Presented at the 8th International Conference on Concentrating Photovoltaic Systems , 16-18 April 2012, Toledo, Spain

Front-side Interconnected Large Area Concentrator Cells For Compact Concentrator Modules

Maike Wiesenfarth[1], Marc Steiner[1], Henning Helmers[1], Gerald Siefer[1], Eduard Oliva[1], Frank Dimroth[1], Gil Shelef[2], Guy Polonsky[2], Yuri Flitsanov[2], Abraham Kribus[2] and Andreas W. Bett[1]

[1]*Fraunhofer Institute for Solar Energy Systems ISE, Heidenhofstr. 2, 79110 Freiburg, Germany*
[2]*Tel Aviv University, Faculty of Engineering, 69978 Tel Aviv, Israel*

Abstract. In this paper a new solar cell design is introduced where solar cells are interconnected in series via the front surface only. Indoor measurement results of single solar cells and compact concentrator modules consisting of 14 series-interconnected solar cells are presented. The epitaxial structure is a metamorphic triple-junction concept ($Ga_{0.35}In_{0.65}P/Ga_{0.83}In_{0.17}As/Ge$) produced at Fraunhofer ISE. Indoor measurements show a cell performance of 35.2 % at 334 x1000 W/m² referring to the designated area. Series connected solar cells on the module base plate were measured indoors at 280 x with an efficiency of 27.4 % considering total module area. In addition, outdoor measurements of the modules were performed at Tel Aviv University in a dish system showing module electrical efficiency of 22.8%. For combined electrical and thermal energy a total efficiency of 64.1 % has been achieved.

Keywords: Dense array receiver, compact concentrator module, CPV module, CPVT, solar cell, series interconnection, module design, packing factor, solar cell efficiency, module efficiency.
PACS: 88.40.jp, 88.40.ff, 88.40.hj

INTRODUCTION

Compact concentrator modules (CCM) or dense array PV receivers are usually used in mirror dish systems. The photovoltaic receiver in the focus of the dish, has a size of several square centimeters. The receiver consists typically of solar cells with a size up to 5 cm² which are mounted very closely to each other on an actively cooled substrate. To obtain a low current, high voltage device and therefore minimize the ohmic losses, a series interconnection of the solar cells is preferred. In this paper a special solar cell architecture and a suitable interconnection method is presented. This architecture allows interconnection of the solar cells in series on the front side by wire bonds. The electrical insulation between the solar cells is realized by a metallized heat sink and a small distance between the solar cells. Thus, high packing densities of the solar cells on the cooler can be realized. As the modules are actively cooled the thermal energy can also be used and therefore the solar energy is used more efficiently. Such a system is called CPVT system standing for concentrator PV and thermal [1].

SOLAR CELL AND MODULE DESIGN

The epitaxial solar cell structure is a metamorphic triple-junction solar cell made of np-$Ga_{0.35}In_{0.65}P/Ga_{0.83}In_{0.17}As/Ge$ as described in [2]. It is grown by metal organic vapor phase epitaxy (MOVPE). However, any standard solar cell structure on a conductive wafer substrate can be used. The front side series interconnection is realized by adding a processing step. During this step, a metallization pad for the rear side p-contact of the bottom germanium sub-cell is applied on the solar cell surface (contact-p-front). This contact is achieved by etching off the epitaxial layers of the solar cell down to the p-doped germanium substrate, see FIGURE 1. Contact pads are applied onto the germanium. A series connection can be realized by connecting one solar cells n-contact with the p-contact of the neighboring solar cell by metallization pads located on the front surface. The rear side of the solar cell is fully covered with metal in order to improve lateral current distribution with high electrical conductivity. The solar cell architecture is patent pending as described in [3].

