ADVANCED III-V MULTIJUNCTION CELLS FOR SPACE

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ABSTRACT

III-V solar cells have become the dominant power generation technology in space, due to their unparalleled high efficiency, reliability in the space environment, and ability to be integrated into very lightweight panels. As remarkable as these attributes are, new types of space III-V solar cells are continually reaching new heights in performance. Commercially-available multijunction solar cells with 30% conversion efficiency under the AM0 space spectrum are just around the corner. Understanding of radiation resistance and thermal cycling reliability has reached levels never before attained, and is resulting in new standards of reliability. A flurry of research activity has resulted in very-thin, flexible, and extremely lightweight space solar cells and panels in several groups around the world, capable of being folded or rolled into a smaller stowage volume for launch than has been possible to date. This approach combines the very high efficiency and reliability of III-V multijunction cells with the thin, flexible PV blanket functionality normally associated only with thin-film polycrystalline or amorphous PV technology. This paper discusses the latest developments in III-V space solar cell technology, and explores opportunities for still higher performance in the future.

INTRODUCTION

The last decade has seen a remarkable explosion in the technology of photovoltaic cells designed for use in space [1-3]. During this relatively short time, multijunction III-V solar cells have become the standard for space power generation, at long last fulfilling their theoretical promise to deliver higher efficiency than the best single-junction cells. Early concerns about controlling the composition and thickness of the multiple semiconductor layers that make up a multijunction solar cell, and about the transparency and conductivity of tunnel junction layers, have largely fallen by the wayside. Overcoming these obstacles is now an accomplished fact, but similar questions still arise as we look to the future of space photovoltaics. The historical perspective provided by the development of today's triple-junction cells suggests that we will find ways to tap the higher theoretical efficiency of new multijunction cell designs, and to achieve the level of control needed to grow even more complex cell architectures, such as 5- and 6-junction solar cells.

The weight and volume of a stowed solar array have always been paramount concerns for photovoltaic power generation systems on satellites, due to the tremendous cost of lifting a payload into orbit. Now III-V multijunction cell technology seems poised to combine the stellar efficiencies of this type of cell with the high specific power (W/kg) and very small stowage volume of flexible photovoltaic blanket arrays.

Reliability of space cells under the extreme conditions of launch and space operation is also critically important. Radiation exposure, thermal cycling, vibration, atomic oxygen, contamination from volatile materials, and electrostatic discharge are all part of operating in the space environment, and must therefore be part of the qualification process for space cells and panels. As a result of extensive environmental testing, space solar cells have reached new heights of predictable performance.

High-Efficiency Multijunction Space Solar Cells

Figure 1 charts the AM0 efficiency distributions for the last four generations of multijunction space cells produced at Spectrolab, Inc., the dual-junction (DJ), triple-junction (TJ), improved triple-junction (ITJ), and ultra triple-junction (UTJ) solar cell products. Each successive generation of high-efficiency space solar cell has not only shifted upward in average efficiency, but has also had a striking reduction in width of the distribution, indicating better uniformity and reproducibility for each new type of these production space cells.

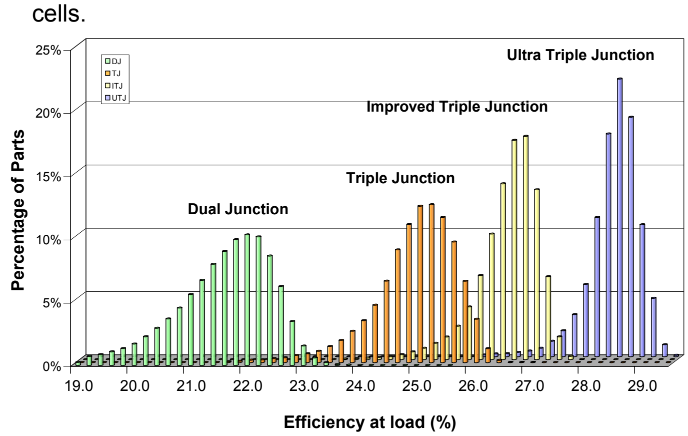

Fig. 1. AM0 efficiency distributions of 4 generations of Spectrolab space solar cells.

