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SPACE SOLAR CELLS – 3G30 AND NEXT GENERATION RADIATION HARD PRODUCTS

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ABSTRACT

The 3G30-Advanced, AZUR SPACE's latest qualified solar cell product, provides highest end-of-life efficiencies in space. The cell reaches 27.8% at a fluence of 5 E14 cm^{-2} and 26.5% at a fluence of 1 E15 cm^{-2} 1 MeV electrons.

The cell mass can be reduced to a minimum by substrate thinning, the cell cost can be reduced by implementation of large area configurations and even higher radiation hardness can be achieved by using AZUR's proprietary 3G30-1E16+ design. Various configurations are currently in production.

The increasing demand for cells suited for LEO applications, made AZUR to develop a novel upright metamorphic triple junction solar cell with a BOL efficiency of 31% designed for a fluence of 1 E14 cm^{-2} 1 MeV electrons. This cell design is already in production.

AZUR's next generation product 4G32 comprises an upright metamorphic 4-junction device with 28.5% EOL (1 E15 cm^{-2} 1 MeV electrons) efficiency. Hence, the 4G32 even surpasses the EOL efficiency of the lattice-matched 3-junction cell 3G30-Advanced. It utilizes the excess current of the Ge subcell by a metamorphic cell concept and a fourth junction added to the stack. This cell will be qualified by mid-2017.

This paper summarizes the results and achievements for various 3G and 4G solar cell products from AZUR SPACE, including radiation hardness and cell formats.

1. INTRODUCTION

Future telecommunication satellites continue to require more power for technologies, such as 3D TV and ultra HD TV. The electrical power supplied by solar generators increases correspondingly. High-performance, lightweight and cost effective solar generators are required in order to decrease cost. For the solar cell, this translates into high end-of-life [EOL] efficiency, low weight and low production costs.

Besides this, the demand for cells with even higher radiation hardness also increases. Solar electric orbit raising or orbits with high particle irradiation intensity are the main reasons.

On the other hand, the demand for cells suitable for LEO missions also increases. This requires cells with high beginning-of-life [BOL] efficiencies.

AZUR SPACE is active in all three market segments.

AZUR's latest best-in-class solar cell product in the market "3G30C-Advanced" provides a high end-of-life efficiency of 27.8% [1]. Low production costs have been accomplished by a lean cell design and by optimized production processes. In order to reduce the mass of a panel to a minimum, the 3G30C-Advanced may be thinned down to about 80 µm. Customers can also select from various formats. Starting from the classical 4 x 8 cm² size and leading to enhanced cell shapes, such as AZUR's "halfpipe design" wafer utilization and packing density on the panel can be increased while production cost is further reduced.

The move toward solar electric propulsion even increases the demand on radiation-hardness of the solar cell compared to rapid conventional chemical orbit raising. Since the cell collects an increased dose of high-energy particles during multiple traverses of the Van Allen Belt, the target equivalent fluence of 1 MeV electrons increases from about 4 E15 cm^{-2} up to 5 E16 cm^{-2} and more. AZUR has developed a new product segment to meet this demand. The advancement of the radiation-hardening technology from the 3G30C yields a new class of solar cells called 3G30C-1E16+ for increased EOL requirements. This cell yields an efficiency of 21.2% at a fluence of 1 E16 cm^{-2} 1 MeV electrons.

The move toward constellation programs and other LEO missions requires cells with high BOL efficiency. In order to meet these demands, AZUR has developed the 3G31C solar cell design. This cell comprises a metamorphic triple-junction solar cell adapted for a fluence of 1 E14 cm^{-2} 1 MeV electrons and yields BOL efficiencies of up to 31%.

Next generation solar cells will exceed the EOL efficiencies of the 3G30C-Advanced and utilize the excess current of the Ge subcell. Metamorphic solar cell concept [2] have demonstrated considerable potential. Upright and inverted devices lattice-matched or metamorphic all target approximately the same bandgap combination, although achieved with different materials [3]. AZUR SPACE proposed a 4-junction solar cell design [4] in order to reach EOL efficiencies of 28.5% at 1 E15 cm^{-2} 1 MeV electrons. The upright cell concepts keep epitaxy costs low and are highly compatible with standard cell processing and well-established lay-down technology.

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All these developments follow AZUR's roadmap for LEO, GEO and MEO missions, as shown in Fig. 1.

