Key aspects in the modeling of concentrator III–V solar cells and III–V thermophotovoltaic converters

© Carlos Algora[¶]

Instituto de Energía Solar–Universidad Politécnica de Madrid E.T.S.I. Telecomunicación,
28040 Madrid, Spain

(Получена 9 февраля 2004 г. Принята к печати 11 февраля 2004 г.)

The development of III–V concentrator solar cells and thermophotovoltaic converters is at a critical point in which both a sophisticated technology and an accurate modeling are required. This paper emphasizes the aspects relating to the modeling of multijunction solar cells for the concentration of applications as well as with thermophotovoltaic converters. In the case of solar cells the key aspects are:

– Necessity of three dimensional modeling,
– Consideration of real conditions of operation,
– Critical review of material parameters.

For TPV converters, the aforemetioned aspects are also of application. Preliminarily, the material parameters of the less mature thermophotovoltaic semiconductors must be specified or even measured.

1. Introduction

Light concentration together with III–V semiconductor solar cells constitute an strategy that has been proposed as a way to reduce the cost of photovoltaic (PV) electricity up to reach levels close or even lower than those of the electricity produced from fossil fuels [1,2]. Up to now, the highest efficiency for a single junction solar cell at a concentration of 1000 suns has been obtained by a GaAs solar cell with a 26.2% [3] and there is more room for achieving effeciencies in the range of 28–29% [4]. These practical efficiencies achieved at 1000 suns could lead to a price of 2.5–3.0 €/W_p for a turnkey grid connected PV installation. The corresponding price of the produced electricity would be 0.1 €/kWh for a cumulated production of only 10 MW_p [5].

For an additional reduction of these prices thanks to an efficiency increment, the use of multijunction cells (where several cells are used each one with a different band gap and each one converting a narrow range of photon energies close to its band gap) is necessary. For example, if the current space-cell production were applied into 100 sun concentrator cells and learning were assumed for a cumulated production of 1000 MW_p together with a solar cell efficiency of 40%, the price of the PV electricity would decrease below 0.03 €/KWh. The corresponding price for a turnkey PV grid connected installation would be below 0.7 €/W_p [5]. This efficiency value of 40% is not extremely optimistic because Spectrolab has achieved in 2003 an efficiency of 36.9% at 309 suns [6].

The path towards these high efficiencies must be guided by an accurate and reliable modeling of the III–V solar cells. This way, the efficiency loss origins could be determined and consequently, avoided. This aspect is very important because concentrator single junction GaAs solar cells have already achieved practical efficiencies higher than 70% of their upper theoretical limit while in the case of concentrator III–V multijunction cells their practical efficiencies are below the 60% of their ideal limit.

An important challenge in the modeling of III–V concentrator solar cells is the consideration of real operation conditions inside optical concentrators [5]. Between the most important ones are the different illumination spectra as a consequence of the light way through the concentrator optics, the inhomogeneous illumination produced by the optics over the solar cell, the chromatic aberration, the temperature gradients in different parts of the solar cell, *etc*. Therefore, an accurate and useful model must consider all the aforementioned aspects [7].

In the case thermophotovoltaic (TPV) converters, their modeling should also consider the particular conditions of each system where they will operate. All the key aspects in the modeling of multijunction solar cells can be applied to TPV devices. But in addition, there are specific problems because the TPV semiconductor materials are less known and less mature (GaSb, GaInSb, InGaAs, *etc*) so, there are less reliable material data [8].

2. Concentrator III–V solar cells

The Solar Energy Institute of Madrid pioneered several years ago the simultaneous modeling of the whole concentrator solar cell. In the past, the existing models considered only a part of the cell. We proposed to take into account all the parts of the solar cell: semiconductor structure, ohmic contacts, ARC, external connections like wire bonding, *etc*. Additional aspects like a given geometry and size of the solar cell were also considered. This way, we achieved a wide experience in the two-dimensional (2-D) modeling that was applied to GaAs solar cells [9,10] and GaSb TPV converters [11].

