Chapter 11

Solar Cell Efficiency vs. Module Power Output: Simulation of a Solar Cell in a CPV Module

Egbert Rodríguez Messmer

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/52707

1. Introduction

In the past few years Concentrating Photovoltaics (CPV) has moved from R&D and pilot projects (typically installations below 500 kilowatts) to multi-megawatt power plants. The starting point of the commercial deployment of this technology was in 2006 when the Institute for Concentration Photovoltaic Systems (ISFOC) purchased several CPV power plants of different technologies and provider that were installed in Puertollano (Spain). Each supplier provided a power plant that had a size between 200kW and 500kW. These power plants are operating since 2008 and the results are very promising [1]. After these first installations several MW-size power plants have been installed ([2], [3] and [4]), and the first multi-megawatt CPV power plants are under construction, like a 150MW power plant that Soitec is developing for the San Diego Gas & Electric in California [5], demonstrating here with that CPV technology can be a cost efficient alternative to conventional silicon-based flat-plate photovoltaic (PV) plants in areas of high direct solar irradiation.

A CPV module consists typically of a high-efficient solar cell and a concentrator that concentrates light and that can be made out of a mirror, a parabolic dish or lenses. These modules are then mounted on a 2-axis tracking system to make sure that the module is always perpendicular to the sun, so that the light spot reaches the active area of the solar cell. A CPV system is therefore more complex than a conventional PV system, and, in order to be commercially competitive with standard systems, it is important to control its cost figure. When making a cost analysis of a CPV system, from manufacturing of solar cells to a finished installation [6], the cost figure is given in terms of a monetary unit per Watt (€/W or $/W). This cost figure should be kept as low as possible, and can be done either for a complete installation including all the costs relative to the deployment of the system or it can be done partly, considering only the module or the module and tracking system.There are two possibilities to reduce the value of this cost figure, which are either reducing the cost of the system, which is typically done reducing the cost of the raw materials or optimizing production processes, or by increasing the output power of the CPV module, which can be achieved by reducing possible sources of losses inside a module (these can be optical, electrical o thermal).The advantage of increasing the output power of a module is that this has an important impact to other related costs, since also the manufacturing and installation costs are reduced due to the need of fewer modules or even trackers for a CPV power plant of a given size.

The output power of a CPV module can be optimized by reducing the internal losses that appear in the module design. Therefore a good match of the materials from which a module is made should be aimed. The need of a good match is especially true for the interaction between the solar cell and the optical system, where the solar cell can be adapted in size, light spectrum, concentration ratio and interface to the optical system. In practice it is very difficult to achieve good matching of different materials, since the different parts of a CPV module are made by different manufacturers. These might have different interests as compared to a system developer, so that a compromise is needed. In order to keep the manufacturing cost of the CPV module low, all elements of the module should be standardized, but, on the other hand, CPV module manufacturer want to have components that are customized to their own module design to maximise their output power. Some CPV module manufacturer use parabolic dishes to concentrate light, while others use lenses, and also the concentration ratio at which the modules work differ from manufacturer to manufacturer. This means that from a technological point of view, a CPV module manufacturer desires to have components that are customized to its own system.

To go more into detail in this issue of matching of materials inside a CPV module, and to analyse its effect on module performance, the interface between solar cell and optical system of the module is analysed in this chapter. A solar cell can be designed to have either a maximum efficiency when it is measured as a stand-alone device (having air as the surrounding medium) or to have maximum efficiency when it is surrounded in any other optical medium that is used inside the CPV module (e.g. glass or an optical encapsulant). This fact has an important impact technically and commercially. The solar cell efficiency is usually defined when it is measured in air, and should for commercial purpose be designed to have maximum efficiency under these conditions. On the other hand, if the solar cell is going to be operated embedded in an encapsulant and a lens, the CPV manufacturer should choose a solar cell that is designed for this operating condition, even though the solar cell will have less efficiency when measured at air. In summary, it is important to consider a CPV module as one system during its development, and not composed of independent components that have to be developed independently.

In order to explain better how the embedding medium affects the solar cell performance and to quantify this effect, a series of simulations has been done with a simulation program that has been developed by Isofotón in collaboration with the University of Granada (Spain). This program is called ISOSIM and is able to simulate the performance of a multijunction solar cell, including its anti-reflection coating (ARC) and taking into consideration the concentration and the medium in which the solar cell is used (e.g. air or an optical gel to couple

http://dx.doi.org/10.5772/52707

the light from the lens to the solar cell). It is also possible to add optical layers on top of the solar cell structure and simulating thereby a CPV module.

For the sake of simplicity, in this chapter it has been considered a double junction solar cell that is operating at a temperature of 320K (50ºC). The obtained results give a qualitative indication on the effect of different parameters, but quantitatively the effects that are described in this chapter will exceeded at real operating conditions. On one hand the solar cells that are used are triple-junction cells and also the operating temperature is usually higher. It is estimated that when adapting the solar cell to an optical system instead of using a standard solar cell, an increase of output power of up to 10% can be achieved.

2. Outline of experimental work

In this Chapter, first, the capabilities and performance of the simulation program are explained, followed by several studies that show which factors affect the performance of a solar cell outside and inside of a CPV module.

The first study shows that the performance of a solar cell does not depend only on the material and thickness of the AR- coating layer(s), but also on the refractive index of the surrounding medium in which this solar cell is measured or operated. A solar cell does not have the same efficiency when it is operated in air (refractive index of 1) or when it is operated in a medium of refractive index of e.g. 1.5, (if the solar cell is covered by glass).

Afterwards the performance of the solar cell in air and when it is assembled in a CPV module will be compared. It has been analyzed the current matching of the double-junction solar cell, varying the thickness of the base of the top cell, and it has been identified the limiting subcell (either top-cell or bottom-cell), which is attributed to be due to different spectral losses (absorption or reflection) in the materials and interfaces of the elements of the system.

In the last part a practical example is given, in which the power output of a CPV module is quantified when it is assembled either with a double-junction solar cell that has been optimized having air as the interface or a solar cell that is optimized to the CPV module. It shows that even if the variation in efficiency of the solar cell is little, the difference in output power can be significant. This chapter summarizes previous work that has been done with the ISOSIM package ([7], [8] and [9]).

3. ISOSIM software and experimental parameters

There are currently several approaches and solutions proposed from module manufacturer and system integrator that develop CPV modules. On the market are currently several techniques to concentrate the light, since many companies have developed their own proprietary technological solution. The type of concentrator can be either based on mirrors, dishes, or lenses, and using only primary optics or also secondary and even tertiary optics. In order to maximize the output power of a module, solar cells have to be optimized for each optical system. The problem that arises is that a solar cell that has been optimized for a given optical system does not necessarily have an optimum performance also in another optical system. It is also difficult for a solar cell manufacturer to predict how a solar cell will perform inside a given module type. To take into consideration various types of concentrator technology, and to be able to analyze also a stand-alone solar cell, the simulation software is organized in layers, in which each layer represents a material with its own material properties and function. In this manner it is possible to simulate any type of CPV module and at any operating condition (temperature, concentration ratio).

