DEVELOPMENT AND PRODUCTION OF EUROPEAN III-V MULTI-JUNCTION SOLAR CELLS

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ABSTRACT: GaInP/GaAs/Ge triple-junction cells became commercially available in the 90ies by US manufacturers. Today these triple cells are the most common power generator in space due to their high efficiency and radiation hardness. In Europe, AZUR SPACE and the Fraunhofer ISE have teamed up in the development and industrialisation of III-V multi-junction solar cells. The 2nd generation of a European III-V multi-junction cell, the AZUR 3G-ID2* space cell, has now become commercially available with a state-of-the-art BOL efficiency of 28% (AM0, 1367 W/m², T=28°C) and has a very radiation hard design with a remaining factor of 88% (10¹⁵ MeV electrons/cm²) resulting in an excellent EOL efficiency of 24.6%. The next generation space cell will also be based on the lattice-matched GaInP/GaInAs/Ge triple cell concept. For future generations of space cells various concepts are under investigation, such as 4J, 5J and 6J cells as well as cell concepts based on metamorphic growth. Additionally a lattice-matched GaInP/GaInAs/Ge triple-junction concentrator cell concept. For future generations of III-V multi-junction concentrator cells is emerging. AZUR SPACE is presently offering a 35% efficient lattice-matched triple-junction concentrator cell (3C-35%). This rising interest in concentrators promises exciting times for III-V and a renewed synergy between space and terrestrial.

Keywords: Multijunction Solar Cell, Space Cells, Concentrator Cells

1 INTRODUCTION

In the beginning of modern photovoltaics in the 50ies, the first market for solar cells existed in space. While different solar cell concepts and materials have always been investigated for space application (e.g. thin film), it was Si that provided power for space over many decades. However, in the middle of the 50ies GaAs based multi-junction solar cells came into focus for space application due to their high efficiency and radiation hardness.

The concept of multi-junction in combination with III-V semiconductors with a variety of bandgaps and lattice constants had been well known since the 50ies but lay dormant for two decades. The renewed interest was fostered by several technological breakthroughs. One was the development of metal-organic vapour phase epitaxy (MOVPE) reactors during the 80ies. While MOVPE technology has become the growth method of choice due to its aptitude for multi-layer structures of different materials with high quality, large area and high throughput. Another breakthrough was certainly the use of GaInP as top cell material [2] instead of AlGaAs, which suffered from low diffusion length due to the affinity of aluminium for oxygen. These technological breakthroughs led to the development of the GaInP/GaAs/Ge triple-junction cell, which became commercially available in the 90ies by US manufacturers. Since cost is less of a “show stopper” in space application, these triple-junction cells are the most common power generator in space today due to their high efficiency and radiation hardness. Technology has continuously been improved and average lot efficiencies above 28% (AM0) have been reached as well as high remaining factors of 86% after typical irradiation testing with 10¹⁵ cm² MeV electrons [3,4].

For terrestrial application, GaInP/GaAs/Ge triple solar cells can only economically be used in concentrator systems. However, their high efficiency makes them highly attractive for this approach. In fact, concentrator photovoltaics is presently drawing more and more attention fostered by the increasing terrestrial market and the present shortage in wafer silicon as well as by the prospect of using III-V multi-junction concentrator cells, which have now become commercially available with average efficiencies of about 35% (AM1.5d low AOD, C ≈500) and best cells only recently surpassing the efficiency threshold of 40% [5].

In Europe, AZUR SPACE Solar Power GmbH and the Fraunhofer Institute for Solar Energy Systems (ISE) have teamed up in the development and industrialisation of III-V multi-junction solar cells. Development projects are financially supported by the European Space Agency (ESA/ESTEC) and the German Aerospace Center (DLR) with respect to space application and by the EU with respect to terrestrial concentrators (“Full spectrum”). This paper gives an overview of the development and production status of European III-V multi-junction solar cells.

2 SPACE CELLS

Space application has provided a small but relatively stable and slowly growing market for III-V multi-junction cells over the last years. The civil space market is in the order of about 500.000 solar cells corresponding to 0.5 MW and about 100.000.000 € per year. The most important parameter of a space solar cell is the end-of-life (EOL) efficiency after typical missions of 15 years in orbit. Due to the high launch costs, also the weight of the
solar cell plays an important role.

