DEVELOPMENT, COST REDUCTION AND CUSTOMIZED DESIGN OF INDUSTRIAL CONCENTRATOR SOLAR CELLS WITH EFFICIENCIES APPROACHING 40% AND ABOVE

W. Guter1, W. Bensch1, R. Kern1, W. Köstler1, M. Meusel1, G. Strobl1, S. van Riesen2, T. Gerstmaier2, A. Gombert2, F. Dimroth3, A.W. Bett3
1AZUR SPACE Solar Power GmbH, Theresienstr. 2, D-74072 Heilbronn, Germany
2Concentrix Solar GmbH, Bötzingen Str. 31, 79111 Freiburg, Germany
3Fraunhofer ISE, Heidenhofstr. 2, 79110 Freiburg, Germany

ABSTRACT
Present developments of the lattice-matched In0.50Ga0.50P/In0.01Ga0.99As/Ge triple-junction solar cell incorporating a high bandgap top cell achieve average efficiencies of up to 40%. Metamorphic cell structures will further raise efficiencies above 40%. Both developments reduce the cost for CPV by increasing the performance of today’s CPV systems. In order to directly decrease cell costs a lean production process with optimized MOVPE cycle time is under investigation. Due to the high amount of cells per wafer, precise cell testing with high throughput is an important issue. For highest performance on the module level, the cell design needs to be adapted to the customers’ needs according to the concentrating ratio, optics used and installation site. This work summarizes recent achievements in CPV development, cost analysis and customizing.

INTRODUCTION
III-V Multi-junction solar cells provide today’s highest photovoltaic conversion efficiencies. Due to their high power to weight ratio these cells have become the dominating device for applications in space. Within the last years, multi-junction cells have also entered the terrestrial market and now are pushing the concept of concentrator photovoltaics (CPV). Recent record cell efficiencies of more than 41% [1-3] show the potential of CPV to restructure the terrestrial PV sector. Together with Fraunhofer ISE, AZUR SPACE has carried out intensive research regarding device architectures, material studies, epitaxial structures and processing. Continuous improvement of production processes at AZUR SPACE has recently led to space solar cells with efficiencies up to 30.6% (AM0) and terrestrial concentrator cells with an average efficiency of 39.5% (500 x AM1.5d).

FROM SPACE TO EARTH – CELL DEVELOPMENT

High-bandgap top cell
In space applications high bandgap In0.50Ga0.50P (1.9 eV) is already used as top cell for In0.50Ga0.50P/In0.01Ga0.99As/Ge triple-junction solar cells. This adapts the triple-junction stack better to the extraterrestrial AM0 spectrum than low bandgap In0.50Ga0.50P (1.8 eV). Current-matching of top and middle cell is optimized and the voltage is increased by about 100 mV. The origin of the different bandgaps for In0.50Ga0.50P is long range ordering on the (111) planes, lowering the bandgap by about 100 meV [4]. This ordering has been suppressed by modified growth conditions and lead to efficiencies of up to 30.6% for AM0 [5]. The terrestrial AM1.5g spectrum, and even more so the AM1.5d spectrum, are red-shifted to the extraterrestrial AM0 spectrum. In order to achieve current-matching for the top and middle cell under AM1.5 the thickness of the top cell has to be increased. This step requires a relatively high minority carrier diffusion length in In0.50Ga0.50P. As the disordered material inherently provides a lower minority carrier lifetime this is a challenge. Fig 1 compares the quantum efficiencies of disordered In0.50Ga0.50P top cells with increasing thickness. The increasing red-response indicates a sufficient material quality for the use in concentrator triple-junction solar cells.

After adapting the cell structure to AM1.5g conditions, these cells intended for the 2009 solar car race reached an efficiency of 34.1% under one sun [5]. AZUR SPACE’s 3C40 structure adapted to AM1.5d with a target efficiency of about 40% makes as well use of this high-bandgap top cell with higher voltage. Fig 2 shows that average wafer efficiencies of 39.5% have now been achieved with this design.
Metamorphic structures

In order to achieve efficiencies above 40% metamorphic cell structures developed at Fraunhofer ISE [6] are currently transferred to AZUR SPACE. These triple-junction solar cells feature an almost optimal bandgap combination of 0.7/1.2/1.7 eV for AM1.5d by the use of In$_{0.65}$Ga$_{0.35}$P and In$_{0.17}$Ga$_{0.83}$As on an activated Ge substrate and have already achieved efficiencies of up to 41.1% [1]. The top and the middle cell are grown lattice-matched to each other, but the lattice-mismatch of 1.1% to the Ge substrate has to be overcome by a metamorphic In$_{x}$Ga$_{1-x}$As buffer (Fig 4). This buffer shifts the lattice-constant to higher values, and relaxes strain due to misfit by the generation of misfit dislocations. A relaxation of about 60% for the compressively strained structure is achieved.

