EVOLUTION OF SPACE SOLAR CELL AND ARRAY TECHNOLOGY FOR THE NEXT DECADE

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ABSTRACT

In the past five years, impressive progress has been accomplished in the development of space solar cell and array technology. Efficiency of cells has been approaching 33% AM0 (over 40% AM1.5G). Due to the major focus on efficiency, continued rise in these values will continue. In addition, space solar array technology has continued impressive progress compared to conventional arrays flying commercially. Specific power of these arrays exceeds 200 W/kg and lightweight designs are included in NASA's Vision for Space Exploration. Some of these arrays also demonstrate excellent radiation resistance enabling new missions.

1. BACKGROUND

There has been a remarkable explosion in the efficiency of space and terrestrial solar cells over the past decade [1-4]. The key to unlocking this explosion has been the versatility of the III-V family of compounds suitable for solar cell development. This tool box of compounds, coupled with thickness and composition control of the many layers in these cells has fueled this exceptional surge in efficiency. It is clear that the $GaInP_2$/GaAs/Ge high efficiency, triple junction architecture has gained wide acceptance across the world for space power generation. Space efficiencies in excess of 30% have been demonstrated and the uniformity control of the fabrication process has been remarkable.

The ability to control layer composition and thickness has led to a reevaluation of the limit efficiency of space solar cells, with the result that efficiencies over 35% can be anticipated in the next few years. Triple junction cells will be surpassed by four, five and six junction cells with even better quality control than now. In addition, new work shows that disordered structures will also add new avenues to increased efficiencies.

As a result of these advances in cell technology, array technology has also been advancing. While the conventional rigid substrate (aluminum honeycomb) array is essentially standard throughout the industry, new designs are beginning to emerge. These newer designs offer lighter weight, better packing density and, in some cases, lower cost and increased radiation tolerance. These features will lead to new missions and new capability in space over the next decade.

2. HIGH EFFICIENCY MULTI-JUNCTION SPACE SOLAR CELLS

In the United States, there are two manufacturers of space solar cells: Emcore Photovoltaics, Albuquerque, NM and Spectrolab, Inc., Sylmar, CA. Both companies have been at the forefront of cell development and each share efficiency records in an intense competition. Each company will be discussed in alphabetical order.

2.1 Emcore Photovoltaics

Emcore Photovoltaics has achieved an average lot efficiency of 28.5% (1 sun, AM0, 135.3 mW/cm^2) for manufacturing quantities of the GaInP2/GaAs/Ge (BTJ) solar cell. Fig. 1 is a current-voltage curve for a typical BTJ cell. For a batch of over 1,000 large area (27.55 cm^2) cells the average efficiency was 28.5%, the Voc was 2.703 mV fill factor was 84% and the Jsc was 17 mA/cm^2. The BTJ device is designed to have a high radiation tolerance, which is a natural byproduct of layer design. These data show a continued improvement in radiation tolerance of the cells as layer thicknesses and composition are improved. The ability to control layer thickness and composition are vital to increasing radiation tolerance and further advances will be shown in later cells.

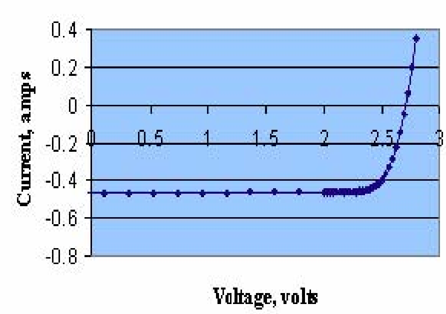

Fig. 1 Current-voltage curve for a 27.55 cm^2 BTJ solar cell.

Fig. 2 is a histogram for over 700 cells in a carefully controlled manufacturing run, indicating the peak performance has been increased to near to 29.1%. The lower performing part of the distribution has been reduced and the whole efficiency distribution has been shifted to higher values. With proper manufacturing control, the distribution can be shifted to higher efficiencies. In fact, at the top end of this distribution, a solar cell with cover glass has reached 30.1% efficiency. This level of efficiency represents the upper part of the efficiency histogram for the BTJ cell.

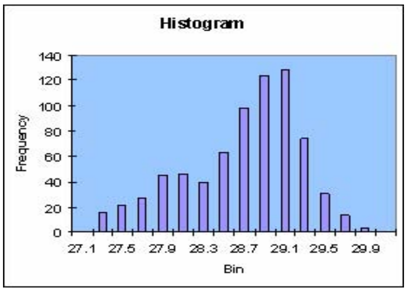

Fig. 2 Histogram of AM0 efficiency of 700 BTJ cells

The results of the BTJ device provide the basis for development of a device (ZTJ) that can consistently achieve greater than 30% efficiency in manufacturing. There are two possible ways to improve the average lot performance: improve the device design and improve manufacturing engineering. In order to improve device design, the typical BTJ device performance was compared to results from theoretical modeling. The modeling indicated that, for the $GaInP_2$, GaAs, and Ge trio of materials, current could be improved by about $0.5mA/cm^2$. The modeling effort also showed that voltage improvements in the ZTJ device would have to come from modifying the $GaInP_2$/GaAs/Ge architecture by increasing the band gap of the top junction. Since the band gap of the $GaInP_2$ junction is lower than ideal for matching with the GaAs junction, the $GaInP_2$ base region is thinned for current matching. Implementing these changes has led to a slight increase in average lot efficiency (to 29.5%) for a batch of 77 ZTJ cells.

