Commercialization of New Lattice-Matched Multi-Junction Solar Cells Based on Dilute Nitrides

July 8, 2010 — March 7, 2012

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Subcontract Report
NREL/SR-5200-54721
April 2012

Contract No. DE-AC36-08GO28308

NATIONAL RENEWABLE ENERGY LABORATORY

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Prepared under Subcontract No. NAT-0-99013-03

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Background

The current state of the art production solar cell for High Concentration PV applications is a triple junction (3J) cell, shown schematically in Figure 1, with lattice matched layers throughout the device structure and containing a Ge bottom cell. Today's commercial multi-junction cells used in CPV systems (Figure 1) have average efficiencies of about 39.5% under standard test conditions (25^{o}C, AM1.5D, 50 W/cm^2). Improvements in material quality and grid design will provide some performance gains but production cell efficiencies are not expected to exceed much above 40% with this material set. However, calculations have shown that it may be possible to extend practical multi-junction cell efficiencies to about 50%, an 11% absolute efficiency gain over today's products. These potential efficiency gains are very significant factor in driving down the installed cost of PV systems to $1/W and below. Achieving these efficiencies requires changing the material composition of the junctions from that of Figure 1.

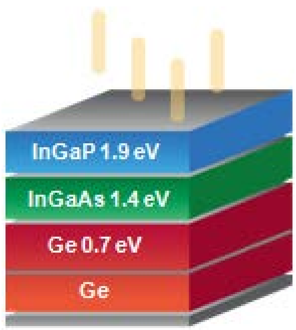

Figure 1: Schematic cross-sectional view of a typical 3J cell used in production for CPV applications.

The most desirable approach to a higher efficiency 3J cell design is to replace the Ge cell with a dilute nitride, GaInNAs, having a ~ 1 eV bandgap, such as shown in Figure 2. Such a design would continue to be lattice-matched throughout the structure and would have a bandgap combination with the potential for efficiencies ≥43%. Despite numerous early attempts at making cells of this design, the dilute nitride junctions were of poor quality resulting devices with low efficiency. The problems associated with making GaInNAs compounds led most people in the field to pursue metamorphic cell designs to achieve efficiencies >40%.

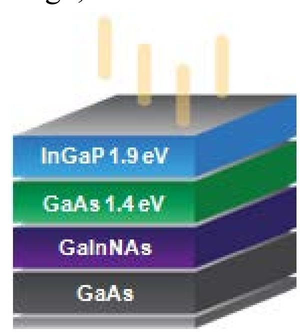

Figure 2: Schematic of a lattice-matched 3J cell with a 1 eV GaInNAs bottom cell.

Solar Junction was formed to develop for solar cell applications, a dilute nitride technology developed at Stanford University for IR lasers. Significant progress was made on improving the dilute nitride and developing the other technology necessary to make III-V triple-junction solar cells. The PV Technology Incubator subcontract was awarded to Solar Junction to shorten the transition time from promising prototype to commercial ready product.

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Objectives

The overall objective of this Incubator subcontract was to complete the work necessary to make commercial ready solar cells using the dilute nitride technology. The specific objectives of this program were aimed at completing the development of a triple-junction solar cell that incorporates a GaInNAs ~1eV subcell to the point of commercial readiness, and determining the cell reliability and, if necessary, identifying and eliminating process or material related issues that lead to early-life cell failures. There were three major objectives for Phase 1, each of which focuses on a key element of the solar cell that determines its performance in a commercial CPV system. One objective was to optimize the quality and performance of the key individual components making up the solar cell structure and then to optimize the integration of these components into a complete triple-junction cell. A second objective was to design and test anti-reflective coating that maximizes the light coupled into a 3J cell with a ~1 eV bottom cell bandgap. The third objective was to develop Highly Accelerated Life Tests (HALT) protocols and tools for identifying and correcting potential reliability problems. The Phase 2 objectives were a continuation of the work begun in Phase 1 but aimed at optimizing cell performance for commercial requirements. Phase 2 had four primary objectives: 1) develop a glass-matched anti-reflective coating (ARC) and optimize the cell/ARC to give good performance at 60C operating temperature, 2) optimize the cell for good operation at 60C and high concentration, and 3) complete the light biased HALT system and use it to determine what, if any, failures are observed, and 4) determine the reliability limits of the optimized cell.

