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Pending Issues in the Modeling of Concentrator Solar Cells

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This article, published in the Proceedings of the 19th European Photovoltaic Solar Energy Conference, Paris, 2004, presents the ability of ***ATLAS-Luminous3D*** to simulate heterostructure Solar Cell

Abstract

The modelling of concentrator solar cells for real conditions of operation inside optical concentrators is a subject almost untreated. Consequently, this work highlights the main specific situations that should be included in a realistic modelling. The results of a 2-D modelling applied to the case of a 1000 sun GaAs concentrator solar cell inside a TIR-R concentrator are presented. The necessity of going towards a 3-D modelling is also stated. This task is being carried out now at IES-UPM. Keywords: concentrator cells, modelling, III-V semiconductors.

1. Introduction

In the last years, a great activity is being carried out in Europe, United States and Japan in order to achieve commercial PV modules for terrestrial applications based on concentrator III-V solar cells operating at 200-1000 suns [1, 2, 3]. This activity, which is in the search of a real breakthrough, is requiring very accurate models for concentrator solar cells that conduct to the highest efficiency of PV modules. In order to increase the performance of such concentrator solar cells, a modeling as accurate as possible is necessary to guide the technological approaches. Concentration operation imposes several conditions that should be theoretically assessed in order to achieve realistic results. This is, a model considering real operation conditions as it is proposed in [4].

However, standard procedures for characterizing concentrator cells are usually far away from reality. For example, the use of the AM1.5D spectrum with normal incidence of light onto the solar cell is a common practice in characterisation. Obviously, this type of procedures have had such a great influence on the field of simulation and optimisation, that in fact, the majority of simulation results have assumed the AM1.5D spectrum, normal incidence of light, etc. However, a good solar cell at these "standard" conditions could become in an average solar cell when operates inside an optical concentrator.

Accordingly, it is necessary to detect the pending issues in the modelling of concentrator solar cells when considering the situations appearing in their real operation. In our opinion, the most influencing ones are:

- Different illumination spectra from the standard ones, as a consequence of the pass of light through a given optics.
- Inhomogeneous illumination distribution on the solar cell because of the focusing of light.
- Light impinging the cell within a cone, as a consequence of the different areas of the optics and solar cell.
- Chromatic aberration.
- Temperature gradients. At the horizontal plane, they appear as a consequence of the inhomogeneous illumination. At the vertical plane, as a consequence of the different light absorption at the different junctions in a tandem cell.

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Volume 15, Number 2, February 2005

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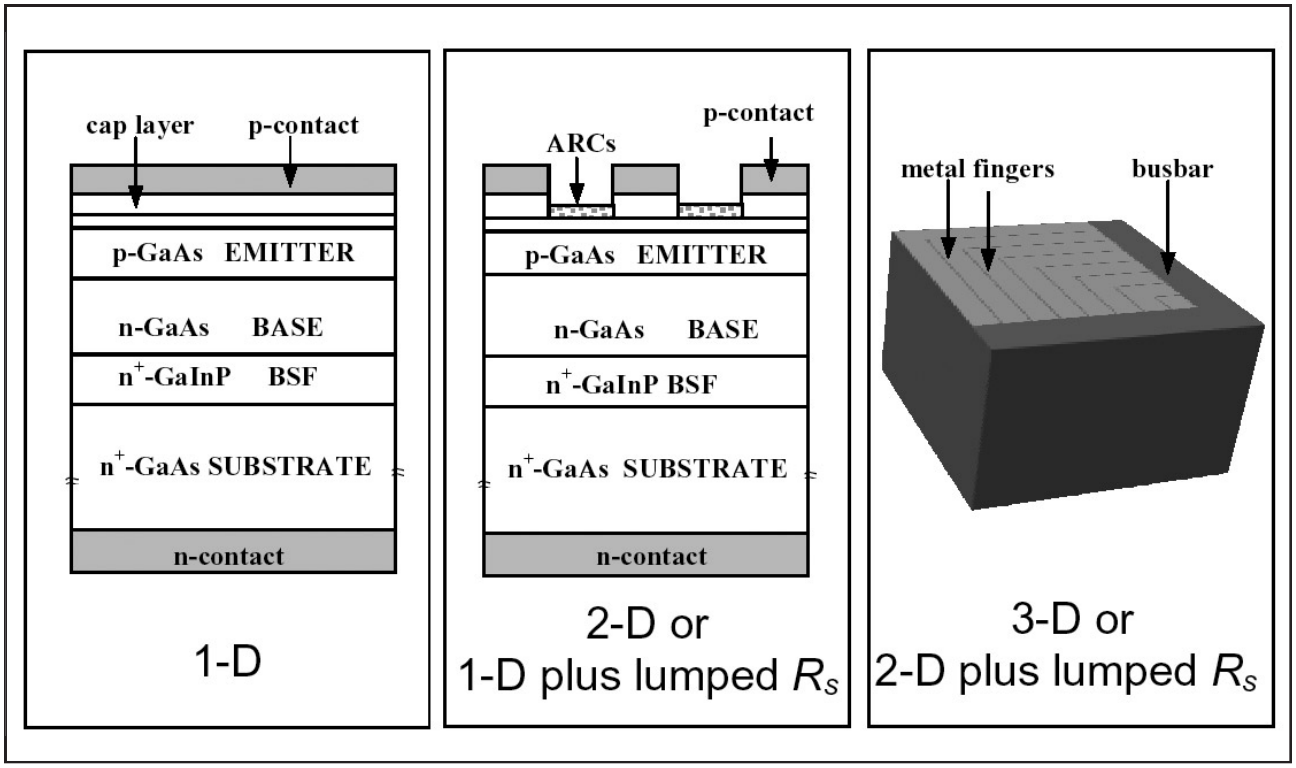

