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DEVELOPMENT OF III-V-BASED CONCENTRATOR SOLAR CELLS AND THEIR APPLICATION IN PV-MODULES

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ABSTRACT

Concentrators have a great potential to achieve cost reduction for solar generated electricity. In this work III-V-based concentrator solar cells for high concentration levels were fabricated. Monolithic and mechanically stacked multi-junction cells were investigated achieving efficiencies up to 33.5 % at C=308 (AM1.5d, 1000W/m², 25 °C). The cells are employed in point-focus Fresnel lens modules. All-glass hermetized modules designed for a concentration level of 120 and 500 obtained efficiencies of up to 24.8 % and 21.7 %, respectively. The modules were characterized under outdoor conditions at Freiburg, Germany.

INTRODUCTION

Concentrators are believed to have a great potential to reduce the costs for solar generated electricity. However, actually there are only a few concentrator systems on the market and the status of the technology development in respect to the market is somewhat “infantile”. The reasons are manifold. In our opinion one important feature of the concentrator technology is that a “system” has to be developed combining the different components like solar cells, optics and tracking systems. In order to optimize a “concentrator system” all the interactions have to be regarded and specifically optimized. This is the main guideline for the work performed at Fraunhofer ISE. Our concentrator system uses point-focus Fresnel lenses, aims for a concentration ratio of 500 and employs high-efficient III-V multi-junction solar cells.

Multi-junction solar cells are realized in several ways: mechanically stacked, monolithically integrated or a combination of both. Mechanically stacked dual-junction concentrator cells based on GaAs and GaSb have obtained efficiencies well above 31 % [1-3] showing the benefit of this approach. However, the drawback is that two substrates are necessary which rises the overall costs. On the other hand, the big advantage of this approach is the use of more simple solar cell structures.

The more sophisticated monolithic multi-junction cell designed for space applications made remarkable progress in the performance during the last years [4-6]. Nowadays efficiencies above 28 % under the one sun AM0 spectrum are reproducibly realized. In respect to concentrator application NREL presented an efficiency of 30.2 % at 180xAM1.5d using the lattice-matched GaInP/GaAs dual-junction solar cell [7]. The Fraunhofer ISE demonstrated efficiencies above 30 % for high concentration levels of >1000xAM1.5d [8]. In this case a lattice mismatched structure of $Ga_{0.35}In_{0.65}P/Ga_{0.83}In_{0.17}As$ was used [9]. Recently companies like Spectrolab started the development of monolithic triple-junction concentrator solar cell for terrestrial application. So far, efficiencies of 32.2 % at 414xAM1.5d were reported [1,10].

In this paper we focus on the progress achieved at Fraunhofer ISE in the development of multi-junction solar cells and we discuss the performance in test concentrator modules.

EXPERIMENTAL

Solar cell fabrication

AlGaAs/GaAs heteroface single-junction solar cells used for the mechanically stacked approach were fabricated by liquid-phase epitaxy (LPE). A simple isothermal process creates the pn-junction by Zn-diffusion into a n-doped GaAs-substrate. Simultaneously the AlGaAs-window layer is grown. More details of this growth process can be found elsewhere [11]. In order to fabricate the pn-junction in infrared sensitive GaSb a pseudo-closed box diffusion process was applied [12]. In this case no special surface passivation layer is necessary due to the strong internal electric field produced by the gradient in the doping level [13].

The growth of the monolithic dual-junction cells was performed on a multi-wafer MOVPE (metal-organic vapor phase epitaxy) AIXTRON 2600G3 reactor with a 5x4-inch susceptor geometry. $Ga_{0.35}In_{0.65}P/Ga_{0.83}In_{0.17}As$ was grown lattice mismatched on a p-doped GaAs substrate. Special attention was given to the internal tunnel structure in order to handle the high current at high illumination levels [8]. More details of the growth process can be found in references [14,15].

A double-layer antireflection coating consisting of TiO_x and MgF_2 was applied. The thicknesses were optimized for the corresponding structure. AuGe/Ni and Ti/Pd/Ag were evaporated as n- and p-contacts, respectively. The contact height was increased up to 3 µm by electrochemical Au-plating. For the mechanically stacked cell the rear side contact has a hole covered with a MgF_2/TiO_x antireflection layer to allow a high transmissivity of photons with λ>1050 nm. The infrared sensitive GaSb cell uses a single-layer antireflection coating made of anodic oxide [16].

