Production Ready 30% Efficient Triple Junction Space Solar Cells

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ABSTRACT

Spectrolab presents its next production GaInP/GaAs/Ge space triple junction solar cell, the XTJ space solar cell, averaging 29.8% efficiency at maximum power (AM0, 28ºC, 135.3 mW/cm^2) at beginning-of-life (BOL) testing of large populations (845 cells) of large-area solar cells without coverglass. Bare cells from this population with area of 26.62 cm^2 have been tested to a maximum efficiency of 31.1% under the same AM0 testing. Additional optical and electrical performance characterization will be presented. XTJ is more than a BOL power improvement over heritage products. Bare cell radiation testing shows power retention at max power (NP_{mp}) of 0.89 and 0.84 after irradiation with 1-MeV energy electrons to a fluence of 5e14 cm^{-2} and 1e15 cm^{-2}, respectively. Environmental degradation testing of XTJ parts shows only 1.7% degradation for more than 4000 hours at 250ºC and no degradation after 90 days at 95% r.h. and 45ºC. Together these characteristics enable XTJ to be a 7% improvement in end-of-life cost of power on space flight panel over Spectrolab's 28% BOL efficient UTJ. Finally, XTJ engineering confidence thermal cycle testing and qualification status to the AIAA S-111-2005 standard will be elaborated.

INTRODUCTION

Over the past 51 years Spectrolab, a Boeing subsidiary has produced the highest power space solar cells. Spectrolab's heritage stretches from silicon solar cells that flew to the moon with the Apollo astronauts to today's cells for large commercial satellites, the state-of-the-art Ultra Triple Junction (UTJ) GaInP/GaAs/Ge solar cells with minimum specification average 28.0% efficiency at load point (AM0, 135.3 mW/cm^2, 28ºC, 2.31V load point). In the recent generation of multijunction III-V based devices, Spectrolab has improved its products with an average of 0.8% abs efficiency improvement per year.

This improvement has come with large scientific and development efforts for each generation. Most notably these efforts have spanned growth of III/V GaAs single junction on Ge substrates[1-2], addition of a GaInP top subcell to fabricate some of the first dual junctions for space[3-4], inclusion of the Ge junction to fabricate a true 3J monolithic device[4-5] and improvements to the fabrication methods optimizing band gap combinations to produce the latest Improved Triple Junction (ITJ)[6] and Ultra Triple Junction (UTJ)[7-9] devices. These devices have operated in many flight configurations and some, such as DJ products, have operated on orbit for almost a decade.[10]

To continue this trend Spectrolab presents XTJ as the last evolution of the upright GaInP/GaAs/Ge a cell, averaging near 30% at beginning-of-life (BOL) in ground testing of production scale product. This paper will present the results of engineering confidence testing on the XTJ design including BOL characteristics for cells produced on Spectrolab's manufacturing line. With substantial effort taken to improve multiple aspects of multijunction solar cells, XTJ is a comprehensive improvement over the traditional 3J products available on the market.

EXPERIMENT

Eight hundred forty five large area XTJ bare cells were fabricated for engineering confidence testing in multiple production lots using Spectrolab standard production equipment. All wafers used were grown on three of Spectrolab's production metal-organic vapor phase epitaxial reactors. In this process, certain key production parameters were systematically varied to ensure that the population produced not only represented what was achievable by production, but also included intentional variation beyond the upper and lower control limits. Thus, data could be collected for the worst-case scenario. In all, these parts represent roughly1/3rd of the final 845 parts, or about 300 parts. Using this design variation formalism for development, one may generate with confidence an absolute minimum average in efficiency and very mature distribution. Thus the data presented here will run slightly lower than that anticipated in production. These values are shown only as confidence data and specification production values will be set at completion of full space qualification. The data shown in a spirit of sharing the rigor under which XTJ was developed.

The distribution of efficiency at maximum power for the 845 bare cells of the final design is shown in figure 1.