In Figure 2 the efficiency of Spectrolab space solar cells is plotted versus the year those cells were first flown on a spacecraft, stretching back to silicon cells in the late 1960's. The trend of increasing beginning-of-life (BOL) efficiency takes a sharp turn upward in the late 1990's, with the advent of multijunction cells, increasing by nearly one absolute percent in efficiency per year. This growth rate is projected to continue with the new solar cells in development today: the XTJ solar cell with 30% minimum average AM0 efficiency; and a new generation of cells with 4 to 6 junctions, the nJ cell with 33% efficiency.

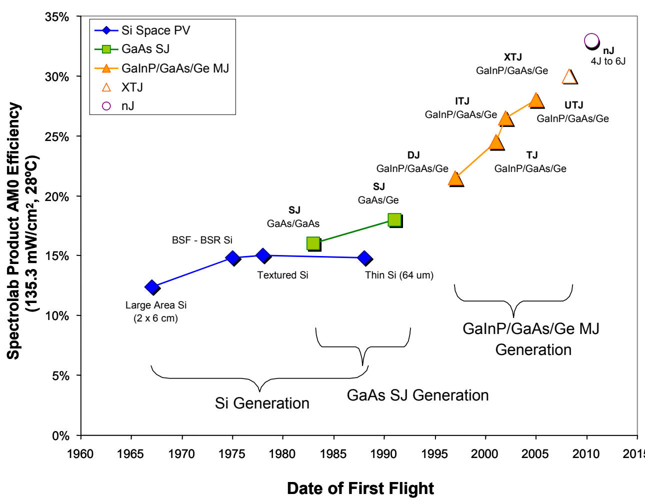

Fig. 2. Space solar cell efficiency versus the year each new solar cell product was first launched into orbit.

The drive toward commercially-available space cells with an average efficiency of 30% has resulted in prototype quantities of XTJ cells with record AM0 efficiencies, giving confidence that the performance targets of the XTJ cell can be met relatively soon. The distribution of 125 demonstration cells with average AM0 efficiency of 30.3%, and 31.0% maximum efficiency, is shown in Fig. 3. The distribution of UTJ cells processed at the same time is shown for comparison. These prototype XTJ cells still need to go through qualification, but their measured performance gives confidence that space solar cells with 30% minimum average efficiency will be commercially available soon.

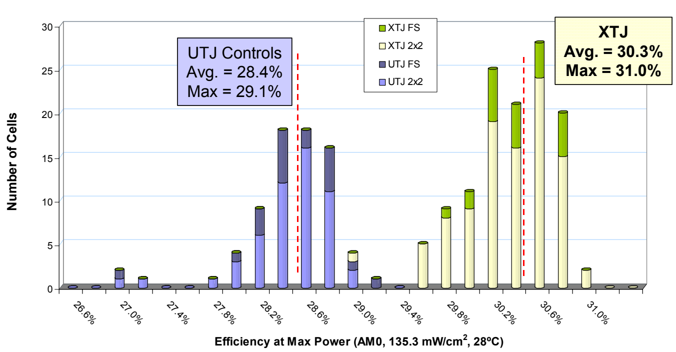

Fig. 3. AM0 efficiency distribution for 125 XTJ bare cells, with areas of 4 cm^2 and >26 cm^2, tested using calibration standards traceable to balloon flight reference cells.

To achieve higher efficiencies, a more radical departure from conventional 3-junction space cell architecture is needed, one which has a higher theoretical efficiency ceiling. One such approach is the use of metamorphic, or lattice-mismatched materials, to tune the bandgaps of the individual subcells of a multijunction cell to the solar spectrum for maximum conversion efficiency [4-7]. Another approach is to divide the solar spectrum more finely using a greater number of junctions, such as 5- and 6-junction cells [4,8]. Fig. 4 shows the partition of the solar spectrum by the bandgaps in a AlGaInP/ GaInP/ AlGaInAs/ GaInAs/ GaInNAs/ Ge 6-junction cell. Schematics of 5- and 6-junction solar cells, including a ~1.1-eV GaInNAs subcell lattice-matched to Ge, are shown in Fig. 5.