Fresnel lens test modules

Concentrator test modules were fabricated based on the concept of the all-glass design as developed in a co-operation between Ioffe-Institute and Fraunhofer ISE [17,18]. The Fresnel lens structure is made by a stamp process in a 2 mm thick silicone film supplied on glass as superstrate. The aperture of each Fresnel lens is 4x4 cm². In combination with the solar cells of 4 mm in diameter a geometric concentration ratio of 123 is realized. The height of the modules is 75 mm and high optical efficiencies were obtained [18]. A test module with an even slightly higher optical efficiency of > 88 % was fabricated (see figure 3). Here, an antireflection coated glass was used as superstrate [19]. This antireflection coating was made by a sol-gel process described elsewhere [20]. The cells were mounted on copper plates in order to distribute the heat effectively. Furthermore, for the test module the copper plates were mounted on an aluminum heat sink. The aperture area of this module is 192 cm². In the conventional "all-glass" design the copper plates are mounted directly on a glass sheet which acts as the rear side of the hermitized modules. Thus, problems related with the difference in thermal expansion coefficients are overcome. The aperture area of this "standard" module is 768 cm².

It is noteworthy to mention that two different Fresnel lens structures were applied. One of the Fresnel structures consists of two zones with different focusing distance [18]. The peripheral zone has a focal length of 75 mm and the central zone has a slightly larger value. Therefore, the local maximum concentration in the center of the solar cell is reduced. This type of Fresnel lens was used in the modules with a geometrical concentration ratio of 123. Fresnel lenses with only one focal length of 75 mm were used in the case of a higher concentration ratio of 500.

RESULTS AND DISCUSSION

Mechanically stacked multi-junction solar cells

Mechanically stacked dual-junction solar cells made of LPE-grown GaAs and Zn-diffused GaSb solar cells exhibit an efficiency of 31.1 % at 100xAM1.5d, 1000 W/cm². A test module operating in a 2-terminal mode revealed a maximum outdoor efficiency of 23 % at 717 W/m² direct normal irradiation. A more detailed discussion about the interconnection scheme and an analysis of the module losses can be found in reference [21].

In order to increase the efficiency we fabricated mechanically stacked triple-junction solar cells using a $Ga_{0.35}In_{0.65}P/Ga_{0.83}In_{0.17}As$ monolithic dual-junction cell as the top cell and GaSb as the bottom cell. Due to the high sub-bandgap absorption in p-doped GaAs [22] the tandem structure was grown on n-doped GaAs wafers. This requires an additional tunnel junction between the buffer and the active n-on-p dual-junction device. Another possibility is to use semi-insulating GaAs which minimizes the optical absorption losses. Here one has to consider electrical losses in the base layer of the solar cell [23]. The resistive losses become more and more important for high illumination levels. Figure 1 shows a photograph of the realized mechanically stacked triple-junction device.

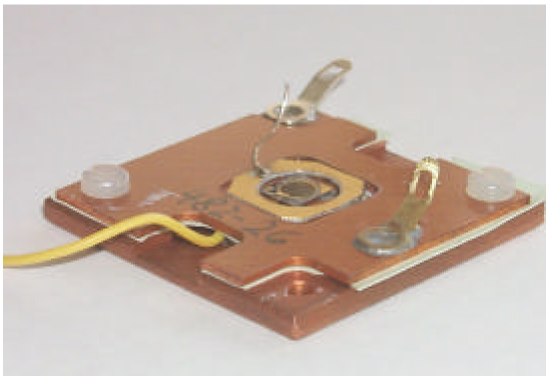

Figure 1: Photograph of the mechanically stacked triple-junction cell consisting of a monolithic $Ga_{0.35}In_{0.65}P/Ga_{0.83}In_{0.17}As$ dual-junction top cell and a GaSb bottom cell.

The cell area is 0.1326 cm². A prismatic cover was applied to reduce the grid shadowing losses. The cell was characterized at NREL and ISE CaLab using the procedures given in [24]. A more detailed description of the analysis performed at Fraunhofer ISE can be found in [23]. Figure 2 shows a comparison of the determined efficiencies versus concentration in the different laboratories. The maximum efficiency of the triple stack obtained at NREL was 32.5±1.6 % at 270xAM1.5d, whereas a value of 33.5±1.7 % at 308xAM1.5d was measured at ISE CalLab. Considering the given uncertainties the measured efficiency values are in good agreement. However, a relative difference of 6.5 % for the the 1-sun I_{SC} of the top dual-junction cell determined at both laboratories was found, which exceeds the given uncertainties for this parameter of ±2 % and ±3 %, respectively.