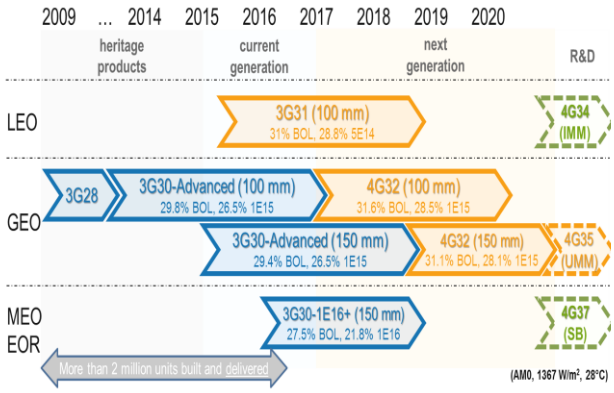

Figure 1. Product roadmap of AZUR for three market segments. Colours indicate cell technology: lattice-matched (blue), UMM (orange), inverted metamorphic (IMM, green) or semiconductor bonded (SB, green). Today more than 2 million cells have been delivered.

2. 3G30 SOLAR CELL PRODUCTS

All 3G30 solar cell products are based on a triple-junction design with subcells made from InGaP, InGaAs and Ge, all lattice-matched to the Ge growth substrate.

2.1 Radiation Hardness

AZUR's proprietary and fully patent protected end-of-life concept bases upon the selection of radiation-hard semiconductor materials, such as InGaP and Ge, an advanced cell design for increased minority carrier diffusion length in the InGaAs cell and a distributed Bragg reflector (DBR) for a reduced thickness of the InGaAs cell (Fig. 2).

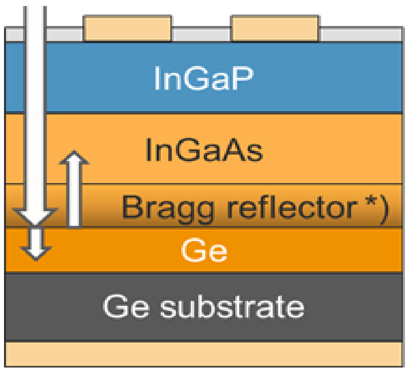

Figure 2. Structure of the 3G30C solar cell with a bandgap sequence of 1.9, 1.4 and 0.66 eV and AZUR's proprietary and patent protected EOL design including a distributed Bragg reflector (*).

High-energy particles indeed do impair the InGaP material. But temperatures around 25°C are sufficient to reduce the displacement damage by annealing to a great extent.

The Ge material is an indirect-gap semiconductor used for a relatively thick Ge subcell (>> 20 µm). The carriers generated by phonon-induced absorption hardly contribute at BOL. Hence, the reduction of diffusion length hardly affects the cell performance at EOL. Furthermore, the Ge subcell generates substantial excess current (~40%) compared to the other two subcells. A minor reduction of current density does not affect the triple-junction solar cell performance.
However, high-energy particles significantly affect the InGaAs material [5]. Annealing of the displacement damage requires temperatures well above 100°C [6]. This is usually undesired for geostationary satellites. Continuous and intensive research by AZUR SPACE and partners lead to a unique radiation-hardening approach. On the one hand, the layers are designed to increase minority carrier diffusion lengths and to reduce surface recombination. On the other hand, a distributed Bragg reflector is implemented to reduce the cell thickness and thus lower the minimally required diffusion lengths while maintaining the cell's optical thickness for light absorption.
AZUR's radiation-hardening concept yields the highest available EOL performances as summarized in Tab. 1.

3G30	BOL	5E14	1E15	3E15	1E16
V_{OC} [mV]	2700	2564	2522	2424	2324
I_{SC} [mA]	520	514	502	461	397
V_{mp} [mV]	2411	2290	2246	2174	2085
η [%]	29.5	27.8	26.5	23.4	18.7

Table 1. Average efficiencies of AZUR's 3G30C at different fluences of 1 MeV electrons. The cell is designed for the 8 E14 cm^{-2} range (1367 W/m²).