Summary

All the milestones for this program were achieved and in most cases, particularly those related to cell performance, more samples were supplied than was required, and the deliverables substantially exceed the performance milestones. Moreover, the cell deliverables sent to NREL for evaluation were cells 4 mm or 5.5 mm, nearly 5 to 10 times larger in area than the 2 mm cells called for in the subcontract, and one of the most common sizes in the CPV industry. For the entire program there were 12 separate cell performance milestones, the most important of which was the 3J cell efficiency. Phase 1 had 2 3J efficiency milestones and Phase 2 had three. For the Phase 1 milestone calling for 38% efficiency, NREL measured a peak efficiency of 41.1%, about 2% higher than the data sheet values of commercial cells at that time. The efficiencies measured in Phase 1 exceed the Phase 2 cell performance milestones in the subcontract's original Statement of Work. Cells submitted to NREL as part of this subcontract, although not as deliverables, were measured to have a new World Record cell efficiency of 43.5%, breaking the previous World Record by 1.2% absolute. In addition to improved cell performance, during Phase 1 a modeling capability for designing ARCs was developed and verified by comparing the measured current from a cell using a specific ARC with the current predicted by the model. This model was then used to design a new ARC giving lower reflectivity and a corresponding higher cell current. Again the prediction of the model was verified by measured cell properties. In Phase 2, the modeling capability was used to design a glass matched ARC, the type most in use in the CPV industry, which was tuned to the band structure of a 3J cell with a dilute nitride bottom cell. Finally, tools and test methodologies were developed that enable HALT to be applied to cells to determine the operating and destruct limits and to determine or set bounds on the lifetime of the cells in typical CPV operating conditions. As part of this effort a novel HALT

system was built that enabled cells to be subjected to light at concentrations up to 80 W/cm^2, (800 suns) while the cell temperature could be held or cycled between -100C and +180C. As part of the Phase 2 effort the system was modified to enable the light to the cell to be interrupted at a maximum rate of 10 times/second. Tests using interrupted light at >500 suns on cells held at 180C showed no evidence of failure after a total of >22 sun-years of operation at 100C. Another key outcome of the reliability efforts of the program was from high temperature storage tests done independently of the HALT test. There were two key outcomes of this activity: 1) single junction GaInNAs cells showed no evidence of failure under the equivalent of at least 100 years of on-sun time operating at 100C and 2) we can conclude with 95% confidence that the probability of device failure after 30 sun-years of operation at 100C is less than 1.5%, and mostly less than 0.5%. Based on these results there is no reason to believe that dilute nitrides in and of themselves pose a reliability problem for CPV applications and that 3J cells using dilute nitrides have very low probability of failure during the expected 20-30 year life of a CPV power plant.

Phase 1 Scope of Work

The Phase 1 work plan is divided into 3 primary tasks, each with several subtasks that form the basis for the 15 different deliverables. The tasks are organized so that work on them can be done in parallel. The technical approach to these tasks was to use design simulation and modeling to guide the analysis and process development needed for improvement. Design of experiments was also used to optimize processes. Solar Junction has a proprietary data collection system that captures all significant information and data regarding fabrication of the solar cell. Data visualization software enables rapid analysis of the data flowing from the DOE. These tools were used throughout Phase 1 to speed the development activities.

Phase 1 is expected to result in: a well defined process for making a triple-junction solar cell, with a GaInNAs bottom sub-cell, that will have a cell efficiency ≥38% at >100-suns; an ARC modeling capability that results in an ARC design that, when applied to a 3J cell with a ~ 1 eV bottom cell, gives a minimum short circuit current density (J_{sc}) ≥ 11.5 mA/cm^2 in each junction; and HALT test platform and test fixture identified, built and tested, and initial HALT tests completed on GaInNAs cells and GaAs reference cells.

Task 1 - Development of a Triple-Junction III-V Solar Cell Using GaInNAs as the Bottom Cell

Making good quality dilute nitride materials does not guarantee a successful 3J cell. A high performance 3J cell requires that all three junctions be high quality solar material and that the tunnel junctions be able to support the current densities typical of CPV cells. Even though the ultimate objective is to demonstrate 3J cells with high efficiency, the technical approach to this task was to first optimize each individual subcell and demonstrate J_{sc} and open circuit voltages (V_{oc}) for each subcell that are necessary to achieve the target efficiencies of the integrated 3J cell. In addition the top and bottom tunnel junctions were optimized to achieve and demonstrate low resistance when under optical concentrations typical of CPV systems. Once all the key elements were optimized and the fabrication processes understood, they were integrated into a 3J cell structure and further optimized to meet the target 3J efficiency goals.

