STUDY OF NON-UNIFORM LIGHT PROFILES ON HIGH CONCENTRATION III-V SOLAR CELLS USING QUASI-3D DISTRIBUTED MODELS

I. García *, C. Algora, I. Rey-Stolle and B. Galiana
Instituto de Energía Solar, E.T.S.I. Telecomunicación, Universidad Politécnica de Madrid
Avda. Complutense s/n, 28040 Madrid, Spain
igarcia@ies-def.upm.es • Tel: +34 91 4533555 • Fax: +34 91 5446341

ABSTRACT

The quasi-3D models based on distributed circuit units are a powerful tool to analyse the performance of a solar cell from the point of view of its electrical behavior. Quite accurate models have been developed in the past that reproduce the experimental data of single-junction solar cells very closely. These models help in the determination of the origin of the peculiarities of the dark and one sun or high concentration experimental I-V curves. They also allow the design of the front grid, the analysis of the impact of the electrical parameters of the solar cell on the performance of the final device, etc.

In this work, these models are used to study the effect of non-uniform profiles, generated by the concentrator optics, on the performance of a concentrator solar cell. The design of the front grid is then optimized to minimize the losses introduced by the light distribution, even taking into account the effect of the tracking system misalignment. As an introductory application example of multijunction solar cells analysis with this kind of modeling, the effect of the chromatic aberration on a double junction solar cell is presented.

INTRODUCTION

Concentrator III-V solar cells have experienced a fast increase in efficiency in the last years [1]. The main improvements have been achieved through the optimization of the semiconductor structure. Besides, the fabrication process and, specially, the pattern and electrical characteristics of the front grid have a decisive influence on the electrical performance of the final device, specially at high concentrations, affecting primarily the fill factor. Moreover, as the efficiencies go up the absolute impact of the fill factor on the solar cell efficiency becomes higher. Thus, the possible detrimental effect of the metallization on the fill factor should be minimised. On the other hand, concentrator solar cells work, in their final application, under non-uniform light profiles produced by the concentrating optics, making this task more challenging. All these reasons make sensible the use of a suitable simulation tool as an aid in the prediction of the electrical characteristics of the final solar cell device and in the optimization of the front grid.

The effects on the solar cell derived from a non-uniform profile have a distributed nature [2]. Thus, a 3D model must be applied to study them. In the following sections, the effects of the light profile generated by a practical optical system on the performance of a GaInP top cell is studied. Two applications are presented: the effect of the non uniform irradiance on the I-V curves, and the design of the front grid, taking into account the non uniform profiles and the position of the light spot. Finally, the simulation of multijunction devices with this model is introduced briefly analyzing the influence of the chromatic aberration produced by the concentrator optics on a GaInP/GaAs double junction solar cell.

THE QUASI-3D MODEL

The quasi-3D models based on distributed circuit units are an easy-to-use and powerful tool to study the electrical characteristics of any semiconductor device, being solar cells a particular case. In fact, quite accurate models have been achieved in the past that reproduce the experimental curves of single-junction GaAs solar cells very closely [3]. These models consist in dividing the device into sufficiently small portions and assigning an equivalent circuit to each one [4-5]. In a single junction solar cell, the circuit model for the portions with metal would look like the one displayed in figure 1. Each part of the device which can contribute to its electrical behaviour is considered in the model, as can be observed. For a multijunction device, this model is also used for each subcell, and a component is added to series connect them, simulating the effect of the tunnel junction.

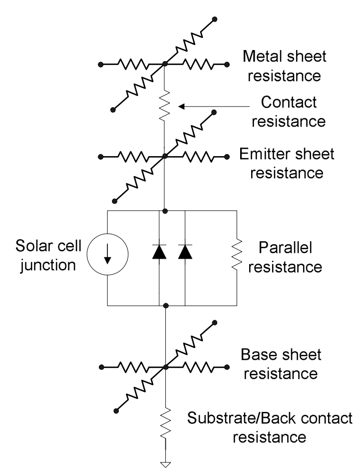

Fig. 1. Equivalent circuit of a single-junction solar cell, used in the distributed model.

Once divided into portions and assigned a model to each one, the equivalent circuit of the complete device, usually in the order of 100,000 nodes, is generated. The circuit solving is then carried out with Pspice®.

