THE DEVELOPMENT OF >28% EFFICIENT TRIPLE-JUNCTION SPACE SOLAR CELLS AT EMCORE PHOTOVOLTAICS

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Abstract

Emcore Photovoltaics has been in volume production of high-efficiency multi-junction solar cells for spacecraft applications since 1999. Emcore's current heritage product is the advanced triple-junction (ATJ) n/p InGaP/InGaAs/Ge solar cell. The ATJ cell exhibits a beginning-of-life (BOL) minimum average conversion efficiency of 27.5%, under air-mass zero (AM0) illumination conditions, making it the highest efficiency flight cell available in the market to date. The efficiencies of flight cells in a ship lot range from approximately 26.0% to 29.5%. A new version of the ATJ cell that is also in volume production at Emcore, incorporates a monolithically integrated p/n GaAs bypass diode. This cell is called the ATJM. Using the ATJM cell as the baseline platform, an optimized solar cell is being developed that is mechanically identical to the heritage ATJM cell, but exhibiting a minimum average efficiency of about 28.5%. The development lots of this 2nd generation ATJM exhibit typical BOL performance parameters of Voc of 2,650 mV, Jsc of 17.3 mA/cm^2, and fill factor of 84%, under illuminated AM0 conditions. In this paper, the manufacturing aspects of the ATJ & ATJM cells, as well as, the development aspects of the 2nd generation ATJM solar cells will be presented.

Introduction

High-efficiency III-V compound semiconductor multi-junction solar cells have been providing power for earth-orbiting satellites, as well as, interplanetary programs for many years. Higher conversion efficiency and better radiation hardness of the multi-junction cells, as compared to the traditional silicon cells, are the primary factors why these cells are attractive to a whole host of users. In applications where the solar panel area is restricted or high power demands are required, multi-junction cells are typically employed.

The efficiency and radiation hardness of multi-junction solar cells have significantly improved in recent years [1-3]. In the late 1990s, for example, the highest efficiency cells in volume production in the space solar market approached the 25% mark. Currently, it stands at greater than 27%. Concurrently, the unit price of these cells have also declined, leading to a much improved cost ($) per watt.

Currently, Emcore Photovoltaics is in volume production of high-efficiency triple-junction (TJ), advanced triple-junction (ATJ), and ATJ with a monolithically integrated diode (ATJM) solar cells for space flight applications. The minimum BOL lot average efficiency for these cell types are 26.0%, 27.5%, and 27.5%, respectively. These multi-junction cells are of n/p polarity and are composed of InGaP/(In)GaAs III-V compounds epitaxially grown on Ge wafers. In this paper, we will describe the performance and manufacturing aspects of the ATJ & ATJM cells. As well, data will be presented for the development of the next generation ATJM cell with a targeted minimum average efficiency of 28.5%.

Experiment

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

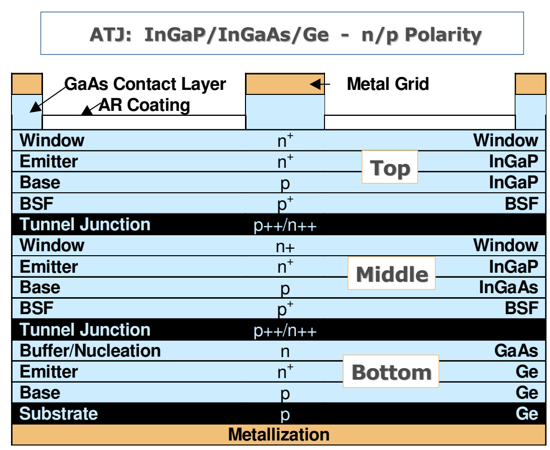


Fig. 1 – Cross-sectional schematic diagram of the InGaP/InGaAs/Ge ATJ cell

The solar cell structures are grown on 100-mm diameter (4 inch) Ge substrates with an average mass density of about 86 mg/cm^2. The epitaxial layer uniformity across a platter that holds 12 or 13 Ge substrates during the OMCVD growth process is better than 99.5%. Each wafer typically yields two large-area solar cells. The cell areas that are processed for production typically range from 26.6 to 32.4 cm^2.

The epi-wafers are processed into complete devices through automated robotic photolithography, metallization, chemical cleaning and etching, anti-reflection (AR) coating, dicing, and testing processes. The n- & p-contact metallization is mostly comprised of

Ag with a thin Au cap layer to protect the Ag from oxidation. The AR coating is a dual-layer TiO_x/Al_2O_3 dielectric stack, whose spectral reflectivity characteristics are designed to minimize reflection at the coverglass-interconnect-cell (CIC) or solar cell assembly (SCA) level, as well as, maximizing the end-of-life (EOL) performance of the cells..