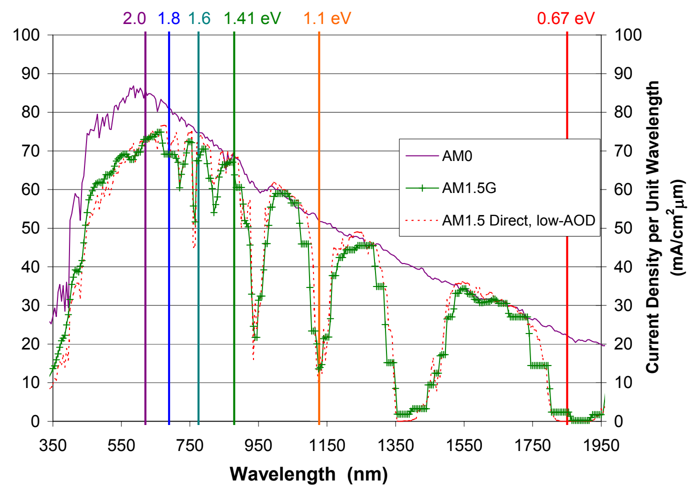

Fig. 4. Wavelength partition of the AM0 space, and terrestrial AM1.5 Global and AM1.5 Direct, low-AOD spectra, by the subcell bandgaps of a 6-junction cell.

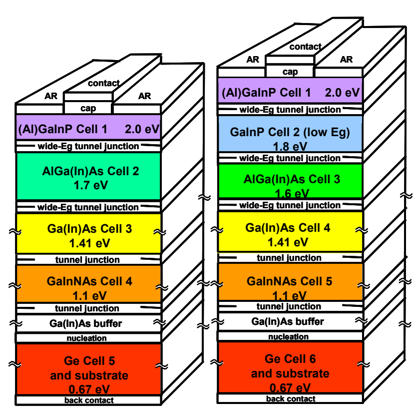

Fig. 5. Monolithic, series-interconnected, 5-junction and 6-junction cell structures.

The measured quantum efficiencies of the individual subcells of a 6-junction cell are plotted in Fig. 6, superimposed on the AM0 solar spectrum. The quantum efficiency and AM0 spectrum are plotted with photon energy on the x-axis, with the subcell response cutoff showing the bandgap of each subcell clearly. Subcell 1 (the top subcell) is current matched to the other subcells in part by making it very thin, since its bandgap difference

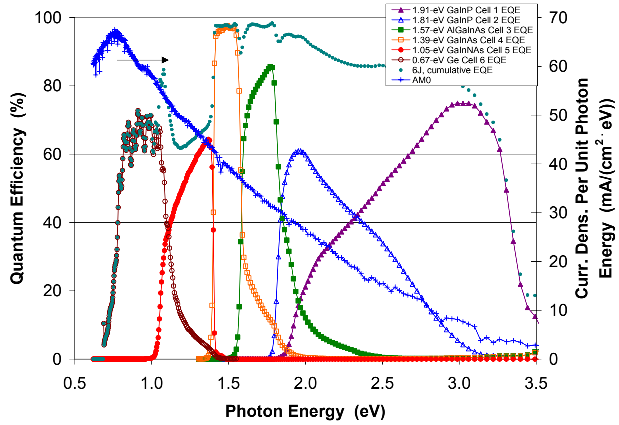

Fig. 6. Measured quantum efficiency of the six individual subcells that compose a 6-junction GaInP/ GaInP/ AlGaInAs/ GaInAs/ GaInNAs/ Ge solar cell. The sum of the quantum efficiencies is also plotted, along with the AM0 current density per unit photon energy.

from subcell 2 is not sufficient to allow subcell 2 to current match the other subcells otherwise. The GaInP subcell 2 can be seen to have significant response at high photon energies (>2 eV) as a result.

The theoretical efficiency of 3-junction space solar cells, as well as 4 to 6-junction cells, can be improved by the use of a higher bandgap AlGaInP top subcell with a disordered group-III sublattice, rather than GaInP [9-11]. Figure 7 plots the measured external quantum efficiency and photoluminescence data from recent investigations of AlGaInP subcells ranging up to 2.1 eV in bandgap.

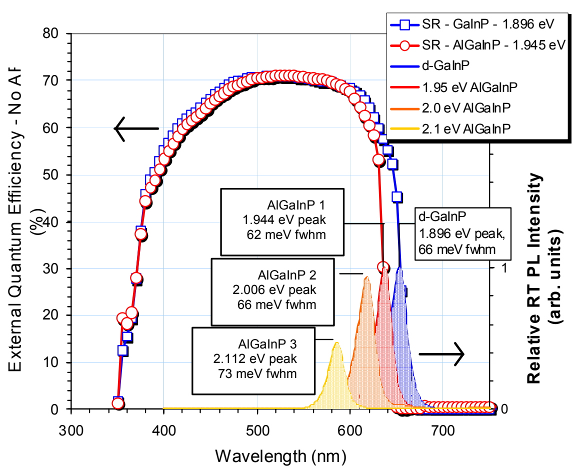

Fig. 7. External quantum efficiency (no AR coating) and photoluminescence measurements of AlGaInP cells.