2.1 Production – AZUR 3G-ID2* 28%-class

As described earlier [6], the cooperation between AZUR SPACE and Fraunhofer ISE has led to the development of the 2nd generation of European space multi-junction cells, the “3G-ID2* 28%-class”, which has been qualified in 2006 on bare cell, SCA, coupon and panel level [7]. It is equipped with an integral bypass diode (ID2*) and shows a state-of-the-art beginning-of-life (BOL) efficiency of 28% (AM0, 1367 W/m², T=28°C). Furthermore, the cell is very radiation hard with a remaining factor of 88% after irradiation with 10¹⁵ 1MeV electrons/cm² resulting in an excellent end-of-life (EOL) efficiency of 24.6% (Table I). Figure 1 shows the external quantum efficiency for BOL and EOL. Since the GaInAs middle cell shows the strongest degradation, the triple cell is designed to be top cell limited at BOL and current-matched at EOL in order to reach the maximum EOL efficiency. The complete degradation curve for irradiation with 1MeV electrons is plotted in Figure 2.

Finally Figure 3 shows production data of 32,000 “3G-ID2* 28%-class” cells.

![Figure 2: Degradation curve of the AZUR 3G-ID2* 28%-class for irradiation with 1MeV electrons.](image1)

![Figure 3: Distribution of I_{OC} (V_{OC}=2.3V) of 32,000 “3G-ID2* 28%-class” cells.](image2)

<table>
<thead>
<tr>
<th>$\Phi_{1MeV}$ [1MeV e⁻/cm²]</th>
<th>I_{SC} [mA]</th>
<th>V_{OC} [V]</th>
<th>I_{MP} [mA]</th>
<th>V_{MP} [V]</th>
<th>$\eta$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>BOL</td>
<td>506</td>
<td>2.667</td>
<td>487</td>
<td>2.371</td>
<td>28.0</td>
</tr>
<tr>
<td>5x10¹⁴</td>
<td>501</td>
<td>2.534</td>
<td>472</td>
<td>2.229</td>
<td>25.8</td>
</tr>
<tr>
<td>RF_{E14}</td>
<td>0.99</td>
<td>0.95</td>
<td>0.97</td>
<td>0.94</td>
<td>0.92</td>
</tr>
<tr>
<td>1x10¹⁵</td>
<td>486</td>
<td>2.480</td>
<td>458</td>
<td>2.205</td>
<td>24.6</td>
</tr>
<tr>
<td>RF_{E15}</td>
<td>0.96</td>
<td>0.93</td>
<td>0.94</td>
<td>0.93</td>
<td>0.88</td>
</tr>
</tbody>
</table>

Table I: Qualification data of the “3G-ID2* 28%-class” space solar cell (A=30.18 cm²). The table shows initial (beginning-of-life, BOL) solar cell parameters (AM0, 1367 W/m², T=28°C) as well as parameters after irradiation with 5x10¹⁴ and 1x10¹⁵ 1 MeV electrons per cm² and the corresponding remaining factors RF.

![Figure 1: External quantum efficiency (EQE) of the AZUR 3G-ID2* 28%-class lattice-matched GaInP/GaInAs/Ge triple cell before (BOL) and after irradiation with 10¹⁵ 1MeV electrons/cm² (EOL).](image3)

2.2 Development of space cells

The next generation European space solar cell, which is already under development, will also be a lattice-matched GaInP/GaInAs/Ge triple-junction cell. The BOL efficiency will be pushed as close as possible towards 30%, which is thought to be the practical limit for this lattice-matched approach in terms of production average. Additionally, the cell will also be available with reduced thickness and weight. One approach is to go towards 80 to 100 µm thick cells (Figure 4) and high efficiencies greater 29% have already been reached also for cells on thin substrates (Table II). Another approach under investigation is the use of 20µm thin cells transferred to the cover glass (SCA). Furthermore, a future trend is to double cell size (Figure 5).

![Figure 4: Development of space cells](image4)

<table>
<thead>
<tr>
<th>substrate</th>
<th>I_{SC} [mA]</th>
<th>V_{OC} [V]</th>
<th>I_{MP} [mA]</th>
<th>V_{MP} [V]</th>
<th>FF [%]</th>
<th>$\eta$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>150 µm</td>
<td>522</td>
<td>2.733</td>
<td>499</td>
<td>2.435</td>
<td>86</td>
<td>29.4</td>
</tr>
<tr>
<td>100 µm</td>
<td>526</td>
<td>2.719</td>
<td>502</td>
<td>2.391</td>
<td>83.8</td>
<td>29.1</td>
</tr>
</tbody>
</table>

Table II: Best cell BOL parameters (AM0, 1367 W/m², T=25°C) of the next generation cell presently under development at AZUR SPACE. Data for growth on 150 µm and on 100 µm thin Ge substrates is given.
Figure 4: Space solar cell (A=30.18 cm\(^2\)) on 100 µm thin Ge substrate weighing 1.8 g. The weight reduction compared to 150 µm Ge substrates is 28%.