For best EOL performance, the cells have n-on-p polarity, and were designed to exhibit high power remaining factors after exposure to 1-MeV electrons. 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 (e.g., 1-MeV electrons, 1E15 e/cm^2), the InGaP top cell and the middle 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. The InGaP top and InGaAs middle cells are lattice matched to the Ge substrate.

Advanced Triple-Junction (ATJ) Solar Cell Production

Emcore has been in volume production of ATJ solar cells since late 2001. Greater than 60,000 large-area cells have been shipped for both LEO & GEO flight programs. The minimum average BOL lot efficiency for the flight cells are 27.5% (28°C, one-sun, 135.3 mW/cm2), with efficiencies ranging from about 26.0% to 29.5%. A typical current-voltage (I-V) plot of the ATJ cell is shown in Figure 2. An efficiency histogram of production ATJ cells is also shown in Fig. 3.

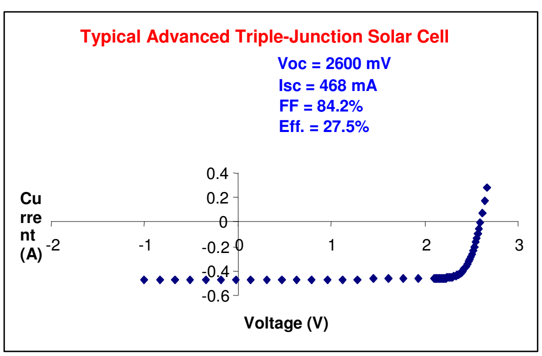


Fig. 2 – Typical ATJ illuminated I-V plot (Cell area of 27.5 cm^2)

The superior electrical performance of the ATJ cell in comparison to the TJ cell, for example, is illustrated in Fig. 4, where typical external quantum efficiency (QE) results for the ATJ and TJ cells are shown. As seen in the figure, significant gains were realized in the "blue" response of the bottom Ge cell, as well as, the "red" response of the top InGaP cell. In addition, the conventional GaAs middle cell was replaced with an InGaAs cell for the ATJ. Unlike GaAs, the InGaAs layers (~ 1.5% In concentration) are "perfectly" lattice-matched to the Ge substrate.

The ATJ solar cell was designed to exhibit the best EOL performance. As part of a comprehensive space qualification program, ATJ cells were exposed to 1-MeV electron irradiation at fluences of 5E13, 1E14, 5E14, 1E15, and 3E15 e/cm^2. The cells were also exposed to 0.6, 1, 2, and 12 MeV electrons, as well as, to 0.05, 0.1, 0.3, 1, 2.5, and 10 MeV protons. The full results for the proton and electron irradiation tests, including the relative damage coefficients (RDC) are complied in an internal Emcore report that is available for customer review.

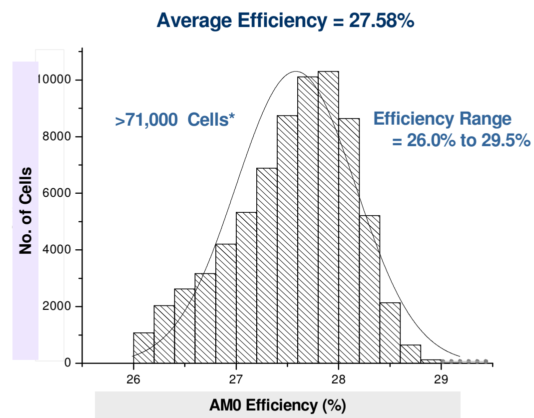
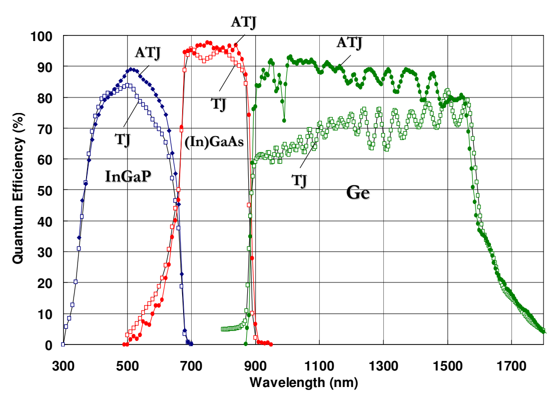


Fig. 3 – A histogram of a typical shipping lot



(>70,000 ATJ flight cells)

Fig. 4 – Typical external quantum efficiency comparison for the TJ and ATJ cells

The ATJ solar cell was designed to exhibit the best EOL performance. As part of a comprehensive space qualification program, ATJ cells were exposed to 1-MeV electron irradiation at fluences of 5E13, 1E14, 5E14, 1E15, and 3E15 e/cm^2. The cells were also exposed to 0.6, 1, 2, and 12 MeV electrons, as well as, to 0.05, 0.1, 0.3, 1, 2.5, and 10 MeV protons. The full results for the proton and electron irradiation tests, including the relative

damage coefficients (RDC) are complied in an internal Emcore report that is available for customer review.