Figure 1. Definitions of 1-D, 2-D and 3-D modeling by using as example a concentrator p/n GaAs solar cell.

Thereby in connection with the consideration of these new issues in the modelling, a new calculation strategy should be applied. Effectively, the aforementioned pending issues have an inhomogeneous distribution in the horizontal or in the transversal plane of the solar cell. Therefore, an evolution from the previous onedimensional (1-D) models towards a two-dimensional (2- D) or three-dimensional (3-D) model should be undertaken.

2. Definitions for 1-D, 2-D and 3-D Modeling

When simulating semiconductor devices, a common rule for designing what is a 1-D, 2-D and 3-D model is that shown in Figure 1.

In a pure 1-D model, the whole structure varies only in one direction (as in Figure 1, left). This situation corresponds to a solar cell with a front metal covering its whole surface. Therefore, no pure 1-D model can simulate any solar cell! However, many people use 1-D models because they analyse the semiconductor structure without the consideration of the contact effects.

A 2-D model accounts for variations in two directions (as in figure 1, centre). This situation applies to any solar cell because there is a vertical variation due to the different semiconductor layers plus a horizontal variation due to the metal fingers of the front contact. In order to simplify the physic-mathematic treatment, many people use a 1-D model for the semiconductor equations while including the series resistance as a lumped parameter to take into account the horizontal variation imposed by the front contact geometry.

Finally, a 3-D model accounts for variations in the three directions (as in figure 1, right). This situation applies to many solar cells having their front metal grid with variation in more than one direction (like the circular ones).

But in addition to the characteristics of a given solar cell that recommend a 2-D or 3-D modelling, the external conditions can definitively force a 3-D analysis. This is the case, for example, of a solar cell illuminated with a non-uniform beam from a concentrator.

Therefore, any concentrator solar cell operating under real conditions should be analyzed with a 3-D model. One the main problems for computing a concentrator solar cell with a 3-D model is the large size of the solar cell. All the 3-D electronic device simulation software tools are conceived for microelectronics. Therefore, when such programs are applied to solar cells their calculation capabilities are not enough for a complete 3-D analysis. In fact, as it is described in [5], some attempts of using such programs for solar cells have been restricted for 2-D purposes.

A very interesting approach for avoiding this limitation and to analyze concentrator solar cells by a 3- D model with distributed parameters can be seen in [6].