The software used for the simulations has been specifically designed for the analysis of multijunction solar cells in order to get a tool to aid the design of solar cells and concentrator PV systems. This software, that is called *ISOSIM*, is capable of modelling the performance from stand-alone single junction solar cells up to the performance of multijunction solar cells inside a CPV module under real operating conditions. The simulation program solves the Poisson and continuity equations by using a procedure optimized for multilayer structures. It includes the radiative interband, Shockley-Read-Hall and Auger recombination mechanisms, and computes the generation function of electron-hole pairs from the optical parameters of the cell materials. The dependence of these optical parameters on the photon energy has been included, taking into account the doping level and its effect on bandgap narrowing. The software uses the Rakic model for the calculation of the complex dielectric function, absorption coefficient, extinction and refraction index calculation, with the Gaussian broadening proposed by Kim. Additionally, several effects are included in the software, such as indirect transition contributions, the shift in the optical band gap due to doping, and free-carrier absorption, among others. The material parameters of several anti-reflection coatings were obtained either empirically by ellipsometry measurements or extracting them from the SOPRA database of refractive indexes [10].

The program also takes into consideration the optical medium that surrounds the solar cell, which can be either air which represents the case of a stand-alone solar cell that is measured, or any other medium, representing the case of a solar cell that is mounted in a CPV module (e.g. epoxies, solar glasses, optical gel). Apart of that, also the illumination spectra (space, terrestrial or any customized spectra), the concentration of the light source and the temperature of the solar cell can be modified for simulations. It is therefore possible to simulate the whole system, considering solar cell, lenses, optical gels that are used to couple optical components, possible air gaps between lenses inside the module, concentration ratio and operating temperature. It is therefore possible to estimate the total loss of a system if e.g. a wrong choice of materials or of its process parameters has been chosen for the manufacturing of a CPV module.

For the simulations in this chapter, I-V curves and spectral response of a stand-alone solar cell are obtained by simulating a typical solar cell structure. If not otherwise specified, the structure used for the studies in this chapter (Figure 1.) see is a dual-junction GaInP/GaAs solar cell with the two photovoltaic junctions connected by a GaAs tunnel junction, and the antireflection coating consisting of a double layer of TiO_2 and Al_2O_3 [11]. Light concentration

http://dx.doi.org/10.5772/52707

and operating temperature were fixed at 1000 suns and 320 K, respectively. It has been used the AM1.5D spectrum and has also been assumed a shadowing loss of the solar cell of 2% due to the area below the grid. Some of the parameters of the materials that are used for simulations show high dispersion. For instance, the band-gap of GaInP depends on the ordering level, and could vary from 1.66 eV for a fully ordered lattice to 2.01 eV for a totally disordered one. For the simulations presented in this article, we assumed that the band-gap of GaInP is 1.9 eV at 300K. In a previous paper in which we presented this software, it has been shown that the results of the simulations obtained by the ISOSIM software match reasonably well with experimentally observed results [7].

Contact layer 0.2μm	GaAs $n=6e18\ cm^{-3}$	Antireflection (AR) coating	
Window	AlInP	0.025μm	$n=4e17\ cm^{-3}$
Emitter	GaInP	0.1μm	$n=2e18\ cm^{-3}$
Base	GaInP	1μm	$p=1.5e17\ cm^{-3}$
BSF	GaInP	0.06μm	$p=3e18\ cm^{-3}$
TJ	GaAs	11nm	$p=1e19\ cm^{-3}$
TJ	GaAs	11nm	$n=1e19\ cm^{-3}$
Window	GaInP	0.1μm	$n=1e18\ cm^{-3}$
Emitter	GaAs	0.1μm	$n=1e18\ cm^{-3}$
Base	GaAs	3.5μm	$p=8e16\ cm^{-3}$
BSF	GaInP	0.07μm	$p=3e17\ cm^{-3}$
Buffer	GaAs	0.2μm	$p=3e17\ cm^{-3}$
Substrate	GaAs		p-type

Figure 1. Structure of the double junction solar cell used for the analysis in this chapter. The layers in light blue are the ones corresponding to the top-cell, the grey ones to the tunnel junction and the green ones to the bottom cell [12].

Coverglass	n=1.5	D=4mm
Encapsulant	n=1.5	D=1mm
Primary lens	n=1.5	D=4mm
Air gap	n=1	D=10mm
Secondary lens	n=1.5	D=4mm
Encapsulant	n=1.5	D=1mm
Solar Cell with AR coating		

Figure 2. Schematic representation of the layer sequence that light has to pass through until it reaches the solar cell. It represents a CPV module that is made out of a primary and secondary lens.

The structure of the ISOSIM simulation program makes it possible to add several layers and their parameters (thickness, doping level and gradient, doping type, composition, recombination velocity, recombination time constant, refractive index). It is also needed to specify the function of each layer, like e.g. *optical layer* for the window layer of the solar cell or the layers that represent the optical system (e.g. lenses, encapsulating material, air gaps between materials, cover glass). For running a simulation, the parameters that are specified are concentration ratio (in suns), solar cell operating temperature, shadowing loss, series resistance of the contact layer and refractive index of the medium that surrounds the solar (e.g. n=1 if the simulation should be done considering that the solar cell is measured in air). This high degree in flexibility makes it possible to simulate almost any type of multijuncion solar cells and any type of CPV module.

For the simulations presented in this chapter, three different type of simulations were made, a solar cell that is in air (refractive index is 1), a solar cell that is surrounded by a medium with refractive index equal to 1.5 (e.g. glass) and a solar cell that is mounted in a CPV module that is made of a cover glass, primary and secondary lenses, encapsulating materials, and an air gap between primary and secondary lens. A schematic description is shown in Figure 2.

In order to show the usefulness of the simulation software for the prediction of the behavior of solar cells under real operating conditions (i.e. under light concentration and at temperatures higher than room temperature), several figures are shown (Figure 3. to Figure 7.). These simulations can be of interest to extrapolate the measured parameter at room temperature to real operating conditions. The two parameters that affect mostly the solar cell performance when it is mounted in a CPV module are the operating temperature and the optical coupling of the sunlight to the solar cell. Even if the short-circuit current I_{sc} increases slightly with increasing temperature (Figure 3.), the predominant effect is the decreases of the open-circuit voltage V_{oc} (Figure 4.) and the fill-factor FF (Figure 5.), reducing the solar cell efficiency (Figure 6.) and thereby also the output power of a module. Figure 7 shows the efficiency of the solar cell when the concentration is increased. The temperature is set to 320K. It shows the typical shape of this type of curves, although the maximum in efficiency is in our simulation at a concentration of around 2000 suns, which is higher than typical values observed experimentally [13]. More details about the performance of the ISOSIM software, as well as the discussion of the figures shown here can be found elsewhere [7].

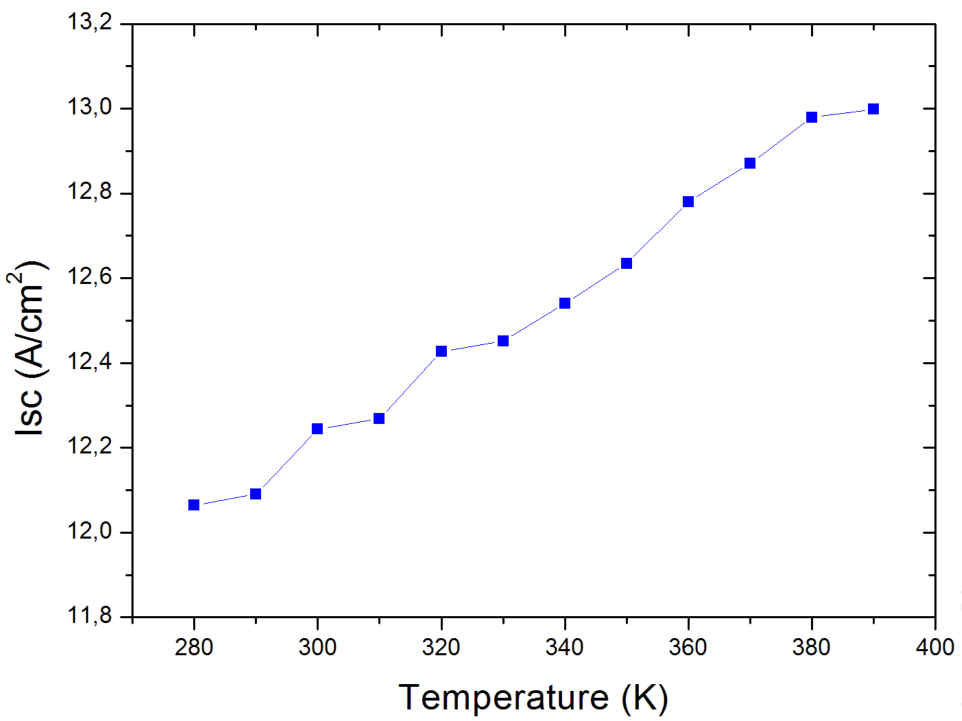

Figure 3. Simulation of the short-circuit current density (I_{sc}) of a double-junction solar cell as a function of temperature at a concentration of 1000 suns.

