EVOLUTION OF FULLY EUROPEAN TRIPLE GAAS SOLAR CELL


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ABSTRACT

The first generation of fully European triple junction solar cells is of 27% class (RWE3G-27%class) with an area of 8cmx4cm minus two cropped corners and an ID2 integral by-pass diode concept in which the adjacent cell is protected. An additional by-pass diode concept for extreme temperature applications is available by using a new structure of external Si diode. It is planned to use this triple junction GaAs cell (RWE3G-27%class) for several European satellite projects such as Aeolus, Pleiades, Herschel (one section) and Proba 2. The paper reports the production experience and the output with this 27% class triple cell in the framework of these projects.

The second generation is of 28% class (RWE3G-28%class), with the same configuration and area. This cell has an improved EOL performance of \( R(P_{\text{max}}) \geq 0.85 \). Details on qualification testing and first production experience for this cell type will be presented.

Finally the current development results for the third generation - 29% to 30% class cell - with further improved EOL performance of \( R(P_{\text{max}}) = 0.88 \) and monolithic by-pass diode will be reported together with a road map of further potential development using cell structures made from III-V material system.

1. INTRODUCTION

High efficiency solar cells will be the preferred photovoltaic component on future spacecrafts. Therefore the availability of such cells in Europe is of vital importance for the European Space Industry. In agreement with ESA and with Deutsches Zentrum fuer Luft- und Raumfahrt (DLR) of Germany a long term road map was set up by RWE Solar Power GmbH and their European partners FhG-ISE and Umicore reflecting the development targets required to keep pace with the main competitors in USA (Fig. 1). The basic development activities were started in 2001. During the first two phases first generation triple junction cells of the 27%-range were successfully developed (RWE3G-27%class). In the third phase starting on April 1st, 2003, and ending on October 31st, 2004, the road map objectives could be fully met by the development of a second generation triple junction (TJ) solar cells of the 28% class with AM0-efficiencies up to 29% (RWE3G-28%class). In parallel basic developments for the next generation solar cells with alternate materials and 5 junctions continue to be made. These next generation solar cells with efficiencies close to 30% and an EOL remaining factor of more than 0.88 are currently under development.

Fig. 1 Road Map for the development of multi-junction cells

2. FUNDAMENTALS

The work on the step by step development of triple-junction solar cells was carried out by ISE and RWE Space both using AIX 2600G3 reactors with a capacity of 8x100mm-wafers. The Ge wafers were provided by Umicore on customer’s request with variation of resistivity, off-angle, thickness and diameter.

In order to optimize the substrate, the epitaxial growth process and the cell structure extensive material characterization was performed on test structures such as:
- measurement of layer thickness by selective etching and by reflectance anisotropy spectroscopy (RAS)
- (spatially resolved) high-resolution X-ray diffractometry (XRD)
- electrochemical capacitance-voltage profiling (ECV-profiling)
- spatially resolved photoluminescence spectroscopy at room temperature (PL mapping)
- time resolved photoluminescence at room temperature (TRPL)
- (spatially resolved) Hall van-der-Pauw measurement (Hall)
- secondary ion mass spectroscopy (SIMS).

The complete triple cells and subcells were characterized by the following tests:
- IV-characterization by triple source sun simulator
- quantum efficiency
- spectrometric characterization

3. FIRST GENERATION TJ-CELLS

In 2003 RWE/ISE succeeded in realizing the first generation of European n-on-p Ga_{0.51}In_{0.49}P/Ga_{1-x}In_{x}As/Ge triple-junction solar cells (RWE3G-27% class) reproducibly with a minimum average efficiency of 26.8% (Tab. 1). The degradation behaviour due to 1MeV-electron irradiation was comparable to that of US competitors at lower fluences. For typical GEO EOL fluences of 1E+15 equivalent 1MeV-electrons/cm² the state of the art remaining factor of 0.85 was not yet achieved. But the cell was suitable without any disadvantages for application in missions subjected to moderate fluences like ADM-Aeolus (Fig. 2), Pleiades (Fig. 3), Herschel-Planck (Fig. 4) and Proba-2 (Fig. 5).