The design of the solar cell was first optimized by simulations and afterwards manufactured at Fraunhofer ISE. The length of the metallization grid fingers and therefore the solar cell width was optimized regarding shading and ohmic losses as well as losses due to gaps between the cells. The optimum performance is obtained with a solar cell width of 6.13 mm parallel to the grid lines. The length of one solar cell is 20.32 mm, vertical to the grid lines. The shape of the bus bar at the negative terminal is optimized to provide a pad for the wire bond (0.058 mm²) and a bus to connect individual grid fingers. The bus bar at the positive terminal (contact-p-front) is larger (0.103 mm²) in order to get a good electrical contact to the basis of the bottom cell.

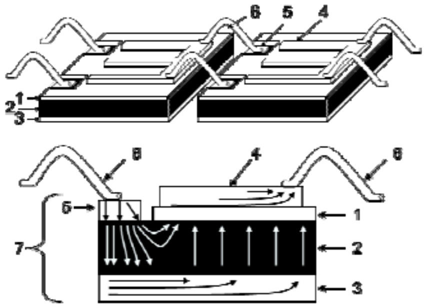

FIGURE 1. Top: Principle of electrical interconnection of two solar cells on the front surface – with 1: 3J solar cell, 2: doped conductive semiconductor substrate, 3: rear metallization for lateral current distribution, 4: front surface metallization – front contact, 5: second front surface metallization – contact-p-back, 6: electrical contact. Bottom: Cross-section of the solar cell 7 with current distribution visualized by arrows schematically.

Tel Aviv University manufactured several modules with 14 solar cells interconnected in series. Each solar cell is protected by a bypass diode. The baseplate after assembly and a complete module with cooler, encapsulation and homogenizer is displayed in FIGURE 2.

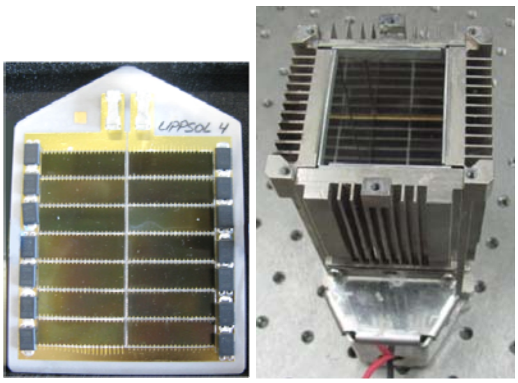

FIGURE 2. Left: Module base plate with 14 solar cells assembled on a substrate, electrically interconnected in series; each solar cell is protected by a bypass diode. Right: Complete module with base plate encapsulated with a conformal coating and glass cover and assembled with a cooler and homogenizer.

EXPERIMENTAL RESULTS

Analysis of the Solar Cell Performance

The solar cells were characterized indoors at Fraunhofer ISE with a multi-source sun simulator (MuSim) [4] at one-sun standard test conditions and a flash simulator [5] for high intensity illumination. In FIGURE 3 the IV-curve of solar cell 2700-07-29 under 334x (1000 W/m², 25 °C) is shown. The power at maximum power point (MPP) is 13.73 W.

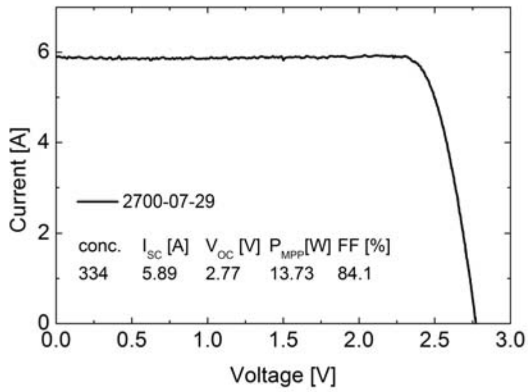

FIGURE 3. Measurement of IV-curve with the flash simulator at an illumination intensity of 33.4 W/cm² for cell 2700-07-29.