3. Case of Study: 1000 SUN GaAs Solar Cell Inside a TIR-R Concentrator

In order to show the effects of the pending issues described in the Introduction, it is necessary to choose a given case. We have chosen the case of a 1000 sun GaAs solar cell inside a TIR-R concentrator for the following reasons:

- The 1000 sun GaAs solar cell has an area of 1 mm2, following the patent described in [7]. Therefore, its size is much closer to those of microelectronic devices successfully analyzed with the commercial 3-D electronic device simulation programs.
- The 1000 sun GaAs solar cell plus the TIR-R concentrator are being developed in order to achieve a commercial product [1].
- The combination of such solar cell plus the TIR-R concentrator is well known for us so, all the required data for the analysis are available.

The TIR-R concentrator exhibits very interesting characteristics like concentrations higher than 1000 suns, acceptance angle: 1.3º (for 90% relative transmission), aspect ratio < 0.3, total planarity of the front surface etc. [8]. Many of its optical properties required in the present analysis can be found in [9].

We have used the ***ATLAS*** simulation software from Silvaco [10]. In this paper, we present only 2-D analyses because, as a starting point, the effects of including the pending issues can be clearly shown.

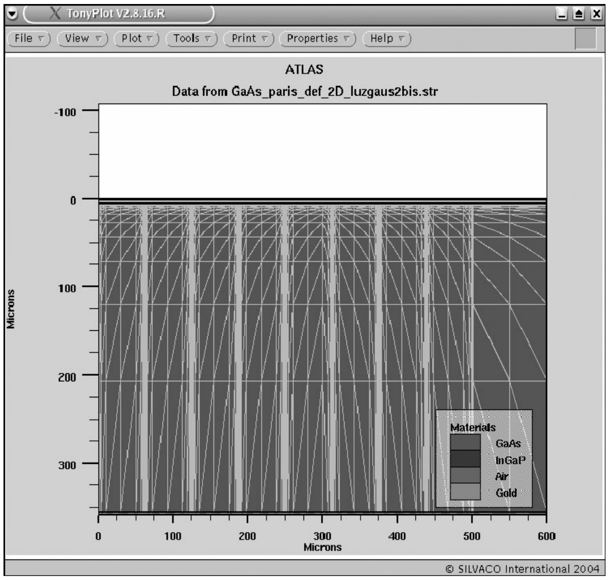

Figure 2. Cross-section of a half GaAs solar cell (500 microns for the active area plus 100 microns for the bus bar). The mesh for the 2-D calculations is also shown.

In addition, even for the small size of the simulated solar cell, about 14,000 nodes with a calculation time of about 90 minutes are required for one half of the cell (see Figure 2). Therefore, an optimization of our computing procedures should be carried out for the future 3-D modelling. A draft consideration of the 3-D analysis shows that about 350,000 nodes and about 10 hours will be required for simulating a quarter of the cell (0.6 x 0.6 mm), what is enough considering its symmetry.

4 Which Spectrum?

In the last years, the classical AM1.5D spectrum as defined by ASTM 891-87 has been questioned as being a good reference for concentrator solar cell characterization [11] and consequently, for its simulation and optimization. Several works proposed the AM1.5G as the most appropriate spectrum while others stated a redefinition of the AM1.5D with a lower aerosol optical depth (low AOD).

However, the influence in the final performance of the solar cell when choosing one or other standard spectrum is negligible in comparison with the variation in the spectrum produced by the spectral transmission of the optical concentrator. As Figure 3 shows, for wavelengths lower than 900 nm (close to the cut-off wavelength of GaAs), the transmission variation of TIR-R is almost negligible. Nevertheless, for wavelengths higher than 1300 nm the spectral transmission variation becomes important being much more restrictive than the consideration of one or another standard solar spectrum. Such a spectral transmission should be carefully considered when multijunction cells are modelled and optimised.

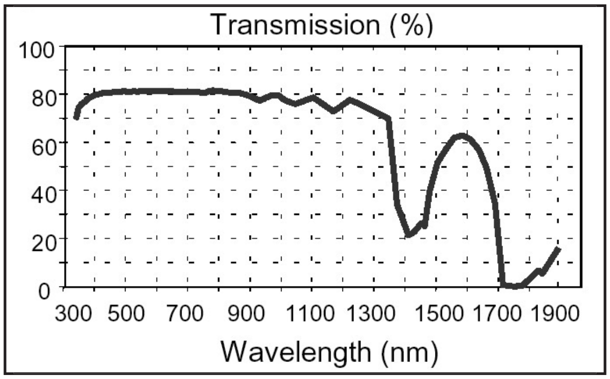

Figure 3. Spectral transmission of the TIR-R concentrator.

