FLATCON^{TM}-MODULES: TECHNOLOGY AND CHARACTERISATION

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ABSTRACT

High-efficiency III-V solar cells can be used cost-effectively in high-concentration modules. The Fraunhofer ISE - in co-operation with the Ioffe Institute St. Petersburg - has developed the FLATCON^{TM}-modules: **F**resnel **L**ens **A**ll-glass **T**andem-cell **CON**centrator modules. A 500x concentration is obtained by using Fresnel lenses which are fabricated directly on a glass sheet. The module housing is made totally out of glass. High-efficient dual-junction cells of $Ga_{0.65}In_{0.35}P/Ga_{0.83}In_{0.17}As$ are applied. Outdoor measurements showed module efficiencies of > 22 %. Furthermore, a new tracking system as well as a monitoring measurement set up has been installed. The latter allows a continuous monitoring of up to 20 modules. First results are presented.

1. INTRODUCTION

Today, photovoltaics for terrestrial application is based - to more than 95 % - on silicon material. Looking to space photovoltaics the III-V multi-junction solar cells gained more and more market share during the recent years. Besides the better radiation hardness, the higher efficiency of these cells was the driving force to substitute the Si solar cells for space applications. For example, an efficiency of 29.7 % (@AM0) was reported for a triple-junction cell made of GaInP/GaAs/Ge [1], which is close to the practical limit for this choice of materials. However, the drawback of these high-efficiency multi-junction solar cells based on III-V materials is their high cost. This rises the question how to decrease the cost and benefit from these high-efficiency solar cells on earth. For sure, the cell cost cannot be lowered to be comparable to Si-based standard solar cells. Consequently, the solution is to use less of the expensive semiconductor material. This is possible if the sunlight is concentrated with an optical concentrator. Therefore, by combining the more expensive high-efficiency cells with cheap optical concentrators, there is a good chance to lower the costs of PV-generated electricity. Going this pathway is also justified by several studies showing the benefits of concentrator technology for photovoltaic energy production [2-5].

One of the challenges for the concentrator technology is to develop high-quality concentrator systems. A huge variety of such systems is possible. This is related to the fact that for each main component of a system, i.e. optics, tracking and cells, a large number of options are available. Thus, discussing concentrator systems it is useful to distinguish between the different systems by a rough classification. This classification is mainly driven by the concentration ratio and the applied cell technology. In our opinion it is useful to distinguish between three classes:

1. Low concentration; this covers a range of concentration from 2 to 10. Si cells which are currently in production are applied. No tracking or one-axis tracking is used.
2. Medium concentration; this covers concentration ratios below 100. Modified Si cells are used. A one-axis tracking is mandatory.
3. High concentration; this covers the concentration ratios above 100 and can reach up to 1000. High sophisticated Si solar cells may be used in the range up to 250, while III-V solar cells can be applied for higher concentrations. A precise two-axis tracking is necessary.

In this paper the high concentrator option is addressed. We will describe the specific concentrator system FLATCON^{TM}. FLATCON^{TM} is the abbreviation for a specific type of concentrator module: **F**resnel **L**ens **A**ll-glass **T**andem-cell **CON**centrator. It consists of small size Fresnel lenses with an area of 4x4 cm². 48 of these Fresnel lenses are manufactured on a glass superstrate. The Frensel lenses concentrate the sunlight onto dual-junction cells made of $Ga_{0.65}In_{0..35}P/Ga_{0.83}In_{0.17}As$ with a designated area of 0.0314 cm². A geometrical concentration ratio higher than 500 is realised in this module. The module housing consists completely, i.e. side walls, front and rear side, of glass. Fig. 1 shows a photograph of the FLATCON^{TM} module.