2.2 Cell Types and Assemblies

In order to comply with existing module designs the 3G30C is offered in the well-established 4 x 8 cm² design with cropped corners.
In order to optimize production cost, AZUR transferred production from 100 mm wafer technology to 150 mm technology. This allows cell sizes of up to 6 x 12 cm² in the cropped corner format. AZUR's latest enhanced "halfpipe design" with an area of up to 82 cm² further optimizes wafer utilization as well as packing density on the module. This leads to a doubled cost reduction on panel level. Fig. 3 shows some cell formats.
In order to reduce cell weight, a combined grinding and etching process is used to thin down the Ge substrates to 80 µm. This represents a cost effective trade-off between weight reduction and yield in production and handling. Other cell thicknesses are also feasible.

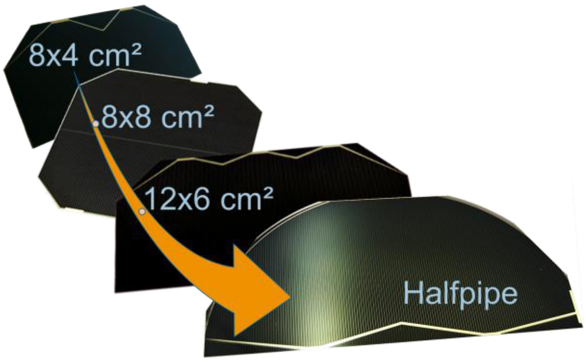

Figure 3. Different 3G30C solar cell formats ranging from 30 cm² to 70 cm² active area.

AZUR SPACE has advanced its bare cell technology to a higher integration step. Typical solar cell assemblies (SCAs) feature multiple configurations of integral and external bypass diodes, coverglass thickness down to 50 µm and multiple toe interconnectors for welding reliability. Fig. 4 shows two examples.

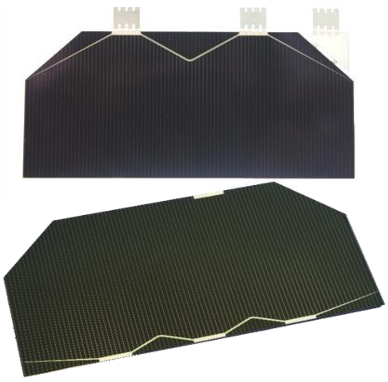

Figure 4. 3G30A assembly with external Si bypass diode (top) and a 3G30C with integral bypass diode (bottom).

2.3 3G30-1E16+

Solar electric orbit raising makes completely new demands on the solar generator and the solar cell. Power demand rises, as the solar generator is also used to power the ion thrusters during raising of the satellite. During the journey, the spacecraft traverses the Van Allen Belts multiple times and hence is exposed to a higher dose of high-energy particles than during conventional chemical orbit raising.
AZUR SPACE has used its unique skills in radiation hardening to develop an unequalled EOL design for a solar cell. The 3G30C-1E16+ is optimized for 1 MeV electron fluences above 1 E16 cm^{-2}. Tab. 2 summarizes some results measured on this device. At high fluences this cell clearly exceeds the already excellent performance of the 3G30C-Advanced. At 1 E16 cm^{-2} an average efficiency of 21.2% has been reached. This outshines all past EOL solar cell designs. Fig. 5 compares the two exceptional devices vs. fluence.

3G30-1E16+	BOL	1E16	2.5E16
V_{OC} [mV]	2700	2352	2256
I_{SC} [mA]	470	457	414
V_{mp} [mV]	2457	2070	1993
η [%]	27.4	21.2	17.9

Table 2. Average efficiencies of AZUR's 3G30C-1E16+ at different fluences of 1 MeV electrons (1367 W/m²).

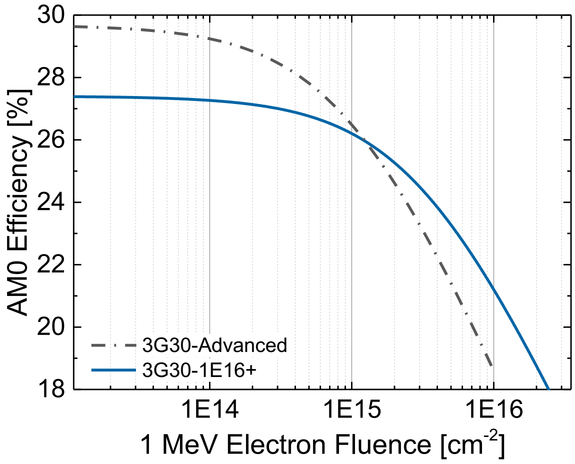

Figure 5. Comparison of AZUR's 3G30C and 3G30C-1E16+ depending on 1 MeV electron fluences.

