Renewable Energy 38 (2012) 31–39

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Very high fluxes for concentrating photovoltaics: Considerations from simple experiments and modeling

Alexis Vossier [a,1], Daniel Chemisana [b], Gilles Flamant [a], Alain Dollet [a,*]

[a] PROMES laboratory, CNRS, Tecnosud, rambla de la thermodynamique, 66100 Perpignan, France
[b] University of Lleida, c/ Pere de Cabrera s/n, 25001, Lleida, Spain

ARTICLE INFO

Article history:
Received 21 December 2010
Accepted 22 June 2011
Available online 31 July 2011

Keywords:
Concentrating photovoltaics
Very high concentration
Multi-junction solar cell
Cell characterization
Cost analysis

ABSTRACT

Among commercial photovoltaic technologies, concentrating photovoltaics (CPV) has the highest solar energy-to-electricity conversion efficiency; however, CPV electricity costs are still higher than thin film or silicon PV costs, mainly because of the additional components needed (optics, tracker) and the very high price of III–V multi-junction solar cells. To date, most commercial CPV systems operated at maximum concentrations of about 500 suns; but even at this concentration level, multi-junction cells retain a significant contribution to the total cost of the system. Further increasing the concentration ratio seems an interesting route for decreasing CPV electricity costs since the efficiency of concentrator cells theoretically increases with increasing illumination levels whilst the part of the solar cells in the total system cost decreases.

In this work, single, dual and triple-junction III–V solar cells designed to operate at concentrations of only a few hundred suns have been characterized under natural sunlight concentrated up to about 3000 suns. The cells were not damaged by the various series of measurements; furthermore, the electrical power delivered by the cells was found to increase with increasing concentration up to its maximum value despite the decrease in conversion efficiency observed above 200–300 suns. Calculations were also performed to complement the experimental results: the importance of optimizing the cell grid layout for ultrahigh concentration was first illustrated and finally a cost analysis suggested that a non-negligible decrease of solar electricity costs could result from increasing the concentration ratio used in commercial CPV systems.

1. Introduction and goal

The first photovoltaic concentrators started to be developed 40 years ago [1]. For a long time, only prototypes and demonstration plants were built throughout the world, but Concentrating Photovoltaics (CPV) has recently entered the PV market. Several commercial CPV plants are now in operation and tens and even hundreds MW of CPV plants will soon be installed. Earlier CPV systems used silicon solar cells and operated at concentration ratios rarely exceeding 100 suns; the high cost and the insufficiently-proven reliability of these systems as compared to more mature PV technologies largely explained that CPV failed to attract investors. CPV technologies regained interest in the late 1990's, with the tremendous development of multi-junction (MJ) solar cells based on III–V semiconductors, the performances of which now greatly surpass those of silicon cells, with today's best efficiencies above 41% [2,3] and even 42% [4] for GaInP-GaInAs-Ge triple-junction cells.

For a long time, people considered concentrations ranging from 100 to 200 suns as an upper bound for operating concentrator cells because of limitations due to series resistance and heat extraction [5]; nevertheless, most current CPV systems operate around 500 suns and recent surveys on CPV technology [6,7] confirmed the tendency for commercial systems to move toward higher concentration ratios. Since the current delivered by the solar cell is roughly proportional to the solar flux absorbed, the underlying idea supporting the use of ultrahigh concentrations in CPV is simply that the higher the concentration, the lower the MJ cell area required for producing a given amount of electricity. As MJ cells are—and should remain for a long time—very expensive (representing typically 30% of the total cost of a CPV system working at $\approx$500 suns) and because they are partly made of rare and toxic elements, the use of much higher concentrations could be a very interesting route for decreasing both environmental impact and electricity costs of CPV systems.

* Corresponding author. Tel.: +33 468682212; fax: +33 468682213.
E-mail address: dollet@univ-perp.fr (A. Dollet).
1 Present address: Department of Solar Energy & Environmental Physics, Jacob Blaustein Institut for Desert Research, Ben-Gurion University of the Negev, Sede Boqer Campus, Israel

0960-1481/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.renene.2011.06.036

However, there are still many questions to address and many problems to resolve before using ultrahigh concentrations in commercial CPV systems. For instance, what is the maximum concentration that MJ cells are able to withstand without damage or failure resulting from cell overheating or from too high current densities? What maximum concentration should be used in order to preserve good cell performances and lifetime? Is there a particular value of the concentration ratio that minimizes CPV electricity cost?

Measurements of photovoltaic characteristics of III–V solar cells under very high concentrations have already been reported in previous studies; however most of them were performed by using flash lamps instead of prolonged illumination under concentrated natural sunlight. Flash lamp experiments do not represent well what could happen in real ultrahigh concentration systems; for instance, the duration of irradiation is usually so short that no significant heating of the cell can be observed. A few experiments using ultrahigh concentration of natural sunlight have been reported but mostly on small size or partially irradiated cells [8]. High-irradiation experiments have extremely rarely been conducted on large III–V cells, mention should be made of those conducted on a 10 x 10 cm dense CPV array composed of monolithic interconnected GaAs cells at concentration up to 1000 suns [9] in the framework of the HICON-PV European research project.

