PROGRESS IN THE MULTIJUNCTION SOLAR CELL MANTECH PROGRAM

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Introduction

The development of $GaInP_2$/GaAs/Ge multijunction solar cells has progressed rapidly since the early 1990s under various U.S. government programs. In early 1995, with the demonstration of >20% efficiency, 2x2cm, dual and triple junction $GaInP_2$/GaAs/Ge solar cells, the successful laboratory development of multijunction solar cells was completed. Then, in September 1995, the joint Wright Laboratory/Phillips Laboratory/NASA Lewis Multijunction Solar Cell Manufacturing Technology (ManTech) Program began to improve multijunction cell performance and scale them up to production size and quantity to support Air Force and commercial satellite programs. The first milestone of the program has been reached and the purpose of this paper is to present the results of the program so far.

The objectives of the Multijunction Solar Cell ManTech Program are to increase $GaInP_2$/GaAs/Ge lot average cell efficiency to 24-26%, increase the cell size to $\geq 16cm^2$ while maintaining high efficiency, and limit the per cell costs to ≤1.15X state-of-the-art GaAs/Ge cells. Advanced manufacturing technology and process control techniques such as in-situ process monitoring and real time process feedback are being used to optimize multijunction solar cell growth processes to achieve these goals.

Another objective of the program is for production multijunction solar cells to be available as a drop-in replacement for arrays currently using GaAs/Ge technology. Therefore, the program requirements call for ManTech multijunction solar cells to have the same physical qualities as GaAs/Ge cells including thickness, mass, radiation resistance, and contact strength (See Table 1). Having characteristics similar to GaAs/Ge cells should minimize concerns about inserting multijunction cell technology into new or upgraded space systems. Also, as a drop-in replacement, multijunction cells offer the benefit of increased power for a given solar array size or reduced solar array mass for a given power level.

Overall, the program cost and performance objectives carry the potential to increase solar array specific power (W/kg) by 33%, reduce array size by 25%, and decrease array cost per watt ($/W) by 15% or more over GaAs/Ge cells. Additional mass and cost savings in the spacecraft attitude control subsystems and payloads will be realized as a result of increased solar cell efficiency. All of these sizable savings are working together to position $GaInP_2$/GaAs/Ge multijunction solar cells as the next state-of-the-art solar cell technology.

Table I - Multijunction ManTech Program Requirements

Parameter	Requirement
Lot Average Efficiency (bare, glass optimized AR coating)	24%
p/p_0 @ $1x10^{15}$ 1MeV electrons	0.75
Cell Area	16 cm^2
Thickness	5.5 mil
Contact Integrity, Ag/Kovar weld	>300g w/ <0.2% loss

Two experienced space solar cell manufacturers, Spectrolab, Inc and TECSTAR/Applied Solar are working with the government team to meet the program goals, which consist of two phases. The Baseline Definition phase focused on cell performance improvements in 2x2 cm cells, and was completed in December 1996. The Optimization and Validation phase, which will focus on manufacturing process optimization, began in May 1997. Phase II, which runs for 24 months, will culminate with a 16,000 cm^2 production demonstration as a primer for full scale production of multijunction solar cells.

This paper will discuss progress made in Phase I of the program and give an overview of Phase II but will focus on side-by-side testing results collected by Phillips Laboratory and NASA Lewis on Phase I deliverable cells from both vendors. Cell performance, pre- and post-radiation, and temperature coefficient results on initial production multijunction solar cells will be presented and discussed. The data shows that this technology meets the objectives of the program, and that, in the interim before a new solar simulation standard becomes widely available, the measurement techniques being used by the major space solar cell manufacturers are providing adequate testing results for solar array design.

Phase I Discussion

Several material systems for high efficiency photovoltaic energy conversion have been investigated, but at this point, the $GaInP_2$/GaAs/Ge material system, which is being pursued in this program, is considered the most mature and manufacturable. The current design builds on GaAs/Ge technology by monolithically integrating three materials with different bandgaps into a single cell structure to take advantage of a greater portion of the solar spectrum and achieve higher efficiencies than single junction cells. Small area $GaInP_2$/GaAs tandem cells have been shown to be capable of near 26% efficiency [1] at 1-sun, AM0 conditions, and with this in mind, the goals of the Multijunction Solar Cell ManTech Program were set at a challenging level for the production environment.

Phase I of the program was the Baseline Definition phase, which was intended to improve cell performance and identify the best cell design to be transitioned to production in Phase II. At the beginning of Phase I, Spectrolab and TECSTAR were both manufacturing 20-22% efficiency dual and triple junction cells [2,3], the relationships between current matching, radiation resistance, and temperature coefficient were beginning to be documented, and it was unclear whether the dual or triple junction cell would be the best baseline cell for Phase II. Therefore, both vendors entered the program pursuing parallel dual and triple junction cell developments anticipating a downselect to one primary technology before the end of Phase I. However, the specific approaches taken by Spectrolab and TECSTAR did diverge shortly after the start of Phase I.