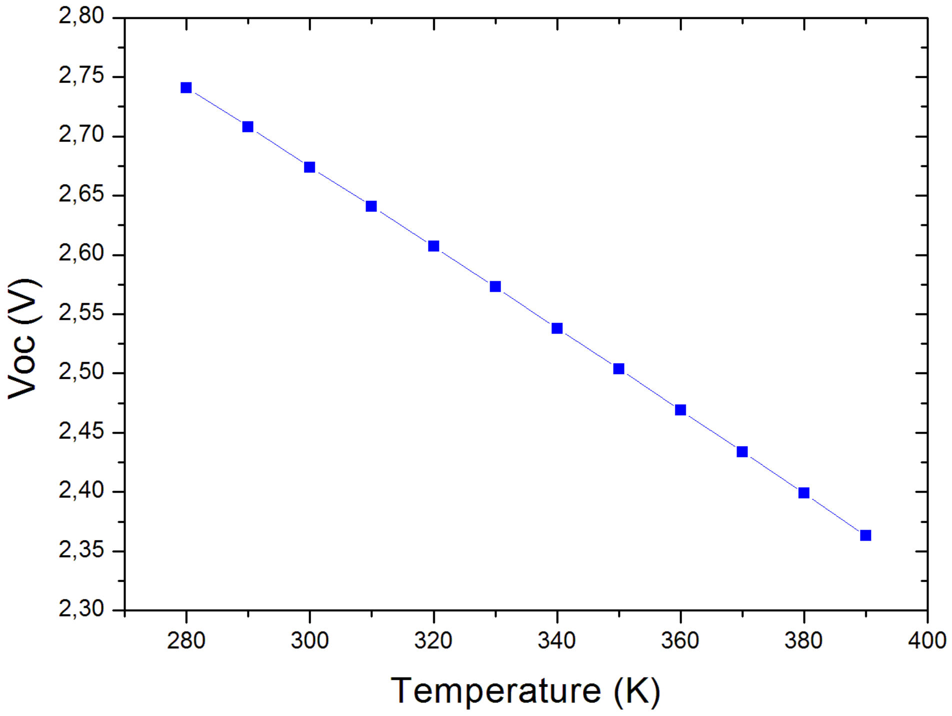

Figure 4. Simulation of the open-circuit Voltage (V_{oc}) of a double-junction solar cell as a function of temperature at a concentration of 1000 suns.

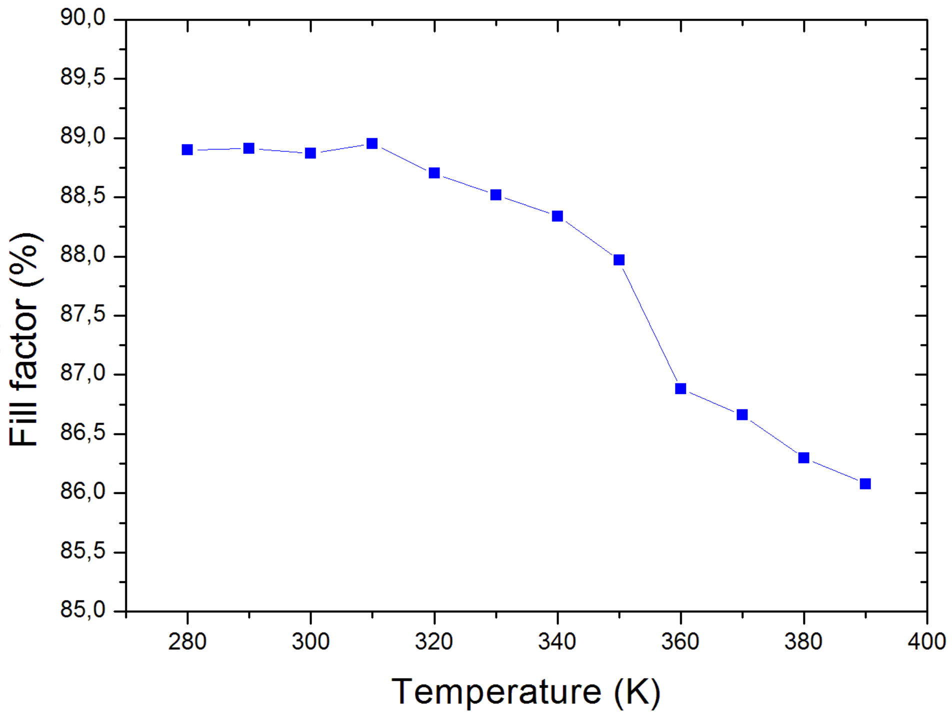

Figure 5. Simulation of the fill factor (FF) of a double-junction solar cell as a function of temperature at a concentration of 1000 suns.

http://dx.doi.org/10.5772/52707

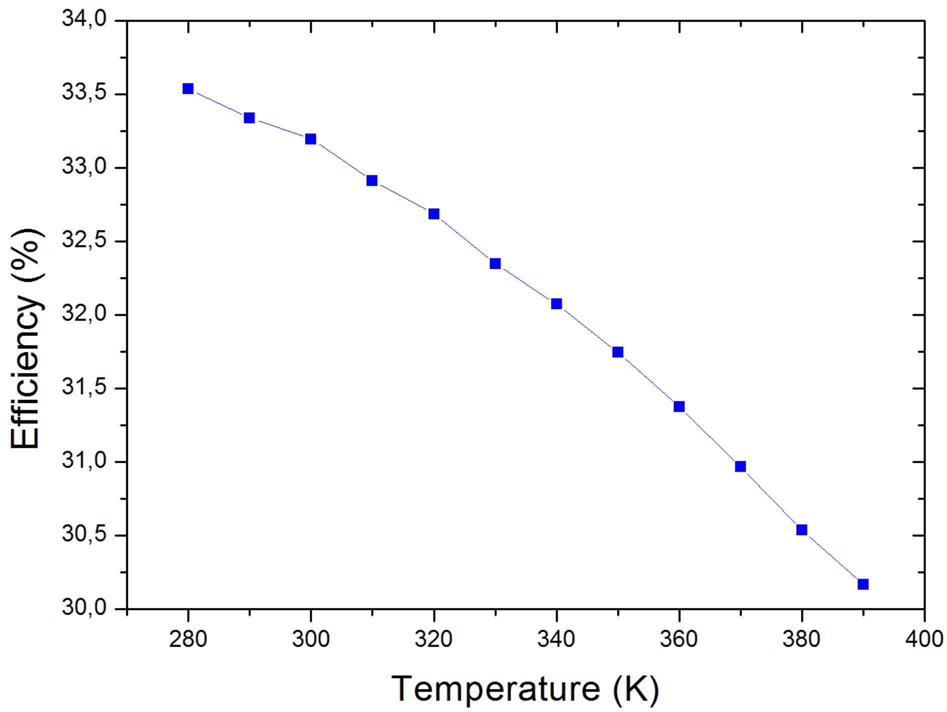

Figure 6. Simulation of the efficiency of a double-junction solar cell as a function of temperature at a concentration of 1000 suns.