CASE STUDY A: EFFECT OF NON-UNIFORM LIGHT PATTERNS ON THE I-V CURVE

The concentrator solar cells front grid patterns designed considering that a uniform distribution of light will impinge on the device are not optimized for practical purposes. When dealing with a concentrator system, the light distribution produced is not uniform, having typically a gaussian-like profile, with higher intensities at the center and lower at the borders of the solar cell. The optimum front grid design for this case differs significantly from the one used with uniform light distributions.

The quasi-3D model allows the assignment of a different light power density to each portion the solar cell is divided into. Thus, any light pattern can be used in the simulations. A particular case is the existing aspheric+DTIR double stage optics (A+DTIR hereinafter). In fig. 2, the concentration level is plotted against the position, for the A+DTIR light profile. An imaginary case with a smoother shape is also plotted and simulated for comparison. These light profiles where applied to a distributed model of a concentrator GaInP top cell with a 1-sun J_{sc} of 14 mA/cm^2 and J_{01} and J_{02} recombination currents of $1.26 \cdot 10^{-26}$ mA/cm^2 and $4.57 \cdot 10^{-14}$ mA/cm^2, respectively. The emitter sheet resistance is 500 $\Omega/\square$. The front grid pattern (an inverted square design) is displayed in the inset of fig. 2, and the electrical properties of the metallization can be found in [3]. This front grid is optimum for the solar cell under study working at a concentration of 1000 suns, under uniform illumination. The simulation for the case of 1000 suns uniform light was also performed. In all the cases analyzed, the total light power impinging the solar cell is kept constant, being the only difference the distribution of the irradiance, according to the profiles explained above.

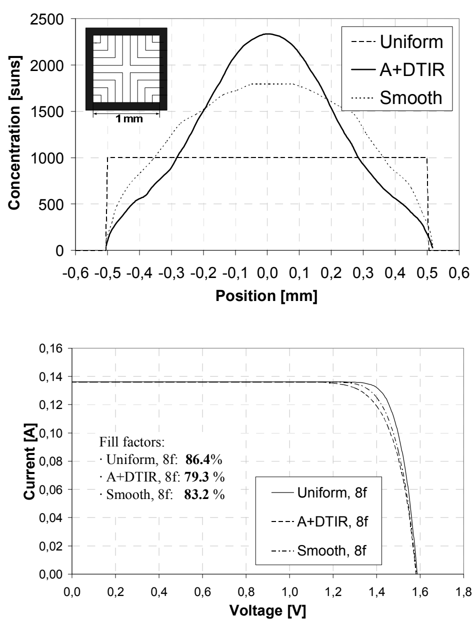

Fig. 2. Light profiles studied and the I-V curves of a single junction GaInP concentrator solar cell illuminated with them (the integrated light power is kept constant).

The I-V curves resulting from the simulation are plotted in the lower graph of fig. 2. As could be expected, the fill factor decreases as the non-uniformity of the light increases. In fact, since the front grid is optimized for uniform illumination, at a concentration of 1000 suns, the areas with higher concentration will exhibit a lower "local" fill factor. Although there is also a region with a light intensity lower than the equivalent to 1000 suns, the overall result is, in this case, an important reduction in the fill factor of the device. Thus, the efficiency of the device decreases (see data in table 1).

This result suggests the need for designing front grids adequate for the light distribution we expect to have, in order to maximize the efficiency of the solar cell device. Intuitively, the solution appears to be a front grid with a variable finger density. In the A+DTIR case, the higher density should be in the center of the front grid, where the light intensity is higher. However, as will be seen in the next section, a front grid with equally spaced fingers can be advantageous, even with non-uniform light.

CASE STUDY B: DESIGN OF THE FRONT GRID FOR NON-UNIFORM CONCENTRATED LIGHT PATTERNS.

As mentioned above, the performance of the solar cell under an A+DTIR concentrated light profile should improve if we design the front grid properly. Particularly, making the density of fingers higher where a higher intensity of light is impinging the solar cell should bring about an increase of the fill factor. The simulations carried out are displayed in fig. 3.

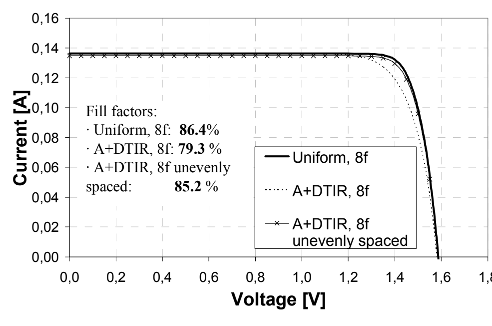

Fig. 3. Effect of the non uniform profile on the I-V curve for different front grid designs.