Figure 5: Large area triple-junction space solar cell (8cm x 8cm with cropped corners).

Another development topic is the study of lattice-matched triple cells under low-intensity-low-temperature (LILT) conditions in a severe radiation environment. An important task is the simulation of these operating conditions within the ISE Calibration Laboratory (ISE CalLab) and the adaptation of corresponding cell characterisation techniques (Figure 6, Table III).

Table III: IV-characteristics of triple-junction space solar cells (A=4 cm\(^2\)) under low intensity 3.7% AM0 (51 W/m\(^2\)) conditions and varying temperature.

The question exists, what type of III-V multi-junction cell will be the future generation after the lattice-matched GaInP/GaInAs/Ge triple-junction cell. Already in 1998 it was suggested to add a 4\(^{th}\) junction between the GaAs and Ge with a bandgap of about 1.0 to 1.1 eV [8, 9]. Among other materials GaInNAs, which can be grown lattice-matched to Ge, has been studied most for this purpose. However, up to now the material has shown many problems and diffusion length has been too low to be used in a quadruple-junction (4J) cell. Study of GaInNAs continues and in Europe the University of Marburg has specialised in this field [10].

In the meantime alternative approaches are investigated, such as the concept of quintuple- (5J) and sextuple-junction (6J) cells (Figure 7). Starting from the triple cell, the 5J cell is achieved by splitting each of the top two junctions of the triple cell into two. Thus, the 5J cell has half the current of a triple-junction cell. Aluminium is added to the first (AlGaInP) and third junction (AlGaInAs) to achieve a higher bandgap and cell voltage. The 5J cell has twice the voltage of a triple cell [10]. While the BOL efficiency of such a lattice-matched 5J cell will be about the same as for triple cells, the thinner absorber layers of the 5J cell promise higher radiation hardness. Due to the low current of the 5J cell, a GaInNAs subcell can here more easily be introduced than in a triple cell forming a 6J cell with higher BOL and EOL efficiency.

Figure 6: IV-characteristics of triple-junction space solar cells (A=4 cm\(^2\)) under low intensity 3.7% AM0 (51 W/m\(^2\)) conditions and varying temperature. Open circuit voltage and short circuit current change as expected for the temperature dependence of the bandgaps.

To correctly measure the efficiency of 5J and 6J cells, a 6-source solar simulator is presently developed at Fraunhofer ISE. Therefore, investigation of experimental 5J cells is up to now limited to analysis of the current by external quantum efficiency and to measurement of the
open-circuit voltage, which is hardly dependant on the simulator spectrum. Figure 8 shows the external quantum efficiency (EQE) of a 5J solar cell manufactured at Fraunhofer ISE for BOL and EOL [11]. Hardly any degradation can be observed. Further on, the open-circuit voltage of about 5.2 V is also very radiation hard with a remaining factor of 95%. From this data it can be concluded, that 5J cells will reach an efficiency remaining factor well above 90% and therefore significantly above that of triple-junction solar cells.

Figure 8: External quantum efficiency (EQE) of a 5J cell epitaxially grown at Fraunhofer ISE at BOL and after irradiation with $10^{15}$ cm$^{-2}$ 1 MeV electrons (EOL).

Besides going towards more junctions there also exists the approach of using materials with more suitable bandgaps by lattice-mismatched and metamorphic growth, respectively, (see section 3.2). Especially feasible for space is the concept of inverted metamorphic growth of GaInP/GaAs/GaInAs triple cells, which is based on an epitaxial lift-off technique and results in a flexible light weight solar cell (see e.g. [12]). Additionally, quantum dot or quantum well structures could play an important role in future III-V multi-junction solar cells.

3 TERRESTRIAL CONCENTRATOR CELLS

Due to the high cost of III-V multi-junction solar cells, they can economically be used for terrestrial application only in concentrator systems. However, best cell efficiency of triple cell concentrators has increased over the last 7 years from 32% to above 40% [5], which makes them highly attractive for this approach and has contributed to the renewed interest in concentrator systems. A terrestrial market for III-V multi-junction concentrators is presently emerging, which might match the space market within the next few years not only in terms of W but also in terms of wafers and €. A significant difference of epitaxial structures for terrestrial application compared to space structures is the thickness of the top cell. A thicker top cell has to be used for terrestrial cells in order to current-match the top and middle cell current for the terrestrial direct spectrum. Additionally, the tunnel diodes have to be optimised for the high current densities in concentrator cells in the order of 10 A/cm$^2$.