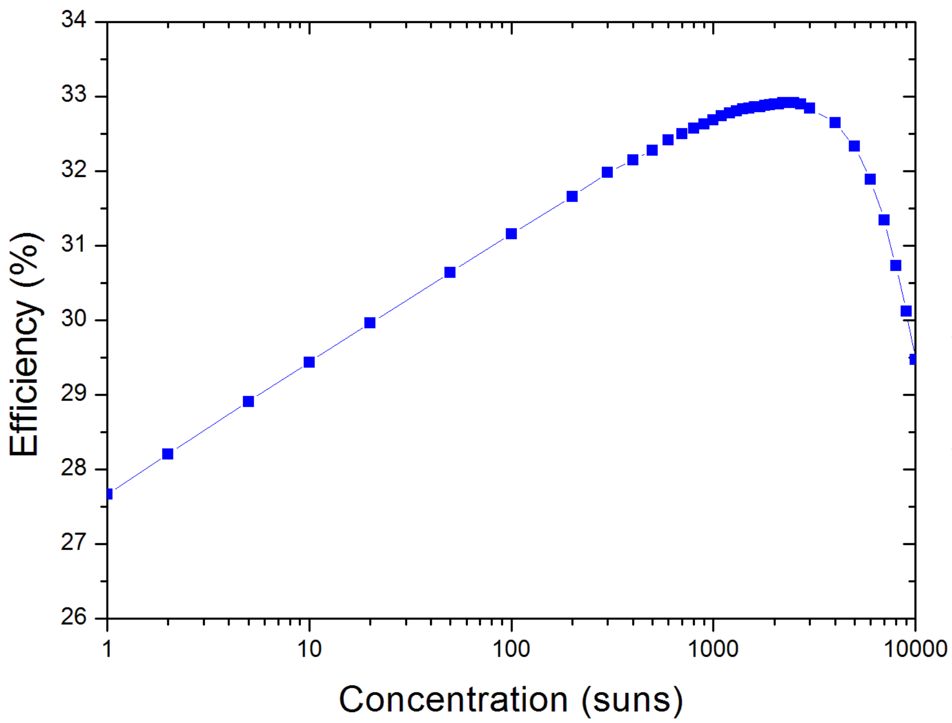

Figure 7. Simulation of the solar cell efficiency of a double-junction solar cell as a function of light concentration at a temperature of 320 K.

4. Effect of the surrounding medium on solar cell efficiency

There are currently several techniques used to concentrate light inside a CPV module. They can be made of primary and secondary lenses, as in the case of the examples given in this chapter, of only a primary lens or a (parabolic) mirror. To avoid losses due to changes in the refraction index, encapsulating materials might be used when using a secondary lens. The refraction index of this type of gels can be chosen to achieve the highest efficiency in the module. In all cases sunlight has to be properly guided and matched from air through several materials of different refractive index to the solar cell until if finally reaches each single junction of a multijunction solar cell, where the light is recombined. This leads to the question on how much is the output power of the CPV module affected due to the optical system. To analyze this issue, several simulations are made on a double-junction solar cell as the one described earlier.

The obtained results can be extrapolated to a triple-junction solar cell, at least qualitatively, since the third junction (typically made out of a germanium p-n junction) generates much more current than either the 1st or 2nd junction, and it does therefore not limit the multijunction solar cell. Figure 8 shows the simulated I-V curves of a triple-junction solar cell and all of its subcells, the bottom cell (typically a Ge cell, red curve), the middle cell (typically an InGaAs cell, green curve), the top cell (typical an InGaP cell, blue curve) and the resulting I-V curve of the triple junction solar cell (grey curve). This figure shows a triple-junction cell in which the top cell is the limiting subcell and also that the Ge junction generates much more current than any of the other two.

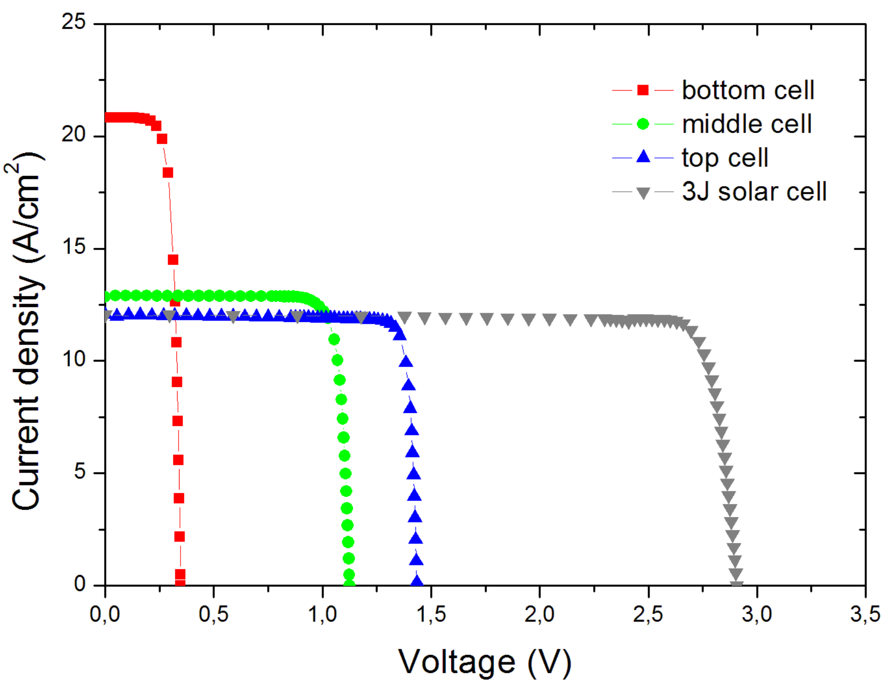

Figure 8. I-V curves of a triple-junction solar cell. There are given the three I-V curves of the subcells (top-cell, middle-cell and bottom cell) and the resulting I-V curve of the resulting 3J cell.

http://dx.doi.org/10.5772/52707

The efficiency of a double-junction solar cell with two different ARC layers, either a double layer of TiO_2/Al_2O_3 or a single layer of Si_3N_4 is analysed. The refractive index of the surrounding medium has been increased from 1 (air) to 1.5 (e.g. glass). The result of the simulated efficiency is shown in Figure 9 for a given thickness of the ARC layer. If the solar cell would be operated in air (n=1) the best choice would be to use a TiO_2/Al_2O_3 double layer and the solar cell would have an efficiency of 31.14%. But, if the solar cell would be operated in a medium with a refractive index higher than 1, e.g. 1.5, a Si_3N_4 single layer would be a better choice, yielding an efficiency of 31.87%. It can also be observed that if the solar cell has been optimized for being measured in air (ARC double layer of TiO_2/Al_2O_3), the efficiency of the system is reduced by around 1% when it is being operated in a medium with a refractive index of 1.5. On the other hand, a solar cell that has an ARC layer that is optimized to a medium with n=1.5, has a lower efficiency when measured at air. In the case that the solar cell is operated in a medium of n=1.5 and a wrong antireflection coating has been chosen (in this example TiO_2/Al_2O_3 instead of Si_3N_4), the solar cell would have an efficiency of 30.16% instead of 31.87%, having a loss in efficiency of 1.71%. It should be remembered that these values depend very much on the material and thickness of the ARC layer, and each system configuration has to be analysed separately.