The result is an increase of the fill factor of almost 6% absolute, to a value 1% absolute below the one obtained with 1000 suns uniform light. Although the short circuit current decreases (see table 1) due to the higher effective shadowing factor, the overall result is an increase in the efficiency to a value close to the uniform light case.

In fig. 4 it is shown the voltage map of the surface of the solar cell working at the maximum power point (MPP), for the three cases presented in fig. 3. The higher the voltage drop, the warmer the color in the color plot. From fig. 4c it

978-1-4244-1641-7/08/$25.00 ©2008 IEEE

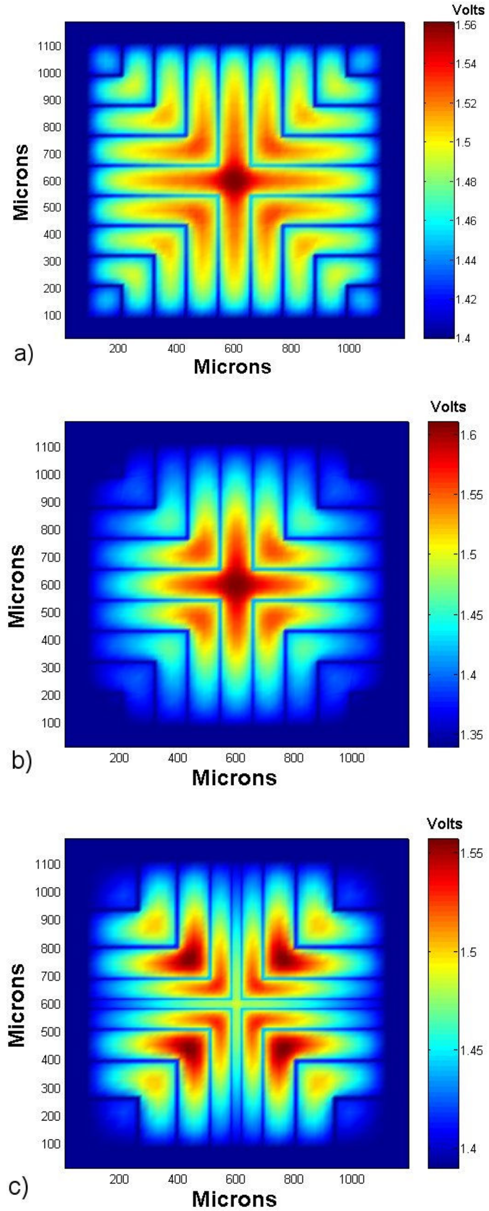

Fig. 4. Voltage map at the MPP for: a) uniformly distributed light, b) A+DTIR light distribution, and c) A+DTIR light distribution with unevenly spaced fingers front grid.

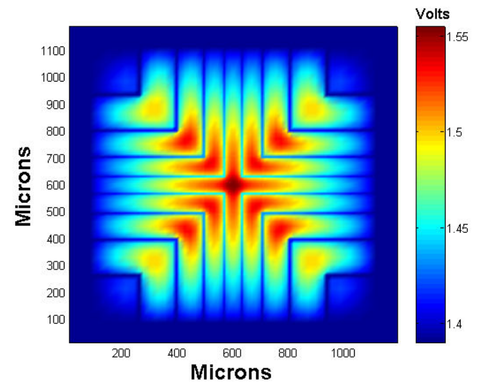

Fig. 5. Voltage map at the MPP for the improved grid used with a A+DTIR distribution of light.

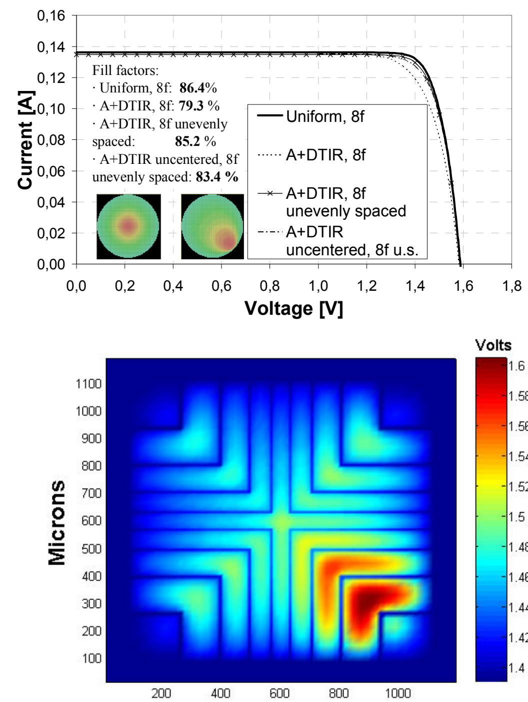

Fig. 6. Top: I-V curves obtained with the A+DTIR profile and an unevenly spaced fingers front grid, for an aligned and misaligned light distribution; Bottom: voltage map at the MPP for the misaligned case.