The remaining power factors after 1-MeV electron exposure for fluence levels of 5E14 & 1E15 e/cm^2 were 0.89 & 0.85, respectively. As a result, for a typical GEO mission of 15-20 years, the solar cell degradation in output power is estimated to be in the range of 11–15%.

ATJM Solar Cells

The ATJM cell is created by the addition of p/n homo-junction GaAs layers on the surface of the ATJ cell. The monolithically integrated GaAs diode protects the cell over which it resides during circuit shadow conditions in space. During the processing of the ATJM, the additional p/n GaAs diode layers are removed from the active surface areas of the cell, except where the small monolithic diode pad is to be located. To maximize diode reliability, except for the metal weld pad, all exposed areas of the diode are protected by the AR-coating dielectric layers. The stringing interconnects welded to the diode pad complete the circuit. This is illustrated in figures 5 and 6, where a schematic cross-sectional diagram & a photograph of an ATJM solar cell are shown, respectively.

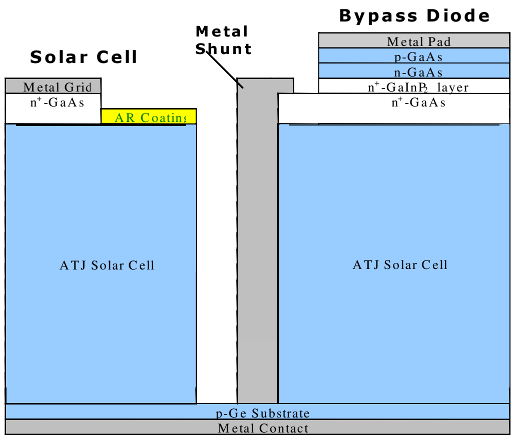


Fig. 5 – Cross-sectional schematic of the ATJM cell

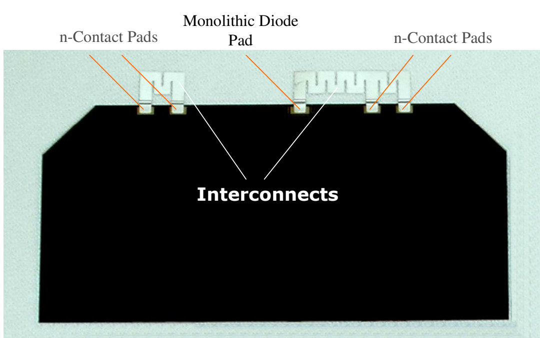


Fig. 6 – ATJM solar cell with welded interconnects

Since the active cell components of the ATJ & ATJM are identical, the electrical performance of ATJM is the same as the ATJ in volume production (see Fig. 3). Typical forward turn on voltage for the monolithic diode is about 1.8 V.

The monolithic diode is also designed for robustness and low reverse bias leakage current. This is illustrated in Fig. 7, where the reverse bias characteristics of the ATJM diode is compared to conventional diodes (homo-junction or Schottky type). As seen in the figure, the diode leakage current is limited to extremely low values of less than 1 µA at reverse bias of up to 30 volts.

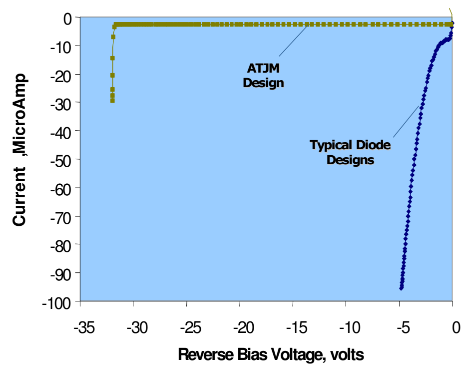


Fig. 7 – Dark reverse bias characteristics of the ATJM monolithic diode

2nd Generation ATJM Solar Cells

A development program was initiated at Emcore to optimize the performance of the ATJM solar cell. The focus of this effort was to achieve higher solar cell electrical performance mainly through the optimization of the OMCVD epitaxial growth parameters and conditions. Since the solar cell device performances is a strong function of the epitaxial growth temperatures and rates, active gas flows, and other parameters, rigorous control of these conditions can result in epi-layers that have low defect density levels. The epi-layers are therefore characterized extensively both during (*in-situ*) & after the growth process. A summary of several tests that are performed to assure epi-layer quality is shown in Table I.