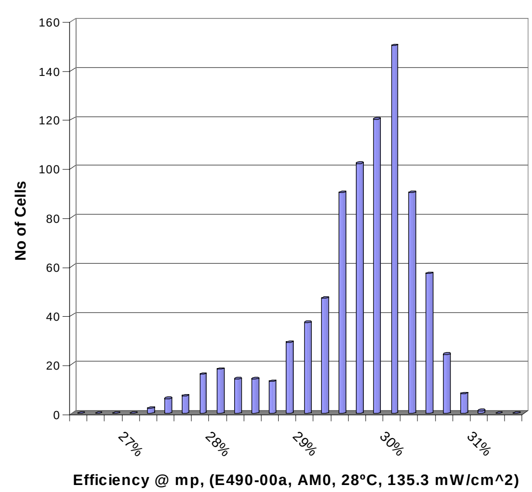

Fig. 1. Histogram of the Efficiency at maximum power for 845 engineering confidence 26.62 cm^2 XTJ bare cells.

These cells were tested under simulated AM0 spectrum (AM0, 135.3 mW/cm^2, E490-00a) at 28ºC using s Spectrolab X-25 solar simulator that was setup using iso-cell standards of XTJ that were spectrally calibrated to UTJ balloon flight standards. The shape of the distribution is a skewed normal population typical of mature multijunction solar cell process. The average of the population is 29.8 +/- 0.4% at maximum power and 29.6 +/- 0.4% at the chosen load point of 2.29V. The peak in the distribution is at 30.2%, which is a good indicator of long-term production efficiency. The population was yielded for cells below 27% efficiency. In short, almost all the cells generated is represented in figure 1. The maximum cell efficiency was 31.1% produced in these builds. In previous measurements, XTJ early designs yielded bare cells reaching 31.5% efficiency at maximum power for a 26.62 cm^2 bare cell under similar conditions.

Given the stress conditions which produced this distribution mentioned above, we anticipate that XTJ will average 29.7% efficiency at a load point of 2.29V and above 30% efficiency at maximum power in long-term production.

Table 1 shows the typical illuminated current-voltage (LIV) characteristics of the XTJ cells produced in the engineering confidence builds in comparison with the UTJ specification values. Note that XTJ represents an increase in current density at short-circuit (J_{sc}) and at max power (J_{mp}) over UTJ. Meanwhile, open circuit voltage (V_{oc}) and maximum power voltage (V_{mp}) drop slightly from UTJ values.

Table 1 – Typical LIV characteristics of XTJ engineering confidence builds. (AM0, 135.3 mW/cm2, 28ºC, bare cell)

Type	V_{oc} (V)	V_{mp} (V)	J_{sc} (mA/cm^2)	J_{mp} (mA/cm^2)	FF (%)	Eff_{mp} (%)
XTJ	2.628	2.333	18.10	17.29	84.8	29.8
UTJ	2.665	2.350	17.05	16.30	84.0	28.3

Under radiometric testing of XTJ parts, the solar absorptance, α, for both bare cells and coverglass parts (CIC's) is reduced from that of UTJ. Under 5 mil CMG AR coated coverglass, as a typical glassed example, α drops for from 0.926 ± 0.003 for 6 measured UTJ cells to 0.889 ± 0.009 for 24 measured XTJ cells. This reduction in absorptance will translate to a corresponding reduction in operating temperature on panel of about 2 to 3ºC, depending on panel conditions. As the efficiency of all pn-junction solar cells reduce with temperature, this reduction in temperature elevates the operating efficiency of XTJ over UTJ on panel in addition to the gains in 28ºC BOL testing quoted above.

ENVIRONMENTAL TESTING

While an improvement in BOL efficiency is useful, space flights are typically designed with end-of-life (EOL) conditions as the mission limit. The XTJ confidence build parts were tested under multiple environmental conditions to ensure high performance throughout the anticipated mission lifetime. IT should be re-emphasized that these values are only taken as preliminary measurements of XTJ devices and do not constitute a specification values, which will be set at time of completion of the qualification.