Task 1 is comprised of 5 subtasks with nine separate deliverables, each focusing on an important aspect of making a commercially useful 3J solar cell. For each of the nine deliverables the subcontract called for five devices, 2 x 2 mm in size, to be submitted for evaluation. We delivered 8 to 10 samples either 4.0 x 4.6 mm or 5.5 x 6.6 mm in size, 4.5 to 9 times larger in area than called for in the subcontract. In particular, all samples submitted for cell efficiency measurements were 5.5 x 6.6 mm in size, the most common size being used by CPV system manufacturers.

Three of the subtasks, 1.1.1, 1.1.2 and 1.1.3, were aimed at optimizing the performance of each of the three subcells used in the 3J design of Figure 2. The milestones for the deliverables of these subtasks were the measured values of 1-sun J_{sc} and V_{oc} measured at 500 suns. For the InGaP and GaAs subcells, the milestones were 1-sun $J_{sc} \geq 13.0$ mA/cm^2 and V_{oc} measured at 500 suns of ≥ 1.5 V and ≥ 1.1 V for InGaP and GaAs respectively. Subtask 1.1.3, optimization of the GaInNAs layer, had 3 progressively more difficult milestones culminating in achieving a 1-sun Jsc ≥ 15 mA/cm^2 and $V_{oc} > 0.55$ V at 500 suns. The significance of these milestones is that if subcells good enough to achieve these results can be integrated together into a 3J cell without much additional losses, it should be possible to achieve the efficiency goals of the program. All the cells tested by NREL met or exceeded the goals and in many cases substantially exceeded the goals, even those the tests were done on cells of much larger area than called for in the subcontract.

Tunnel junctions are key elements of a 3J device. There are two, each made from different materials, in all 3J cells. Tunnel junctions need to be highly conductive so current can pass without loss but the layers are then highly adsorptive, which requires that they be very thin in order for light to pass unabated to the lower junctions. Accurate measurements of low resistivity are difficult. For these deliverables special die were prepared with each die having several different test structures and each test structure having a different radius. Data was taken from 8 different test die over about ¼ of a full wafer. For the bottom junction, Solar Junction submitted measurements on 8 different test structures on 8 die, making a total of 64 different resistivity measurements. For the top junction 4 different test structures on 8 die were used for a total of 32 different measurements. The two milestones for subtask 1.1.5 were to demonstrate a top and bottom tunnel junction with resistivity of ≤ 10 mΩ-cm^2 under 500 suns of illumination. NREL measurements gave resistivity of < 2.0 mΩ-cm^2 for both junctions, much less than the original target.

Having demonstrated the ability to make good quality components, the next steps were to combine these elements into a 3J device and optimize the process to achieve the two 3J cell efficiency milestones. Subtask 1.1.4 had two milestones, D8 and D9, for 3J cell efficiency. For D8 the milestone was an efficiency of $\geq 30\%$ at concentrations > 100 suns, when measured using a concentrating solar simulator. The milestone for D9 was $\geq 38\%$ at concentrations > 100 suns. For both D8 and D9, Solar Junction submitted 10 cells 5.5 x 6.6 mm in size to NREL for characterization. Six cells were measured for each milestone. Of the samples tested for the 30% milestone of D8, one cell was measured to have 39.4% efficiency and the remaining five samples tested were measured at greater than 40% efficiency. The highest efficiency measured was 40.9% at 353 suns concentration. This greatly exceeds the milestone.

Of the six samples submitted for the 38% milestone of D9, all were measured close to or higher than 41% peak efficiency with two having a peak efficiency of 41.1% at about 300 suns. Figures 3 and 4 are the NREL data for the 38% milestone.

NREL

PV Cell & Module Performance Group

Concentrator Cell Test Report

Date: January 13, 2011
Manufacturer: Solar Junction
Structure: GaInP/GaAs/GaAs-GaInNAs triple junction
Wafer ID: C-285-2-A780
Simulator: Spectrolab X25, Spectrolab HIPSS
Temperature: 25°C
Spectrum: ASTM G173 Direct

Cell ID	Area (cm^2)	Peak η (%) @ Conc. (×)	η @ 100× (%)	η @ 1000× (%)
5	0.3132	41.1 @ 299	40.0	40.2
7	0.3127	41.1 @ 298	39.9	40.9
9	0.3132	40.9 @ 296	39.9	39.0
14	0.3123	40.7 @ 298	39.5	40.5
20	0.3121	40.9 @ 300	39.7	40.9
29	0.3121	41.0 @ 300	39.8	40.6