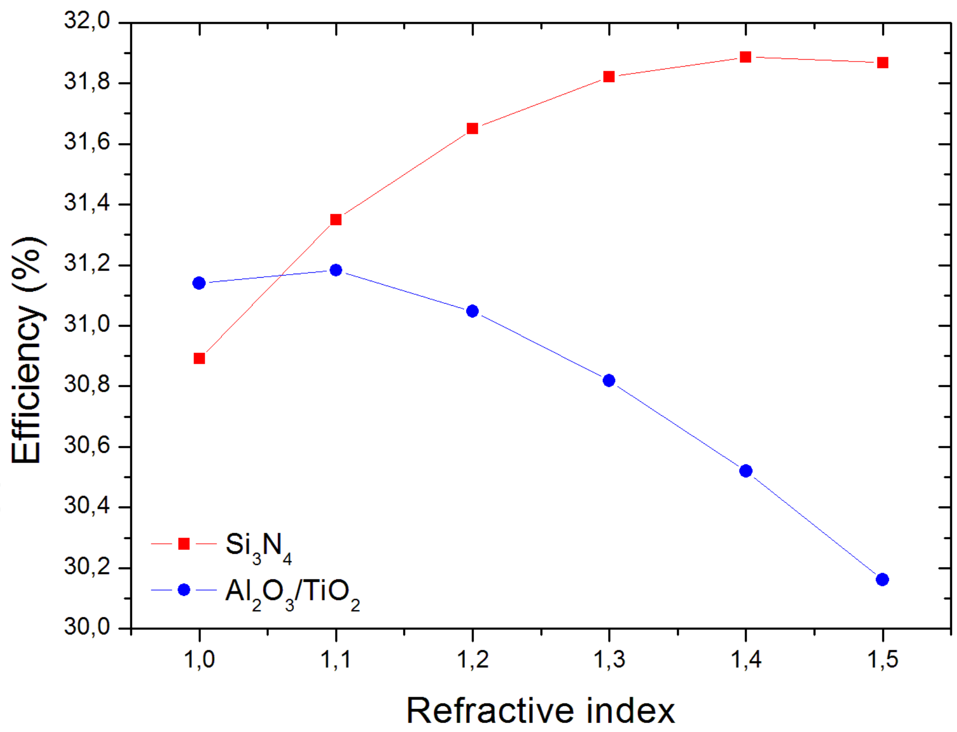

Figure 9. Solar cell efficiency as a function of the refractive index of the surrounding medium, for two alternatives of anti-reflection coatings.

This is a simplified example of how important the condition in which the solar cell operates is. If the solar cell would be encapsulated in a medium with a refractive index of 1.5, the situation would be as described above. In reality CPV modules are in general much more complex, and even more layers might interfere with the sun rays on its way to the solar cell. This means, on one hand, that if the solar cell is optimized to be operating in air, the expected decrease in efficiency when operating in the CPV module might be even higher than in the previous simulations. On the other hand, if the complexity of the module increases, it is also much more difficult to optimize a solar cell to be operating in that specific CPV module. In any case, according to these simulations, it is strongly recommended not to develop separately the solar cell and the optics of the CPV module, rather than optimizing the system as one unit.

5. Effect of AR coating material on solar cell efficiency

Anti-reflection coatings are needed to match the refractive index of the solar cell window layer to the surrounding medium, increasing thereby the amount of light that penetrates into the photovoltaic structure [11]. These must be carefully designed to have the highest transmission and the broadest bandwidth. The tuning of these could yield by multijunction solar cells to different limiting cell configurations, since different spectral parts of the sunlight are absorbed or reflected differently during operation. For this reason, our software is capable to handle spectral responses of complete systems and with different irradiation spectra.

In this section the design of the AR coating is analysed. With a correct design of the AR coating, the solar cell can be adapted to the surrounding medium, reducing losses due to unwanted reflections. It is possible to increase the final efficiency of the cell, increasing it up to around 30% of its initial value in a cell/air interface. As this medium is fully dependent on the system design (epoxy, air, lens, potting, etc.), the AR coating should be designed taking into consideration the design of the CPV module. We performed some simulations with several materials that are typically used as AR coating in optoelectronic devices. These are aluminum oxide (Al_2O_3), titanium dioxide (TiO_2), silicon nitride (Si_3N_4), and magnesium difluoride (MgF_2). The result for a double-junction solar cell is shown in Figure 10.

This figure shows that there is a strong dependence of the efficiency of a solar cell on the material of the antireflection coating and on its thickness. The efficiency can therefore be maximised e.g. when it is measured in air. Whenever we change the medium from air to a different higher refractive index medium (glass, epoxy, lens, potting, etc.), results vary. Figure 11 shows simulations for the same solar cell as in Figure 10 but considering that the solar cell is mounted in a CPV module. This means that the optical system has a big influence in modifying the spectral performance of the CPV system.

Comparing Figure 10 and Figure 11 we see that the behaviour of the efficiency against AR coating thickness differ if the solar cell is either measured on air or mounted inside a CPV module. It is observed e.g. that an efficiency of 29% of a standalone solar cell with an approximately 80 nm thick MgF_2 AR coating layer, has only 24% efficiency when this solar cell is mounted in the CPV module.

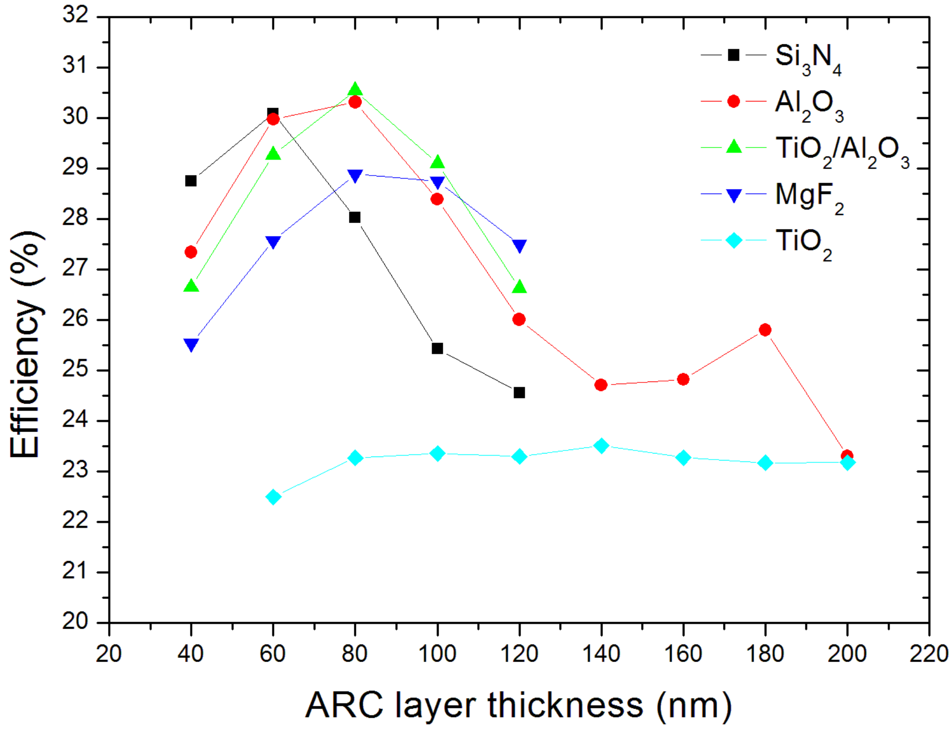

Figure 10. Stand-alone solar cell efficiency vs. AR coating thickness for several materials.