5. Non-Uniform Illumination

For normal incidence of the sunlight, the TIR-R concentrator produces an irradiance distribution over the 1 mm2 solar cell of about 1000 suns as average with a maximum value of 1850 suns.

When the sunlight is tilted within the acceptance angle of the concentrator, the maximum irradiance goes up. Therefore, we have considered here as a representative

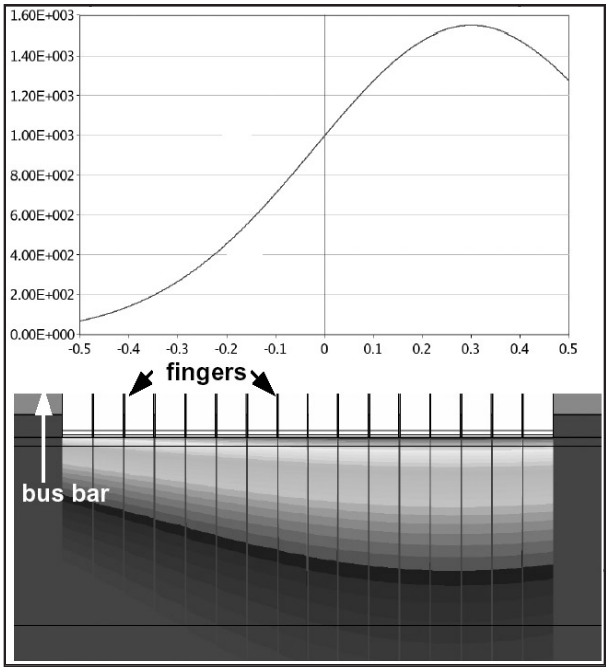

Figure 4. 2-D irradiance profile (in suns) over a complete section of the 1 mm2 solar cell. The integration of such profile produces an average of 1000 suns. The horizontal scale is in mm (top). Photogeneration produced by the top profile over the GaAs solar cell. The vertical dimension of the cell is magnified and takes about 5 microns (bottom).

example of the worst case, the sun placed at 0.8° from normal incidence. In such case, the irradiance distribution on the solar cell is shown in Figure 4 (top).

This profile is applied to a complete section of the GaAs solar cell. As Figure 4 (bottom) shows all the elements of the solar cells are included in their proper scale: bus bars at horizontal extremes separated by 15 metal fingers with a thickness of 0.5 microns and a width of 3 microns. The semiconductor structure includes all the layers: cap (n-GaAs), window (n-GaInP), emitter (n- GaAs), base (p-GaAs), BSF (n-GaInP) and GaAs substrate (although in Figure 4 the substrate is not shown due to the magnification).

The photogeneration in figure 4 is shown in a grey scale from 1023 (black) to 1025 e-h pairs/cm^3/s (white). As can be seen, the depth of the photogeneration reproduces the shape of the irradiance profile. There are many magnitudes whose variation across the solar cell section could be shown. Anyway, the most important implication of the non-uniformity of light is its effect in the whole performance of cell, that is, the illumination IV curve that is shown in Figure 5.

As can be seen, the non-uniform illumination increases the deleterious effect (voltage drop) of the series resistance. The main losses are in the grid, front contact and emitter. Consequently, a proper design of the solar cell for real condition operation should reconsider the front grid parameters in order to minimize this effect.

