all, maximum efficiencies and corresponding bandgaps were calculated resulting in cells having an optimum design for a given reference spectrum. The global maxima of efficiencies and optimum bandgaps are shown in Fig. 2. The efficiency limits increase from about 40 % for a single junction cell to almost 70 % for a six junction (6J) cell. The optimum bandgaps are strongly dependent on the spectrum. Furthermore, it is shown that the efficiency limits under the AOD 085 spectrum in general are slightly higher than under the AM1.5d spectrum. In addition, the optimum bandgaps for the AOD 085 spectrum are higher than those adapted for AM1.5d. This is caused by the higher blue share in the AOD 085 spectrum.

It has to be mentioned that finding the global maximum becomes more and more challenging as more bandgaps are included in the cell. Besides the global maximum there exist many local maxima that only have slightly lower efficiency. Thus, for real outdoor spectra one of the local maxima could yield a higher power output or efficiency, respectively.

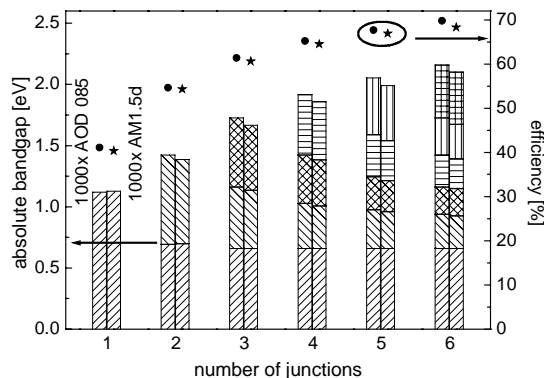


Figure 2: Calculated optimum bandgap combinations for different numbers of junctions. The calculation was performed using both the AM1.5d (right columns) and the AOD 085 spectrum (left columns) at a concentration of 1000x1000 W/m². The lowest bandgap is set to 0.66 eV for three and more junctions being the bandgap of Ge.

In the next step the bandgap combinations given in Fig. 2 are fixed and efficiencies and power outputs are calculated using the measured outdoor spectra. The efficiency vs. time of day is shown in Fig. 3. For both the AOD 085 and AM1.5d matched solar cells, peak efficiencies increase with increasing number of junctions, proving that a solar cell matched to one of the reference spectra performs well under outdoor conditions, too.

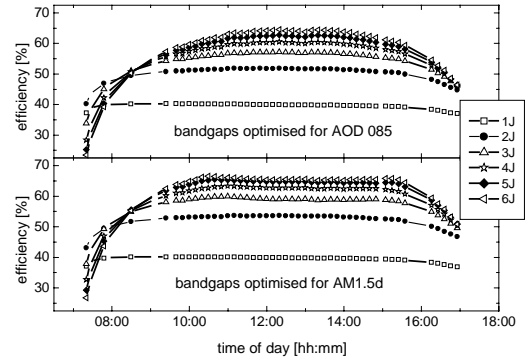


Figure 3: Variation in efficiency vs. time of day. The upper graph shows the efficiencies for the bandgaps adapted for AOD 085 conditions while the lower graph contains the efficiencies for the bandgaps optimised for AM1.5d.

In the morning and evening, when the spectrum is more red rich, the cells with more junctions show a larger drop in efficiency. To decide whether this drop results in a significant loss the daily power output of all bandgap combinations is calculated and compared (Fig. 4). Obviously, bandgap combinations optimised for the AM1.5d spectrum are better adapted to the spectral conditions on that day indicating a low blue share in the measured outdoor spectra. Comparing the energy production of 4, 5 and 6 junction cells one can recognise that even the 4J cell optimised to AM1.5d outperforms the 6J cell optimised to AOD 085. However, one should keep in mind that here only one day is considered.

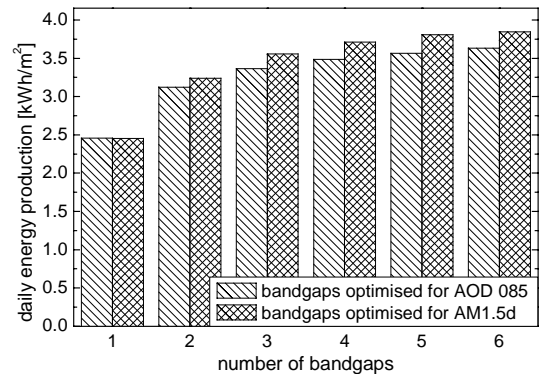


Figure 4: Energy production of bandgap combinations optimised for AOD 085 and AM1.5d (see Fig. 2), respectively, calculated for one day (Fig. 1).