can be inferred that the finger separations set chosen for the unequally spaced grid is not optimum, though better than the equally spaced fingers configuration. In figure 5, the voltage color plot obtained with an improved version of the grid is shown. It can be seen that the new fingers separation set produces a more regular voltage distribution and with a maximum voltage drop value below the one obtained with the previous case. This is indicative of a better electrical performance of the device front grid. The improvement in the merit figures of the I-V curves can be seen in table 1.

CASE STUDY C: EFFECT OF ACCEPTANCE ANGLE ON THE SOLAR CELL ELECTRICAL PERFORMANCE.

So far, the non-uniform light patterns studied are symmetric and centered in the solar cell device. However, this is not expected to be the case in most practical situations. The final application of the concentrator solar cells is in a panel which follows the sun position by means of a tracker. The alignment of this system with respect to the sun is, though within the concentrator optics acceptance angle, not perfect. This leads to a light pattern moving around the solar cell active area throughout the day. It is interesting to analyze the effect of this fact on the performance of the solar cell.

The light patterns shown in the inset of figure 6 are applied to the solar cell device with 8 fingers not equally spaced. The first case is the light pattern produced by the

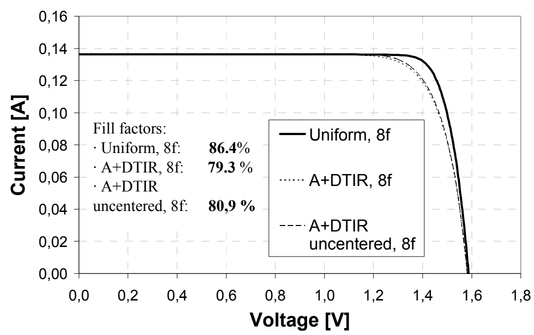

Fig. 7. Influence of the misalignment when using an equally-spaced fingers configuration.

A+DTIR optics, and the second one is the same pattern but displaced, to emulate a partial misalignment in the concentrator system. The result shows a decrease of the fill factor of almost 2 % absolute. This variation is due to the fact that, in the misaligned situation, an area with a very low density of fingers is being illuminated with the most intense part of the light pattern (note also the increase in the short circuit current in table 1).

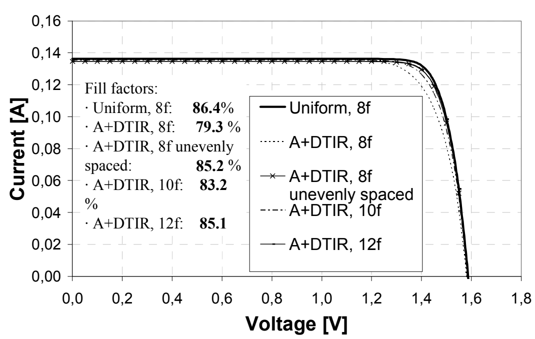

Fig. 8. Influence of the number of fingers in the front grid, with the non uniform light profile.

This variation is much less pronounced in the case of uniformly spaced fingers as can be observed in fig. 7 (though the absolute values are below the ones obtained with the 8 unevenly spaced fingers). Since the density of fingers is roughly constant in the whole active area, the electrical performance of the solar cell is much less affected by the symmetry of the light distribution (for a given number of fingers and integrated light power). Therefore, the use of uniformly spaced fingers is preferred in this case. However, it was also examined the possibility of increasing the number of fingers in the front grid so as to obtain fill factor values closer to the uniform light distribution case. It has to be worked out if the decrease in short circuit current, due to the increased shadowing factor, can be counterbalanced with the benefits in terms of fill factor. In figure 8 the results are shown.