For dual junction cells, the approach was identical; p/n $GaInP_2$/GaAs structures. The approaches differ in the formation of the triple junction cell using the Ge substrate. Spectrolab reverses the cell polarity, and uses an n/p junction in the Ge substrate to form the third cell, and TECSTAR forms a controlled n/n AlGaAs/Ge heterointerface at the Ge substrate, which gives the cell a voltage boost. In this paper, cell structures are named according to the number of n/p or p/n junctions contained in the cell. Therefore, the Spectrolab active germanium cell is called a triple junction, and the TECSTAR active germanium cell a dual junction-plus.

The results of experimental studies, optimizations, and baseline production runs in Phase I were used to define the baseline design for Phase II. Specifically, work centered on understanding the effect of the Ge substrate quality, junction characteristics, and lattice orientation on the overall cell efficiency and attempts to increase the bandgap of the $GaInP_2$ top cell for increased cell voltage and efficiency. This work led to several very encouraging results including lot average efficiencies of 24.2% and 22.4% and best cell efficiencies of 25.5% and 24.1% at Spectrolab and TECSTAR respectively [4,5]. However, the Phase I baseline production demonstrations also indicated that for $GaInP_2$/GaAs/Ge in the manufacturing environment, the voltage boost from the Ge substrate is probably needed to meet the 24% lot average efficiency requirement of the program, and each vendor has selected a form of active germanium cell for the primary baseline design. Table 2 summarizes the baseline cell structures and major results of the Phase I program.

Table II - Summary of major Phase I results

	Spectrolab	TECSTAR
Baseline cell decision	n/p triple junction	p/n dual junction-plus
Polarity choice reasoning	Identical 2J and 3J processes Projected radiation resistance	Direct extension of GaAs/Ge line Control of Ge interface voltage
Ge cell formation	n/p Ge junction	n/n AlGaAs/Ge heterointerface voltage boost
Best dual junction cell efficiency	23.7%	22.8%
Best triple junction cell efficiency	25.5%	24.1% (dual junction-plus)
Best large area cell efficiency	24.3% (13.78 cm^2)	22.1% (16.6 cm^2)
Lot average of Phase I deliverables	24.2%	22.4%

At the end of Phase I, Spectrolab and TECSTAR each delivered 150 multijunction solar cells for evaluation by Phillips Laboratory and NASA. The purpose of the joint testing program was to verify the Phase I results with a direct side-by-side comparison of the cells from each vendor and to investigate the scope of the problem of accurate multijunction cell measurements and correlation with other testing systems. The test program included near AM0 Langley plot and I-V curve traces on the NASA Lewis Learjet aircraft as well as pre- and post- radiation performance and temperature coefficient measurements at Phillips Lab and NASA.

Learjet Cell Performance Measurements

Solar simulator measurements of multijunction solar cells are the subject of much user community discussion because a standard testing method has not yet been adopted. The objective of Learjet testing of Phase I ManTech cells was to test cells from each vendor side by side in a near-AM0 environment to remove simulator error from the discussion of the results. Cells from each contractor were flown on the Learjet, and Langley Plot Isc data as well as I-V curves at 25°C and 70°C were collected. The Isc results compared favorably with contractor provided data, and I-V curves showed fill factors from 0.8-0.85 with no evidence of significant current mismatch between the top and middle cells. Tables 3 and 4 show Learjet Isc results for the cells flown, and the results show reasonable agreement between contractor data collected on modified X-25 and dual source Hoffman simulators and the NASA data. The Learjet results do not reduce the need for a standard test method for multijunction solar cells, but they do indicate that, in the meantime, the individual contractor testing methods are making reasonably accurate cell measurements.

Table III - Comparison of TECSTAR and Learjet Isc Data

Cell	TECSTAR I_{sc}	Lear I_{sc}	% Diff
1	64.1	63.27	-1.295
2	63.8	62.52	-2.006
3	64.2	63.79	-0.639
4	60.6	61.49	1.469
5	60.9	62.84	3.186
6	62.7	62.02	-1.085
7	60.4	Unreliable data	N/A

Table IV - Comparison of Spectrolab and Learjet Isc Data

Cell	Spectrolab I_{sc}	Lear I_{sc}	% Diff
1	61.6	61.73	0.211
2	62.4	62.37	-0.048
3	63.9	63.39	-0.798
4	63.4	62.23	-1.845
5	61.9	62.27	0.598
6	63.6	63.10	-0.786
7	63.0	61.45	-2.460