2.1. Necessity of three-dimensional modeling

However, the complexity of concentrator multijunction solar cells requires the three-dimensional (3-D) modeling. Development of custom tools for 3-D modeling is one

¶ E-mail: algora@ies-def.upm.es

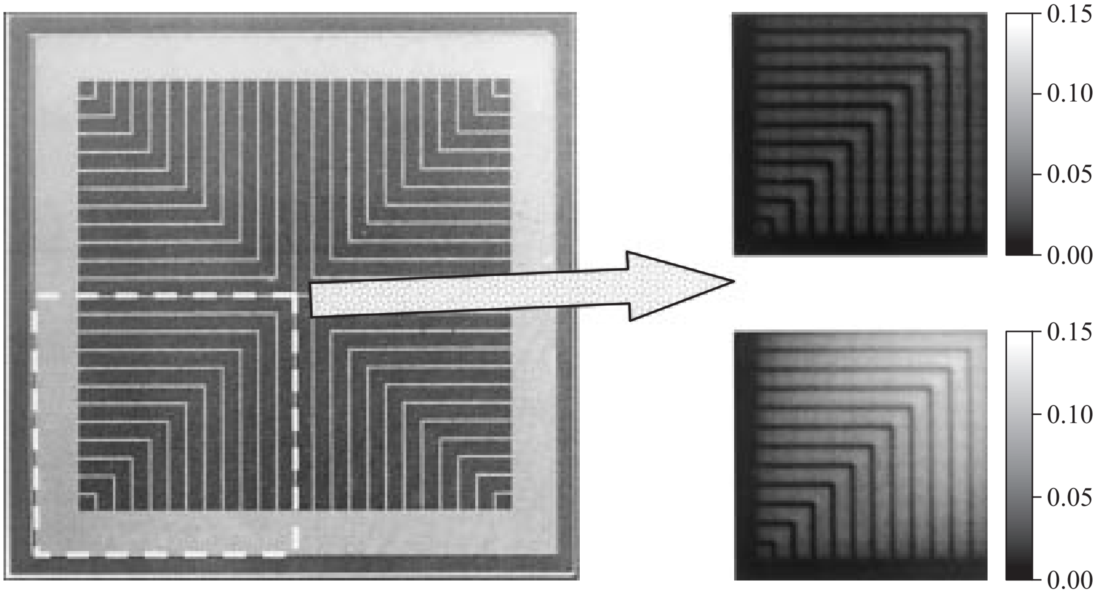

Figure 1. (Left) Photograph of a *p*-on-*n*-GaAs solar cell manufactured and designed for operation at 1000 suns. Its size inside the bus bar is 1 mm^2. The quarter marked with a dotted line is analyzed by the 3-D model of [14] whose results are presented at right. (Right) Voltage drop in a grey scale from 0.00 to 0.15 volts. The illumination is uniform with an intensity of 1000 suns. Two cases are analyzed: (top) a good front contact characterized by a thickness of 1 micron, a resistivity of $2.2 \cdot 10^{-6}\,\Omega \cdot cm$ and a specific contact resistance of $5 \cdot 10^{-5}\,\Omega \cdot cm^2$; (bottom) a medium quality front contact characterized by a thickness of 1 micron, a resistivity of $2.2 \cdot 10^{-5}\,\Omega \cdot cm$ and a specific contact resistance of $10^{-4}\,\Omega \cdot cm^2$.

possibility whose main advantage is the more familiar implementation of custom-made models as well as a good control of the whole simulation program. But on the contrary, the development of a very complicated calculation strategy is required and the flexibility for depicting and drawing multiple effects (like variation of voltage, current lines, *etc*) is highly limited.

An alternative is the use of commercial programs. Traditionally, the PC-1D has been widely used but mainly for 1 sun silicon solar cells. For III-V solar cells, its use has been very restricted. Lately, the use of very powerfull programs whose use is very extended in microelectronic device (like Atlas^{TM} from Silvaco, Dessis^{TM} from ISE TCAD or Taurus-Medici^{TM} from Synopsys) has started in several PV research groups. Although the potential of these simulation tools for multijunction cells has been already applied, their use have been restricted for 2-D purposes [12,13].

A very interesting example of the use of commercial programs not specifically designed for the modeling of semiconductor devices is that of the PSPICE^{TM}. The method fo the 3-D simulation requires firstly, the division of the whole solar cell in elementary subcells. After this, each subcell is modelled by circuit elements composed of diodes, resistors and current sources. Finally, the resulting non-linear circuit is solved with the PSPICE^{TM} simulation tool. This approach together with the details of the method and results can be found in [14].