In preliminary testing under 1-MeV electron irradiation of 2x2 cm^2 samples fabricated at the same time as the large cell parts above, the XTJ parts degrade in a very similar manner to its heritage UTJ design. Figure 2 shows the maximum power retention of 6 samples per group under 1-MeV electron irradiation performed under standard conditions at the JPL PRESSL facility. Note that XTJ has the exact same degradation rate

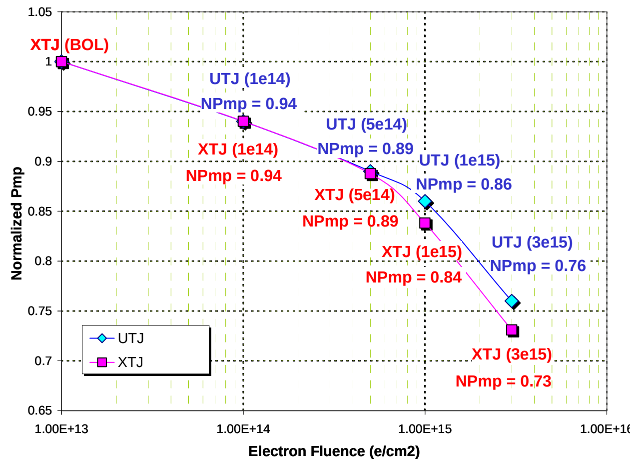

Fig. 2. Relative degradation rate in normalized maximum power (NP_{mp}) for XTJ and UTJ 2x2 cm^2 cells under 1-MeV electron irradiation.

as UTJ up to a fluence of 1e15 electrons/cm^2 at which point it degrades slightly faster at an NP_{mp} of 0.84.

Table 2 shows the characteristics of XTJ and UTJ for voltage, current, & efficiency retention at 28ºC. XTJ cells under 1-MeV radiation degrade nearly identically to UTJ cells. [11-12]

Table 2 – Preliminary normalized parameter retention under 1-MeV electron fluence, in e-/cm^{-2}.

Parameter	1 x 10^{14}	5 x 10^{14}	1 x 10^{15}
NP_{mp}	0.94	0.89	0.84
NJ_{mp}	1.00	0.98	0.95
NV_{mp}	0.94	0.90	0.88
NJ_{sc}	1.00	0.99	0.97
NV_{oc}	0.94	0.90	0.88
NFF	1.01	1.00	0.98

Irradiation under 3-MeV proton was performed on XTJ samples and UTJ control samples.3-MeV was chosen as a comparison to fully-penetrate the epitaxial layers of UTJ and XTJ, with a stopping range within the Ge subcell. Figure 3 shows the results of the retained power for XTJ and UTJ control samples. Note that XTJ for all fluences tested (1e11, 5e11, and 1e12 p/cm^2) showed a slightly higher power retention than the UTJ control samples by 2%. XTJ parts showed a slightly better voltage retention in both max power and open circuit voltage than their UTJ controls. Otherwise the parameter retention was identical.

The results are encouraging. However, due to the small sample size, they are not significant enough to pronounce XTJ performance under proton radiation is improved over

UTJ. Full qualification testing with multiple proton energies and fluences will be required to accurately characterize the response. .

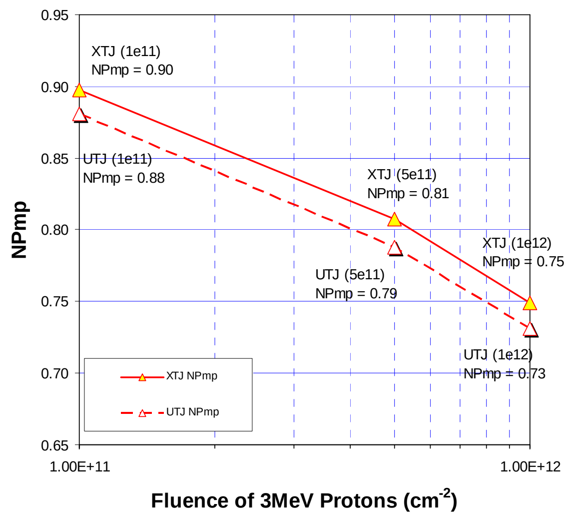

Fig. 3. Relative degradation rate in normalized maximum power (NP_{mp}) for XTJ and UTJ 2x2 cm^2 cells under 3-MeV proton irradiation.

