

MULTIJUNCTION SOLAR CELL DEVELOPMENT AND PRODUCTION AT SPECTROLAB

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INTRODUCTION

Development of multijunction space solar cells is much like that for any high technology product. New products face two major pressures from the market: improving performance while maintaining heritage. This duality of purpose is not new and has been represented since ancient times by the Roman god Janus.[1] This deity was typically represented as two faces on a single head: one facing forward and the other to the rear. The image of Janus has been used as symbolism for many combined forces of dual purpose, such as the balance in life between beginnings and endings, or between art and science. For our purposes, Janus represents our design philosophy balance between looking to the future for improvement while simultaneously blending past heritage.

In the space photovoltaics industry there are good reasons for both purposes. Looking to the past, a product must have a space flight heritage to gain widespread use. The main reason being that this is an unforgiving business. Spacecraft are expensive to build, launch and operate. Typically once a satellite is launched, in-field service for a power systems problem is near impossible.[2]Balanced with this is looking forward. New missions typically require more power than previous programs or attempt new objectives such as a new orbit. And there is always the cost pressure for both the satellite itself as well as the launch costs. Both of which push solar technology to improve power density at a lower cost.

The consequence of this balance in a high-risk environment is that space PV develops as a series of infrequent large technology steps or generational changes interspersed with more frequent small technology steps or evolutionary changes. Figure 1 gives a bit of clarification on this point. It depicts the historical progress in space solar cells tracked by efficiency against first launch date for most major products introduced by Spectrolab. The first generation is the Si-based technology reaching a peak values near 15% AM0 (herein denoted for max. power, AM0, 1.353 W/cm², 28°C). The GaAs single junction device generation supplanted this technology with first flight of GaAs on GaAs substrate in 1982.[3] More recently this generation has been supplanted by the multijunction solar cell GaInP/GaAs/Ge generation. The first launch of a commercial satellite powered by multijunction technology was in 1997 (Hughes HS 601HP) using solar arrays based on Spectrolab's dual junction (DJ) cells. The cells at that time were an impressive 21.5% efficient at beginning-of-life (BOL).[4] Eight years later, the multijunction device has evolved through several versions. The incorporation of an active Ge subcell formed the Triple Junction (TJ) product line at 25.1% efficient, on orbit since November 2001. The evolution of the TJ into the Improved Triple Junction (ITJ) at 26.8% efficient has been on orbit since June of 2002.[5]

Currently, multijunction solar cells based in the GaInP/GaAs/Ge triple junction design are the dominant space PV generation. The efficiency of the highest power devices reaches over 28.3% (max power, AM0, 135.3 mW/cm², 28°C) for Ultra-Triple Junction (UTJ) enabling many space missions providing power for GEO missions up to a possible 30 kW on a single satellite.[5-6] The current market pressure to ever increasing on-orbit power are driving the standard triple-junction (3J) to its limits. This paper details the current status of Spectrolab's space PV products, and updates the progress toward the introduction of the first ever 30% efficient product, the XTJ, due in mid-2006.

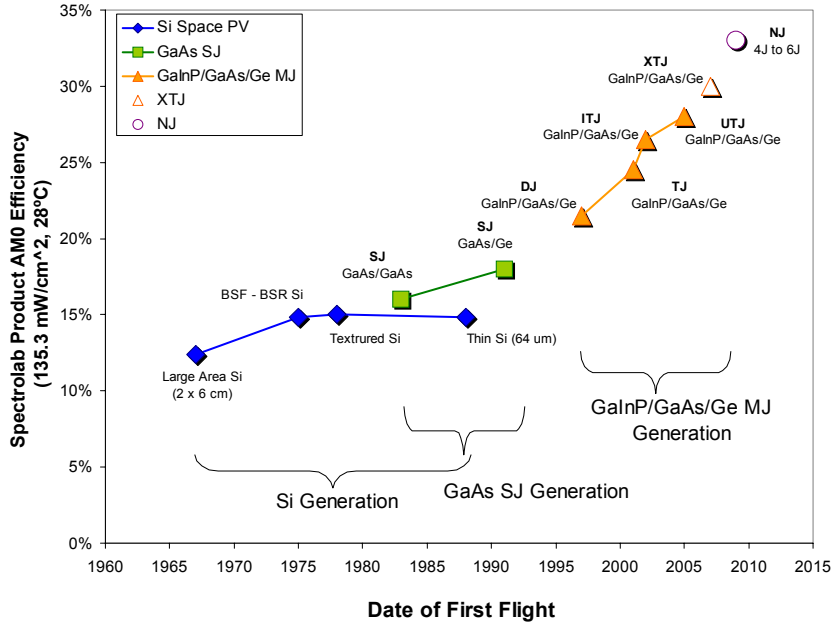


Figure 1 Historical product efficiency against date of first flight. Open points are for planned products and estimate flight dates.