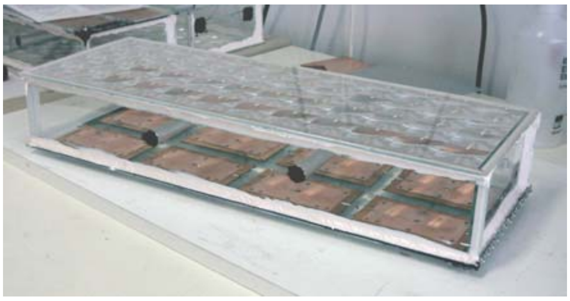

Figure 1: Photograph of a FLATCON^{TM} module. 48 Fresnel lenses concentrate the sunlight to dual-junction cells with a diameter of 2 mm. A geometrical concentration ratio of 500 is realised. The aperture area of one FLATCON^{TM} module is 768 cm².

The basic idea of the FLATCON^{TM} module was developed in the early 1990´s. At that time a co-operation between the Ioffe Institute, St. Petersburg, Russia and the Fraunhofer ISE, Germany was initiated with the aim to develop a complete concentrator system, not only components. The challenge for the concentrator technology is that the components have to fit properly together otherwise one may lose performance even if the single components are perfectly optimised.

The first concentrator modules used single-junction GaAs solar cells with a diameter of 4 mm. The geometrical concentration was 123. These modules achieved efficiencies in the range of 17-18 % [6-7]. Due to the progress in the development of high-efficiency and high concentration dual-junction cells [4,8], the GaAs single-junction cells were replaced by lattice mismatched $Ga_{0.65}In_{0..35}P/Ga_{0.83}In_{0.17}As$ dual-junction cells. A test module was fabricated and the specific challenges of characterisation of monolithic multi-junction cells under concentration were addressed. Efficiencies as high as 24.9 % under real operation conditions were determined [9]. However, as cost studies pointed out [4] higher concentration ratios are more favourable for the sophisticated III-V multi-junction solar cell. As a consequence, the cell diameter was reduced from 4 mm down to 2 mm while maintaining the aperture area of 16 cm² for the Fresnel lens concentrator. This paper will present experimental results for the 2 mm dual-junction cells and for the FLATCON™ modules equipped with these cells.

2. $Ga_{0.65}In_{0.35}P/Ga_{0.83}In_{0.17}As$ DUAL-JUNCTION CONCENTRATOR CELLS

Lattice mismatched $Ga_{0.65}In_{0.35}P/Ga_{0.83}In_{0.17}As$ dual-junction solar cell structures were grown by metal organic vapour phase epitaxy (MOVPE). An industrial size AIX2600G3 with a capacity of up to 24 2-inch wafers was used. More details on the growth process can be found elsewhere [8]. The same solar cell structure as successfully used for the 4 mm solar cell was grown. The best 4 mm solar cells have shown a maximum efficiency of 31.1 % at 300xAM1.5d and efficiencies above 30 % within the concentration range of 80 to 1000 [10]. Thus, the applied solar cell structure has shown to be efficient. However, to fabricate 2 mm solar cells a new grid design was developed. We used an in-house developed optimisation program which is based on the equations described in [11]. While the 4 mm cell had a prismatic cover to reduce shadowing losses, we omitted the prismatic cover for the 2 mm cell. Thus, a radial grid design as described in [11] was realised. The shadowing losses for the designated area (only the grid fingers) are in the range of 5 %. Standard technology, i.e. double layer antireflection coatings and gold based electroplated contacts were used. More details can be found elsewhere [8].

Fig. 2 shows a typical quantum efficiency of the $Ga_{0.65}In_{0.35}P/Ga_{0.83}In_{0.17}As$ dual-junction solar cell. Fig. 3 shows the dependence of the efficiency on the concentration ratio. Here one has to note, that it is currently under discussion which is the most suitable reference spectrum for tandem concentrator solar cells reflecting the "real world". This question has a strong impact on the optimised structure of monolithic multi-junction cells. While the AM1.5d standard spectrum is used for the rating of concentrator solar cells so far, however, an unrealistically high aerosol optical depth (AOD) value of 0.27 was assumed for its calculation [13]. Moreover, there is some evidence that these spectral conditions are not ideal for the optimisation of multi-junction cells [12]. Therefore, a new spectrum was suggested based on calculations using the program SMARTS and an AOD @ λ=500 nm of 0.085 [13]. In this paper we refer to it as "AOD". For comparison we considered both spectrums during our analysis of the dual-junction cells. Using the quantum efficiency shown in Fig. 2, one can calculated the expected short circuit currents of each subcell assuming different spectral conditions. Performing this calculation shows the big influence of the spectral conditions for optimising a dual-junction solar cell. While for AM1.5d spectral conditions the top cell is limiting the current of the device, it changes for the new AOD spectrum. Here, the bottom cell limits the overall current. However, these calculation show that the cell was designed for AOD spectral conditions because in this case both subcells generate nearly equal currents.