Table 3 – Preliminary normalized parameter retention under 3-MeV proton fluence, in p+/cm^{-2}.

Parameter	1×10^{11}	5×10^{11}	1×10^{12}
NP_{mp}	0.90	0.81	0.75
NJ_{mp}	0.98	0.95	0.91
NV_{mp}	0.92	0.85	0.83
NJ_{sc}	0.99	0.98	0.95
NV_{oc}	0.92	0.87	0.85
NFF	0.99	0.95	0.93

Table 4 shows the preliminary temperature coefficients as measured over 15ºC to 70ºC for UTJ and XTJ at BOL and after 1e15 cm^{-2} 1-MeV electrons.[11-12] The voltage temperature coefficients are nearly the same for UTJ & XTJ for all fluences. With a temperature coefficient 12.3 µA/ºC/cm^2 for current density at max power (dJ_{mp}/dT) is significantly larger for XTJ than for UTJ for the irradiated parts. While UTJ dJ_{mp}/dT at 1e15 cm^{-2} is 5.0 µA/ºC/cm^2 This increased temperature coefficient arrises from a lower power retention in max power current NJ_{mp} for XTJ after irradiation than for UTJ. Thus the temperature coefficient improvement negates the effect of lower room temperature power retention. At higher temperatures where space panels typically operate, XTJ's NP_{mp} after irradiation and at temperature on panel will be slightly better than for UTJ.

Table 4 – Preliminary Temperature Coefficients

Cell	Parameters	BOL	1×10^{15}
UTJ	dJ_{mp}/dT (µA/cm^2/ºC)	1.0	5.0
UTJ	dV_{mp}/dT (mV/ºC)	-6.5	-6.7
XTJ	dJ_{mp}/dT (µA/cm^2/ºC)	8.1	11.7
XTJ	dV_{mp}/dT (mV/ºC)	-6.5	-6.8

Under humidity exposure for 90 days at 45ºC and 95% relative humidity, 15 welded, 26.62 cm^2 XTJ bare cells (ICs) representing the worst care scenario showed no degradation to experimental error. Under thermal soak at elevated temperature similar characteristics were observed for welded bare cells. Table 5 shows the relative degradation in maximum power observed after a cumulative 4176 hours for the average population of 8 XTJ large size ICs at 200ºC and 250ºC. After 4176 cumulative hours, the XTJ parts degraded 1.1% and 1.7% under 200ºC and 250ºC respectively. From previous experience, typical mission thermal soak load for a standard GEO mission is about 12 hours at these temperatures. In total, 4176 hours accumulated is equivalent to ~348 mission lifetimes. In effect, we should see no degradation over typical GEO mission conditions for XTJ.

Table 5 – Percent degradation in maximum power for XTJ welded interconnect (IC's) bare cells under humidity and/or thermal soak.

Condition	Cumulative soaked time	% deg in Pmp
Humidity, 45ºC, 95% R.H.	90 days	-0.0%
Thermal, 200ºC	4176 hours	-1.1%
Thermal, 250ºC	4176 hours	-1.7%