The present paper aims at providing additional arguments to previous literature supporting the idea that III–V solar cells could probably operate under concentrations much higher than 500 and even 1000 suns in future commercial CPV systems. For that purpose, three types of III–V concentrator cells (single, dual and triple-junction) designed for concentration ratios of a few hundred suns were tested and characterized under natural sunlight concentrated up to about 3000 suns (where 1 sun = 1000 W m^{-2}). From these results and for specific high concentration ratios, calculations illustrating the importance of optimizing the front grid design for maximizing cell efficiency were performed. Finally, a cost-effectiveness analysis was conducted to further demonstrate the potential benefit of operating under higher concentrations in next generation CPV systems.

2. Experimental characterization

The experimental set-up used in this work is depicted in Fig. 1. A heliostat located outside the building tracked the sun and reflected direct solar radiation toward a large parabolic reflector (2 m in diameter) located inside the laboratory. The intensity of sunlight received by the dish was modulated by means of a set of adjustable shutters; the total power density at the focal spot can be varied from 0 (shutters closed) to more than 1000 W/cm^2 (shutters opened). The light intensity map at the focal point of the parabola, previously established by calorimetric measurements, showed that the light intensity distribution in the focal spot was nearly Gaussian.

Because the focal spot diameter ($\approx$ 1 cm) was significantly larger than the diameter of our solar cells (2 mm), a cooled mask was placed above the cell under testing in order to stop the undesirable radiation that otherwise would impinge on the surrounding parts of the cell. A silica rod, the diameter of which was equal to the cell diameter, was inserted in a hole drilled in the cooled mask. The rod served as an optical guide transmitting the concentrated light to the cell by total internal reflections. The light flux impinging on the top of the silica rod was homogeneous (central part of a nearly Gaussian distribution). The copper heat spreader on which the cell was mounted was mechanically and thermally attached to an active cooling system using water as refrigerant fluid.

The current–voltage (I–V) characteristics were acquired in situ with a Keithley 2601 sourcemeter. Direct normal irradiation (DNI)

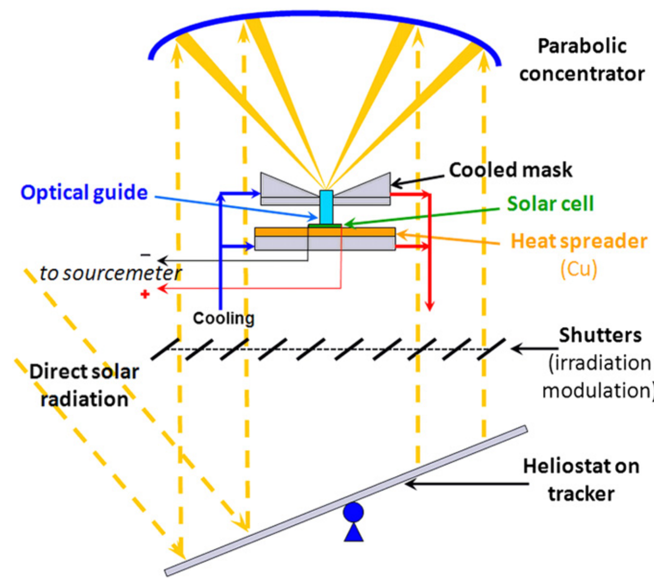

Fig. 1. Schematic of the set-up used for in situ characterization of III–V solar cells under concentrated sunlight.

was measured by using a Kipp & Zonen pyrheliometer precisely directed toward the sun. Radiation spectra with and without the concentration system were recorded by means of a spectroradiometer (Ocean Optics HR4000/NIR256-2.5) capable of measuring absolute irradiance in the range 300–2500 nm. The total power transmitted to the cell was measured at the exit of the optical guide using an Ophir powermeter with thermal head (Ophir 30 A-V1 detector) insensitive to sunlight spectrum variations and capable of measuring power up to 30 W. The concentration ratio (X) of the radiation received by the cell was calculated as follows: for a given value of the tilt angle of the shutters, the power transmitted to the cell and the short-circuit current of the cell were successively measured under stable irradiation conditions; these measurements were repeated for different tilt angles of the shutters in order to check that the short-circuit current delivered by the cell was strictly proportional to the absorbed radiation [5] over the whole concentration range studied. From this procedure, a generation coefficient (G) defined as the ratio between the short-circuit current (I_{sc}) and the solar power (P_{inc}) received [10,11] was derived for each cell tested.

3. Experimental results

3.1. Analysis of the transmitted light

Presented in Fig. 2 are typical radiation spectra recorded before and after solar radiation crossed the concentration system and normalized so that the integral of the absolute irradiance is equal to 1000 W/m^2. It can be seen that the optical system induced a non-negligible change in the photon energy distribution of the concentrated beam, which probably affect the short-circuit current of the cell, especially if it has several junctions.

Three types of III–V concentrator solar cells, each having a diameter of 2 mm, were characterized in this work: i) GaAs single junction (1 J), ii) GaInP/GaInAs dual-junction (2 J) and iii) InGaP/InGaAs/Ge triple-junction (3 J) cell. These cells were provided, mounted on their copper heat sink, by the ISE-Fraunhofer (Freiburg, Germany).

The values of the generation coefficient (G) used to calculate the solar power absorbed by the 3 types of cells are reported in Table 1.