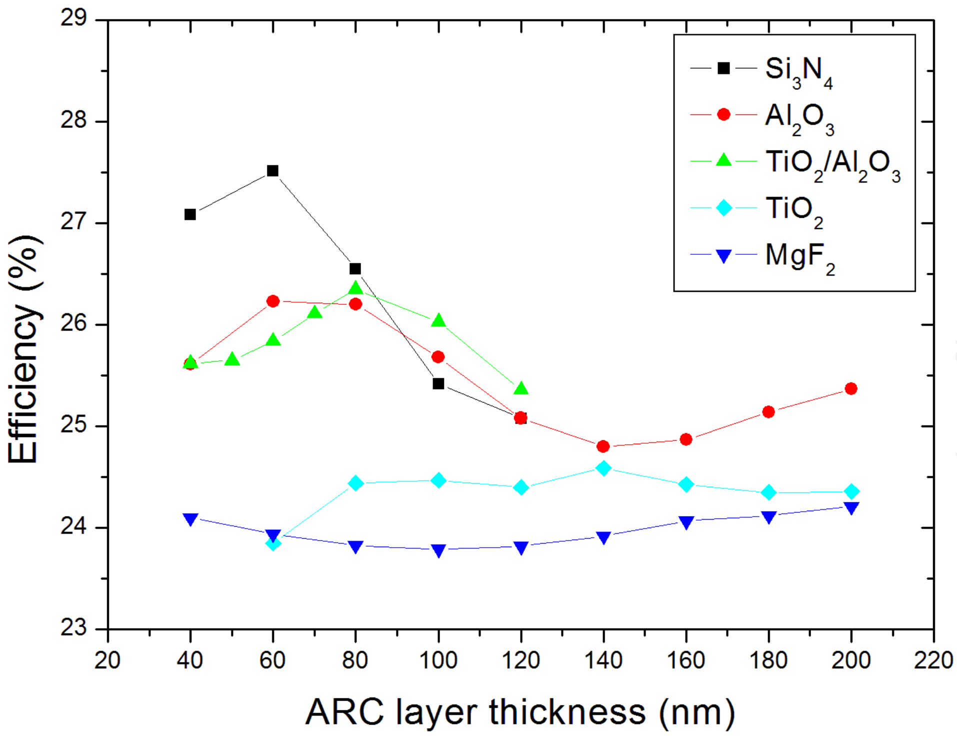

Figure 11. CPV system efficiency vs. AR coating thickness for several materials, using the same cell structure as for the plots in Figure 10.

6. Current matching: Stand-alone solar cell vs. performance in CPV module

In this section the spectral loss of the optical system is analysed. Several simulations were made starting from a double-junction solar cell in which the thickness of the base of the top cell is increased from 500 nm to 950 nm for the case of a stand-alone solar cell, and from 500nm to 1150nm for a solar cell that is assembled in a module. The obtained results are again specific to each configuration of solar cell and type and materials of a CPV module. Nevertheless, the general tendency of the results that is observed (i.e. the switching from a top-cell limiting configuration to a bottom-cell limiting configuration with increasing top-cell base thickness) is generally valid.

Figure 12 shows the behavior of the efficiency when increasing the thickness of the base of the top-cell of a double-junction solar cell. It can be seen that when increasing the thickness from 500nm until approximately 700nm, also the efficiency increases. This shows (and is confirmed by the plots of the I-V curves not shown here) that the top-cell of the double-junction solar cell is limiting. Increasing the thickness of the base further, from approximately 800nm to 950nm the efficiency decreases, and the bottom-cell is the limiting one. The reason for the drop in efficiency is on one hand that the series resistance of the top-cell increases, and that there is more light absorbed in the top-cell and therefore less light available for current generation in the bottom-cell.

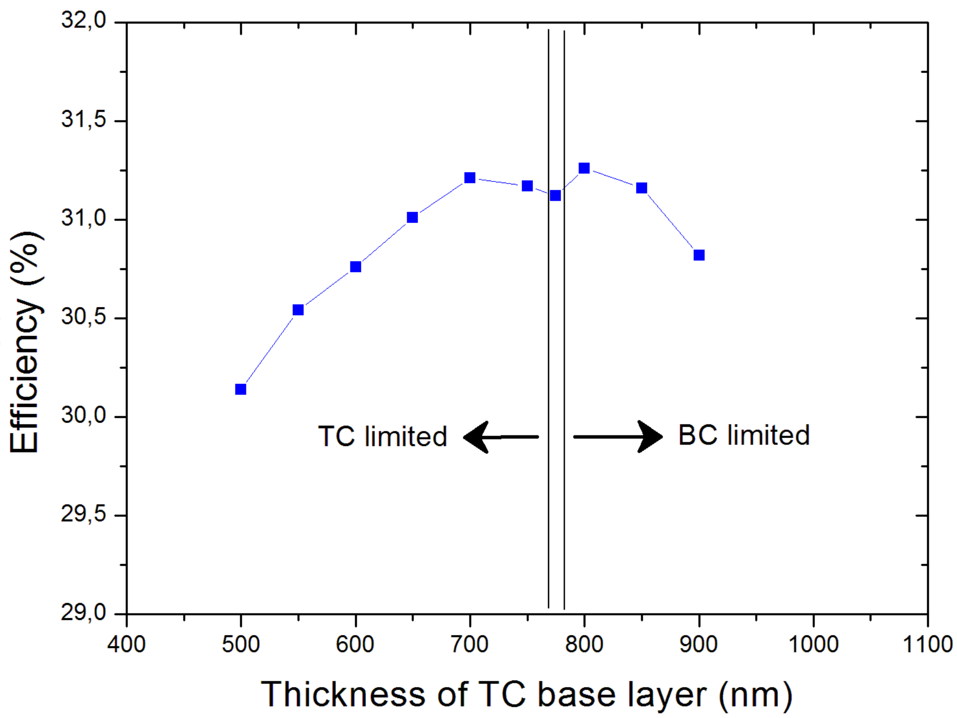

Figure 12. Simulation of the efficiency of a stand-alone double-junction solar cell as a function of top cell base thickness.