Fig. 1 is an example of the great usefulness of this method. The voltage drop in different parts (bus bar, metal fingers and uncovered regions) of a GaAs solar cell at 1000 suns is shown. Depending on the front contact properties, the voltage drop can be very severe. Thus, a medium or bad quality front metal contact appears as an important origin of resistive losses.

2.2. Consideration of real conditions of operation

An important effect that can be evaluated by this method is the effect of light inhomogeneity on the solar cell when operates inside a concentrator. Fig. 2 shows the same GaAs solar cell but now illuminated by a light spot with a 4000-sun peak at the centre of the cell and zero intensity close to the bus bar. This way, the average light intensity is 1000 suns when the spot is integrated through the whole solar cell. Now, Fig. 2 shows that the voltage drop is more severe than in Fig. 1. Even, there is a voltage drop of 0.15 V across several metal fingers when the quality of the contact is medium.

Voltage losses of both Fig. 1 and 2 influence the final efficiency in the way presented in Fig. 3. As can be seen, the efficiency losses due to an inhomogeneous light on the GaAs solar cell when operates at an average intensity of 1000 suns is 0.5% (absolute) when front contact is good while the losses increase until 1.6% (absolute) for a medium quality contact.

This example of non-uniform illumination introduces the necessity of modeling the concentrator solar cells under real conditions. At present, the characterization of concentrator solar cells is commonly performed by means of the AM1.5D spectrum and by using normal incidence of light onto