Figure 3: Table showing the NREL measurements on samples submitted for Milestone D9

As Figure 3 shows, all but 1 cell had efficiency >40% at 1000 suns concentration, a clear indication that these cells were very high quality in all respects. As part of the process improvement, cells were submitted to NREL for evaluation but not as deliverables against contract milestones. Cells from one of the wafers proved to be a verified World Record cell efficiency. Three cells were measured and all had efficiencies >43.0% with the highest being 43.5% at 418 suns concentration. The I-V curve for this cell is shown in Figure 5. At ~ 1000 suns, all cells measured > 42.0% efficiency. These cells had a 5.5 x 5.5 mm aperture, the same most of the deliverables for the program and the most common size used commercially.

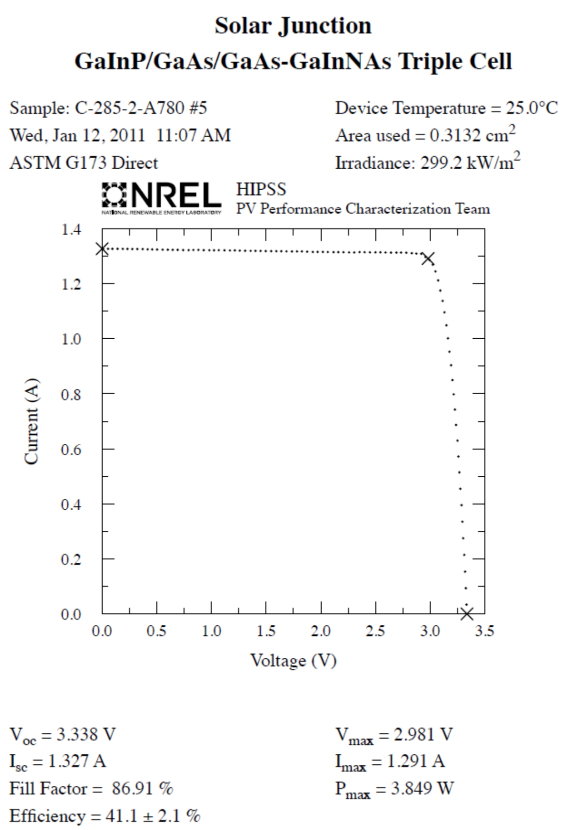

Figure 5: I-V Curve of a sample submitted for Milestone D9 measuring 41.1% peak efficiency

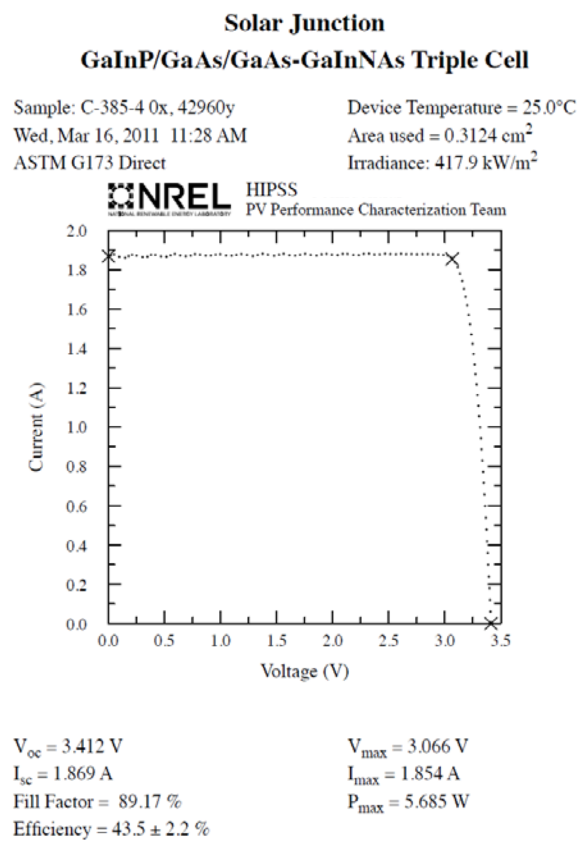

Figure 4: I-V Curve of a sample measuring a World Record 43.5% peak efficiency

Task 2 - Antireflective Coating Development for a Triple-Junction Cell with a GaInNAs Bottom Cell

To achieve the efficiency milestones of Task 1, it is important to have an antireflective coating (ARC) that couples light efficiently into all three junctions. ARCs used for current 3J cells with a Ge bottom junction that typically produces large excess current, may not be suitable for cells with a ~1 eV bottom junction where the current generation in each cell is more evenly matched. The goal of Task 2 is to develop an ARC simulation capability for modeling the impact of and designing ARCs on a 3J cell using a GaInNAs bottom junction.

