

## Radiation-Hard High-Efficiency Multi-Junction Solar Cells for Commercial Space Applications

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**ABSTRACT:** In this paper, we present the results of testing and volume production of radiation-hard high-efficiency large-area InGaP/GaAs/Ge triple-junction solar cells. Minimum average conversion efficiency for the large-area flight cell production lots is 26.0% (28°C, one-sun, 135.3 mW/cm<sup>2</sup>), with efficiencies in the range of 24.5% to 27.6%. The power remaining factors after 5E14 and 1E15 e/cm<sup>2</sup> 1-MeV electron irradiation are 91% and 87 %, respectively. Emcore’s next generation product is the InGaP/InGaAs/Ge advanced triple-junction (ATJ) solar cell. Minimum average efficiency for the large-area flight cell production lots is currently ≥27.5% (28°C, one-sun, 135.3 mW/cm<sup>2</sup>), with cell efficiencies ranging from approximately 26.5% to 28.5%. A monolithic bypass diode option will also be available with the ATJ cell. The high volume production of the advanced triple-junction solar cell is to commence in November of 2001.

**Keywords:** Space Solar Cells – 1: Multi-Junction Solar Cells – 2.

### 1. INTRODUCTION

High-efficiency multi-junction solar cells have been providing power for multitudes of earth orbiting spacecrafts for the past several years. Telecom satellites with large power needs (12-20 KWe), in particular, have been able to utilize the more efficient multi-junction cells that have enabled smaller area solar arrays. Two main factors have largely contributed to the rapid acceptance of multi-junction solar cells in place of the more traditional silicon cells for space applications. These are higher solar to electric conversion efficiency and better radiation hardness.

All of the major manufacturers of III-V compound multi-junction solar cells have been able to significantly enhance the efficiency and radiation tolerance of these solar cells for the past several years [1-4]. At the same, the unit price of the cells have also declined, leading to a much improved cost (\$) per watt.

Currently, triple-junction flight-quality space solar cells produced by various high volume manufacturers exhibit minimum shipping lot beginning-of-life (BOL) average efficiencies in the range of 26.0% to greater than 27.5%. The remaining power factors after exposure to 1 MeV electron irradiation vary in the range of 0.83 to 0.87 for a dose of 1E15 e/cm<sup>2</sup>. In this paper, we will present the results for the volume production of InGaP/GaAs/Ge triple-junction, as well as, the next generation InGaP/InGaAs/Ge advanced triple-junction (ATJ) solar cells at Emcore Photovoltaics.

### 2. EXPERIMENT

The InGaP/GaAs/Ge triple-junction, as well as, the InGaP/InGaAs/Ge advanced triple-junction solar cells are epitaxially grown via the Emcore made E400 and E450 production organometallic chemical vapor deposition (OMCVD) reactors on 140 μm uniformly thick germanium substrates. A schematic cross-sectional diagram of the solar cell structures are shown in Figure 1.

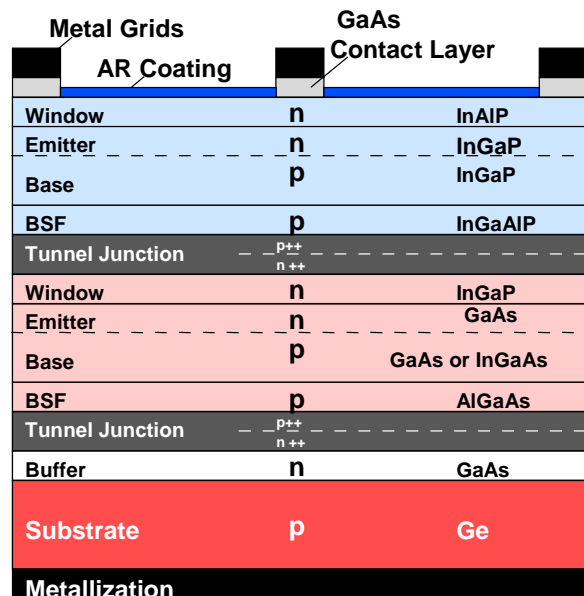


Figure 1. Cross-sectional schematic diagram of the InGaP/(In)GaAs/Ge (Advanced) triple-junction cell

The solar cell structures are grown on 100 mm diameter Ge substrates with an average mass density of about 84 mg/cm<sup>2</sup>. The epitaxial layer uniformity across a platter that holds 12 or 13 Ge substrates during OMCVD growth is better than 99.5%. Each wafer yields two large-area solar cells. The cell areas that are processed for production range from 26.6 to 32.0 cm<sup>2</sup>. The results reported in this paper, however, refer only to cell areas of 27.5 cm<sup>2</sup>.