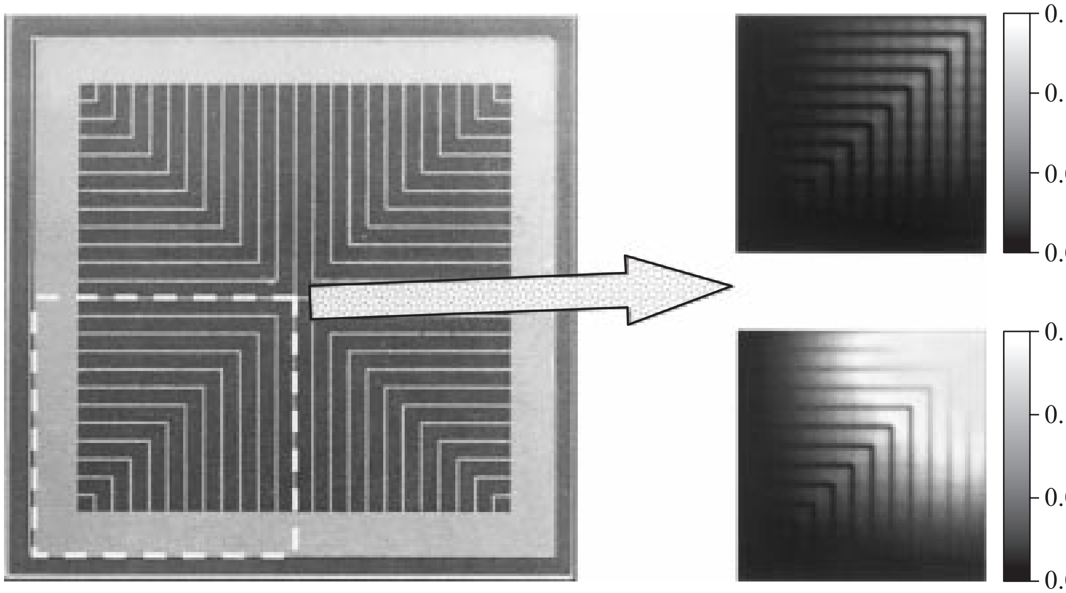

Figure 2. (Left) Photograph of a *p*-on-*n*-GaAs solar cell manufactured and designed for operation at 1000 suns. Its size inside the bus bar is 1 mm^2. The quarter marked with a dotted line is analyzed by the 3-D model of [14] whose results are presented at right. (Right) Voltage drop in a grey scale from 0.00 to 0.15 volts. The illumination is non-uniform with an average intensity of 1000 suns and a peak of 4000 suns at the center of the solar cell and zero intensity close to the bus bar. This way, the average light intensity is 1000 suns when the spot is integrated through the whole solar cell. Two cases are analyzed: (top) a good front contact characterized by a thickness of 1 micron, a resistivity of $2.2 \cdot 10^{-6}\,\Omega \cdot cm$ and a specific contact resistance of $5 \cdot 10^{-5}\,\Omega \cdot cm^2$; (bottom) a medium quality front contact characterized by a thickness of 1 micron, a resistivity of $2.2 \cdot 10^{-5}\,\Omega \cdot cm$ and a specific contact resistance of $10^{-4}\,\Omega \cdot cm^2$.

the solar cell. Obviously, this type of procedures have had such a great influence on the field of simulation and optimization, that in fact, the majority of simulation results have assumed AM1.5D spectrum, normal incidence of light, *etc.* However, a good solar cell at these „standard" concentration conditions could become an average solar cell when operates inside a real optical concentrator.

Therefore, for concentration applications the efficiency record tables have a relative importance because they inform about the technological level of a laboratory or a

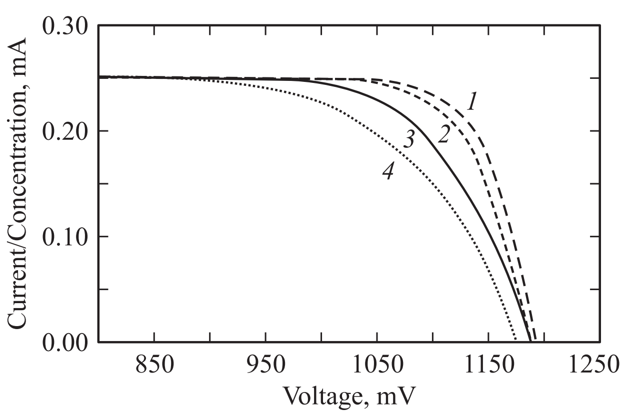

Figure 3. Illumination *I-V* curves of the concentrator solar cell considering the four cases covered in figures 1 and 2, illumination 1000 suns average: *1* and *2* — good quality front contacts, *3* and *4* — medium quality front contact, *1* and *3* — uniform illumination, *2* and *4* — non-uniform illumination.

company but do not inform about the real performance of concentrator solar cells. Consequently, concentrator III–V multijunction solar cells should be designed (and of course manufactured) to match a given concentrator (*vice versa*).

A kind of real operation appears because of the large area of given concentrator compared to the solar cell size. Light impinges the solar cell with the shape of an inverted cone, pyramid, *etc.* (depending on the shape of the optics). So, the sine law of concentration forces an increase of the light angle impinging the cell when concentration increases. Therefore, light impinges the cell forming a wide-angle cone for high concentrations. The modeling of this situation was stated in [15] and was applied to the practical TIR-R concentrator in [16]. In order to model the wide-angle cone of light, the light power distribution at each angle must be known.

Other example of real conditions is the spectrum variation. This has been a recent topic of study but only from the point of view of its variation during the day (more weight of the red or blue part of the solar spectrum) or even during the year. The goal was to maximize the energy produced by the concentrator solar cell [17]. However, it is much more important to consider the change in the spectrum produced by the optical concentrator. Therefore, once the average solar spectrum is determined, its modification by the optical concentrator must be taken into account. Fig. 4 shows a clear example where the spectral transmission of the TIR-R concentrator is presented [18]. As can be seen,

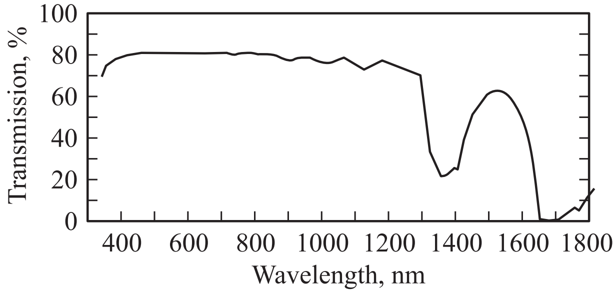

Figure 4. Spectral transmission of the TIR-R concentrator like the one described in [18].

the weak transmission in the infrared region must be taken into account in a correct design of a multijunction solar cell in order match the current of the different junctions. The aforementioned examples of real situations presented in this section and the resulting modeling and treatment can be found in [7].