3. 3G31 SOLAR CELLS

The 3G31C solar cell is based on a triple-junction design with subcells made from InGaP, InGaAs and Ge. This is the same material combination as used for the 3G30C. However, the alloy composition of the arsenides and phosphides features an about 5%(abs.) higher In content. As a result, the bandgaps are shifted to longer wavelengths (Fig. 6) and the upper subcells exhibit a lattice-mismatch of less than 0.5% to the Ge growth substrate. This cell concept is called upright metamorphic (UMM).

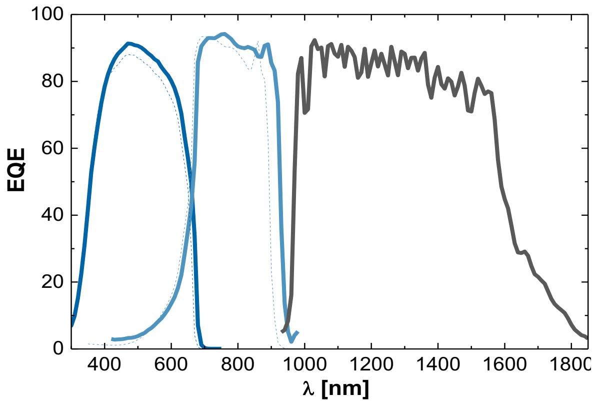

Figure 6. Quantum efficiency of AZUR's 3G31C (solid) vs. the top and middle cell of 3G30C (dashed).

The 3G31C features a step graded buffer structure with three steps and overshoot layer made from InGaAs (Fig. 7). This buffer structure generates misfit dislocation to dissipate strain and simultaneously avoids the penetration of threading dislocations into the photoactive layers. This technology has been developed for many years by AZUR SPACE and partners and has been introduced into the 3C44 [7], AZUR's current metamorphic triple-junction solar cell for CPV applications. Now, this technology also found its use for space solar cells. In addition to the metamorphic buffer, the structure features a distributed Bragg reflector, also shown in Fig. 7.

In production, this structure yields BOL efficiencies of 30.7% (Tab. 3). It still features upright processing and may be combined with a thinning process to reduce thickness from 145 µm to 80 µm.

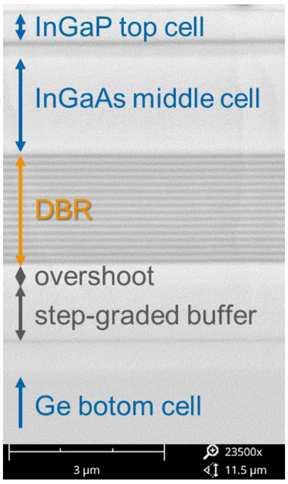

Figure 7: REM cross-section of the 3G31C. A distributed Bragg reflector (DBR) and a step-graded metamorphic buffer with overshoot complement the three subcells.

3G31	BOL	1E14
V_{OC} [mV]	2605	2549
I_{SC} [mA]	565	552
V_{mp} [mV]	2330	2272
η [%]	30.7	29.5

Table 3. Efficiencies of AZUR's 3G31C at BOL and at a fluence of 1 E14 cm^{-2} 1 MeV electrons (1367 W/m²).

4. 4G32 SOLAR CELL PRODUCTS

The 4G32 solar cell is based on a four-junction design with subcells made from AlInGaP, AlInGaAs, InGaAs and Ge. The upper subcells exhibit a large lattice-mismatch to the Ge growth substrate. Hence, again AZUR has chosen an upright metamorphic (UMM) approach for this solar cell structure.

4.1 Mechanical Design

The about 1.5% lattice-mismatch between the Ge substrate and the InGaAs subcell is compensated by a step-graded metamorphic buffer structure similar to the 3G31C. Fig. 8 illustrates the layer structure. Since the lattice-mismatch for this device is much stronger than for a 3G31C, it is essential that the misfit dislocations dissipate 100% of the strain and that the threading dislocation density stays below 10^6 cm^{-2}. AZUR SPACE currently implements metamorphic buffers in three products: the 3C44 (for CPV), the 3G31 (for LEO) and the 4G32 (for GEO).