Relaxation values of (99 ± 1)% have been calculated from the measurements of Fig 5. The oversooting is a very effective tool to adjust relaxation. Even values above 100% (tensile strain) have been reached. Another important requirement on the buffer is to prevent the generated dislocations from penetrating into the photoactive layers of the structure. Photoluminescence (PL) measurements of In$_{0.17}$Ga$_{0.83}$As/In$_{0.65}$Ga$_{0.35}$P double hetero structures grown on the metamorphic buffers already provide useful information to compare the material quality of layers grown on different buffers (Fig 6). The exact value for the defect density is obtained by selective etching with KOH and counting the etch-pit density (EPD). Fig 6 shows that PL and EPD measurements correlate well. High defect density results in low PL intensity. The optimized buffer structures provide dislocation densities below 3 x 10$^5$ cm$^{-2}$. Varying the buffer parameters, such as number of steps or step thickness easily increases the EPD above 10$^6$ cm$^{-2}$.

These results have been used to adapt the materials from the lattice-matched triple-junction cell design from AZUR SPACE to the metamorphic solar cell structure 3C40+ with target efficiencies above 40%.
COST ANALYSIS

One approach to cut system costs is to increase the cell efficiency. By constant improvement of the cell structures and the adaptation of the cell to our customers’ systems we meet this requirement. In order to reduce cell production costs, AZUR SPACE has developed a strategy with main focus on substrate cost, cycle time, uptime and cell testing (Fig. 7). Since the substrate causes about one quarter of the costs for the solar cell wafer, it is important to work with substrate suppliers on the optimization and qualification of their materials. An important goal is also to switch to 6-inch substrate technology which will be a main driver in cost reduction. The MOVPE cycle time has been reduced by using high growth rates, streamlining the cell structure and automated loading of substrates. These developments directly reduce cell costs and have been implemented into the 3C38 cell structure, providing an average efficiency of 38% for small cell sizes. Concerning production performance and uptime, different MOVPE reactor types are being investigated.

With thousands of cells on one CPV wafer the accurate and cost effective acceptance testing of all these cells becomes a non negligible cost factor. AZUR SPACE successfully installed automated flashing units with adjustable spectral conditions for IV characterization at up to 2000x and testing speeds between 0.6 and 1.7s per cell, both depending on cell size (Fig 8).

Figure 7 Distribution of costs for a solar cell wafer between substrate, epitaxy and cell processing. The focus for possible savings lies on the wafer cost, MOVPE cycle time and cell testing.

Figure 8 Comparison of the energy output from 3C35 type triple-junction solar cells in CX-75 FLATCON® modules from Concentrix Solar tested from 8.07.-29.07.2009 in Sevilla (Spain). The error bars result from the standard deviation over several modules.

CUSTOMIZED DESIGN

The efficiency of CPV structures is difficult to define as it depends on the customized cell designs which vary strongly regarding cell size, grid design and concentrating optics. Typically, higher efficiencies are achieved on small cells (< 5 x 5 mm²) compared to larger ones (about 1 cm²) because of the shorter current paths to the busbar. The optimal grid design strongly depends on the illumination profile of the concentrating optics. AZUR SPACE has been developing different frontside grid layouts and adapts the grid design to the needs of the customers. Fig 8 shows such a development for Concentrix Solar with different grid types on 3C35 concentrator cells. The cells have been mounted in CX-75 FLATCON® modules on tracking units and tested outdoors in Sevilla (Spain) on Concentrix’s field testing site for about three weeks during July 2009. The modules use a silicone on glass type Fresnel lens which leads to a Gaussian illumination profile. Grid type A clearly outperforms the other types tested and hence is best suited for the optics used.