The epi-wafers are processed into complete devices through automated robotic photolithography, metallization, chemical cleaning and etching, anti-reflection (AR) coating, and testing processes. The n- & p-contact metallization is mostly comprised of Ag with a thin Au cap layer for better weldability. The AR coating is a dual-layer TiOx/Al<sub>2</sub>O<sub>3</sub> dielectric stack, whose spectral reflectivity characteristics are designed to minimize reflection at the

coverglass-interconnect-cell (CIC) or solar cell assembly (SCA) level.

For best end-of-life (EOL) performance, the cells have n-on-p polarity, and were designed to exhibit record power remaining factors after exposure to 1-MeV electrons up to a fluence of  $1E15$  e/cm<sup>2</sup>. Under BOL conditions, the InGaP cell is designed to be thinner than optimum as to make the entire solar cell structure to be current limited by the top cell. Under EOL conditions (1-MeV electrons,  $1E15$  e/cm<sup>2</sup>), the InGaP top cell and the middle GaAs (or InGaAs) cells are current matched. The Ge bottom cell typically produces enough excess current as to be of no concern in the EOL optimization design.

### 3. TRIPLE-JUNCTION SOLAR CELL PRODUCTION

Emcore has been in volume production of InGaP/GaAs/Ge multi-junction solar cells since late calendar year 1999. Greater than 100,000 large-area cells have been shipped for flight programs. The minimum average efficiency for the shipped cells are 26.0% (28°C, one-sun,  $135.3$  mW/cm<sup>2</sup>), with efficiencies ranging from 24.5% to 27.6%. A typical current-voltage characteristics of this cell type is shown in Figure 2.

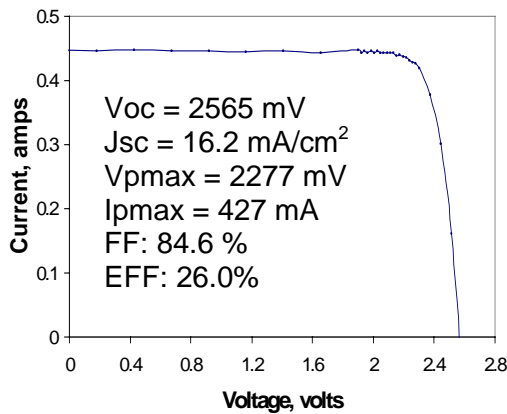


Figure 2. Typical I-V characteristics for a 26.0% triple-junction solar cell

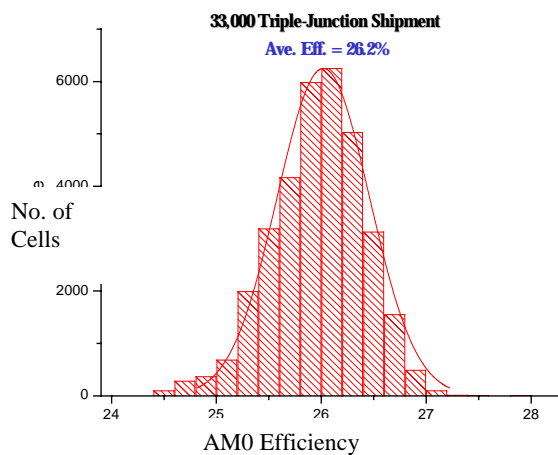


Figure 3. A histogram of the most recent 33,000 triple-junction solar cells shipped for flight programs.

Through manufacturing practices, the yielded average cell efficiency at Emcore has increased to 26.2%. A histogram of the latest 33,000 cell shipments is shown in Figure 3.

As part of the space qualification program, the triple-junction cell was exposed to 1-MeV electron irradiation at fluences of  $5E13$ ,  $1E14$ ,  $5E14$ ,  $1E15$ , and  $3E15$  e/cm<sup>2</sup>. The cells were also exposed to proton irradiation of energies ranging from 50 KeV to 10 MeV. The full results for the proton irradiation test, including the relative damage coefficients, is reported in a paper in the current proceeding [5]. The results for the 1-MeV electron exposure is shown in Figure 4.