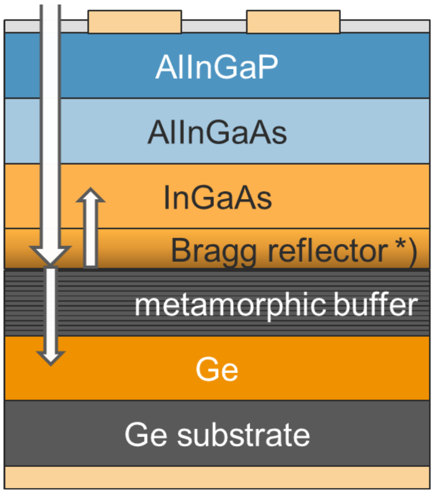

Figure 8. Structure of the 4G32C solar cell with a bandgap sequence of 1.9, 1.4, 1.1 and 0.66 eV and AZUR's proprietary and patent protected EOL design.

4.2 Radiation Hardness

The 4G32C achieves an almost optimal bandgap sequence of 1.9, 1.4, 1.1 and 0.66 eV (Fig. 9) with subcells made from AlInGaP, AlInGaAs, InGaAs and Ge, respectively (Fig. 8). The external quantum efficiency from Fig. 9 depicts the high quality of each subcell and the well-balanced current generation in all four subcells.

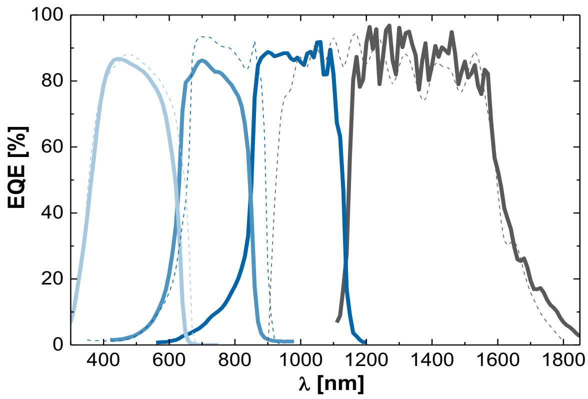

Figure 9. External quantum efficiency of the four sub-cells of AZUR's 4G32C (solid) vs. the 3G30C (dashed).

Exceptional radiation hardness of the cell is achieved by the implementation and adaption of AZUR's proprietary EOL design.
The 4G32C employs the radiation hard semiconductor materials AlInGaP and Ge. This is comparable to the 3G30C, where InGaP and Ge are used.
The InGaAs cell benefits from a distributed Bragg reflector similar to the radiation-hard 3G30C structure. This allows reducing the cell's thickness while keeping its optical thickness for light absorption constant (Fig. 8). However, the reflectivity range is adapted to the 4J design and the materials fit the lattice of the metamorphic buffer. The external quantum efficiency of the InGaAs subcell (Fig. 9, around 1000 nm) also shows the reflectivity of the DBR by an increased signal in the longer wavelength region from 1000 to 1100 nm.
A thinner AlInGaAs cell reduces the impact of a deteriorated minority carrier diffusion length caused by high-particle irradiation in space.
A total remaining factor of 95% in V_{OC} after 1 E15 cm^{-2} 1 MeV electrons is feasible. This outperforms the 3G30C's remaining factor by about 1% and facilitates efficiencies of up to 28.5% EOL (1 E15 cm^{-2} 1 MeV electrons). Fig. 10 shows plotted IV characteristics of the 4G32C measured at BOL and at EOL with efficiencies of 30.7% and 27.8%, respectively. Tab. 4 summarizes the relevant IV parameters at different 1 MeV electron fluences.
The production of the qualification lot for the 4G32C with a thickness of 80 µm is scheduled for the end of 2016, in order to facilitate a full qualification according to ECSS by mid-2017 [8].
The advancement program for the 4G32C is scheduled for the next three years and includes further improvement of the Al-compound subcells regarding material quality, further enhancement of radiation-hardness as well as the shift to 150 mm wafer technology. The rightmost column of Tab. 4 shows the target EOL performance for the 4G32C-Advanced.