For the calculation of the solar cell efficiency an area needs to be defined (compare TABLE 1). Usually the efficiency of CPV cells is given with respect to the designated area as defined in [6]. Using the designated area, the efficiency of solar cell 2700-07-29 is 35.2 % with an illumination intensity of 33.4 W/cm². However, for dense array modules the solar cell area including the bus bars and non PV-active semiconductor material and also the area between the solar cells is illuminated. Here, this area is called "chip area + gaps". Referring to this area, the efficiency of the solar cell is 29.6 %.

TABLE 1. Electrical efficiency of solar cell 2700-07-29 referring to different definitions of area.

Area	Definition	Area in cm²	Efficiency at 334x 1000 W/m²
Designated area	Active cell area incl. grid	1.165	35.2 %
Full cell area	Area within mesa border + bus bars	1.211	33.9 %
Chip area	Area within sawn edges	1.252	33.8 %
Chip area + gaps	Including gaps between cells on module level	1.387	29.6 %

The current distribution (see FIGURE 1) and the difference between contacting a solar cell via the back surface (contact-p-back) and contacting the solar cell via the front as proposed here (contact-p-front) was investigated. Therefore, solar cell 2700-07-19 was mounted to a substrate. All wire bonds are interconnected so the cell could be contacted either way. The sample was measured with the flash simulator. FIGURE 4 shows the IV curves at 100x, 295x, and 490x. The difference in maximum power output at 100x (1000 W/m², 25 °C), between contact-p-front and contact-p-back is ΔP_{MPP}=0.04 W. However, the loss increases with the illumination intensity because of the additional series resistance due to the contact pad (6), semiconductur substrate (2) and rear metallization (3) (compare FIGURE 1). At 490x the power loss is ΔP_{MPP}=1.14 W. For a current I_{MPP} of 7.75 A this corresponds to a lumped series resistance between contact-p-front and contact-p-back of R_{490x}=0.019 Ω.

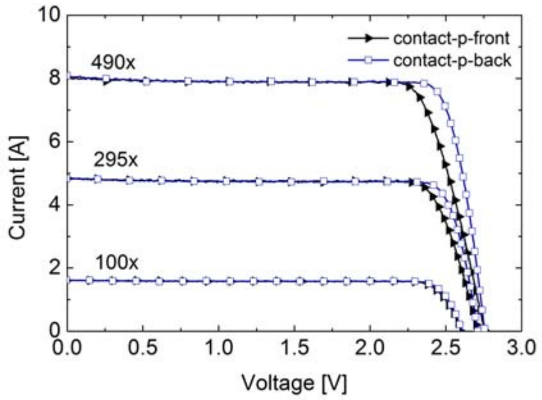

FIGURE 4. IV curves of solar cell 2700-07-19 under concentration. The cell was contacted either via the front surface (contact-p-front) or back surface (contact-p-back).

To determine the current distribution a test structure was used. This test structure consists of contact pads, which are applied to the germanium with the same process technology and material as for contact-p-front. The pads are located at regular intervals next to each other. The resistance between two contact pads is obtained by the measurement of an IV-charactistics, while contacting two contact pads at a time. FIGURE 5 shows the resulting increase in resistance as a function of increasing distance between two pads. This resistance consists of the resistance of the contact pad, contact resistances at the semiconductor interfaces, the resistance of the Ge-substrate and of the metallization. The figure shows a linear increase of the resistance after a minimum distance of two pads. The reason for that is the much lower lateral conductivity of the back metallization compared to the lateral conductivity of the Ge-substrate. Therefore, the current flows nearly vertically from the contact pad through the substrate to the metallization as long as the distance between the pads is much higher than the thickness of the Ge-sustrate. Therefore, the linear fit shown in Figure 5 can be used to separate the contact resistance between the pad and the rear side metallization, i.e. the two metal/semiconductor-interfaces plus the sheet resistance of the germanium from that of the metallization of the solar cells rear side. Thus, the slope of the fit corresponds to the lateral conductivity of the metallization and the y-intercept corresponds with twice the resistance between contact pad and rear side metallization. The method is similar to the TLM-method [7].