As a measure of solar cell quality, it is desirable to achieve a small bandgap-voltage offset, $(E_g/q) - V_{oc}$, so that V_{oc} is as close to the bandgap as possible [4,8]. The offset between bandgap and open-circuit voltage was measured to be a low 453 mV for AlGaInP cells with 1.94 eV bandgap, indicating long minority-carrier lifetime in these Al-containing subcells.

From the quantum efficiency measurements in Fig. 6, the GaInNAs subcell 5 is clearly the lowest performing subcell. However, even with this relatively low quantum efficiency, the ~1.1-eV GaInNAs subcell is capable of generating greater than 8 mA/cm^2, allowing it to be current matched to the other subcells in the series-interconnected, 6-junction cell stack. The GaInNAs subcell can be influenced strongly by the thermal profile (annealing) that it sees after it is deposited, depending on its growth conditions. The GaInNAs subcell in a 6-junction cell will necessarily experience a substantial thermal treatment due to the growth of the upper 4 subcells on top. Fig. 8 shows the quantum efficiency of AR-coated GaInNAs subcells after anneals with a high and low thermal budget.

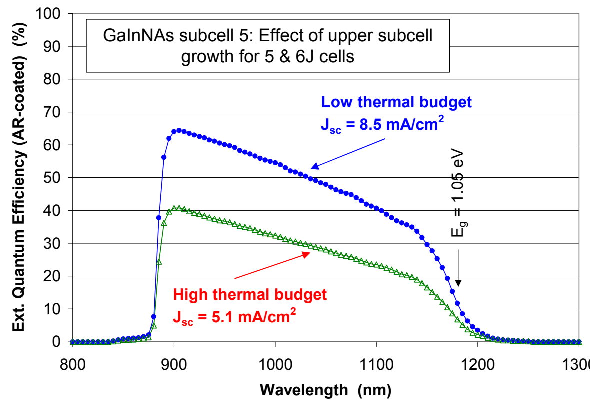

Fig. 8. Effect of post-growth annealing on measured quantum efficiency and integrated AM0 current density of AR-coated GaInNAs solar cells.

Fully integrated 6-junction solar cells with active GaInNAs subcells have been grown and tested [4,8]. Fig. 9 plots measured light I-V curves of three 6-junction AlGaInP/ GaInP/ AlGaInAs/ GaInAs/ GaInNAs/ Ge solar cells with three different anneal conditions for the GaInNAs subcell, and with measured V_{oc} reaching over 5.3 volts.

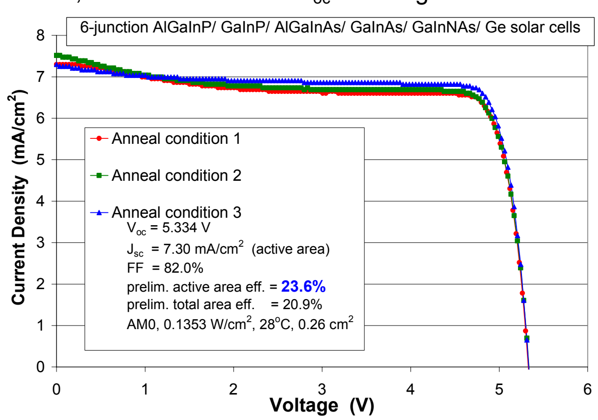

Fig. 9. Illuminated I-V curves of fully-active, monolithic 6-junction cells with V_{oc} over 5.3 volts.

Achieving the correct spectral balance for 6-junction cells under the simulated solar spectrum is difficult, and is an active area of development for space solar simulators. The V_{oc} measurements are quite accurate even if the cells are unbalanced in current, but the J_{sc} is strongly dependent on imbalance in the simulated spectrum. Preliminary short-circuit current density is 7.3 mA/cm^2 and active-area efficiency is 23.6%, for the heavily metallized grid pattern used on these early prototype 6-junction cells. GaInNAs subcells and fully-integrated 6-junction cells with an active ~1.1-eV GaInNAs subcell have now been grown on 100-mm-diameter Ge wafers at Spectrolab, with good uniformity in a production-scale MOVPE reactor.