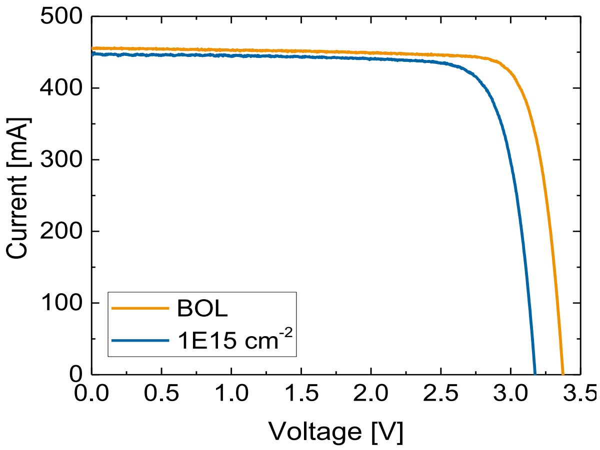

Figure 10. IV characteristics of AZUR's 4G32C (1367 W/m²) at beginning-of-life and at a 1 MeV electron fluence of 1E15 cm^{-2}.

4G32	BOL	1E15	5E15	1E15 target
V_{OC} [V]	3.37	3.18	3.01	3.25
I_{SC} [mA]	454	445	390	445
V_{mp} [V]	2.92	2.73	2.62	2.79
η [%]	30.7	27.8	22.7	28.5

Table 4. Performance of the 4G32C after irradiation with 1 MeV electrons (1367 W/m²) and target value for 4G32C-Advanced.

5. FURTHER CONCEPTS

Alternative approaches to surpass the 30% efficiency level at a fluence of 1 E15 cm^{-2} 1 MeV electrons use other technology building blocks, also investigated by AZUR and partners.
Inverted metamorphic four-junction solar cells developed in cooperation with Fraunhofer ISE can also reduce the dissipation of excess current in the bottom cell. The bottleneck with this concept is the low radiation-hardness of the three (In)GaAs-based subcells. In order to bring this concept to a success, we are working on advanced cell designs with several distributed Bragg reflectors for improved radiation-hardness. A scalable metal-bonding process has already been established.
Another cell approach assembles the optimal bandgap combination from subcells grown on different substrates. Thus, we follow an approach of direct semiconductor bonding with transparent layers. Fig. 11 shows a scanning acoustic microscopy image (SAM) of two solar cell wafers based on GaAs and InP substrates bonded at Fraunhofer ISE with a very homogeneous bonding area and only a very small number of voids. These voids can be correlated to surface defects on the bonding interfaces as shown in Fig. 11 on the right.

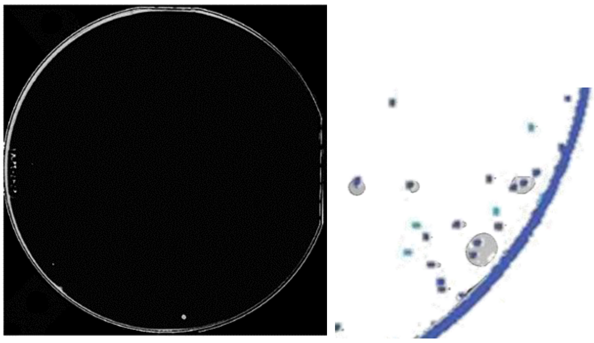

Figure 11. Scanning acoustic microscopy (SAM) image of a cells based on InP and GaAs wafers successfully semiconductor bonded (left). Voids (grey areas) arise from larger surface defects (right, dots).

6. SUMMARY

AZUR's space qualified 3G30C-Advanced provides the world's highest EOL efficiencies and is available in several sizes and formats up to 82 cm². The cells may be thinned down to 80 µm or less in order to reduce weight.

Solar electric orbit raising requires radiation-hard designs up to an equivalent 1 MeV electron fluence of 5 E16 cm^{-2}. This demand can be met by the enhanced cell design of the 3G30C-1E16+, yielding efficiencies of 21.2% at 1 E16 cm^{-2} 1 MeV electrons.

The third market segment of LEO missions requires high BOL efficiencies. AZUR SPACE has developed a 3G31C cell design to meet these demands.

The 4G32C is AZUR's next generation product, succeeding the 3G30C. It bases upon a four-junction upright metamorphic solar cell structure and implements AZUR's proprietary EOL design. The cell achieves extraordinary EOL efficiencies of 27.8% at 1 E15 cm^{-2} 1 MeV electrons. Qualification will be completed in 2017. The 4G32C-Advanced will reach 28.5% at 1 E15 cm^{-2} 1 MeV electrons

7. ACKNOWLEDGEMENT

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