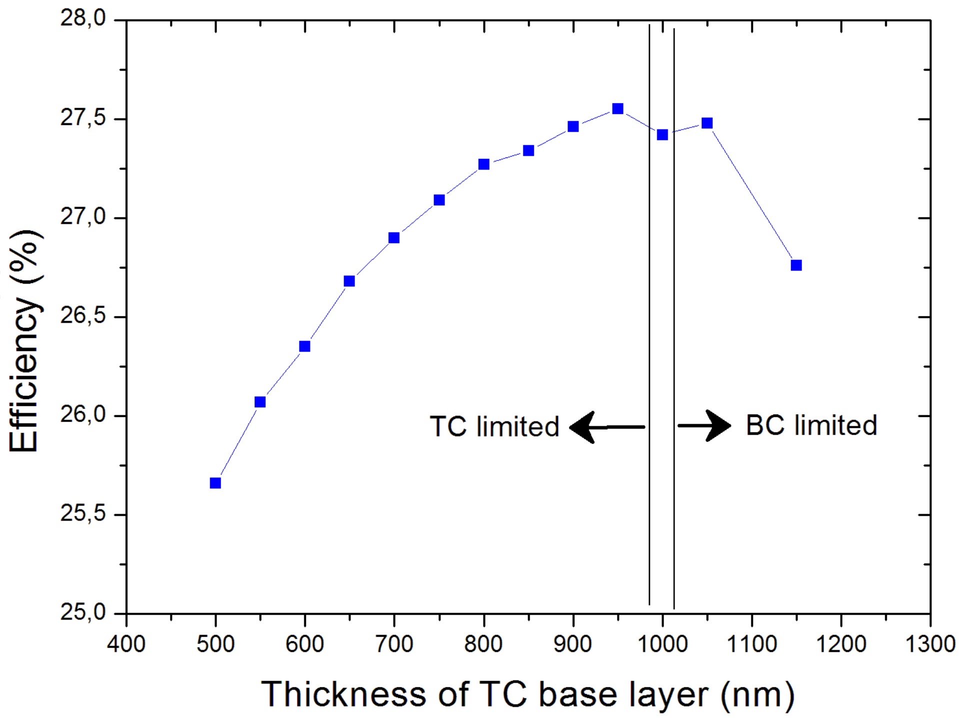

Figure 13. Simulation of the efficiency of a double-junction solar cell that is mounted inside a CPV module as a function of top cell base thickness.

The same series of simulations have been done for a solar cell mounted in a double lens CPV system like the one shown in Figure 2 and the result is plotted in Figure 13. Even though the general tendency of switching from a top-cell limiting configuration to a bottom-cell limiting configuration is true in both examples, the thickness at which this switching occurs is different, and occurs at higher thickness when the solar cell is mounted inside a module. This figure shows that when embedding the cell in the CPV system the current matching for the individual solar cell in a dual junction solar cell moves towards around a 1000 nm-thick top-cell base. This can be explained by the fact that part of the sun light gets either absorbed by the materials of the system or get reflected on the interfaces of them, so that less light is available for generating current in the solar cell. It also follows that the efficiency of the solar cell and system is lower than that of only the solar cell.

Continuing with the analysis of the system as a whole, it can be seen that the efficiency of this system is in all the range lower than that of a stand-alone solar cell. As an example two solar cells with different width of the top-cell base will be compared, one of 750 nm and the other one of 950 nm. If the final design of a solar cell is with a 750 nm thick top cell base, its efficiency is 31.21%, and if the final design is with a 950 nm thick top cell base, its efficiency will be 30.82%. If these two solar cells are mounted in the system, the first solar cell will have an efficiency of 27.09%, and the latter one an efficiency of 27.55%. This means that the solar cell with a top-cell base thickness of 750 nm performs better when it is operated in air (i.e. 0.39% higher), whereas the solar cell with a top cell base thickness of 950 nm performs better when it is mounted in the module. According to these simulations, if the thickness of the base of the top-cell is increased from 650 nm to 950 nm in a solar cell that is going to be operated in the optical system described earlier, the overall system efficiency would be increased by 0.46%. The very important conclusion of this analysis is, once more, that the priority should be to optimize the module efficiency and not only the solar cell efficiency.

The previous simulations can be complemented with simulations of the spectral response of a solar cell. In Figure 14 is plotted the spectral response of the solar cell for a stand-alone solar cell of a 650 nm and a 950 nm thick top-cell base. This figure is similar to the ones measured on real devices, like e.g. in [14]. Figure 15 shows the same plot for a solar cell that is mounted in a CPV system. When increasing the width of the top-cell base, the generated current in the top cell increases (blue curve). This behaviour is also true when the solar cell is inserted in a module, even though it is less enhanced.

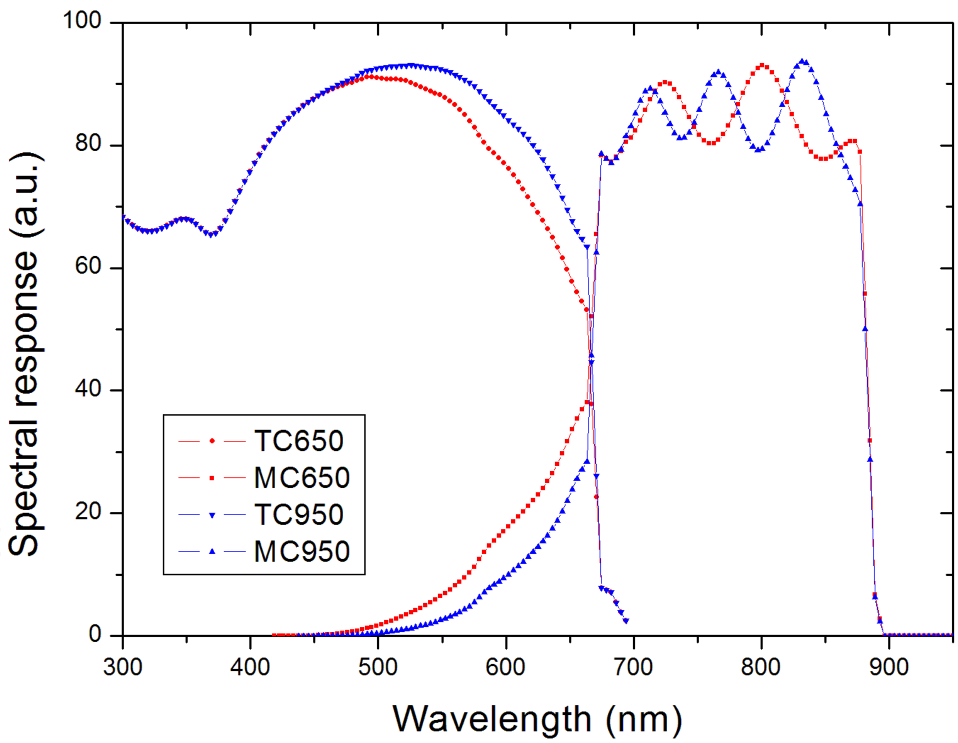

Figure 14. Simulation of the spectral response of a double-junction solar cell for two different TC base thicknesses (650 nm and 950 nm).

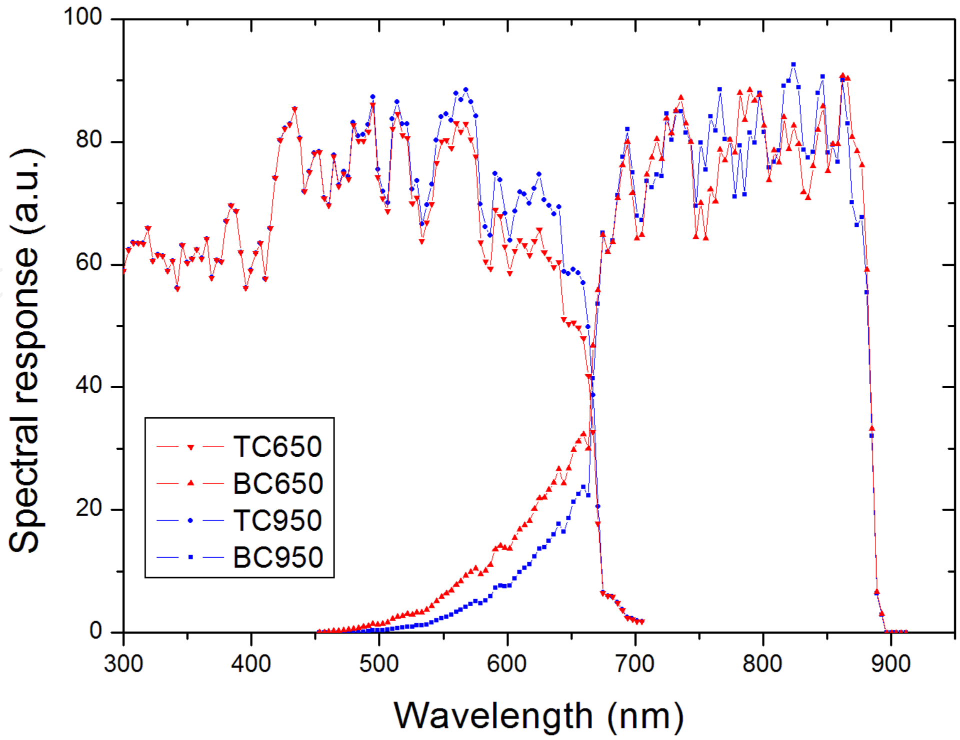

Figure 15. Simulation of the spectral response of a double-junction solar cell mounted inside a CPV module. The simulations are made for two different top cell base thicknesses (650 nm and 950 nm).