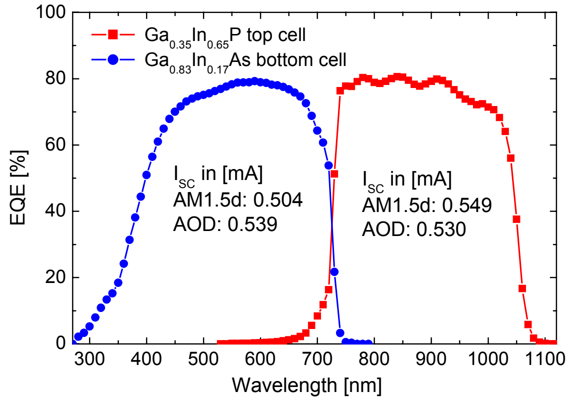

Figure 2: External quantum efficiency measurement of a 2 mm $Ga_{0.65}In_{0.35}P/Ga_{0.83}In_{0.17}As$ dual-junction concentrator solar cell. The short circuit current which would be achieved in the sub cells under the standard spectrum AM1.5d and the new spectrum AOD were calculated and are given in the insert.

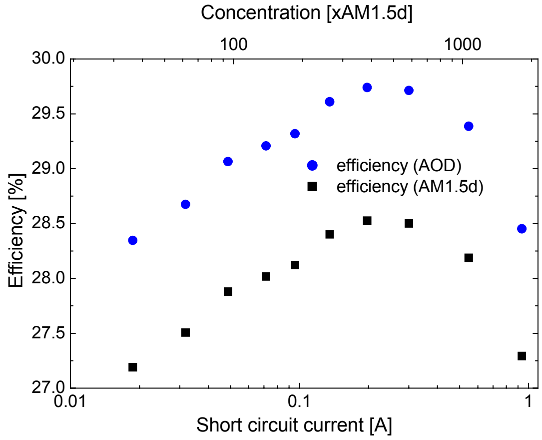

Figure 3: Efficiency versus short-circuit current for a 2 mm dual-junction cell. The efficiency is determined for AM1.5d and AOD spectral conditions. The top axis shows the calculated concentration ratios based on the AM1.5d spectral conditions. Note that the concentration ratios for the AOD spectrum differ slightly.

Assuming AM1.5d spectral conditions efficiencies > 28.5 % were determined for concentration ratios between 380 and 580 (see Fig. 3). Regarding AOD spectral conditions, the efficiencies were > 29.7 % for concentration ratios between 368 and 560. This demonstrates that a very small dependence of the efficiency on the concentration was realised in this cell.

Moreover, it is important to note that the efficiency does not drop rapidly if the concentration ratio increases further. Even at concentration ratios as high as 1817 the efficiency is still 27.3 % for AM1.5d and 28.5 % at a concentration ratio of 1743 for AOD spectral conditions. To our knowledge this is the highest reported efficiency for multi-junction solar cells at such high concentration levels.

The small decrease of the efficiency even at very high concentration is also of practical interest. Using Fresnel lenses as the concentrating optics a Gaussian light distribution is obtained. Fig. 4 shows a calculation of the expected light distribution using our Fresnel lens design. In the centre of a 2 mm cell a concentration of 2500 is found while the averaged geometrical concentration is 500. On the other hand, testing of concentrator solar cells in the laboratory does mean to illuminate the cell with a homogenous intensity profile. Therefore, this measurement does not simulate the reality in a Fresnel lens concentrator module. Thus, for practical reasons it is very important not only to look for the maximum efficiency but also how the cell performs in a certain concentration range.