HISTORICAL PROGRESS IN MULTIJUNCTION PHOTOVOLTAICS

Prior to embarking on a description of the state of the art 3J devices, it is instructive to recap the status of previous generation of devices. To enable the comparison, a schematic cross-section of a typical 3J device is shown in Figure 2. All generations of DJ through UTJ in production share this same basic structure. For a Dual Junction device, the same epitaxial layers on the Ge substrate are present. The Ge substrate is just treated such that no junction is formed.

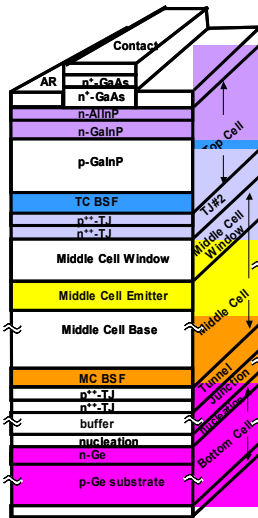


Figure 2. Schematic of the internal semiconductor layers in GaInP/GaAs/Ge multijunction solar cell.

Since the inception of the GaInP/GaAs/Ge Dual Junction occurred within past decade, it and other succeeding versions of 3J devices are still in production at Spectrolab. Figure 3 shows a histogram of the progression of device technologies tested at bare cell. The figure shows the efficiency at load voltage for each product. Common efficiencies at maximum power will be slightly higher. The figure also shows all devices with an area greater than 24 cm² fabricated for each product since tracking with the database began in approximately 1998. To date Spectrolab has produced over 2 million large area cells. The figure demonstrates the progression in average efficiency for each successive product with a step of approximately 1.5% absolute in efficiency for the three 3J products. As each product is introduced not only is the efficiency increasing but also the distributions become narrower. Each succession in technology simultaneously represents an improvement in manufacturing technology and base achievable efficiency. As the devices progress in efficiency, so are the techniques to manufacture them. This trend becomes key in achieving the most of any generation as will be discussed later.

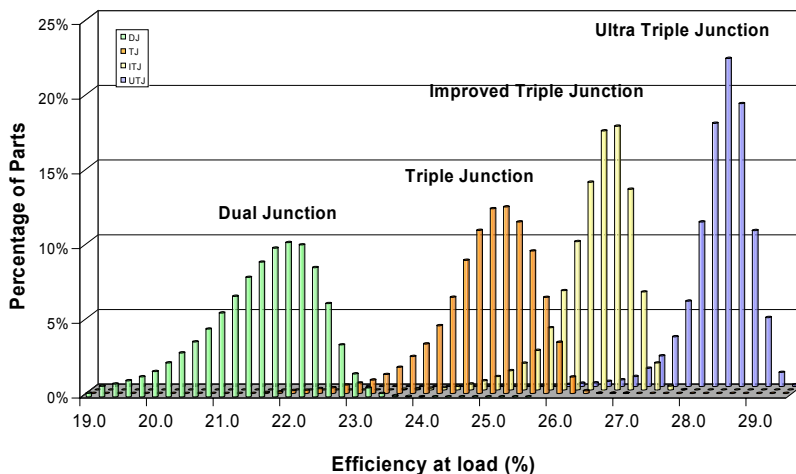


Figure 3. Efficiency at load voltage for all large area >24 cm² multijunction solar cells produced at Spectrolab.

With over 90,000 large area (>26 cm²) UTJ devices now fabricated, a few (28 to be exact) have reached over the 30% barrier. Figure 4 shows the Illuminated Current-Voltage (LIV) curve for a UTJ production bare cell that achieved 30.20% efficiency (max power, AM0, 135.3 mW/cm², 28°C). At the time of this paper’s publication UTJ cells will be on orbit providing power to more than one mission.