Tab. 1 BOL electrical data of RWE first generation TJ solar cells (RWE3G-27% class)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol/Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short Circuit Current</td>
<td>$J_{sc}$ [mA/cm²]</td>
<td>16.5</td>
</tr>
<tr>
<td>Current at $P_{mp}$</td>
<td>$J_{mp}$ [mA/cm²]</td>
<td>15.95</td>
</tr>
<tr>
<td>Voltage at $P_{mp}$</td>
<td>$V_{mp}$ [mV]</td>
<td>2.275</td>
</tr>
<tr>
<td>Open Circuit Voltage</td>
<td>$V_{oc}$ [mV]</td>
<td>2.575</td>
</tr>
<tr>
<td>Maximum Power</td>
<td>$P_{mp}$ [mW/cm²]</td>
<td>36.3</td>
</tr>
<tr>
<td>AM0-efficiency</td>
<td>$\eta$ [%]</td>
<td>26.8</td>
</tr>
</tbody>
</table>
The cell qualification per ESA ECSS-E-20-08 Draft A [1] has been successfully performed by Spasolab and RWE Space on RWE 3G cells of 27% class [2], reference missions were ADM-Aeolus and Herschel/Planck. The qualification testing of both an integrated diode (ID2) and for long duration high temperature applications such as Herschel/Planck an external Si-diode are expected to be close to completion at the time of the conference.

4. SECOND GENERATION CELLS

Fundamental studies on test structures as well as epitaxy of single and triple-junction cells have continuously been performed by ISE. The tunnel diodes could be improved with regard to the voltage drop across the tunnel junction yielding an increase in $V_{mp}$, FF and efficiency in consequence. Also the growth of the nucleation layer could be optimized with regard to the quality of the layers grown on top and to the emitter formation in the Ge bottom cell. Improvement of the recombination velocity at the GaInP/Ga(In)As interface could be achieved by choice of suitable growth conditions and optimization of the gas switching sequence. Increasing the top cell bandgap from 1.8eV to 1.87eV improved the efficiency of the triple junction cells by more than 2%.

The findings of the basic studies performed at ISE have been successfully transferred to RWE’s Aixtron 2600 G3 reactors followed by a development phase at RWE Space including consideration of criteria such as reliable process control, process stability, product homogeneity and reproducibility for large scale production. In addition the introduction of a monolithic by-pass diode had to be taken into account. More than 200 TJ-solar cells of the 28% efficiency class with an area of 30.2 cm$^2$ were manufactured. The average efficiency was 27.6% and the maximum was 28.8%. The cells were equipped with a monolithic diode (see chapter 6) using RWE Space patents.

At present the second generation 28%-class TJ solar cells (RWE3G-28%-class) is undergoing a stabilization process improving yield, quality and costs. This cell type is characterized by the electrical data of Tab. 2. The EOL performance is on a par with the US competitors and qualification is in progress to ensure availability for European projects such as Alphabus and Galileosat.

The development activities were accompanied by a matching analysis for the triple junction cells and a round robin test campaign among the leading space companies in Europe.

5. ACTUAL DEVELOPMENT STATUS

The actual developments comprise further increase of the BOL-performance towards the 30% threshold and an improvement of the EOL-remaining factor over 0.85.

By optimization of the antireflective dielectric layers, including the internal structure of the solar cell to account for the interference pattern, and by a revision of the design of the grid fingers the latest developments yielded AM0 efficiencies of more than 29% for 30.2cm$^2$ GaInP/GaInAs/Ge triple-junction solar cell at RWE Space (Fig. 6).

![Fig. 6 AM0 IV characteristics of a 30.2cm$^2$ third generation triple-junction solar cell (RWE 3G-29%-class) at 25°C](image)

Tab. 2 BOL and EOL (1E+15 1MeV-\textit{e}/cm$^2$) electrical data of RWE second generation TJ solar cells (RWE3G-28%-class) at AM0, 28°C

<table>
<thead>
<tr>
<th>Parameter</th>
<th>BOL</th>
<th>EOL</th>
<th>R</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J_{sc}$ [mA/cm$^2$]</td>
<td>16.6</td>
<td>15.9</td>
<td>0.96</td>
</tr>
<tr>
<td>$V_{oc}$ [mV]</td>
<td>2.680</td>
<td>2.495</td>
<td>0.93</td>
</tr>
<tr>
<td>$J_{mp}$ [mA/cm$^2$]</td>
<td>16.0</td>
<td>15.3</td>
<td>0.96</td>
</tr>
<tr>
<td>$V_{mp}$ [mV]</td>
<td>2.372</td>
<td>2.185</td>
<td>0.92</td>
</tr>
<tr>
<td>$P_{mp}$ [mW/cm$^2$]</td>
<td>37.9</td>
<td>33.4</td>
<td>0.88</td>
</tr>
<tr>
<td>$\eta$ [%]</td>
<td>27.8</td>
<td>24.4</td>
<td>0.88</td>
</tr>
</tbody>
</table>

Different attempts have been made to minimize the sensitivity of the cell, and especially the GaInAs subcell, with regard to the impact of charged particles of the space environment. At Fraunhofer ISE a detailed simulation of the optimum triple-junction solar cell structure after irradiation with 1 MeV electrons has been performed taking into consideration variation of dopant densities and profiles as well as the thickness of the active GaInAs layers. The result is an improvement of the remaining factor from 88% to 96% for the short circuit current $J_{sc}$ and from 81% to 88% for the power after irradiation with 1E+15 1MeV-electrons/cm$^2$. This
is an excellent value for a lattice matched GaInP/GaInAs/Ge triple-junction solar cell. Further improvement in BOL and EOL cell efficiency might be expected by metamorphic growth of GaInAs with lower bandgap material. More information is published in [3] and [4].