Table I – Epi-layer characterization tests

Test	Measurement
In Situ Reflectrometry	Epi-Layer Quality
Surfscan	Particles, Haze, Defects
PL- Mapping	Bandgap & Thickness Uniformity
X-Ray	Compsition & Lattice-Matching
Polaron Profiler	Thickness & Doping

The approach of optimizing epi-layer quality results in the development of a higher efficiency solar cell that has the same epitaxial structure as the heritage 1st generation ATJM cell. Additionally, the 2nd generation ATJM cell is mechanically identical to the 1st generation ATJM cell in every respect. This includes the processing parameters such as metallization, anti-reflection coating, Ge substrate, annealing, etc.

The target minimum BOL average efficiency for this cell is 28.5%. Typical electrical performance parameters under AM0 illumination conditions are shown in Table II.

Table II – Typical illuminated electrical parameters for the 2nd Gen. ATJM

Voc (mV)	Jsc (mA/cm2)	Fill Factor (%)	Efficiency (%)
2,650	17.3	84.0	28.5

An efficiency histogram of several solar cell OMCVD epi-layer growth lots is shown in Fig. 8. Several of these lots exhibited an average efficiency that exceeded 28.5% (each lot is comprised of about 26 large-area solar cells).

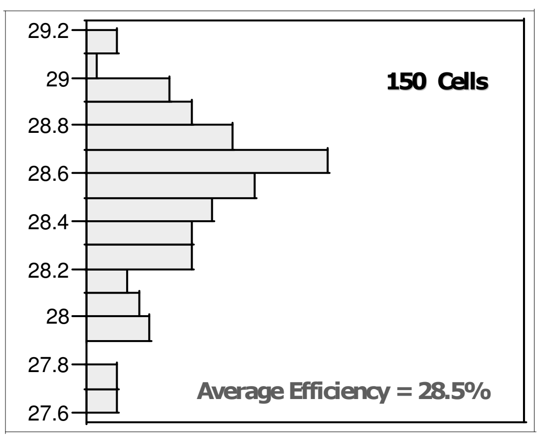


Fig. 8 – One-sun AM0 efficiency distribution for several lots (150 cells) of 2nd Gen. ATJM solar cells

As mentioned earlier, all ATJ-based solar cells were designed for best EOL performance. A comparison of the EOL vs. BOL performance parameters for the TJ, ATJ/ATJM, and 2nd generation ATJM under 1-MeV electron irradiation for two most commonly tested electron fluence levels are shown in Table III.

As shown in Table III, for the first time, EOL cell efficiencies in excess of 24% and 25% are shown for 1-MeV electron irradiation fluences of 1E15 & 5E14 e/cm^2, respectively.

Table III – EOL performance parameters (one-sun, AM0) for TJ, ATJ/ATJM, & 2nd Gen. ATJM cells

Solar Cell Technology	BOL Min. Ave. Efficiency(%)	1-MeV Fluence (e/cm^2)	P/Po	EOL Min. Ave. Efficiency(%)
TJ	26.0	5E14	0.91	23.7
		1E15	0.87	22.7
ATJ/ATJM	27.5	5E14	0.89	24.5
		1E15	0.85	23.4
2nd Gen. ATJM	28.5	5E14	0.89	25.4
		1E15	0.85	24.2

Summary

Emcore Photovoltaics is currently in volume production of n/p InGaP/InGaAs/Ge advanced triple-junction (ATJ) & ATJM (with the monolithic diode) solar cells with a minimum average shipping lot efficiency of 27.5%. The ATJ cell structure exhibits an EOL efficiency of 24.5% (1-MeV electron irradiation, 5E14 e/cm^2 fluence). More than 70,000 ATJ cells have been shipped for various flight programs. Emcore is also in the development phase of a 2nd generation ATJM solar cell. Preliminary development lots have exhibited a BOL minimum average efficiency of 28.5%.

References

[1] M.A. Stan, P.R. Sharps, N.S. Fatemi, F.S. Spadafora, D.J. Aiken, and H.Q. Hou, “Design and Production of Extremely Radiation-Hard 26% InGaP/GaAs/Ge Triple-Junction Solar Cells” in: Proc. 28th IEEE PV Specialists Conf. (IEEE, Piscataway, 2000) pp. 1374-1377.

[2] D.J. Aiken, N.S. Fatemi, C.S. Murray, P.R. Sharps, F.A. Spadafora, and M.A. Stan, “High Efficiency Triple Junction Manufacturing and Development at Emcore Photovoltaics” Proceedings of the 17th SPRAT (2001).

[3] N.H. Karam, et al., 2nd World Conference on Photovoltaic Solar Energy Conversion, (1998), p. 3534.