2.3. Critical review of physical parameter data

On the other hand, one important task to carry out in the modeling is the determination of the optima semiconductor materials as a function of the number of junctions. The traditional approach has been to use lattice matched materials. In the case of 2 junctions the chosen materials have been GaInP/GaAs while for 3 junctions the chosen materials have been GaInP/GaAs/Ge or more recently, GaInP/GaInAs/Ge [6]. However, there are other options based on mismatched materials (so called, metamorphic) which are producing also good efficiencies like $Ga_{0.35}In_{0.65}P/Ga_{0.83}In_{0.17}As/GaAs$ [6,19].

In all these tasks, the common models of semiconductor devices based on the solution of minority-carrier transport equations need to be fed with accurate physical parameters. Therefore, a critical review of material parameters of ternary and quaternary alloys must be carry out. Even now, a mature binary material as GaAs is being reviewed in some of its parameters like the *n*-type band gap narrowing [20]. The case of GaAs is just the „iceberg peak“, because the parameters of many materials less mature are not well known or simply unknown. A typical case is that of the „desired 1 eV material“ for the 4^{th} junction and which more widespread candidate is GaInNAs (the so called „GINA“). In cases like this, there will be a big lack of material physical data so, specific material characterization over semiconductor structures specifically grown for this purpose should be carried out.

3. TPV converters

There are the following parallelisms and differences between PV and TPV:

– In the case of PV, the source is the sun while in TPV, there are many.

– The distance between the source and the converter is fixed in the case of PV (Sun-Earth) while in TPV can be whatever.

– There are standard spectra for PV (AM1.5D, AM1.5G, *etc*) while there are not any one for TPV.

– The efficiency definition is self-consistent for PV while it is in need of condition application in TPV.

Again, as we concluded for the concentrator multijunction solar cells, the modeling of TPV converters should consider the particular conditions of the system where they will be included although in TPV the assumption of particular conditions is even more important. Unfortunately, the TPV device modeling is still at an early stage in which the inclusion of many real conditions seems something utopian. Previously, the following more basic tasks must be undertaken.

The most mature semiconductor material for TPV applications is GaSb. However, its material properties are still under discussion. A good review of the GaSb material properties suitable fo TPV devices was carried out in [21] and was complemented and extended in some aspects in [8]. As can be seen in both references, their publication is very recent showing the scarcity of this type of data. The lack of material parameter models that include their variation with temperature is even more surprising when consider that TPV devices operate at high temperatures (around 50–100°C). Just now in 2004, an analysis on this subject has appeared [22]. Of course, the lack of well-contrasted material parameters is more intense in semiconductors becoming more widespread last years for TPV devices like GaInAs, InGaSb, InGaAsSb, InAsSbP, *etc*. Consequently, a great effort should be developed in the following years.

Other important aspect is the high doping levels used in GaSb devices when they are manufactured by zinc diffusion. At present, this is the preferred technology for GaSb with which doping levels of $10^{20}-10^{21}\,cm^{-3}$ are achieved (zinc diffusion is also applied to produce TPV devices with other materials like InGaAs, InAs, InAsSbP, *etc*). These high doping levels require a specific device modeling like the proposed in [11] which needs material parameters like the presented ones in [8].

Once all these basic tasks have been overcome, the TPV device modeling will take advantage of the modeling carried out previously for III–V concentrator solar cells.

4. Summary and conclussions

The accurate modeling of concentrator III–V multijunction solar cells and III–V TPV converters is absolutely necessary in order to guide the technology to increase the performance of these devices. The present situation in which concentrator solar cells start to be included in complete concentrator systems for demonstration purposes is unique. Therefore, it is compulsory to develop an modeling as accurate as possibly by considering real conditions of operation.

TPV converts have some delay in this aspect and firstly, an intensive work in determining the material parameters of the semiconductors of interest is required. After this, TPV devices will take advantage of the modeling previously developed for solar cells.