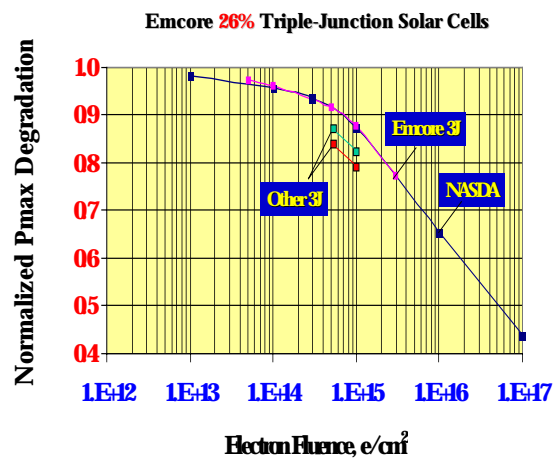


Figure 4. Power remaining factors for 1-MeV electron irradiation

Several points are shown in Figure 4. The light colored data was generated by Emcore. The before and after irradiation electrical results were measured at Emcore, and the cells were irradiated at NASA's Jet Propulsion Lab (JPL). The dark colored data was generated by NASDA of Japan. Both the electrical performance measurements and the electron irradiation were performed in Japan. As shown in the figure, very good consistency was shown by these two independent measurements. The power remaining factors for Voc, Isc, Imp, Vmp, fill factor, and efficiency are also shown in Table I.

Table I. Remaining factors after 1-MeV electron irradiation

Fluence, e/cm <sup>2</sup>	Remaining Factors					
	Voc	Isc	IPmax	VPmax	FF	Eff
$5 \times 10^{13}$	0.971	1.009	1.015	0.973	1.007	0.988
$1 \times 10^{14}$	0.961	1.001	0.991	0.969	0.998	0.961
$5 \times 10^{14}$	0.933	0.989	0.976	0.933	0.987	0.911
$1 \times 10^{15}$	0.918	0.975	0.954	0.913	0.973	0.871
$3 \times 10^{15}$	0.884	0.923	0.885	0.880	0.955	0.779

The triple-junction solar cell was designed to exhibit the best EOL performance. As shown in the table, the power remaining factors after electron exposure is the highest reported for III-V multi-junction flight cells. For a typical GEO mission of 15 years, the solar cell degradation in output power is only about 10%.

#### 4. ADVANCED TRIPLE-JUNCTION SOLAR CELLS

In Early 2001, Emcore entered into a development program to optimize the performance of the triple-junction solar cell. Modeling was performed on all aspects of device performance for all three junctions. Design of experiments (DOE) were then performed to verify the modeling predictions. At the same time, the MOCVD epilayer growth condition was revisited and optimized. The combination of the above approaches led to the development of what Emcore has termed the advanced triple-junction (ATJ) solar cell.

The basic structure of the ATJ cell is the same as the current generation triple-junction cell (see Fig. 1). Modeling results indicated that one of the most critical areas that could be improved was the output voltage of the Ge bottom cell. The Ge diffused junction depth control and front surface passivation (reduction in the surface recombination velocity - SRV) proved to be the keys to enhance the cell voltage. Upon optimizing the above parameters, the average voltage at maximum power ( $V_{mp}$ ) was increased by approximately 75 mV. This improvement alone resulted in an increase in cell efficiency of greater than 0.6% absolute.

The next area that was investigated was the GaAs middle cell. It was determined that by adding slightly more than 1% In to the (In)GaAs composition, the middle cell was not only better lattice matched to the Ge substrate, but the gain in output current outweighed the loss in voltage. Several other minor modifications were also performed on the middle and top cell layers to optimize their performance. The resulting InGaP/InGaAs/Ge cell exhibited significantly higher efficiency.

Emcore is currently in the space qualification and pilot production of the ATJ cell. Space qualification includes 1-MeV electron irradiation, thermal cycling, humidity exposure, mechanical and weld testing, radiometric properties, contact and coating adhesion, and BOL and EOL temperature coefficient measurements. These qualification tests are due to be completed by middle of November 2001, at which point volume production of the ATJ cell will commence.