The technical approach to Task 2 is to develop a software tool that can take cell and coating parameters as inputs and calculate the expected cell J_{sc} for those inputs. The model was validated by comparing the model predictions to the measured results of cells using the ARC design from the model. Once validated the model was used to predict an ARC design that would give a higher current. J_{sc} measurements from samples were used to validate the prediction.

The simulation software was developed at Solar Junction using Matlab program architecture. Inputs to the software are the cell parameters and data such as refractive index, IQE, and thickness of each subcell in the 3J device, refractive index data on ARC materials, input spectrum including angle of incidence, and the refractive index to be matched (air or glass). The software maximizes the J_{sc} of the 3J cell and provides ARC thickness for optimal current output. The model output also gives the cell reflectivity versus wavelength for the ARC, which enables the model to be compared to measured reflectivity over a wide range of wavelengths.

The two milestones for Task 2, D10 and D11 was first to demonstrate that the model prediction and the measured cell characteristics were in good agreement, and that the ARC design resulted in a minimum $J_{sc} \geq 11$ mA/cm^2. The second milestone was to use the software to design an improved ARC that would give $J_{sc} \geq 11.5$ mA/cm^2. The right hand graph in Figure 5 shows the close agreement between the model prediction for an Al_2O_3/TiO_2 ARC and the measured reflectance of that coating applied to a 3J cell. Measurements on 8 cells with this ARC had J_{sc} between 12.48 and 12.68 mA/cm^2, very close the model prediction of 12.79 mA/cm^2. The left hand graph in Figure 5 illustrates the predicted and measured reflectance of an improved SiO_2/TiO_2 ARC. The improvement is particularly noticeable when comparing the reflectivity of the two ARCs at wavelengths in the range between 400 nm and 900 nm. The lower reflectance of the SiO_2/TiO_2 ARC results in a higher J_{sc}. Measurement of 8 cells with the improved ARC had Jsc of 12.8 to 12.9 mA/cm^2.

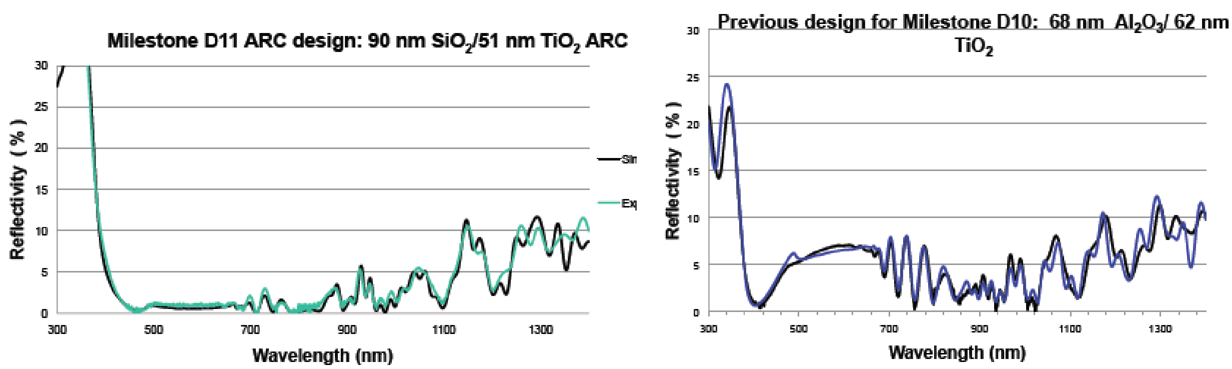

Figure 6: Comparison of the predicted and measured reflectivity for cells coating with different ARCs, showing the close agreement between prediction and experiment.