A more detailed explanation of the cause for the low power output of the AOD 085 is given in Fig. 5, in the case of the 6J cell. Here the change in the current densities over time at the maximum power point of each subcell is shown. The cell optimised for AOD 085 (left hand side) is current limited by the top cell over the

whole day while the other junctions have large excess currents. The current mismatch between all subcells is quite high. On the right hand side the current densities of the AM1.5d adapted cell are shown. Here, the current limitation changes from cell 1 to cell 3 at around 11 o'clock. Especially in the afternoon the currents of all subcells are clearly better aligned and the current of the limiting subcell is always higher than for the AOD 085 adapted cell.

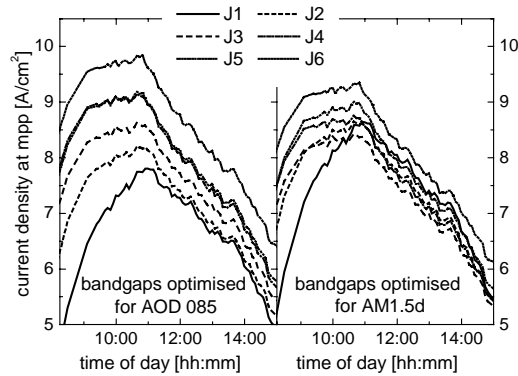


Figure 5: The graph shows the current densities at the maximum power point (mpp) of all six subcells (J1-J6) of a 6J cell adapted to the AOD 085 and AM1.5d spectrum, respectively.

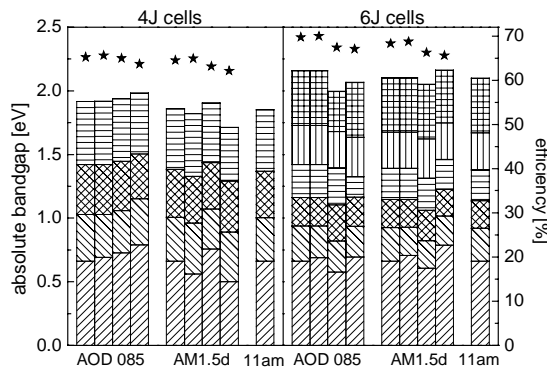


Figure 6: Different bandgap combinations yielding efficiencies almost as high as the optimum bandgap combination for a given reference spectrum. The stars refer to the right hand side axis giving the efficiency limits of the bandgap stack underneath. The bandgap combination labeled “11am” is the optimum using the measured outdoor spectrum at around 11 o'clock as “reference”.

As mentioned above there exist a lot of bandgap combinations yielding efficiencies, under a given spectrum, close to that of the global maximum. In Fig. 6 different bandgap combinations for 4J and 6J cells adapted to AOD 085 and AM1.5d respectively, are shown reaching efficiencies within 95% of the global maximum ($\eta > 0.95 \eta_{max}$). The first column of each group is the best bandgap combination on Ge. The second column represents the global maximum with free floating bandgaps, i.e. bandgaps lower than 0.66 eV are allowed. The stars in the graph refer to the right hand side axis giving the efficiencies under the corresponding reference spectra. The third and fourth column are local

maxima. The column labeled “11am” gives the optimum bandgap combination (on Ge) for the spectrum measured at around 11 o'clock (see Fig. 1) and concentration ratio of 1000.

First, it is noted that quite different bandgap combinations give very similar maximum efficiencies. Furthermore, Fig. 6 also proves that Ge is well suited to being the lowest bandgap material without limiting the efficiency potential of the MJ cell.

This is once more underlined when comparing the energy production of these cell structures, given in Fig. 7, using the measured spectra on the chosen day. The order of the columns is the same as the cell designs in Fig. 6 for which the power output was calculated and integrated over time. The first two columns of each group, representing the best cell design on Ge and for free floating bandgaps, show that the power output is hardly affected by the restriction to Ge as the substrate.