Aknowledgements: The author would like to express his gratitude to Mss. Beatriz Galiana, Mr. Mathieu Baudrit, Mr. Diego Martín and Prof. Ignacio Rey-Stolle for their close collaboration and involvement in the subjects covered in this paper. The author would also like to sincerely express his appreciation to the rest of the previous and present members of the III–V Semiconductors Group of the Solar Energy Institute of Madrid.

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.

References

[1] C. Algora, V. Diaz, J.C. Miñano, A. Luque. In: *Proc. 2nd World Conf. Protovolt. Solar Energy Conversion* (Viena, Austria, 1998) p. 2225.
[2] M. Yamaguchi, A. Luque. IEEE Trans. Electron. Dev., **46** (10), 2139 (1999).
[3] C. Algora, E. Ortiz, I. Rey-Stolle, V. Díaz, R. Peña, V. Andreev, V. Khvostikov, V. Rumyantsev. IEEE Trans. Electron. Dev., **48** (5), 840 (2001).
[4] C. Algora, I. Rey-Stolle, E. Ortiz. In: *Proc. 17th Eur. Photovolt. Solar Energy Conf.* (Munich, Germany, 2001) p. 88.
[5] C. Algora. In: *3th Generation Photovoltaics for high efficiency through full spectrum utilization*, ed. by A. Martí, A. Luque (Institute of Physics, 2004) chapt. 6.
[6] R.R. King, C.M. Fetzer, C.M. Colter, D.M. Edmondson, D.C. Law, A.P. Stavrides, H. Yoon, G.S. Kinsey, H.L. Cotal, J.H. Ermer, R.A. Sherif, H.H. Karam. In: *Proc. 3rd World Conf. PV Energy Conversion* (Osaka, Japan, 2003).
[7] C. Algora, M. Baudrit, I. Rey-Stolle, D. Martín, R. Peña, B. Galiana, J.R. González. In: *Proc. 18th Eur. Photovolt. Solar Energy Conf.* (Paris, France, 2004).
[8] D. Martín, C. Algora. In: *Thermophotovoltaic Generation of Electricity* (AIP Conf. Proc., **653**, 2003) p. 442.
[9] C. Algora, V. Díaz. Sol. St. Electron., **41** (11), 1787 (1997).
[10] C. Algora, V. Díaz. Progr. Photovolt., **8**, 211 (2000).
[11] C. Algora, D. Martín. In: *Thermophotovoltaic Generation of Electricity* (AIP Conf. Proc., **653**, 2003) p. 452.
[12] P. Michalopoulus. *Thesis, Naval Postgraduate School* (Monterey, California, USA, 2002).
[13] G. Létay. Thesis Dissertation, Fraunhofer Institute (Freiburg, Germany, 2003).
[14] B. Galiana, I. Rey-Stolle, C. Algora, M. Baudrit. *Proc. 18th Eur. Photovolt. Solar Energy Conf.* (Paris, France, 2004).
[15] C. Algora, V. Díaz. Prog. Photovolt.: Res. Appl., 7, 379 (1999).
[16] C. Algora, V. Díaz, I. Rey-Stolle. *Proc. 29th IEEE PV Spec. Conf.* (New Orleans, USA, 2002) p. 848.
[17] W.E. MaMahon, S. Kurtz, K. Emery, M.S. Young. *National center for photovoltaics and solar program review meeting* (Denver, CO, 2003).
[18] M. Hernández, P. Benítez, J.C. Miñano, J.L. Alvarez, V. Diaz, J. Alonso. „*Proc. 3rd World Conf. Photovolt. Solar Energy Conversion (Osaka, Japan, 2003) 3P-C3-77*“.
[19] A. Bett. In: *3rd generation photovoltaics for high efficiency through full spectrum utilization*, ed. by A. Martí., A. Luque (Institute of Physics, 2004) chapt. 4.
[20] M.Y. Ghannam, G. Flamand, J. Poortmans, R.P. Mertens. Technical Digest of the International PVSEC-14 (Bangkok, Thailand, 2004).
[21] G. Stollwerck, O.V. Sulima, A.W. Bett. IEEE Trans. Electron Dev., **47** (2), 448 (2000).
[22] D. Martín, C. Algora. Semicond. Sci. Technol., (2004) (in press).

Редактор Л.В. Беляков