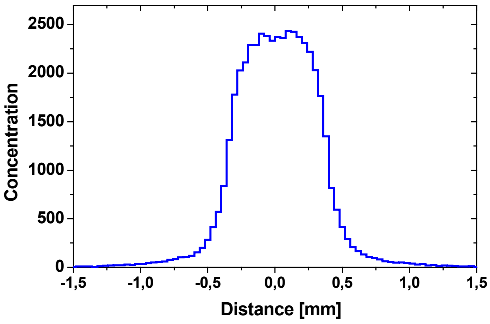

Figure 4: Calculation of the light distribution due to concentration of sunlight by a Fresnel lens which is used in the FLATCON^{TM} module. Courtesy by Dr. Bremerich, Jungbecker, Germany.

3. FABRICATION OF FLATCON^{TM} MODULES

FLATCON^{TM} modules are made completely out of glass and have a total height of only 76 mm. Glass is commonly available, relatively cheap and well accepted in the standard flat plate photovoltaic industry. Besides these benefits the all-glass design was chosen to avoid problems arising from the thermal mismatch due to the use of different materials. Especially the high-concentration approach requires a high overall accuracy in the alignment of cells to the Fresnel lenses and finally of the FLATCON^{TM} modules to the tracker. The overall accuracy of the concentrator system has to be better than 0.5°.

The top side of the FLATCON^{TM} modules is a flat glass surface as for standard flat plate modules. This glass plate acts as a superstrate for 48 Frensel lenses. The Frensel lenses are made of Silicone via a stamp process. A matrix with the inverted Fresnel structure is pressed into a thin Silicone film of 0.2 mm in average. This process was developed by the Ioffe Institute and the Fraunhofer ISE. Fig. 5 shows a photograph of this process. It was shown that this manufacturing process yields in high quality lenses [7]. Moreover, this process is highly reproducible. The optical efficiencies of our Fresnel lenses are in the range of 84-86 %. This efficiency was determined outdoors by measuring the incident power density on the aperture area of the lenses and the short-circuit current of a 2 mm cell made of GaAs.

Figure 5: Photograph of the fabrication process of the Fresnel lenses.

The FLATCON^{TM} modules are hermetically sealed. This protects the Fresnel lenses as well as the cells from environmental influences.

6 cells are mounted on a copper plate and are interconnected in parallel. They are protected by a silicon bypass diode. Eight of these subunits are connected in series (see Fig. 1). The open-circuit voltage of a module is in the range of 16-17 V (see Fig. 6). First outdoor measurements were performed in August 2002. An efficiency as high as 22.7 % was measured for a FLATCON^{TM} module, see Fig. 6. This is the best result obtained so far.

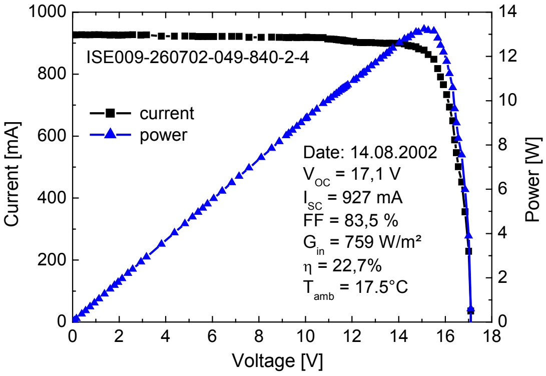

Figure 6: IV- and power curve measured on a FLATCON^{TM} module in August 2002.

4. DEVELOPMENT OF A TRACKING SYSTEM

During the recent years we have developed several tracking systems. A comprehensive description of the development activities can be found in [14]. Recently we installed a tracking system which is able to carry 5 KWp of FLATCON^{TM} modules. The tracker operates autonomously using two in-house developed sensors. One of these sensors has a wide acceptance angle (up to 270°). This sensor is necessary to detect the morning and evening position as well as positions far away from the sun. This might happen during a cloudy day. In the case of clouds (no direct sun) our tracking system stops, thus saving energy. The sensor detects if any direct sunlight is available and the tracker is initialised again. The second sensor has a lower acceptance angle (± 70°) and is used for the precise tracking with the sun in both the azimuth and elevation. It consists of four solar cells and a shadow mask. More details can be found in [14].