As can be observed, if we increase the number of fingers from 8 to 12, the fill factor increases rapidly. Although the short circuit decreases due to the higher shadowing factor, the overall effect is an increase of the efficiency (table 1). For 12 fingers, the efficiency is almost identical as for the case of non uniformly spaced fingers. Moreover, with 12 fingers equally spaced, there will not be problems with the exact position of the light. This means that, for this case, it is better to increase the number of fingers than to modify their separation, a conclusion in line with the result obtained in [6].

Light distribution and front grid	Isc [mA]	Voc [V]	FF [%]	Efficiency [%]
Uniform, 8 fingers	136.3	1.584	85.6	18.50
A+DTIR, 8 fingers	136.3	1.577	79.3	17.18
A+DTIR, 8f unevenly spaced	134.7	1.581	85.2	18.14
A+DTIR, 8f unevenly spaced (improved)	134.9	1.585	85.4	18.26
A+DTIR uncentered, 8f unevenly spaced	135.1	1.581	83.4	17.78
A+DTIR uncentered, 8f	136.3	1.577	80.9	17.39
A+DTIR, 10 fingers	135.5	1.580	83.2	17.82
A+DTIR, 12 fingers	134.6	1.581	85.1	18.10

Table 1. Data summary of the GaInP concentrator solar cell front grid study.

CASE STUDY D: $GaInP_2$/GaAs DJSC CURRENT MISMATCH AND CHROMATIC ABERRATION

When dealing with multijunction solar cells where the different junctions are series connected, a key issue to maximize the conversion efficiency of the complete device is the current matching between subcells. It is known that the current mismatch increases the fill factor, but it always give rise to a lower efficiency due to the reduction of the short circuit current [7]. Thus an exact current matching is desired when designing the solar cell device semiconductor structure.

In a concentrator system, a significant chromatic aberration can appear, especially if the optics setup includes refractive lenses without a homogenizer secondary stage. This leads to a situation where the light spectrum depends on the position on the solar cell surface and, therefore, so does the current matching. The chromatic aberration in a current matched multijunction device gives rise to a reduction in the short circuit current, and an increase in the fill factor [8], which produces a reduction in the conversion efficiency. This is due to the

978-1-4244-1641-7/08/$25.00 ©2008 IEEE

areas in the device where the currents of each subcell are not matched any more due to the chromatic aberration. The impact of this effect on the performance of the solar cell can be studied using the quasi-3D model. We are going to use the GaInP/GaAs double junction solar cell as an example.

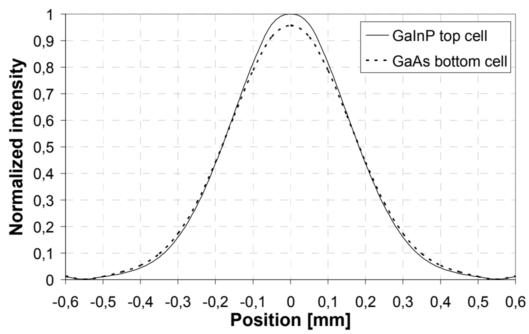

Fig. 9. Simulated chromatic distribution of the primary lens of an A+DTIR concentrator optics set-up.

The equivalent circuit of a double junction solar cell is the result of series connecting a circuit as the one presented in fig. 1 for each subcell, by means of an additional component that models the tunnel junction interconnection. In this case, we are going to use a resistor to emulate an ideal tunnel junction. To simulate the chromatic aberration, we can calculate the values of the current generators which model the photocurrent, according to the External Quantum Efficiency of the solar cell and the properties of the light impinging it (spectral power density). Thus, we can assign different values for the top and bottom cell photocurrents, depending on the position in the solar cell.

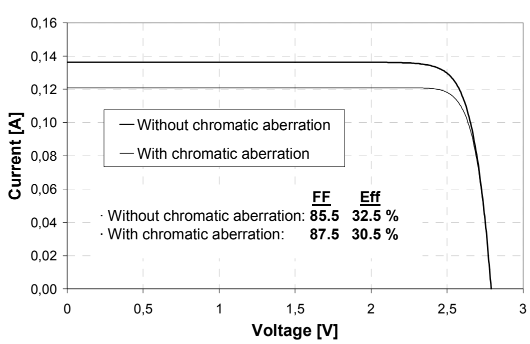

Fig. 10. I-V curve simulation results of a concentrator double junction GaInP/GaAs solar cell with and without aberration in the concentrator optics.