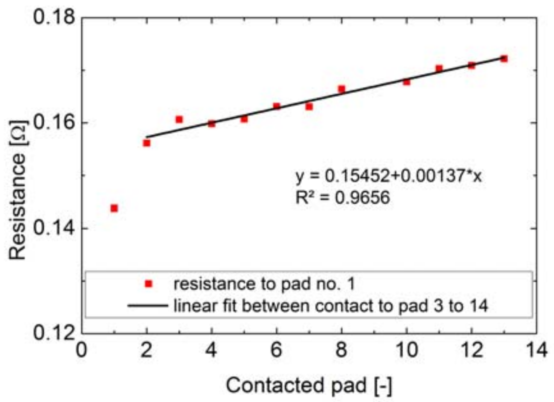

FIGURE 5. The resistance between pad 1 and 2 to 14 was measured for test structures on a germanium solar cell wafer. The measurements were fitted for measurement distance 2 to 13. E.g. measurement distance 2 is the contact between pad 1 and 3.

From FIGURE 5, from the linear fit the resistance $R_{test\ structure}$ between the pad and the back side metallization is determined to be $R_{test\ structure}$=0.07726 Ω. To compare it to the solar cell measurement, the resistance needs to be extrapolated to the same area. Calculated by equation (1) with the area of 21 pads, this yields a resistance $R_{cell\ area}$ of 0.0114 Ω.

$$R_{cell\ area} = R_{teststructure} \cdot \frac{A_{teststructure}}{A_{21\,pads}} \qquad (1)$$

As R_{490x} is larger than $R_{cell\ area}$ it can be concluded that in the solar cell most of the current is conducted directly to the back surface metallization and there distributed. Hence for the solar cell architecture it is important to have the back surface metallization.

In order to further improve the cell performance, the contact resistance can be reduced by increasing the doping level of the germanium substrate (leading to higher conductivity) and/or by optimizing the contact resistance at the metal/semiconductor-interfaces at front and back side to the germanium. This will be investigated in future work.

Performance of Modules

The module base plates without encapsulation were characterized indoors at Fraunhofer ISE. They were measured at the flash simulator under homogeneous illumination with an intensity of 28 W/cm². The IV-curves for four receivers are shown in FIGURE 6. The module UPPSOL-3 has the highest efficiency with 27.4 % referring to the module area (chip area plus gaps).

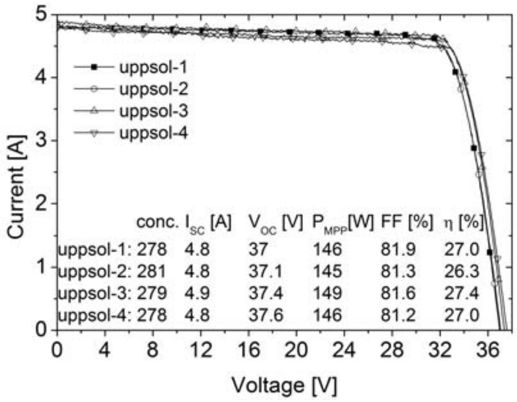

FIGURE 6. IV curves of the bare module base plates under concentrated illumination (280x, 1000 W/m², 25°C) at the flash simulator at Fraunhofer ISE.

The complete modules (see FIGURE 2) were tested outdoors in a dish CPVT system at Tel Aviv University shown in FIGURE 7 and described in [8]. Module UPPSOL-4 achieved a total system efficiency of 63.4 % at DNI of 827 W/m², with a cooling water inlet temperature of 28.6, an outlet temperature of 30.4 °C and a volume flow of 3.07 l/min. An electrical power output of 148.6 W and a solar-to-electricity efficiency of 17.3 % was achieved. With a measured optical efficiency of 76 % and referring to an aperture area of the module of 19.3 cm², the module electrical efficiency was 22.8 % and the fill factor was 0.71 under average incident flux of 33.8 W/cm^2. The outdoor IV-curve of UPPSOL-4 is shown in FIGURE 8.