5. LONG-TERM MEASUREMENTS

Concentrator modules using monolithic multi-junction cells are fairly new. Therefore, long term testing is not yet performed. Moreover, there are no experimental data available showing the yearly energy yield of concentrator modules using dual-junction cells in comparison with flat plate modules. In general, it is known that the efficiency of multi-junction solar cells shows a higher sensitivity to changes in the spectrum compared to single-junction cells. This effect is related to the internal series connection and has been discussed in the literature [15,9,10].

In order to predict the energy harvesting of FLATCON™ more accurately we established a measurement set-up which can monitor the IV-curves of up to 20 modules continuously. Additionally, the weather data is recorded. Several FLATCON™ modules were installed on one of our developed trackers [14]. For comparison, a standard Si-flat plate module mounted at a fixed angle of 45 ° south oriented was measured too.

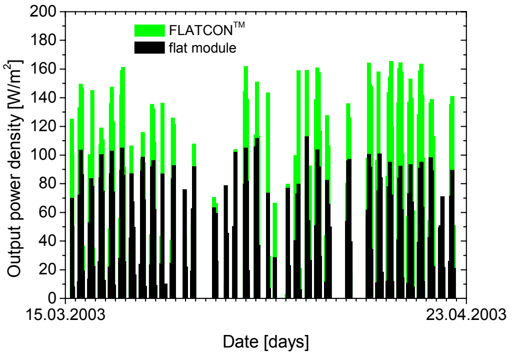

Figure 7: Measured output power density of a FLATCON™ module and a standard Si flat plate module during the course of one month in 2003. The measurement was performed on the roof at the Fraunhofer ISE.

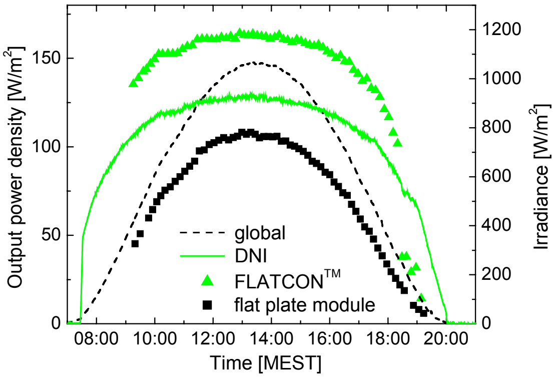

Figure 8: Power output density of a (tracked) FLATCON™ module and a (fixed) Si flat plate module over the course of a day. In addition, the insolation is shown.

Fig. 7 shows the measured output power density of a tracked FLATCON™ module in comparison to a fixed standard Si flat plate module over a period of roughly one month. In average, the FLATCON™ module outperforms the standard Si module by a factor of 1.5. However, one has to mention that this is only true if sunny days are regarded. No measurements were performed at cloudy days. Fig. 8 shows the measurement of the output power densities for the FLATCON™ and Si module in more detail. This measurement was performed during April, 8th 2003. In addition, the measured insolation for direct normal incidence (DNI) and global conditions are visualised. The expected more rectangular shape for the FLATCON™ module is obvious. Again, the 1.5 higher output power density for the FLATCON™ module can be observed.

CONCULSIONS

High concentration and high efficiency concentrator modules have been fabricated and characterised. A special module type FLATCON™ using Fresnel lenses and 2 mm dual-junction solar cells for a concentration ratio of 500 was developed. Efficiencies as high as 29.7 % were measured for the dual-junction cell. Even at concentration ratios beyond 1700 an efficiency of 28.5 % was determined.

The FLATCON™ modules were also measured outdoors and showed a 1.5 times higher power output density compared to a standard Si flat plate module.

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