It is furthermore advantageous to adapt the structure of the multi-junction solar cell itself to the spectrum received on the cell in the system. The incident spectrum may differ from the standard AM1.5d spectrum, depending on the location [8]. Concentrating optics may additionally alter the spectrum received on cell level considerably. This can lead to bad current-match of the sub cells and hence reduce cell efficiency. By adapting the absorption of the top and middle cell in a triple-junction structure AZUR SPACE has customized her CPV cells according to the requirements of the concentrating systems. Recent studies in cooperation with Concentrix Solar used 3C38 type concentrator cells with different top cell thicknesses to vary the current-matching between top and middle cell. The reference cell was adapted to AM1.5d, the other cells for an increased air mass (AM) larger than 1.5. The cells have been mounted in FLATCON® modules from Concentrix and tested on tracking units in Sevilla (Spain).
since May 2010. A typical day in the testing period was blue sky with a DNI rising to about 800-1000 W/m² at noon (Fig 9). The spectrum is blue-shifted to AM1.5d (AM < 1.5) during the day and red-shifted (AM > 1.5) in the morning and evening.

![Figure 9 DNI of the solar spectrum received on May 5 and May 23 (2010) at the field testing site from Concentrix solar in Sevilla (Spain).](image)

Fig 10 shows the DNI-scaled \( I_{SC} \) for two modules consisting of cells with different current-matching during May 23. Both modules are limited by the top cell in the morning and in the evening. Because the top cell current of the cells adapted to an air mass larger than 1.5 is enhanced compared to the middle cell current, this module shows a better performance than the module with cells adapted to AM1.5d during that phase. The peak \( I_{SC} \) is reached when the spectral conditions on cell level match the spectrum the cell was designed for. The cells designed for AM > 1.5 show two very pronounced peaks in Fig 10, whereas the cells designed for AM1.5d show a plateau in \( I_{SC} \) at noon. This dip arises from the current limitation by the middle cell under a blue-rich solar spectrum.

![Figure 10 \( I_{SC} \) scaled with DNI (May 23 in Fig 9) of one module with cells adapted to AM1.5d and one module adapted to AM > 1.5.](image)

Of course \( I_{SC} \) of a module also increases with DNI, usually peaking at noon (Fig 9). Hence the spectral adjustment of the cells can be used to enhance the energy output at a certain time of the day. This gives an additional degree of freedom to maximize or to level the energy output of a module over a day, month or year.

For the month of May the module with cells adapted for an air mass larger than 1.5 shows a 3% higher cumulative energy output than the module with cells adapted to AM1.5d. Hence, the average spectrum received on cell level in May was red-shifted to AM1.5d. Since the spectrum varies stronger during a day than during the year, the yearly cumulative energy output can also be calculated from the measurements performed. Fig 11 shows the scaled monthly efficiency of the two different modules. During summer (low AM) the difference between the modules is about 3%, during winter (high AM) the difference rises above 5%. A DNI-weighted calculation over one year shows that the module with cells adapted to a larger air mass outperforms the module with cells adapted to AM1.5d by about 4%.

These studies show that it is important to optimize the frontside grid for the illumination intensity and profile. It is also beneficial to adapt the cell design to the actual spectrum received.

![Figure 11 Relative efficiency of the module with cells adapted to AM1.5d throughout the years 2008 to 2010 calculated from the measurements during May 2010 and from spectral data measured since 2008. The module with cells adapted to AM > 1.5 was taken as reference.](image)

CONCLUSION

This work summarizes the present achievements from AZUR SPACE regarding cell development, cost analysis and customized design. The diffusion length of disordered \( In_{0.50}Ga_{0.50}P \) has been improved in order to implement this high bandgap material not only in our space products, but also in triple-junction concentrator solar cells. The average wafer efficiency of our 3C40 CPV cell design has been increased to 39.5% ± 0.5% under 500 suns. In order to reach efficiencies above 40%, the metamorphic triple-
junction solar cell developed at Fraunhofer ISE is being transferred to AZUR SPACE. A detailed study of the required metamorphic In\(\text{Ga}_x\text{As}\), buffers led to structures with dislocation densities below \(3 \times 10^{5} \text{cm}^{-2}\) and relaxation values of \((99 \pm 1)\%\). Besides an increase in cell efficiency, cost reduction strategies are driven by decreasing wafer cost, reducing cycle time and establishing high throughput cell testing facilities. From a CPV system perspective it is also important to customize the solar cell to the concentrating modules in order to further enhance efficiencies. An outdoor study with FLATCON® modules from Concentrix Solar and concentrator cells from AZUR SPACE adapted to different spectral conditions shows that the highest energy output per year is achieved with cells adapted to higher air masses than AM1.5d.

ACKNOWLEDGEMENT

This work was supported in part by the Ministry for the Environment, Nature Conservation and Reactor Safety (BMU) under the project WiFerKon (contract number 0325125). The authors would like to thank all the coworkers at Concentrix Solar, Fraunhofer ISE and AZUR SPACE for their support.

REFERENCES