As a result of the $GaInP_2$/GaAs/Ge architecture and the difficulty of further increasing performance in the ZTJ cell, the focus turned to a different approach to continue to increase high-efficiency device performance beyond 30%. A number of approaches have been suggested around the world, including: development of new materials such as InGaAsN, quantum dot cells, mechanically stacked devices, beam splitting to separate junctions (rainbow approach), and metamorphic (lattice mismatched) devices.

The goal of each of these approaches is to be able to include in one complete "system" a sufficient number of junctions such that the complete light spectrum is utilized most efficiently, i.e., no losses through "hot carriers", etc. Each approach has advantages and disadvantages. One metamorphic approach, developed at NREL, has demonstrated greater than 30% efficiencies, both for space and terrestrial applications [5, 6]. A schematic diagram of the inverted metamorphic approach (IMM) is shown in Fig. 3.

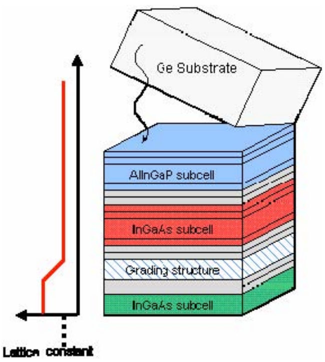

Fig. 3 Schematic diagram of the IMM approach.

Using the IMM approach, Emcore has recently demonstrated a 31.9% 1-sun, AM0 efficiency on a 4 cm^2 cell. In addition to enabling higher efficiencies, the IMM cell is flexible as shown in Fig. 4. The flexibility and exceptional specific power (>1000 W/kg) opens up a number of opportunities for novel space deployment. It appears that the IMM approach will be used in the future to achieve even higher efficiencies.

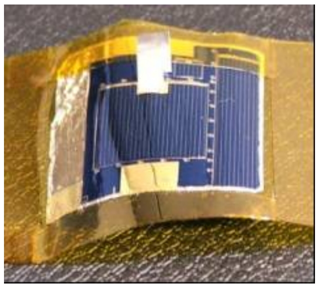
Fig. 4 Picture of a 0.25 cm^2 IMM cell

In summary, Emcore has been aggressive in investigating new cell types and improvements in manufacturing technology to continually serve their space customers better.

2.2 Spectrolab, Inc.

Spectrolab, Inc. has been a mainstay of space solar cell development for over four decades. Over that time period, substantial changes have occurred in the space cell development arena. The industry has moved from silicon to GaAs-based III-V multijunction solar cells. 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.

Fig. 5 charts the AM0 efficiency distributions for the last four generations of multijunction space cells produced at Spectrolab, Inc., the dual-junction (DJ),

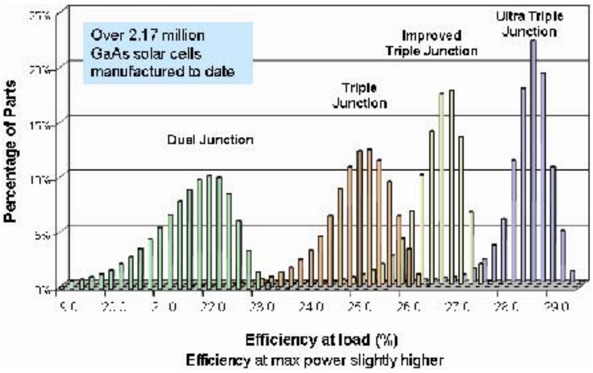

Fig. 5 AM0 efficiency distributions of four generations of Spectrolab space solar cells.

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. UTJ cells now average 28.5% at Pmax.

In Figure 6 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

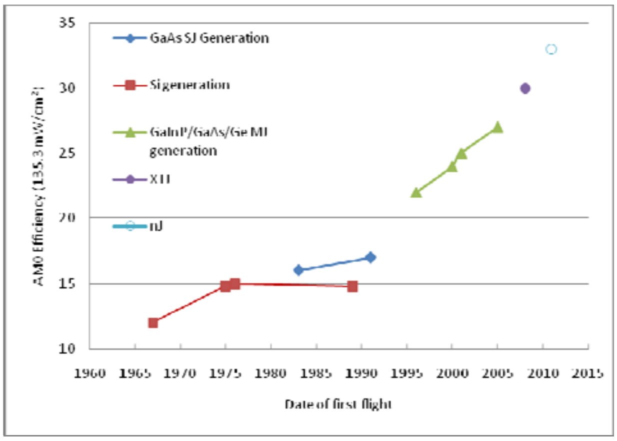

Fig. 6 Solar cell efficiency with first launch to orbit

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.