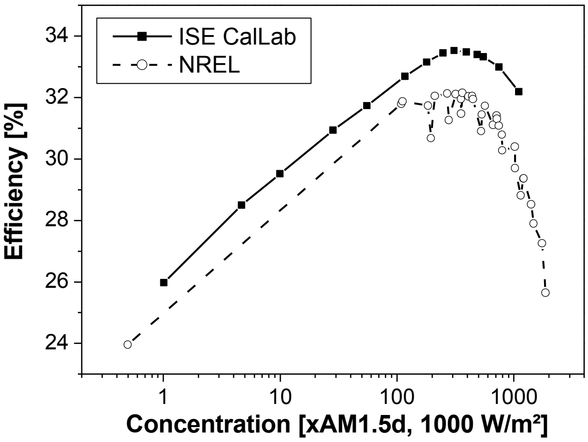

Figure 2: Efficiency versus concentration ratio for AM1.5d, 1000 W/m² spectral conditions. The measurements were performed at ISE CalLab and NREL.

Monolithic dual-junction solar cells

At Fraunhofer ISE lattice mismatched dual-junction solar cells were developed during recent years [9,15]. The use of lower bandgap material compared to GaAs for the bottom cell leads theoretically to higher efficiency values for concentrator applications [25]. Practically, an efficiency as high as 31.1 % at 308xAM1.5d, 1000 W/m² was reported recently [23]. Here it is worth mentioning that the efficiency of this cell is still above 30 % for concentration ratios as high as 1000. These monolithic dual-junction cells were mounted in the test module as described above. Figure 3 shows a photograph of this test module mounted on a tracking system for outdoor measurements.

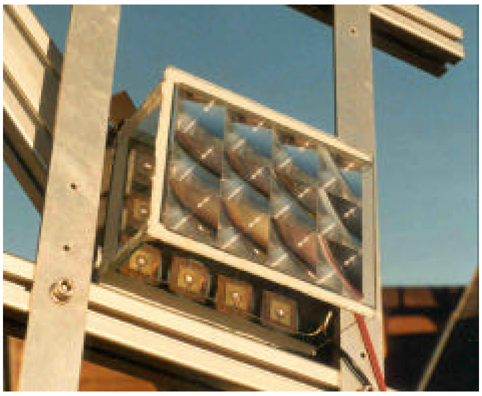

Figure 3: Photograph of the test module equipped with monolithic dual-junction cells. The module is mounted on a tracking system for outdoor characterization.

The characterization of the monolithic tandem concentrator solar cells is more problematic compared to single-junction solar cells due to the stronger dependence on spectral variations [19,26]. This implies that the most practical parameter for modules, the overall yearly energy harvesting is very difficult to predict if only conventional indoor measurements are available. Moreover, there is now a strong discussion which spectrum should be used for the indoor rating to be as close as possible to the reality (see proceedings of this conference). However, in order to characterize tandem concentrator modules under outdoor conditions properly one should not only record the overall direct normal irradiance but also the spectral distribution while measuring the IV-curve of the modules [19]. Figure 4a shows as an example measurements performed on Oct, 2nd 2001 in Freiburg, Germany. Figure 4b shows the simultaneously recorded IV-curves of the test module shown in figure 3. Obviously the sun spectrum changes during the day from more red- to more blue- and back to red-rich. It is interesting to note that the highest efficiency of 24.8 % was measured while the lowest total direct normal irradiance value of 596 W/m² was determined. The reason for this behavior was found by applying the spectrometric characterization technique [27]. It could be shown that the dual-junction solar cells used in the module are accidentally bottom cell limited in respect to the standard AM1.5d spectral condition. Thus, more red-rich spectra will lead to higher efficiencies (see figure 4b). Figure 5 shows the efficiencies determined during the course of one day (Oct. 2nd, 2001).