Flexible, Lightweight Space Solar Cells and Panels

Recently, there has been renewed interest in fabrication of extremely thin III-V multijunction solar cells, for the large savings in weight that can be accomplished, and also for the potential for such thin III-V cells to be flexible [12-14]. They may be integrated into novel, flexible panel designs with not only a very low weight per unit area due to the cells, but also very low weight for the rest of the panel support structures. For instance, thin multijunction cells may be laminated between flexible sheets with metal foil circuitry, resulting in a solar photovoltaic blanket with very high specific power (W/kg), and which may be rolled or folded into a small package with very high power per unit stowage volume (W/m^3). This concept is depicted in Fig. 10, together with a photograph of one of Spectrolab's thin, full-size, flexible 3-junction space cells. With this flexible PV blanket configuration, the lightweight, flexible, small stowage volume features of $CuInSe_2$ and amorphous Si thin-film space solar panels can be achieved, but with AM0 efficiencies approaching 30% due to the thin III-V multijunction cells used.

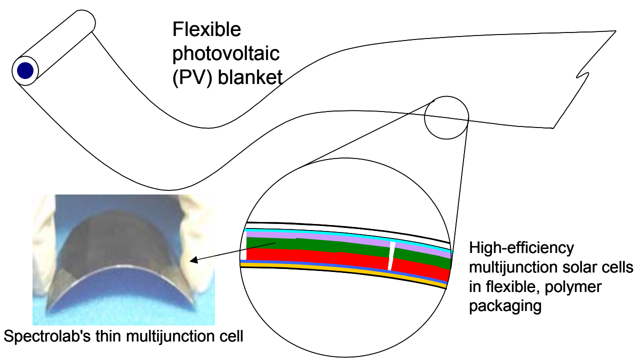

Fig. 10. Schematic of thin, flexible III-V multijunction solar cells, encapsulated in thin polymer layers to form a high specific power photovoltaic blanket, deployed from a rolled up configuration with very small stowage volume.

Preliminary coupons of flexible photovoltaic blankets have been built from thin, large-area (>26 cm^2) 3-junction GaInP/GaInAs/Ge cells, and tested [13]. Figure 11 shows a photograph of a flexible 3-cell coupon conforming to the shape of a 190-mm-diameter metal cylinder, in much the same way as a large flexible panel might be rolled around the spindle of a stowage and deployment mechanism on a satellite. Light I-V measurements of this 3-cell coupon, plotted in Fig. 12, show a specific power of ~500 W/kg at the PV blanket (panel) level.

The 3-junction cells shown in Figs. 10-11 are still thick enough to be free standing. Further gains in reduced weight and flexibility can be achieved by thinning the cell

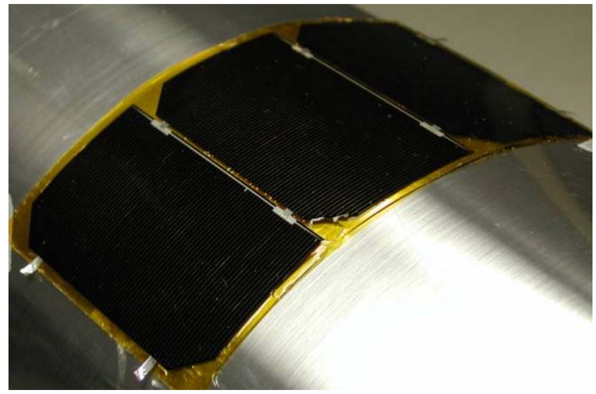

Fig. 11. Photograph of a flexible, 3-cell coupon composed of thin , full-size (>26 cm^2) 3-junction cells.

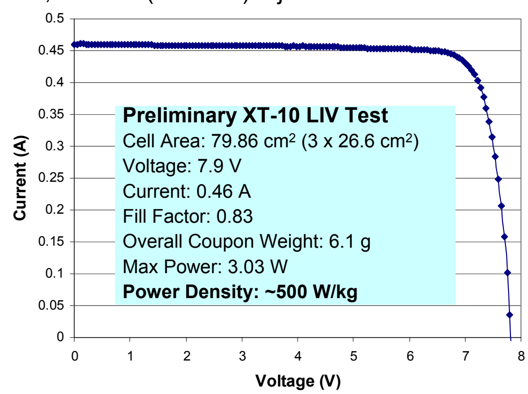

Fig. 12. Measured current-voltage characteristic of the flexible 3-cell coupon with power densiy of ~500 W/kg.

so much that the only layers remaining are the III-V epitaxially grown layers [14]. The Ge or GaAs growth substrate is removed either by lapping or etching it off, or by an epitaxial liftoff process. An attractive part of this latter process is that the growth substrate can be reused, cutting 3-junction cell manufacturing costs markedly. A photograph of a ~10-μm-thick cell with only the III-V epitaxial layers still present, after lapping and etching away the Ge substrate, is shown in Fig. 13. With no Ge substrate, these particular multijunction cells have no Ge subcell and are only 2-junction cells.