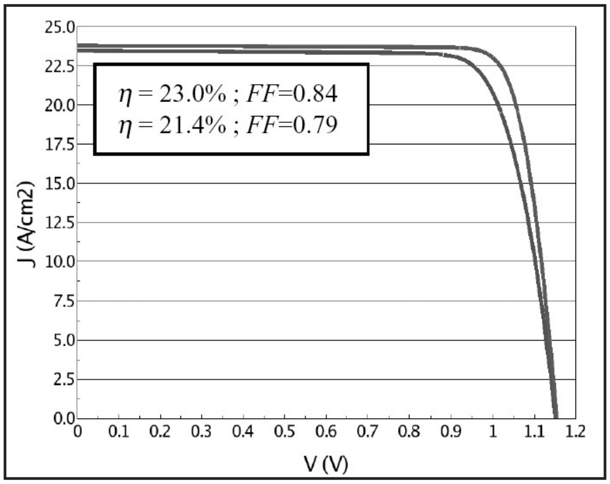

Figure 5. Illumination I-V curve of the concentrator GaAs solar cell when is illuminated with an uniform irradiance of 1000 suns (top curve) and when it is illuminated with the profile of the top of Figure 4 (bottom curve). The front contact parameters are medium quality.

Although here the 2-D simulation contributes to a better understanding of the real operation of the solar cell, the non-uniformity of the light is an excellent example of the need of a 3-D simulation. Effectively, the irradiance profile of Figure 4 is applied only to a portion of the cell while in other regions of the cell a different profile exists. In addition, the number of fingers through the horizontal dimension of the cell (15 in figure 4) also changes across the cell area.

Therefore, a 3-D modelling of the whole solar cell is required. This requirement is even more important when considering multijunction solar cells in which the current matching of the different junctions is fundamental. This 3-D modelling is being carried out at IES-UPM.

6. No Normal Incidence of Light

Because of the large area of the concentrator compared to the solar cell, the light impinges on the cell in the shape of an inverted cone, pyramid, etc (depending on the type of optics). The treatment of the performance of a solar cell operating under wide-angle cones of light was stated in [12].

In [13], the scarce influence of the wide-angle cone of light on the semiconductor structure was analysed. The reason for this is because the critical angle (that is the refracted angle when the incident ray is parallel to the surface) of GaAs is only about 17° so, no big variations of the light path inside the semiconductor are expected. Therefore, in the worst case the light would enter the first semiconductor with an angle of 17° (with regard to the normal) while the angle would be almost 0° for the subsequent layers. So, even a multijunction cell would not be affected in its semiconductor structure optimization.

However, the cone of light does affect the ARCs design because their refraction indexes are much lower than those of III-V semiconductors, so light enters ARCs really tilted. Additionally, geometric considerations of ray tracing should be taken into account like for example over-concentration in the semiconductor regions close to the fingers as consequence of reflection on light in them and photogeneration under the fingers.

7. Chromatic Aberration

This effect has not been detected in the TIR-R concentrator but could have a certain importance in other optics like Fresnel lenses.

8. Summary and Conclusions

The modelling of concentrator solar cells for real conditions of operation inside optical concentrators is a subject almost untreated. This is because, in spite of the existence of a very good previous work on the side of solar cell modelling as well as in the optics (independently considered), there are almost no studies that combine both aspects. So, this work considers jointly the performance of the solar cell and the optics as a whole.

Accordingly, the main pending issues in the modelling of concentrator solar cells when considering the situations appearing in their real operation are: different spectra from the standard ones, as a consequence of the pass of light through a given optics (spectral transmission), inhomogeneous illumination of the solar cell because of the focusing of light, light impinging the cell within a wide-angle cone, chromatic aberration, temperature gradients at both the horizontal and vertical plane, etc.

All these effects (with the exception of temperature gradients) have been included in a 2-D modelling applied to the case of a 1000 sun GaAs concentrator solar cell inside a TIR-R concentrator. For each effect, results in order to increase the efficiency of the cell are derived. Therefore, it is demonstrated that concentrator solar cells should be designed (and manufactured) to match a given optical concentrator (and vice versa). The necessity of going towards a 3-D modelling is also stated. This task is now being carried out at IES-UPM.

Acknowledgements

The authors would like to express their gratitude to the members of the Optics Group of the Solar Energy Institute of Madrid for supplying several optical data about the TIR-R concentrator.

This paper has been supported by the European Commission under contract SES6-CT-2003-502620 (FULLSPECTRUM project) and also by means of FEDER funds for scientific infrastructure managed in collaboration by Spanish Ministry. The Spanish Ministry of Science and Technology has also contributed by means of the research projects with references TIC2002- 01012 and TIC2002-11391-E.

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