Radiation Degradation Results

Spacecraft solar array sizing is done based on the expected solar cell efficiency at the end of the required mission lifetime in a given orbit. This method ensures that full power is available for the mission at end-of-life (EOL). As a drop-in replacement for GaAs/Ge solar cells, it is desirable for multijunction solar cells to have radiation performance similar to or better than GaAs/Ge cells. The radiation requirement for cells manufactured under the ManTech Program is $p/p_0 \geq 0.75$ after $1x10^{15}$ 1MeV electrons/cm^2, which is a common benchmark for GaAs/Ge cells [6]. $GaInP_2$/GaAs tandem cells have been documented with better radiation characteristics than single junction GaAs/Ge [7] due to EOL current match configurations and the slower degradation rate of $GaInP_2$ [8]. To verify and independently document the radiation performance of production cells manufactured for the ManTech Program, Phillips Laboratory and NASA Lewis each measured the pre- and post-radiation performance of a group of cells from each contractor. Phillips Laboratory measured the relative radiation degradation on a group of ten cells using a dual source simulator, and NASA measured a group of five cells with a combination of an X-25 simulator and the Learjet. Cells for each group were selected from the group of 150 deliverable cells so that efficiencies over the range delivered were represented. The ten cells from Spectrolab had a BOL current mismatch of approximately 1% with the $GaInP_2$ top cell current limiting, and the TECSTAR cells measured were current matched for best BOL performance. The irradiations were performed by Dr Bruce Anspaugh of JPL, and the cells received $1x10^{15}$ 1MeV electrons/cm^2 in a single dose. Tables 5 and 6 list the average radiation degradation results for the cells measured by Phillips Lab and NASA.

Table V - Average Radiation Degradation Results, Spectrolab Cells

	Phillips	NASA Lewis
Voc	0.906	0.918
Isc	0.872	0.888
FF	0.971	0.979
p/p_0/Eff	0.766	0.797

Table VI - Average Radiation Degradation Results, TECSTAR Cells

	Phillips	NASA Lewis
Voc	0.920	0.932
Isc	0.834	0.833
FF	0.984	0.995
p/p_0/Eff	0.754	0.772

The results from NASA are 2-4% higher than the Phillips Laboratory results probably due to differences in simulator calibration methods for EOL cells. The dual source simulator was calibrated at EOL with the same standards used for BOL, a $GaInP_2$ cell and a filtered GaAs/Ge cell. This method does not take into account changes in spectral response of the cells after radiation, but the smooth spectrum of the simulator is expected to keep this error small.

At NASA, an irradiated cell was reflown on the Learjet and became a secondary standard for the X-25 simulator. This cell was then used to calibrate the X-25 simulator to collect the other post-radiation data, but some error in the measurement may still be introduced by the spectrum of the X-25. The error investigation for these results is still ongoing and will be reported in the future.

Overall, the results of this testing shows that both types of multijunction cells being developed in the ManTech Program meet the requirement for radiation resistance. Also, the radiation resistance of $GaInP_2$/GaAs/Ge cells is shown to be as much as 6% better at this fluence than single junction GaAs/Ge cells. Future cell irradiations will include higher electron fluences, proton irradiation, and possibly annealing studies.

Temperature Coefficient Results

Temperature coefficient data are also important for sizing solar arrays according to the expected cell efficiency at the array operating temperature, which is determined by several factors including the mission orbit, spacecraft structure, and thermal control system. For $GaInP_2$/GaAs/Ge multijunction solar cells, temperature coefficients are related to the amount of voltage activity in the germanium substrate. For instance, the Spectrolab n/p Ge bottom cell produces more voltage than the TECSTAR AlGaAs/Ge heterointerface, and therefore, larger temperature coefficients for the Spectrolab cells were expected. However, when a cell reaches a temperature where the Ge activity goes to zero, the triple junction cell will assume the temperature coefficient of the analog pure dual junction cell. Phillips Laboratory and NASA Lewis made pre- post-radiation temperature coefficient measurements for Voc, Isc, Pmax, and efficiency on two groups of cells. At Phillips Laboratory, five cells were tested at 28°,40°C, and 60°C with three trials at each temperature. All of the data (45 data points) were plotted together to calculate a linear trend line through the data whose slope is the temperature coefficient. and NASA calculated temperature coefficient similarly. As expected, the Spectrolab cells exhibited larger temperature coefficients at BOL and EOL. Tables 7 and 8 summarize the BOL and EOL temperature coefficient data collected by Phillips Laboratory and NASA.