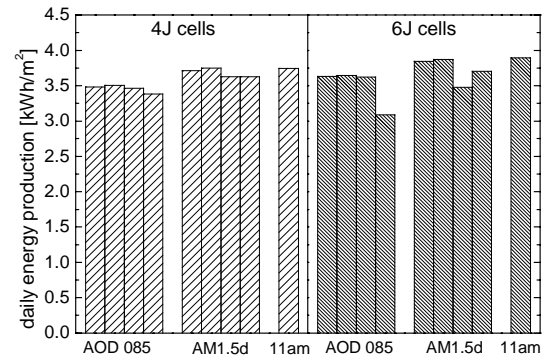


Figure 7: Energy production for the spectra given in Fig. 1 of the best bandgap combinations for AOD 085, AM1.5d and the spectrum at 11 o'clock. All chosen bandgap combinations have an efficiency better than 95 % of the achievable maximum efficiency for the corresponding reference spectra.

The AM1.5d optimised structures result in a higher output than AOD 085. A structure optimised directly for the measured spectrum would only lead to a small further improvement indicating that the real conditions on the investigated day are quite well matched by the AM1.5d spectrum. Obviously, the variation in the energy production is much higher for different 6J cell designs than for 4J cell designs. This shows the increasing spectral sensitivity with increasing number of junctions. Taking the local efficiency maxima (column 3 and 4) of the 4J cell adapted to AM1.5d as an example the lower spectral sensitivity compared to different 6J cells can be demonstrated. The local efficiency maxima have very different bandgap combinations (Fig. 6) but have almost the same power outputs (Fig. 7).

Another proof for the higher spectral sensitivity of 6J cells compared to 4J cells is given in Fig. 8. The different cell designs (Fig. 6) lead to different current limitations of the subcells and thus to varying power curves, which are not only scaled but vary qualitatively. Comparing the different designs of 4J and 6J cells (only AM1.5d) it turns out that the variation in power of different designs is much higher for 6J cells due to their higher spectral sensitivity.

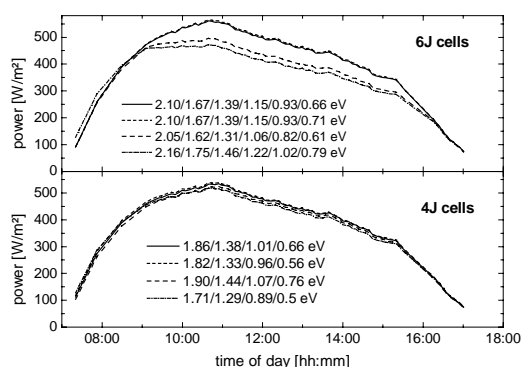


Figure 8: Comparing daily courses of power for different 4J and 6J structures which each achieve an efficiency of 95 % of the absolute efficiency limit for AM1.5d (see Fig. 6). The variation of power output for different 6J designs is significantly higher than in the case of 4J due to the increased spectral sensitivity.

Thus, the gain of a “correctly” chosen reference spectrum for the optimisation procedure has a stronger effect on the daily energy production than additional junctions. Or in other words the risk of lower energy production due to increased spectral sensitivity in the case of 6J cells is significantly enlarged.

4 CONCLUSION

In this paper efficiency limits and corresponding optimised bandgap combinations for III-V concentrator cells were calculated. These bandgaps were used to evaluate the daily energy production under real conditions using measured outdoor spectra of one day. It was shown that increasing the number of junctions leads to higher peak efficiencies as well as higher energy production. However, the increments in power output and efficiency are quite small for more than four junctions. Furthermore, it was demonstrated that with increasing number of junctions the spectral sensitivity increases significantly. Further measurements of daily spectra are necessary to investigate the annual power output of MJ cells. This is ongoing work at Fraunhofer ISE.

Finally, these simulations have an impact on the research trends for MJ concentrator solar cells. For example, comparing the optimum 3J design given in this paper (Fig. 2) with the bandgap combination of the currently established 3J cell (GaInP/GaInAs/Ge) large differences can be found. To improve the efficiency of the 3J cell structure the top and middle cell bandgaps have to be lowered, leading to the lattice mismatched approach suggested in [16].

Another improvement could be achieved with the introduction of an appropriate 1 eV material in the current 3J cell structure resulting in a well adapted 4J cell. Although the 6J cell may be unsuited for terrestrial applications because of its high spectral sensitivity, it should be well suited for space applications where spectral conditions remain constant.

5 ACKNOWLEDGEMENTS

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6 REFERENCES

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