3.1 Production – the 3C-35%
Fraunhofer ISE has a long history in III-V concentrator cell development. Over the last years know-how has been transferred to AZUR SPACE, which is presently going into the terrestrial market with a 35% efficient lattice-matched triple-junction concentrator cell, the “3C-35%”. Present availability of this cell is limited, but production volume will greatly increase in 2008. Figure 9 shows the average efficiency versus concentration for the example of a 3C-35% concentrator cell with an active area of 0.03 cm$^2$ and optimised for a concentration of 380x. The efficiency is slightly above 35% for a wide concentration range. The exact shape of the curve will differ from customer to customer, as different concentrator systems require different size of cells with grids optimised for different concentrations and intensity profiles. Concentrator cells are therefore custom-designed.

Figure 9: Average efficiency versus concentration for a 3C-35% concentrator cell with an active area of 0.03 cm$^2$ and optimised for a concentration of 380x AM1.5d (low AOD, 1000W/m$^2$).

Figure 10: 4” Wafer with close to 1000 concentrator cells. The wafer has been mounted on stretch tape and diced. The cells are now ready for pick-and-place.

3.2 Development
In parallel, lattice-mismatched (metamorphic) triple cells are developed at Fraunhofer ISE, which have the potential for higher efficiencies than lattice-matched triple cells due to the choice of more suitable bandgaps.
Efficiencies above 35% have also been reached for these metamorphic Ga0.35In0.65P/Ga0.83In0.17As/Ge triple cells (Figure 11).

The concept of metamorphic growth is to change from the lattice constant of the substrate to a new lattice-constant by use of a graded buffer. The goal is to achieve relaxation of the buffer layers in order to avoid threading dislocations in the upper active layers (Figure 12). Metamorphic triple cells at Fraunhofer ISE show only little residual strain and some bowing depending on the wafer thickness. There has existed the question, whether this residual strain could lead to cracking of cells or degradation of electrical performance. Figure 13 shows the result of a thermal cycling test performed on these metamorphic triple cells. No mechanical cracking and no significant electrical degradation could be observed.

On the contrary, for the case of 150µm thin wafers electrical performance was improved by thermal cycling. This indicates an annealing effect, driving threading dislocations out of the active layers of the solar cell structure.

3.3 Further challenges in terrestrial application

For the successful terrestrial application of III-V multi-junction concentrator cells several topics have to be considered. Firstly, lessons learned from space, such that the application of a by-pass function is an indispensable requirement for III-V multi-junction solar cells, are of course equally true for terrestrial application.

Another topic will be accurate cell characterisation. Already the 1-sun characterisation of multi-junction solar cells for space takes a lot of effort, since multi-source simulators have to be used to accurately simulate the reference spectrum in regard to each subcell. Additionally, a whole set of calibrated reference cells is used, one spectrally matched single-junction (“component”) cell for each of the subcells of the multi-junction cell. For the characterisation of concentrator cells high intensity is required and typically pulsed (flash) solar simulators are used. Due to the large amount of cells to be measured, throughput and cost of the measurement setup are an important issue.

Finally, reliability will be of utmost importance for the success of this technology. For space application various tests are performed in accordance with the ECSS (European Cooperation for Space Standardisation). However, new tests need to be defined for terrestrial application taking into account the different concentrator systems.

4 SUMMARY

The 2nd generation of a European III-V multi-junction cell, the AZUR 3G-ID2* 28% class, has been qualified and is now in production for projects such as Galileosat and Alphabus. It is equipped with an integral bypass diode (ID2*) and shows a state-of-the-art BOL efficiency of 28% (AM0, 1367 W/m², T=28°C). Furthermore, the cell is very radiation hard with a remaining factor of 88% (10¹⁰ 1MeV electrons/cm²) resulting in an excellent EOL
efficiency of 24.6%. The next generation 30%-class cell will also be based on the lattice-matched GaInP/GaInAs/Ge triple cell concept. For a future generation of space cells various concepts are under investigation, such as 4J, 5J and 6J cells as well as cell concepts based on metamorphic growth.

Additionally a terrestrial market for III-V multi-junction concentrator cells is emerging. AZUR SPACE is presently offering a 35% efficient lattice-matched triple-junction concentrator cell (3C-35%). This rising interest in concentrators promises exciting times for III-V and a renewed synergy between space and terrestrial.

5 ACKNOWLEDGEMENTS

We are indebted to the epitaxial, processing and characterisation staff at Fraunhofer ISE and AZUR SPACE. The authors would like to thank Dr. Rasch, managing director of AZUR SPACE for his continuous support of this program. This work has been funded by ESA, DLR and EU contracts.

6 REFERENCES