Table VII - BOL Temperature Coefficient Data

	Spectrolab		TECSTAR	
	Phillips Laboratory	NASA	Phillips Laboratory	NASA
Voc (mV/C)	-6.9	-6.4	-5.9	-5.2
Isc (mA/cm^2-C)	0.01	0.01	0.004	0.007
Pmax (mW/cm^2-C)	-0.087	-0.085	-0.073	-0.065
Eff (abs %/C)	-0.064	-0.062	-0.054	-0.047

Table VIII - EOL Temperature Coefficient Data

	Spectrolab	TECSTAR
Voc (mV/C)	-7.3	-5.6
Isc (mA/cm^2-C)	0.01	0.01
Pmax (mW/cm^2-C)	-0.087	-0.05
Eff (abs %/C)	-0.051	-0.036

The implications of these data are in the relative benefits of triple junction and dual junction-plus cell technology for various operating temperatures. Figure 1 extrapolates BOL efficiency temperature coefficient trends based on data collected by Phillips Laboratory and NASA to illustrate the trade space around the triple junction and dual junction-plus cell structures, and three things should be noted. First, the actual Phase I data shows that the triple junction structure, even with a higher temperature coefficient, currently has a small efficiency advantage over the dual junction-plus structure to greater than 150°C. Second, at the projected Phase II BOL lot average efficiencies of 25% for triple junction cells and 23.5%

for dual junction-plus cells, the previous trend will continue to hold true. Lastly, the triple junction cell loses its efficiency advantage at about 80°C in the case where the dual junction-plus efficiency increases more than the triple junction during Phase II. This illustration assumes that the temperature coefficients remained constant with cell efficiency improvements, which is a reasonable approximation for the purpose of this discussion. As multijunction cells approach full production in Phase II, this trade space will be updated to reflect the most current results.

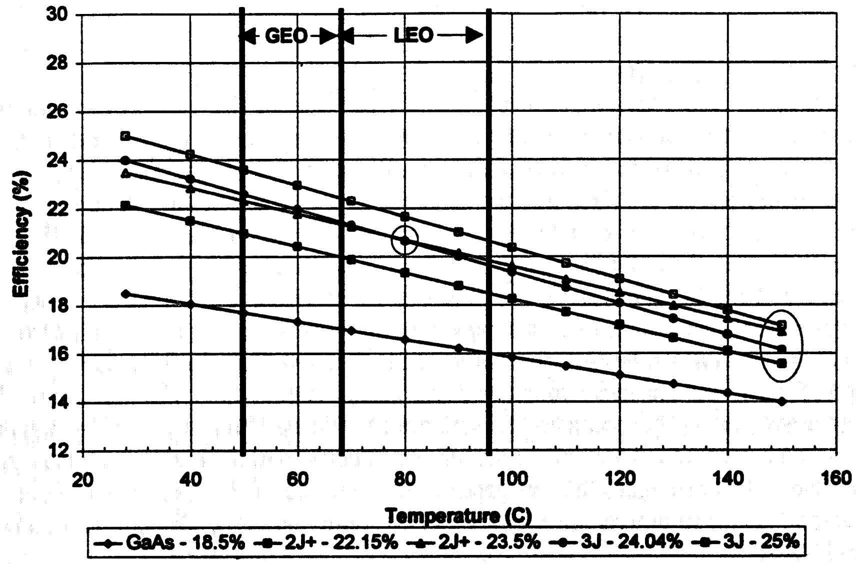

Figure 1 - BOL Temperature Coefficient Extrapolations Based on ManTech Results

Phase II Program Overview

Phase II of the Multijunction Solar Cell ManTech Program will build on the success of Phase I by reducing the manufacturing cost of multijunction cells while maintaining high efficiency. The objectives of Phase II are to produce large area cells with a cell-to-cell cost ≤1.15X GaAs/Ge cells while maintaining high efficiency. Achieving this goal will require improvements in process control and yield so that the main cost increases over GaAs/Ge cells is in material and reactor run time. Increasing cell size from 4cm^2 to 16cm^2 will also results in large solar array cost savings by reducing the parts count of a given solar array by 4 times not including array size savings due to higher efficiency cells.

To reach the cost objective of Phase II, the program is continuing cell growth process improvements including better temperature uniformity control, in-situ, real time process monitoring and control, and design of experiments to identify the critical parameters in the growth process. Some cell optimizations will also occur to push cell efficiencies to the highest level possible, but the baseline established in Phase I will essentially be the product transitioned at the end of Phase II.

Conclusions

The Multijunction Solar Cell Program is bringing high efficiency, large area, cost effective $GaInP_2$/GaAs/Ge solar cells to full production to meet the spacecraft power demands of future spacecraft systems. In Phase I of the program, baseline multijunction solar cell designs have been developed at two domestic vendors, and small scale production demonstrations have shown up to 24.2% lot average efficiencies. The cells also have demonstrated similar physical characteristics and better radiation performance than GaAs/Ge cells. Phase II of the program will focus on increasing multijunction cell size and yield while maintaining high efficiency to reduce solar array cost per watt ($/W) by more than 15%. Together, the Multijunction Solar Cell ManTech Program has positioned high efficiency multijunction solar cell technology to be the next mass produced, state-of-the-art, space solar cell technology.

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