7. Power loss in a CPV module due to a non-matched solar cell

It has been shown in this chapter with the help of a simulation program that the performance of a solar cell depends on the medium in which it operates. A solar cell that is measured in air as a standalone device does not perform in the same way as in a system that is composed of solar cell and optical concentrator system. The system efficiency is typically lower than the efficiency of a standalone solar cell, due to losses that are attributed to (spectral) absorption of the materials and reflections on the interfaces of different type of materials. These losses between a stand-alone solar cell and the efficiency of the system can be minimized, if the right materials are chosen and the solar cell and the optical system are adapted to each other.

In order to get a feeling on how big the impact of the efficiency loss is on the module power output, simple calculations are given. It has been shown in previous sections that due to a wrong choice of anti-reflection coating the loss in efficiency of the CPV system can be 1,71%, and that if the thickness of the base of the top cell is not adapted to the system, it is possible to lose another 0,46% in efficiency. This means that by adapting the ARC and the thickness of the base of the solar cell, it is possible to gain (or not to lose) more than 2% in system efficiency, according to the simulations of the system and parameters described earlier. The simulations were made for a double-junction solar cell, and it can be expected that the loss of 2% that is observed for a non-optimized solar cell will be even higher for a system with a triple-junction solar cell.

As an example, it is assumed that the optimized system efficiency of a CPV module is 30%, whereas the efficiency of the not optimized CPV module is 28%. Assuming that a given CPV module has 10 solar cells of 1 cm^2 of active area each and works at a concentration of 500 suns, then the output power would be 127,5 W for 30% system efficiency and 119 W for 28% system efficiency, assuming an irradiation of 850 W/m^2. With this simple example it is intended to visualize that a seemingly small difference of 2% in system efficiency has an effect of approx. 6,7% on module level and therefore also on the installation cost of a CPV power plant. The effect that a 2% efficiency difference makes on module level depends on its design (number of solar cells, concentration ratio, etc.), and should be therefore only considered qualitatively.

8. Conclusion

In this chapter simulations of double-junction solar cells were discussed. The ISOSIM simulation software is a powerful tool to obtain characteristic curves of solar cells. With this software package it is also possible to understand and predict experimental behaviour of solar cells under real operating conditions. The results obtained in this chapter can be extrapolated to triple-junction solar cells, since typically the third junction is made out of Germanium and is far from limiting the multijunciton solar cell. It has been analysed the efficiency of a solar cell and a system composed of solar cell and additional layers that should represent the optical system of a CPV module. It has been analysed the effect of the anti-reflection coating material and its thickness on the efficiency of the solar cell, and has also been shown that when increasing the width of the base to the top cell, the double-junction solar cell switches from being top cell limiting to bottom cell limiting. These two parameters, the type and thickness of the ARC layer and the thickness of the top-cell base thickness play an important role on the efficiency of the solar cell. When the solar cell is assembled in a CPV module the optimum values of ARC coating material and its thickness and the optimum thickness of the base layer of the top cell changes. This means that in order to obtain maximum module power output, a solar cell and optical system should match each other well, in a way that the design of the solar cell should take into account the optical system of the CPV module or the other way around, the design of the optical system should be adapted to a given solar cell. It is also shown that a small variation in efficiency of a solar cell has a big impact on CPV module power output and therefore also on the installation cost of a CPV power plant.

Author details

Egbert Rodríguez Messmer

Isofotón S.A, Spain

References

[1] F. Rubio, M. Martínez, D. Sánchez, R. Aranda, P. Banda, Two years operating CPV plants: Analysis and results at ISFOC, 7th International Conference on Concentrating Photovoltaic Systems, Las Vegas 2011

[2] SolFocus (May 2010). SolFocus and Victor Valley College Complete the Largest Solar Power Plant of its Kind in North America, Available from: http://www.solfocus.com/en/ news-events/press-releases/2010-05-26.php

[3] Amonix.ParquesSolares de Navarra, Flexible Deployment Leads To Largest CPV Solar Power Plant Under The Sun, Available from: http://www.amonix.com/content/success-stories

[4] Concentrix Solar (February 2010). Concentrix Solar enters the US Market with Megawatt CPV Deployment at a Chevron Facility, Available from: http://www.soitec.com/en/solar-energy/

[5] Soitec press release http://www.soitec.com/events/san-diego/press-room.php (accessed 22 December 2011)

[6] H. Lerchenmüller, A.W. Bett, J. Jaus, G. Willeke; Cost and market perspectives for FLATCON-systems, Proceedings of the 20th European Photovoltaic Solar Energy Conference, Barcelona (Spain) 2005

[7] J.A. López Villanueva, V. Díaz, S. Rodríguez Bolívar, J.A. Jiménez Tejada and E. Rodríguez Messmer; A multijunction solar cell simulation program for the development of concentration systems, Proceedings of 6th Spanish Conference on Electronic Devices, San Lorenzo del Escorial, Madrid (Spain) 2007

[8] V. Díaz, J.A. López Villanueva, S. Rodríguez Bolívar, J.A. Jiménez Tejada and E. Rodríguez Messmer; ISOSIM: A Multijunction Solar Cell Simulation Program, Proceedings of the 4th International Conference on Solar Cell Concentrators, San Lorenzo del Escorial (Spain) 2007.

[9] E. Rodríguez Messmer, V. Díaz, J. Miguel-Sánchez, J.A. López Villanueva; Simulation of the Impact of Design Parameters on the Efficiency of Concentrator Systems with the ISOSIM Package, Proceedings of the 33rd IEEE Photovoltaic Specialists Conference (PVSEC), San Diego 2008.

[10] Software Spectra, Inc., (2011), Optical Data from Sopra SA, Available from: www.sspectra.com/sopra.html

[11] Aiken, D. (2000). Antireflection coating design for series interconnected multijunction solar cells, Progress in Photovoltaics: Research and Applications, 8 (2000), pp 563-570

[12] Olson, J. (2003). Growth and characterization of high efficiency III-V multijunction solar cells for terrestial and space applications, Proceedings of the 10th European Workshop on MOVPE, Lecce (Italy) 2003

[13] R.R. King, D.C. Law, K.M. Edmondson, C.M. Fetzer, G.S. KinseyH. Yoon, D.D. Krut, J.H. Ermer, R.A. Sherif, and N.H. Karam; Advances in high-efficiency III-V multi-junction solar cells, In: Advances in OptoElectronics, Volume 2007, 29523, doi: 10.1155/2007/29523(2007).

[14] I. García, I. Rey-Stolle, B. Galiana, and C. Algora; A 32.6% efficient lattice-matched dual-junction solar cell working at 1000 suns, Applied Physics Letters 94, 053509 (2009).