FIGURE 7. Dish system at Tel Aviv University for electrical and thermal characterization of CPVT receivers.

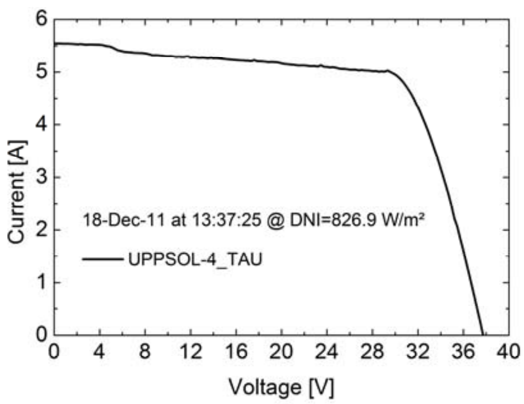

FIGURE 8. IV-curve for UPPSOL-4 measured outdoor in the dish system.

The difference in fill factor between in- and outdoor measurement is mainly due to the difference in illumination profile. The illumination intensity during the outdoor measurement was inhomogeneous over the module area and also over a single solar cell. For the indoor measurement the module was contacted by the metallization of the substrate. For the outdoor measurement, there is an increase in series resistance due to higher losses in the wiring. The voltage is influenced by the illumination intensity and temperature. Finally, the encapsulation and spectrum is different between the measurements.

CONCLUSION

In this paper, a new solar cell architecture for dense array receivers is presented. The solar cells allow series interconnection by metallization pads for n- and p-contact on the front side of the solar cell. The solar cells were successfully manufactured and assembled in dense array receivers that have been tested outdoors in a CPVT system. A total efficiency for a CPVT system of 63.4 % shows that the new cell concept allows high packing factors for solar cells on compact concentrator modules and high efficiencies can be achieved.

ACKNOWLEDGMENTS

The authors would like to thank all colleagues of the “III-V Epitaxy and Solar Cell” department at ISE for their contributions. This work has been supported by the European Commission under the UPP-Sol project (contract number #038386). The authors are responsible for the content of this paper.

REFERENCES

1. H. Helmers, A. Boos, F. Jetter, A. Heimsath, M. Wiesenfarth, A. W. Bett, in *AIP Conference Proceedings 1407*, American Institute of Physics, Melville, N, 2011, pp. 175-179 (2011).
2. W. Guter, J. Schöne, S. P. Philipps, M. Steiner, G. Siefer, A. Wekkeli, E. Welser, E. Oliva, A. W. Bett, and F. Dimroth, in *Appl. Phys. Letters* **94**, 94–96 (2009).
3. R. Loeckenhoff, PCT patent application: WO 2008/107205 (12 September 2008)
4. M. Meusel, R. Adelhelm, F. Dimroth, A. W. Bett and W. Warta, in *Prog. Photovolt: Res. Appl.* **10**, 243–255 (2002).
5. G. Siefer, P. Abbott, C. Baur, T. Schlegl, A.W. Bett, in *Proceedings of the 20th European Photovoltaic Solar Energy Conference,* 495–498 (2005) .
6. M. A. Green, K. Emery, Y. Hishikawa, W. Warta and E. D. Dunlop, in *Prog. Photovolt: Res. Appl.* **20**, 12–20 (2012).
7. H.B. Harrison, G.K. Reves, IEEE electon device letters, vol. 3, pp. 111-113 (1982).
8. A. Kribus, D. Kaftori, G. Mittelman, A. Hirshfeld, Y. Flitsanov, A. Dayan, in *Energy Conversion and Management* **47**, 3582–3590 (2006).