As a final demonstration of the robustness of XTJ, a demonstration 23.5" x 20.5" coupon of 90 CIC's has been thermal cycled at Spectrolab. These panels are composed of XTJ CICs with 5 mil CMG AR coated coverglass, bonded using standard Spectrolab processes, and using P3 bypass diodes and 2 Ag clad kovar extended Mark II interconnects per cell. These cells are divided into 6 circuits of 15 cells each. Each string represents a specific experimental design variation as chosen from the population of engineering confidence cells described above. The coupon was exposed to bake-out under vacuum at 60ºC for 6 hours, followed by 24 hours at 85ºC, then by dryout for 90ºC. The coupon was then cycled for -172ºC to +140ºC for 500 cycles. After 500 cycles no degradation is observed in any of the 6 strings in either room temperature (28C) or at elevated temperature large area pulsed solar simulator (LAPSS) testing. After 1500 cycles is complete the coupon will be cycled with increasing the maximum temperature to 150ºC for an additional 100 cycles and then to 160ºC until destruction. This temperature was chosen as the maximum temperature that the substrate could withstand before it will fail.

Given all the data on performance at BOL, under equivalent electron irradiation, and at elevated temperature, we may then estimate the net effect on the total number of cells required to provide a satellite with a set EOL power requirement. Figure 4 shows a comparison of the number of cells required for a given mission power for XTJ and UTJ cells of same area under some simple assumptions. These assumptions are that the bus voltage was 100V, the glassing gain was identical between XTJ and UTJ, the panel operated at a nominal 70ºC when illuminated, and that the power (voltage and current) at EOL were the same for both cell types. For small power missions to large power missions, XTJ maintains a ~7% decrease in number of required cells. XTJ is more than a small improvement in BOL power. It is a comprehensive engineered improvement to deliver power where the space PV customer needs it: on orbit, at temperature, on panel for their mission.

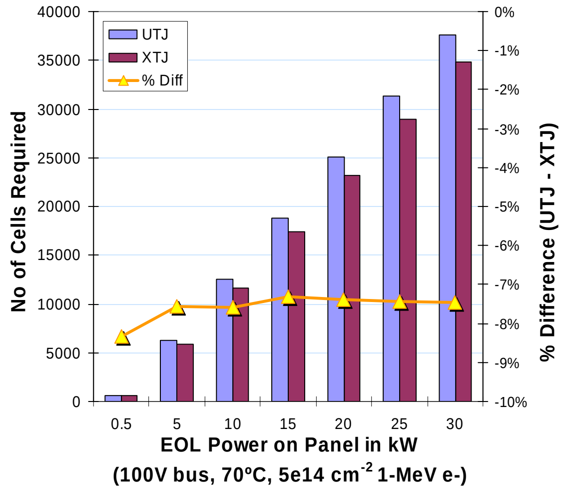

Fig. 4. Number of cells required on panel to meet mission power at EOL at 70ºC, 100V bus, and after 5e14 cm2 1-MeV electrons for XTJ and UTJ. Percent difference in number of cells is shown on the r.h. axis.

With the exceptionally strong battery of development and engineering testing accrued in XTJ development, the cell has passed Spectrolab internal design gates, including internal design review and is now cleared for qualification.

AIAA S-111-2005 QUALIFICATION

To qualify XTJ space solar cells for flight, Spectrolab is under contract with the Air Force MANTECH office to perform the first qualification of a space solar cell to the new AIAA S-111-2005 standard. At present time this qualification effort is ongoing and expected to complete early in 2009. Spectrolab is also pursuing multiple customer specific qualification testing. We anticipate that XTJ will be available to programs not requiring qualification to AIAA S-111-2005 in the middle of 2008.

SUMMARY

In summary, the first 30% efficient space solar cell product, XTJ, has completed its initial engineering confidence testing and is ready to commence qualification to the AIAA S-111-2005 standard. Bare cell distribution with worst-case scenarios show a capability of producing 30% efficient solar cells. Radiometric testing of XTJ bare and CIC cells shows a decrease in solar absorptance, enabling a corresponding reduction in on-panel operating temperature. Robustness is ensured with strong environmental testing of cells, ICs and coupon that shows similar or improved degradation of a 30% BOL cell over heritage flight products at Spectrolab. XTJ will be qualified to the AIAA S-111-2005 standard under the help of the Air Force's MANTECH office.

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