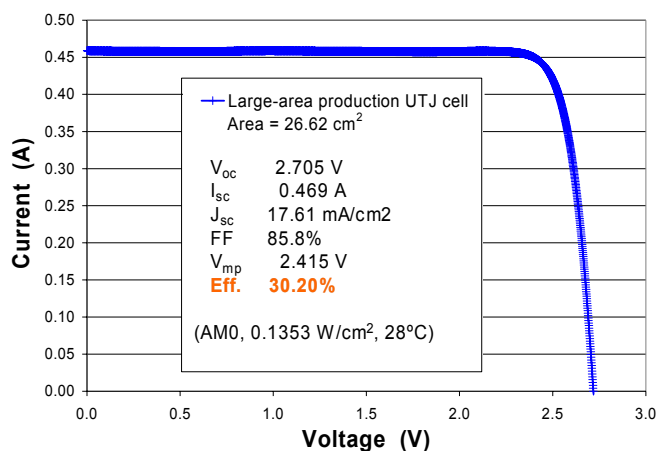


Figure 4. Highest attained efficiency at max power for UTJ production bare 26.62 cm² cell.

PROGRESS TOWARDS A 30% EFFICIENT SPACE SOLAR CELL

Spectrolab has targeted one more design evolution for this generation of MJ technology. The XTJ product is due to be released in mid 2006 and has a target efficiency of 30% at beginning of life (BOL) and 27% at end-of-life (EOL) at an equivalent 1-MeV electron fluence of $5e14 \text{ cm}^{-2}$. XTJ carries with it the heritage of the previous evolutions. Design features that make UTJ and previous products work well are carried forward into XTJ. And it follows our design philosophy of Janus of improving the cell while simultaneously maintaining heritage. However achieving this latest generation is not simple. To elucidate, we turn our focus to exactly why XTJ is different.

The multijunction generation based on GaInP/GaAs/Ge is a nearly mature technology. One descriptive way to observe this is depicted in Figure 5. It shows the peak AM0 efficiency, or record, for a given evolution plotted simultaneously with the production average efficiency at max. power for each MJ product at Spectrolab. In recent years, the maximum attainable efficiency has been slowly increasing, peaking at or very near 30%. As the technology has matured, there appears to be fewer further base efficiency changes to improve the peak efficiency left in this design generation. Meanwhile production efficiency has maintained a 3% absolute efficiency offset between this technology maximum and the average. This gap has narrowed with UTJ to about 2% abs.. To reach 30% efficiency we must rely not only improving this baseline efficiency or maximum achievable, but also improve our ability to manufacture closer to this limit.

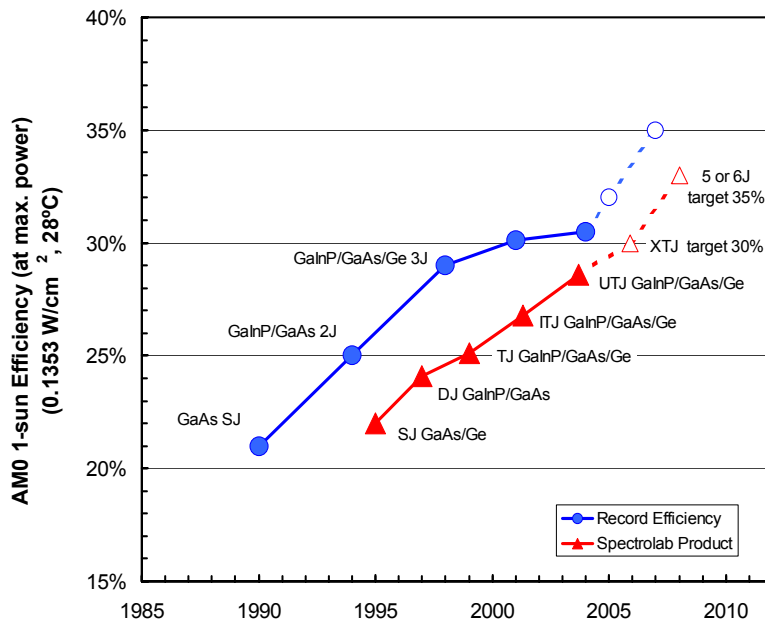


Figure 5. Record (circles) and average (triangles) production efficiency for the multijunction solar cells at Spectrolab. Open points represent future estimates.