6. PROTECTION DIODES

Triple junction solar cells are very sensitive to reverse bias. Therefore the protection of the cells against destructive reverse loads is mandatory.

RWE Space has developed several solutions of by-pass diodes for protecting triple junction solar cells. These are integral diodes, monolithic diodes and for special purposes external Si-diodes.

6.1 Integral Diodes

The integral diode concept utilizes the fact that the TJ solar cell itself is consisting of three diodes connected in series. This allows separating a small multi-junction diode from the cell area by mesa etching serving as a protection diode for the neighbour cell (Fig. 7). According to Fig. 8 the integral diode can utilize all three junctions from the top-, middle- and bottom-cell (ID-type) or only the middle- and bottom-cell junctions (ID2-type). The ID2-type has the advantage of a lower turn-on voltage (Fig. 9).

Fig. 7 Interconnection of cells with integral diode protection

![Fig. 7 Interconnection of cells with integral diode protection](image)

Fig. 8 Principles of ID- and ID2-integral diodes

![Fig. 8 Principles of ID- and ID2-integral diodes](image)

6.2 External Diodes

A common solution in combination with cells having two cropped corners is an external Si-diode. Planar Si-diodes are qualified for a number of space applications operating at higher temperature and can be integrated with the same techniques applied for the solar cell assembly. Fig. 10 shows an external diode layout based on a RWE Space owned patent with both the n- and p-contact on one side [6]. This allows an interconnection with the solar cell from the rear side only (Fig. 11). If same interconnectors as for solar cell interconnection shall be applied the n- and p-contacts can be also located on opposite cell sides.

![Fig. 9 Dark IV-characteristics of different integral diode types (from [5])](image)

![Fig. 10 External diode structure](image)

![Fig. 11 External diode structure](image)
Main advantages of the external diode concept is that the heat produced in the diode is distributed over a greater area which might be of importance for some high temperature applications such as Bepi-Colombo.

6.3 Monolithic Diodes

Several types of p/n- and Schottky- monolithic diodes are under development [5]. Selection of the optimum concept will be made after completion of intensive development and qualification testing. A qualified solution will be offered at the end of 2005. The main advantage of the monolithic by-pass diode concept lies in its simple interconnection technology (Fig. 12).

Fig. 12 Interconnection of cells with monolithic by-pass diodes

Since the monolithic by-pass diode is antiparallel to the cell junction, the interconnection is realized by welding a standard interconnector to the cell and diode which is also used for cells without by-pass diodes.

7. NEXT GENERATION SOLAR CELLS

The roadmap for the development of space solar cells in Europe (Fig. 1) includes 5 and 6-junction devices optimized for high radiation hardness and end-of-life efficiency. At Fraunhofer ISE a 5-junction solar cell is under development consisting of AlGaInP/GaInP/AlGaInAs/GaInAs/Ge [7]. In this structure the thickness of the individual subcells is significantly reduced (between 140 - 1400 nm) and consequently a low minority carrier lifetime has a comparably smaller impact on the current generation of the device resulting in an improved EOL performance. Only well-known materials are used in this 5-junction solar cell structure which is schematically shown in Fig. 1. Compared to a state-of-the-art triple-junction device, the 5-junction solar cell has a significantly higher voltage but smaller current density. Open-circuit voltages up to 5.2 Volts have already been demonstrated for an AlGaInP/GaInP/AlGaInAs/GaInAs/Ge 5J-cell under AM0 conditions ([7], [8] and Fig. 13).

Fig. 13 IV-curve of a 5-J cell measured with a 3-source simulator [7]

8. CONCLUSIONS

The successful development of a triple junction (TJ)-solar cell of the 28% class (RWE3G-28%class) with excellent charged particle stability is another step on the road map to keep RWE and the European space industry in a competitive position for providing economic solutions for high power applications and small (scientific) satellites with area and mass restrictions. Promising research and development results were also achieved in preparation of the next generation solar cells by further optimisation of triple cells or utilizing alternate materials and more junctions. In summary RWE Space/ISE are on a good way to meet all the targets of the multi-junction solar cell road map Fig. 1 for the next years.
9. ACKNOWLEDGEMENTS

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10. REFERENCES

1. ESA standard ECSS-E-20-08 Draft A, Photovoltaic Assemblies and Components, 1.4.2003


6. Patent pending