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. This success provides evidence that the performance targets of the XTJ cell can be met relatively soon. The test production of 288 demonstration cells (>26 cm^2) had an average AM0 efficiency of 30.3% with a maximum efficiency of 31.1%. The distribution of UTJ cells processed at the same time had an average efficiency of 28.4% with a maximum efficiency of 29.1%. These prototype XTJ cells still need to go through space qualification, but their measured performance gives confidence that space solar cells with 30% minimum average efficiency will be commercially available soon.

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 band gaps of the individual subcells of a multijunction cell to the solar spectrum for maximum conversion efficiency. Another approach is to divide the solar spectrum more finely using a greater number of junctions, such as 5- and 6-junction cells. Partitioning the solar spectrum by the bandgaps in a AlGaInP/ GaInP/AlGaInAs/ GaInAs/ GaInNAs/ Ge 6-junction cell will allow full coverage of the AM0 solar spectrum as well as yield a device suitable for terrestrial use. In this manner both stacked cells and IMM structures can be fabricated. One of the true advantages of the IMM process is that thin cells are a natural byproduct. Fig. 7 shows sixteen 1.5 x.1.5 cm dual junction cells (no Ge) that are 10 μm thick on a 50μm thick sheet of Kapton. Thus Spectrolab is proceeding along a similar path as the other supplier, yet with their own particular approaches

Fig. 7 Ultrathin DJ cells

3. SPACE SOLAR ARRAY TECHNOLOGIES

In this section we will discuss new developments in space solar array technology that are leading to lighter weights, higher packing density and increased radiation tolerance.

3.1 ATK Space

ATK Space has been the pioneer of lightweight solar arrays and structures. There are three array options offered: Puma (a conventional planar array), CellSaver (a 2x concentrator), and Ultraflex.

The PUMA produces from 0.5 to 8 kW and has a specific power of 65 W/kg at 8 kW and has performed flawlessly in space. The CellSaver uses metal concentrators between cell strings, all on a single substrate. This keeps the cell temperature low and saves 20- 25% in array mass and cost.

The first ATK UltraFlex solar array flown in space was launched in August as part of NASA's Mars Phoenix mission. UltraFlex is an extremely lightweight flexible blanket array that stows very compactly and unfolds like a fan into its circular shape. The Mars Phoenix UltraFlex solar array wings on the Lockheed built Lander (Fig. 8), are 2.1 meters in diameter, generate 770 watts using Spectrolab UTJ cells, are self supporting in 1g and produce over 118 W/kg specific power (measured) including all structure and mechanisms making them the lightest solar arrays of this size ever flown in space.

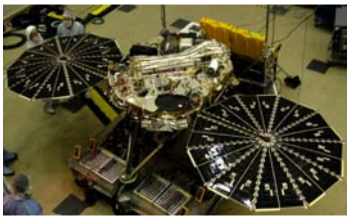

Fig. 8 Ultraflex array on the Phoenix Mars lander

The Ultraflex 175 is also scheduled to fly on NASA's CEV (Crew Exploration Vehicle and the design is scalable to a 15 kW size. Its specific power is up to 175 W/kg with 27% multijunction cells. A major benefit is that it has high packing density.

3.2 ENTECH, Inc.

ENTECH, Inc. has developed the 8x concentration solar array for space use. From 1998-2001, NASA flew the highly successful Deep Space 1 mission that used ion propulsion and the novel SCARLET solar array. The SCARLET array (2.7 kW) performed flawlessly and has evolved into the Stretched Lens Array. The SLA has demonstrated its durability to the space environment through its proven flight history, stringent ground testing, and computation modeling and analysis. The SLA is reliable, scalable, cost-effective, durable, and efficient. It is an optimal candidate for SEP missions to GEO, the moon, Mars, and beyond. Fig. 9 shows a model of the SLA on the ATK SquareRigger platform under illumination.

Fig. 9 SLASR model in sunlight

SLA offers unprecedented performance (>80 kW/m^3 stowed power, >300 W/m^2 areal power, and >300 W/kg specific power), high voltage operation (>300-600 V), and cost-effectiveness (>50% savings in $/W compared to planar arrays). SLA achieves these outstanding attributes due to its 8x optical concentration by employing flexible Fresnel lenses. This minimizes solar cell area, mass, and cost and allows for super-insulation and super-shielding of the solar cells to enable high-voltage operation and radiation hardness in the space environment without detrimental mass penalties. ATK Space will offer the SLA as a product.

4. FUTURE PROJECTIONS

Significant increases in space solar cell efficiency are being demonstrated due to innovative approaches that take advantage on non-lattice matched structures. This trend should continue and allow development of 5- and 6-junction devices that will have efficiencies above 35% AM0. As a byproduct of these fabrication schemes, ultrathin, flexible devices will result. Presuming that interconnection schemes can be developed, these very lightweight cells will be combined with lightweight array structures like the SLA that will demonstrate over 500 W/kg at the array level with radiation tolerance (by both cell and array design), high voltage operation for electric propulsion and costs less than half of today's arrays. Thus the next decade in space cell and array development will usher in new applications and benefits.

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