The first key in closing the gap between the record cells and the manufactured cells is in eliminating internal inefficiencies in the design structure. A classic example of such design inefficiency is the relative current density degradation rate of the subcells. This aspect was tackled in UTJ and was instrumental in helping close the gap to 2% between the product and the record.[5] In traditional multijunction cells, the middle cell current density degrades at a faster rate than the top subcell.[3-4] To achieve the highest possible EOL power the designs are targeted to be current matched at the typical mission lifetime equivalent 1-MeV electron irradiation fluence of about $5e14 \text{ cm}^{-2}$. In UTJ the cells are engineered to degrade at nearly the same rate. This is seen in Figure 6 which shows the normalized spectral response current, N_{JSR} or $J_{\text{SR}}(\Phi)/J_{\text{SR},0}$, from component subcells irradiated under 1-

MeV electron irradiation. The Ge subcell is seen to not degrade under this fluence of electrons. The top and middle subcells degrade at very nearly the same rate, each ending at only 1% difference at $5 \times 10^{14} \text{ cm}^{-2}$ and 1.5% difference at $1 \times 10^{15} \text{ cm}^{-2}$. Thus the cells maintain the current balancing established at BOL. The BOL performance is allowed to approach the maximum possible. Note that this is also accomplished without sacrificing EOL performance on the whole as UTJ retains its power at 0.89 (NP_{mp} at $5 \times 10^{14} \text{ cm}^{-2}$) the same rate as earlier generations.[3-5] XTJ incorporates this same engineering by being built upon UTJ maintaining heritage for reliability.

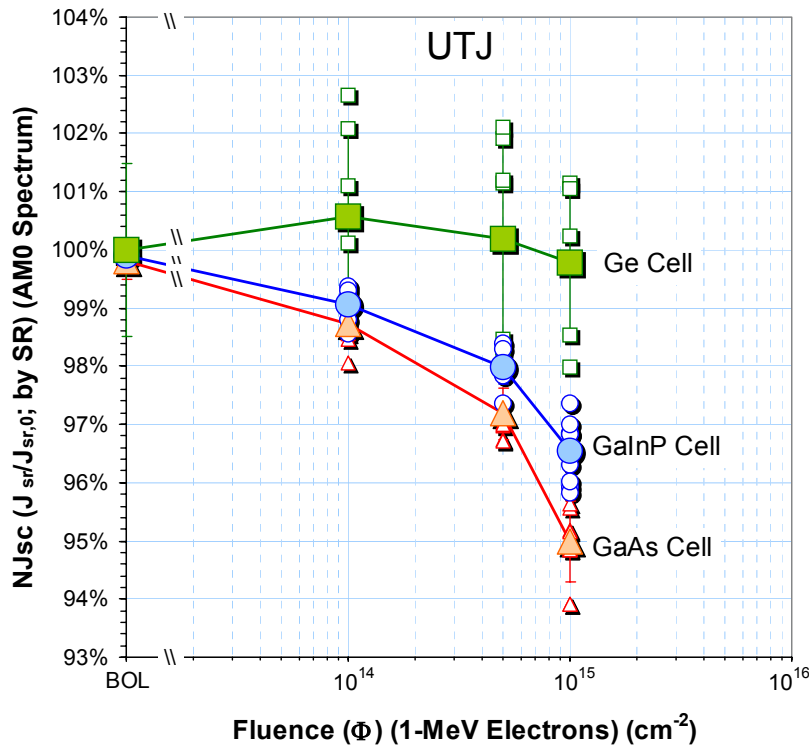


Figure 6. Current retention as measured by spectral response for component subcells in UTJ under 1-MeV electron irradiation plotted against fluence. The filled points are averages for the group and the open points are the individual cells tested. The squares represent Ge subcells, Circles for the GaInP top subcell and the triangles are for the GaAs middle subcell.

The second key to improving 3J GaInP/GaAs/Ge to 30% efficiency is in improving the maximum achievable efficiency. Experiments shown previously and the UTJ product exceeding 30% demonstrate that the base technology can be pushed a little further.[7] As XTJ is still in development and multiple options are still exist for its final structure and performance characteristics, we are unable to share more details than this.

The third key is in improving the manufacturing process to close the gap between the maximum and the average production efficiency. Experiments in XTJ development have focused on this aspect. Figure 7 shows the net results of one such experiment in tightening the efficiency distribution of our manufacturing process for UTJ. The figure depicts the efficiency obtained from two separate wafer processing lots fabricating 24 full-size cells each of 26.6 cm^2 UTJ wafers tested as bare cells. The epitaxial runs were randomly distributed between the lots so only differences in the wafer cell processing are observed. The figure shows a histogram on the left axis for all cells tested. The right axis corresponds to the smooth curve first of a Gaussian probability distribution normalized to 1 for each process. The standard process averages an approximate full width at half maximum (~fwhm) depicted by 2x standard deviation of 0.8% abs. and an average efficiency at max. power of 28.6%, making this batch a nominal

UTJ bare cell lot. The enhanced process increases in efficiency by 0.1% abs. above the standard to 28.7% average. What is important is that the ~fwhm reduces by a factor of 2 to 0.4% abs. The enhanced version then will allow XTJ to eliminate or reduce the low efficiency parts and decrease the gap between the maximum and the average efficiencies.