Fig. 13. Sixteen 1.5 cm x 1.5 cm ultra-thin solar cells on 50-μm-thick kapton sheet.

Radiation and Environmental Reliability

Multijunction III-V solar cells and panels have been subjected to some of the most rigorous environmental tests that any type of photovoltaic device has been asked to endure. As a result of testing under punishing radiation, thermal, and mechanical conditions, our understanding of degradation mechanisms is deeper than ever, and high-efficiency space panels based on III-V multijunction cells are resulting in more stable and reliable operation than previous cell and panel technologies.

Figure 14 plots the cumulative power generated on orbit by ITJ solar cells with AM0 efficiency > 26.8%. The ITJ panels on spacecraft have been operating nominally over a nearly 4 year period. As more experience is gained with ITJ cells and panels in space, confidence in the ITJ cell continues to grow.

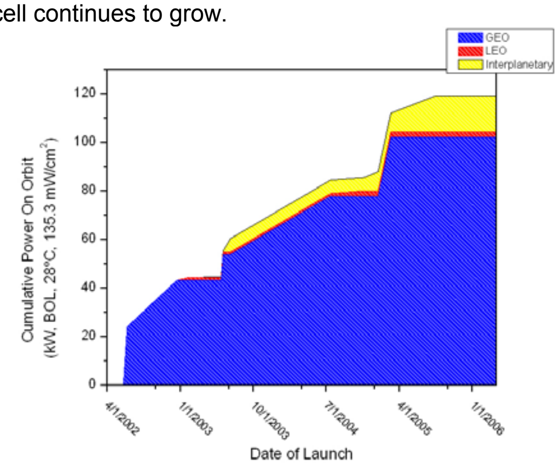

Fig. 14. Cumulative power of ITJ (Improved Triple-Junction) solar cells on panel and in orbit.

Similarly, our understanding of the relationships between multijunction device structure and radiation resistance has become stronger than ever, and end-of-life (EOL) efficiency continues to climb along with beginning-of-life (BOL) power. Radiation characteristics of the UTJ (Ultra Triple-Junction) cell are shown in Fig. 15. As seen

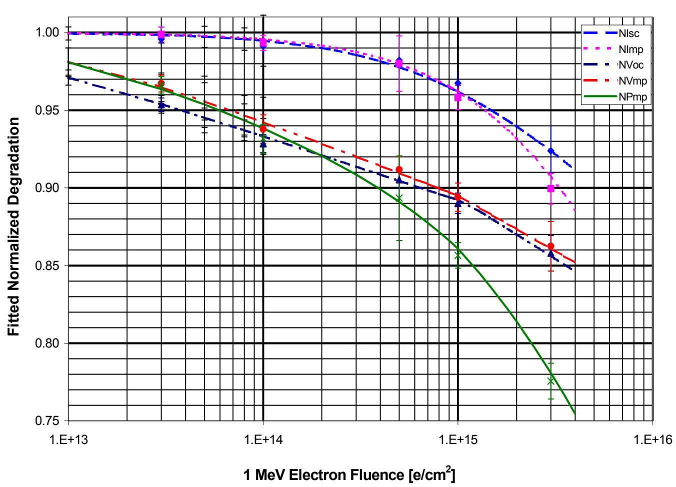

Fig. 15. Radiation degradation vs. 1 MeV electron fluence for UTJ cells with >28.3% beginning-of-life efficiency.

in the chart, voltage degrades more rapidly than current for this type of cell. The resulting relative power at the maximum-power-point, NPmp, is 0.89 for a fluence of 5 x 10^{14} cm^{-3}, and 0.86 at 1 x 10^{15} cm^{-3}.

The experience of the space solar cell industry with thermal cycling of III-V multijunction panels has led to new heights in durability for these panels. Figure 16 plots the progression of the maximum number of thermal cycles passed by multijunction test coupons by year. Temperature range and frequency of the cycles in this test were adjusted to simulate LEO and GEO orbits. Under the LEO simulation, the number of thermal cycles successfully reached the 100,000 mark.