The targeted cell efficiency for ATJ is a minimum average of in the range of 27.5% to 28.0% ( $135 \text{ mW/cm}^2$ ), while maintaining the radiation hardness of the triple-junction cell. A typical I-V plot for the current ATJ is shown in Figure 5.

For the first pilot production run of nearly 200 solar cells, the efficiency range for the ATJ cells was in the 26.5% to 28.5% (with acceptable electrical yield loss values). One feature of the ATJ cell that was noticed to be different from the current triple-junction product was that the efficiency distribution was a great deal tighter. An efficiency histogram of 160 large-area ATJ cells with an average efficiency of 27.5% is shown in Figure 6. An I-V plot for a cell with the highest efficiency observed thus far (28.5%) is also illustrated in Figure 7.

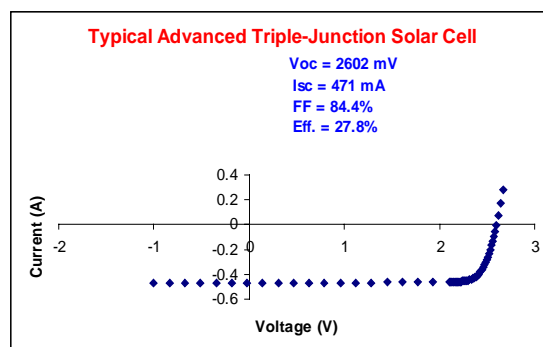
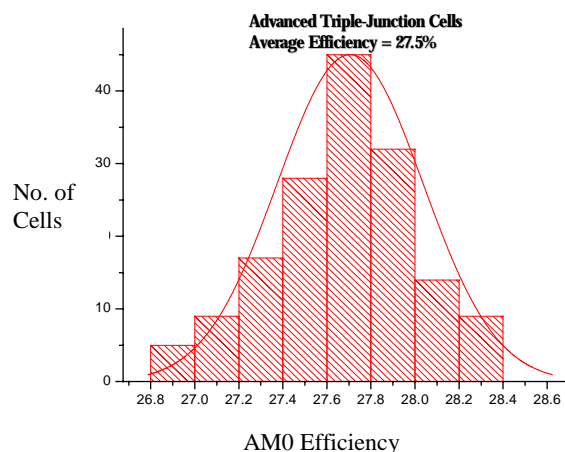


Figure 5. Typical I-V characteristics for an advanced



triple-junction (ATJ) solar cell (area =  $27.5 \text{ cm}^2$ )

Figure 6. A histogram of 160 large-area ( $27.5 \text{ cm}^2$ ) advanced triple-junction (ATJ) solar cells

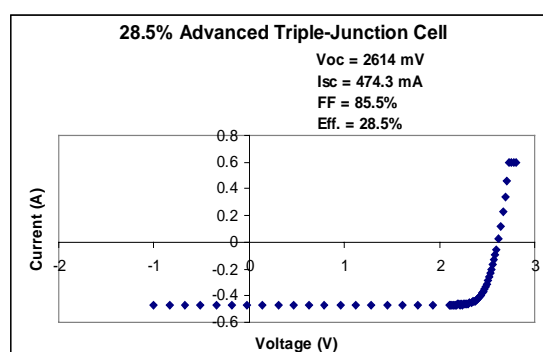


Figure 7. I-V characteristics for a 28.5% advanced triple-junction (ATJ) solar cell (area =  $27.5 \text{ cm}^2$ )

The optimization of each junction in the triple-junction cell stack is most evident when the representative external quantum efficiencies (QE) for the ATJ and the triple-junction cells are compared. The most important difference in the two QE plots is the significantly higher short wavelength response of the Ge bottom cell in the ATJ configuration ( $>900 \text{ nm}$  wavelength). Higher QE response is also observed for both the middle InGaAs cell and the

top InGaP cell. The QE comparison results are illustrated in Figure 8.

Preliminary 1-MeV electron irradiation data at the fluence of  $5E14 \text{ e/cm}^2$  was performed. The results were similar to what was measured for the triple-junction cell (see Table I). This is shown in Table II.