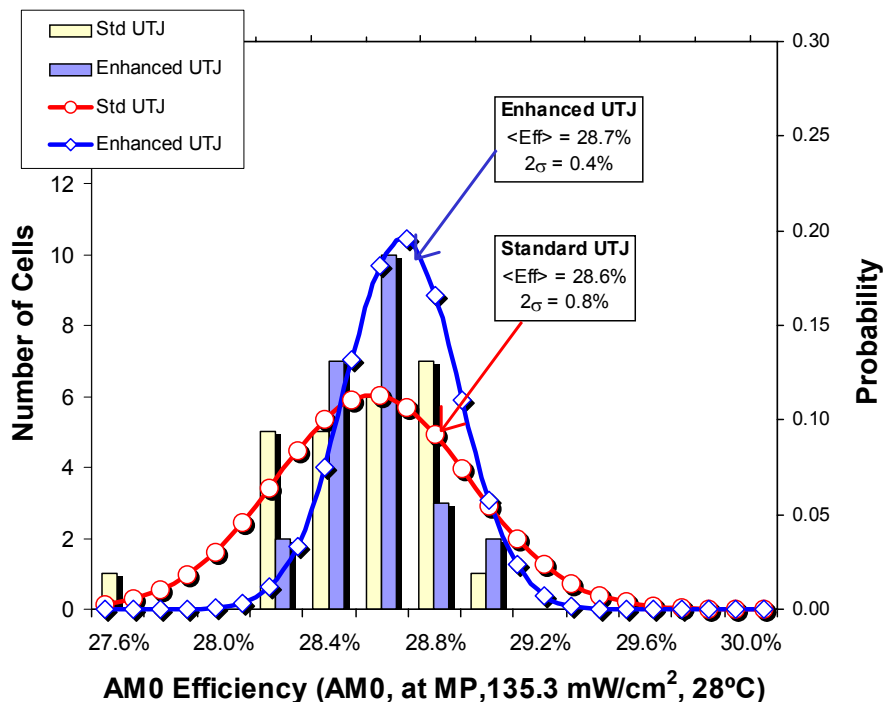


Figure 7. AM0 efficiency (1.353 W/cm², 28C) for large area (26.62 cm²) 52 bare UTJ cells tested with the standard processing lot and the enhanced processing lot.

BEYOND XTJ

One can readily see from Figure 5 that to achieve efficiency beyond 30%, there will have to be a substantial change in architecture. NJ as the targeted product for this break then represents not just an evolution but also a new generation of cell. Currently NJ is only defined by its target efficiency of 33% AM0 BOL. The difficulty then becomes one of making the correct break with the current design structure. There are many proposed ideas on the table and it will take a few years of dedicated research to identify the correct path. And this effort will demand substantial effort in establishing this next generation of technology for reliability and manufacturability.

A few things are clear at this point about what that next generation of cell must do. The cell will take advantage of the heritage multijunction engineering. And the generation must also pose possibility for multiple design evolutions. Beyond those requirements our own creativity and device physics appear to be the only major limits in achieving efficiencies approaching 40%. At Spectrolab, we optimistically look forward to the challenge.

SUMMARY

In the high-risk environment of space, solar cells develop under the dual pressures of maintaining heritage while improving performance. This juxtaposition of opposing forces has led to solar cell products to develop as

generations of devices and each product within that generation being an evolution on a basic a common architecture. The current multijunction generation of GaInP/GaAs/Ge 3J devices began its flight heritage at Spectrolab in 1997 with DJ and now is on orbit as UTJ at 28.3% efficient. As we reach the mature device architecture reaching the last evolution on this generation appears to end at 30%. To reach that efficiency in production, small modifications are being made to the cell epitaxial structure and to the wafer processing. These changes are designed around three main areas. First, We need to remove internal inefficiencies such as the degradation rate under 1-MeV electrons in UTJ where the top and middle subcells degrade at nearly the same rate. Second, we are making small improvements to the base architecture allowing a slightly higher maximum efficiency. And third, we are making improvements in the manufacturing control of the cell. The next cell architecture NJ appears to be a novel generation of products, and will hopefully extend space solar cell efficiencies to 40%.

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