The optics set-up that we are going to deal with as an example is the A+DTIR approach, used in the previous sections, but without the secondary lens. For the complete set-up, the chromatic aberration is negligible thanks to the rays mixing that takes part in the secondary lens. In figure 9, the simulated normalized distribution of light flux sensitive to each subcell in a GaInP/GaAs double junction solar cell, for the A+DTIR primary lens is shown. It is observed that the center of the solar cell is impinged with blue-rich light and the periphery with red-rich light. The double junction solar cell simulated is composed of a GaInP top cell with the same characteristics as the one used in the previous studies and a GaAs bottom cell whose characteristics can be found in [3]. The front grid used is the optimum obtained in the previous studies, i.e., it is an inverted square design with 12 uniformly spaced fingers. The I-V curve results obtained with the quasi-3D distributed model are plotted in figure 10.
As expected, the results show a decrease in the short circuit current and an increase in the fill factor, caused by the current mismatch, being the overall result a decrease in the efficiency. Thus the importance of the secondary lens in the A+DTIR optics set-up, regarding the elimination of the chromatic aberration, is clearly confirmed. Moreover, the potential of the quasi-3D modeling to simulate distributed effects in multijunction solar cell devices has been again proved. A similar study but with a more realistic definition of the tunnel junction, including the three regions of its I-V curve, is ongoing.

SUMMARY AND CONCLUSIONS

Using the quasi-3D models based on distributed circuit units, the effect of non-uniform light profiles, produced by a practical concentrator optics, on the performance of a concentrator GaInP top cell has been studied. The inverted square front grid design has been used as an example. Its geometry has been optimized even taking into account the asymmetries of the light distribution that can appear due to a possible tracker partial misalignment. An important conclusion drawn for this particular case is that the best choice for the front grid design is to use evenly spaced fingers but increasing the number of them with respect to the optimum in the case of uniform light distribution. Finally, the potential of this modeling for the analysis of distributed effects on multijunction solar cells has been briefly explored by analyzing the impact of the chromatic aberration on the performance of a double junction GaInP/GaAs concentrator solar cell. Simulations with other front grid designs and multijunction devices including tunnel junction effects are ongoing.

ACKNOWLEDGEMENTS

This paper has been supported by the European Commission under contract SES6-CT-2003-502620 (FULLSPECTRUM project). The Spanish *Ministerio de Educación y Ciencia* has also contributed with the CONSOLIDER-INGENIO 2010 program by means of the GENESIS FV project and also with the research projects with references TEC2005-02745 and TEC2004-22300-E as well as the Comunidad de Madrid under NUMANCIA program (S-505/ENE/0310). The authors are indebted to César Dominguez and the ISI group for providing the A+DTIR optics data and for useful discussions.

REFERENCES

[1] King, Richard. R, et al "Metamorphic concentrator solar cells with over 40 % conversion efficiency", *Proceedings of the 4th International Conf. on Solar Concentrators*, 2007, p.8.

[2] C. Algora, chapter 5 in "Concentrator photovoltaics", edited by A. Luque and V. Andreev, Springer series in optical sciences, 2007.

[3] Galiana, B., Algora, C., Rey-Stolle, I, and Garcia, I "A 3-D model for concentrator solar cells based on distributed circuit units", *IEEE Trans. Electr. Dev.*, **52**, 2005, p.2552.

[4] H. C. Hamaker, "Computer modeling study of the effects of inhomogeneous doping and of composition in GaAs solar-cell devices," *J. Appl.Phys*, **58**, 1985, pp. 2344–2351.

[5] E. T. Franklin and J. S. Coventry, "Effects of highly nonuniform illumination distribution on electrical performance of solar cells," in *Proc.Solar Australian and New Zealand Solar Energy Society*, 2002.

[6] C. Algora and V. Díaz, "Influence of the series resistance on the guidelines for the manufacture of concentrator p-on-n GaAs solar cells", Progress in Photovoltaics, 8, 2000, pp. 211-225.

[7] S.R. Kurtz, P. Faine, J.M. Olson, "Modeling of two-junction, series connected tandem solar cells using top-cell thickness as an adjustable parameter", J. Appl. Phys., Vol. 68, pp. 1890-1895, 1990.

[8] K. Araki and M. Yamaguchi, "Extended distributed model for analysis of nonideal concentrator operation," *Sol. Energy Mater. Sol. Cells*, **75**, 2003, pp. 467–473.

978-1-4244-1641-7/08/$25.00 ©2008 IEEE