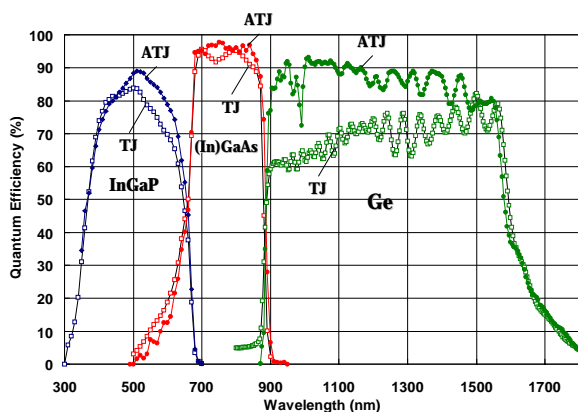


Figure 8. External QE comparison of the ATJ and the triple-junction (TJ) solar cells

Table II. Preliminary 1-MeV electron irradiation results for the ATJ cell under  $5E14 \text{ e/cm}^2$  fluence.

Remaining Factors After Irradiation - $5E14 \text{ e/cm}^2$				
Voc	Isc	Vmp	Imp	Pmp
0.932	0.988	0.917	0.988	0.906

The combination of radiation hardness and higher efficiency results in record EOL performance. A comparison of EOL performance for the ATJ and triple-junction cells is shown in Table III.

Table III. EOL performance comparison (1-MeV electron irradiation) for ATJ and TJ ( $28^\circ\text{C}$ ).

Cell Technology	BOL Eff. (%)	Fluence ( $\text{e/cm}^2$ )	P/Po	EOL Eff. (%)
TJ	26.0	$5E14$	0.911	23.7
ATJ	27.8	$5E14$	0.906	25.2

As shown in the table above, EOL efficiencies of  $\geq 25\%$  are possible for the first time for any monolithically stacked space solar cell. The ATJ solar cell represents a near optimum design for an InGaP/(In)GaAs/Ge triple-junction stack cell structure that is lattice matched to Ge.

In order to increase solar cell efficiency further, better overall cell air-mass zero (AM0) spectrum utilization will

be required. Alternative cell structures that may meet this requirement are the InGaP/GaAs/InGaAsN/Ge quad-junction or lattice-mismatched triple- or quad-junction structures. These cell technologies, however, are still in early stages of development.

Emcore is also in the process of space qualification and pilot production of a monolithic bypass diode, for shadow protection, with the ATJ cell. Unlike conventional monolithic diodes, however, no extra p/n junction layers are grown on top of the main cell structure. In this design, the diode semiconductor layers are imbedded into the cell structure itself. The diode is also designed to have a turn-on voltage similar to a silicon discrete bypass diode ( $\sim 600 \text{ mV}$ ). An I-V plot for the diode is shown in Figure 9.

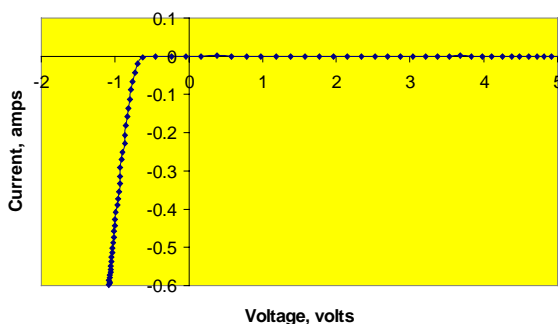


Figure 9. I-V Plot for the monolithic bypass diode

## 5. SUMMARY

Emcore Photovoltaics is currently in volume production of a radiation-hard InGaP/GaAs/Ge triple-junction solar cell with a minimum average shipping lot efficiency of 26.0%. This cell structure exhibits an EOL efficiency of 23.7% (1-MeV electron irradiation,  $5E14 \text{ e/cm}^2$  fluence). Greater than 100,000 multi-junction cells have been shipped for various flight programs.

Emcore is also in the pilot production and space qualification phase of an InGaP/InGaAs/Ge advanced triple-junction (ATJ) solar cell. The BOL minimum average lot efficiency for this cell type will be in the range of 26.5 to 28.5%. In preliminary electron irradiation testing, this structure has exhibited similar radiation hardness behavior as its predecessor the triple-junction solar cell. The ATJ cell has shown record EOL efficiencies of  $\geq 25\%$  (1-MeV electron,  $5E14 \text{ e/cm}^2$  fluence).

## 6. REFERENCES

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