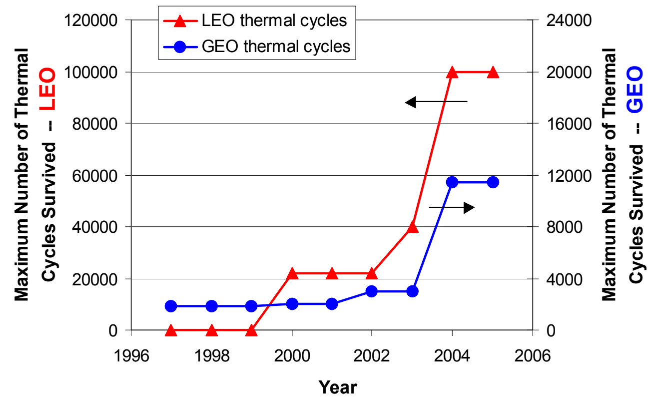

Fig. 16. Maximum number of thermal cycles passed by test coupons using III-V multijunction cells.

The ultimate goal of reliability testing is accurate prediction of the actual power produced on orbit. Over 3 years of data on the power delivered by solar panels populated with Improved Triple-Junction (ITJ) cells from Spectrolab are now available [15], and are shown in Fig. 17. The telemetered power, *i.e.*, the power output measured during panel operation in orbit, is highly stable, and is consistently slightly above the predicted power for the solar panels, by about 2%. This gives outstanding confidence for the actual performance of triple-junction cells under the rigorous conditions of space.

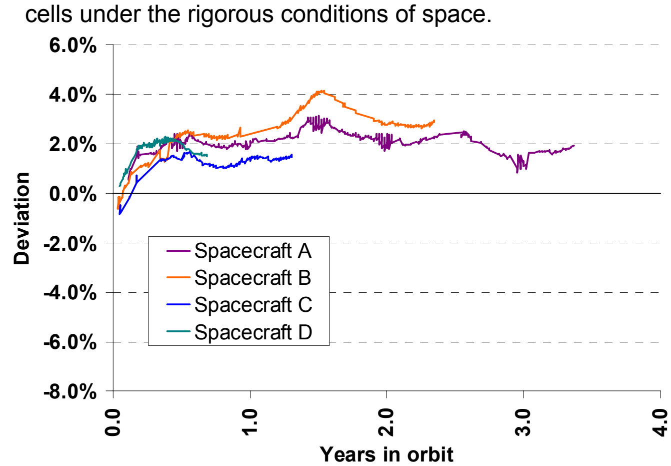

Fig. 17. Relative difference between the actual measured (telemetered) and predicted power of solar panels populated with ITJ cells, during normal operation in orbit [15]. Deviation = ($P_{telemetered}$ / $P_{predicted}$) - 1 .

SUMMARY

III-V multijunction solar cells and panels for satellite power systems are entering an era of higher performance never before seen with this cell technology. Quantitatively, solar cell efficiencies of over 30% under the AM0 spectrum can be achieved reproducibly, and commercially-available 30% cells are just around the corner. Research is underway on new multijunction cell structures such as 5- and 6-junction cells, which can boost AM0 efficiency to the 33-35% range. ~1.1-eV GaInNAs subcells and fully-integrated 6-junction cells have now been grown reproducibly and uniformly on 100-mm Ge substrates. Qualitatively, thin and flexible multijunction III-V cells with radically different mechanical properties are being investigated in research organizations around the globe. These single-crystalline thin-film multijunction cells have as high efficiency as their ~150-μm-thick counterparts, approaching 30%, but their lightweight and flexibility allows them to be used in rollable or foldable arrays as is usually contemplated only for polycrystalline or amorphous thin-film solar cells with significantly lower efficiency. III-V space cells are going through very thorough and rigorous reliability testing, and are being proven out even under harsh conditions, such as 100,000 thermal cycles on a panel coupon. The bottom line is the performance of a solar panel on orbit. Telemetry of the power delivered to the spacecraft by solar arrays on orbit has shown that actual power delivered over a period > 3 years is not only stable, but exceeds the predicted power by ~2%. As a result of all that the space PV community has learned over the past decade, III-V multijunction space solar cells are reaching new heights in efficiency, reliability, and versatility.

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