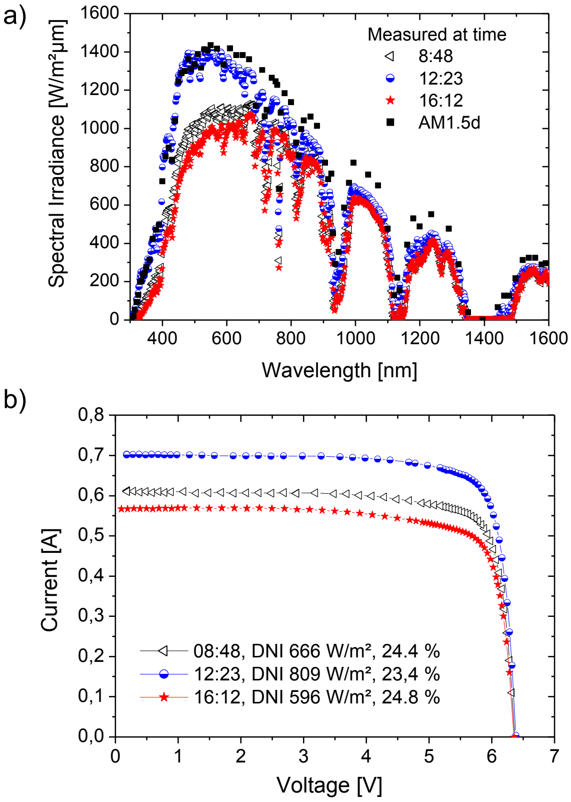

Figure 4a: Measurement of the sun spectrum at Freiburg, Germany, Oct, 2nd, 2001 and for comparison the standard AM1.5d spectrum. 4b: IV-curves recorded simultaneously.

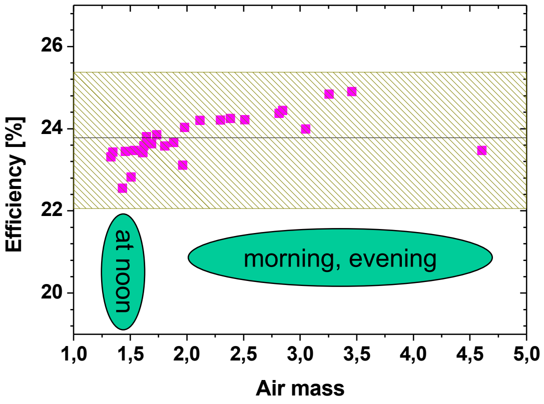

Figure 5: Measured outdoor efficiencies of the test module versus the air mass.

Towards higher concentration ratios

Up to now results for concentration ratios in the range of 100x were presented. However, as discussed in a previous paper [8] a higher concentration would be desirable to further decrease the electricity costs. Multi-junction solar cells working sufficiently at concentration ratios > 1000x were developed at Fraunhofer ISE. Thus, the cell is not the limiting component for high concentration systems. One has to regard the implemented concentrator optics, accuracy for mounting and tracking. For our concentrator system a concentration ratio of 500 seems to be a good compromise as long as no second stage is introduced. Maintaining the 4x4 cm² aperture area of the Fresnel lens requires the employment of newly developed solar cells with a diameter of 2 mm.

All-glass modules with an aperture sizes of 768 cm² were fabricated using the 2 mm cells. The interconnection scheme of the 48 cells were 8 strings in series connection with each string containing 6 cells in parallel. First tests under outdoor conditions were performed. Figure 6 shows the measured IV-curves of two different modules. The maximum module efficiency was 21.3 %. From the shape of one of the IV-curves (module B) one can conclude that the adjustment of the high-concentration cells in respect to the lenses was not perfect. As can be seen from the result obtained from module A this problem can be solved. However, further investigations are necessary.

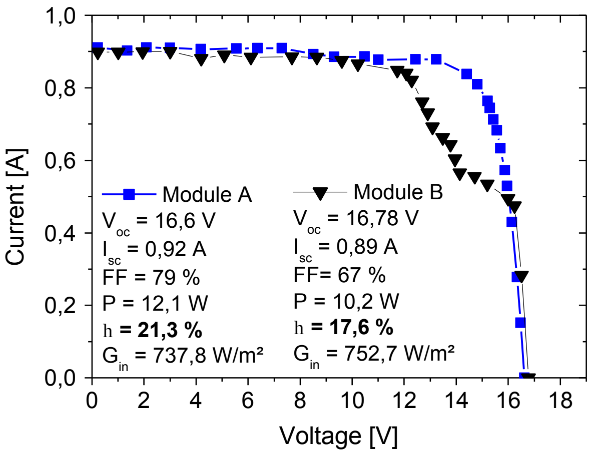

Figure 6: IV-curve measurement of two different 500x all-glass concentrator modules performed under outdoor conditions.

CONCLUSION

We have developed multi-junction concentrator cells for the application in high-concentration modules using point-focus Fresnel lenses as optical concentrators. Modules with geometrical concentration ratios of 120x and 500x were realized and achieved outdoor efficiencies up to 24.8 % and 21.3 %, respectively. In the future the long-term stability of the modules will be tested. A concentrator system in the range of several kWp will be installed at Fraunhofer ISE for demonstration purposes. Furthermore, we will employ triple-junction solar cells which are currently under development.

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