Task 3 - Reliability and HALT Testing of Triple-Junction Cells with a GaInNAs Bottom Cell

Solar Junction's cell design using dilute nitrides is lattice matched throughout the cell just as the current production 3J cells using Ge are. It is therefore expected that our cells will have the same high reliability historically seen in lattice matched III-V 3J solar cells, but this needs to be verified. Dilute nitrides are not expected to have intrinsic reliability problems substantially different from other III-V cell materials, but it is a new material for concentrator solar cells. It is therefore important to demonstrate that it does not introduce new reliability issues reliability in CPV applications. While the overall objective of the reliability portions of the subcontract are aimed at determining the reliability of a 3J cell, one goal of Task 3 is to develop a High Accelerated Life Test (HALT) methodology, a test platform, and test tools that can be used in both Phase 1 and 2 to determine the true operating and destruct limits of the developed solar cells, and to determine or bound the lifetime or mean time before failure of cells in CPV operating environment. A second goal of Task 3 is to use these tools to determine if GaInNAs itself has intrinsic reliability problems that would be likely to show up during a standard 20-30 year CPV deployment.

To do the stress tests for Task 3 and in Phase 2, it was necessary to develop a test platform and assembly process for mounting cells that could be used for stress testing cells without contributing to cell failure. The first objective of Task 3 was to design, build and test such a package and subject it to HALT with test limits beyond what is anticipated for cell testing. The milestones for this objective was to deliver 3 unstressed and 3 stressed packages to NREL. Figure 7 is a drawing of the test fixture. The HALT protocol was developed in conjunction with OPS Ala Carte, a reliability engineering services company, and the tests were conducted using their facility and equipment. The tests were hot and cold step stress, rapid temperature cycling, vibration step stress, and combined environment where vibration and step stress are done simultaneously. All samples except one completed the HALT stresses with no mechanical or electrical failures. One sample exhibited a mechanical problem near the limits of the testing. The problem was caused by incomplete wetting of the epoxy attaching a part. Assembly procedures for the test platform were changed to prevent this problem in the future.

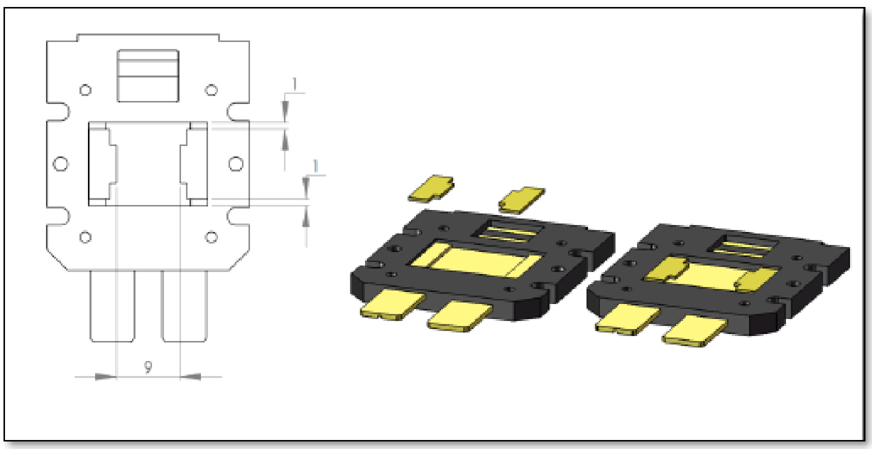

Figure 7: Test platform for mounting cells for HALT and reliability test

Once the test package was validated, the next objective was to develop and validate a cell assembly process that would also survive the anticipated HALT and reliability tests without contributing to device failure. For this test, 12 devices were assembled, 6 GaAs and 6 GaInNAs monotype cells, were die attached and wired bonded to the package shown in Figure 6. Two types of cells were used just to get an early indication if there were any differences between the two types of cells. Prior to test the devices were given a visual inspection and the I-V curves of all devices were recorded. All devices survived the temperature cycling and the hot and cold step stresses. Seven of the devices failed at the top limit of the vibration step stress when the chips separated from their packages. Analysis of the failed devices showed a cohesive failure of the die-attach epoxy as the cause in all cases. However the failure point greatly exceeded any requirements by the solar module specifications IEC 62108 and it also exceeded the vibration standards of Mil-STD-883 used for microelectronics in Military and Aerospace systems. For the devices that completed the HALT cycle, the I-V curves showed no change from the pre-test curves.

With a test package and assembly process developed and verified the next goal of Task 3 was to determine if dilute nitrides presented reliability problems when used in CPV systems with specifications of power degradation less than 20% over the 20 or 30 year life of the system. The technical approach taken was to subject GaInNAs and GaAs monotype cells to the same series of temperature stress tests in ambient air and measure changes in the key electrical parameters to determine degradation and failure. This data was then used to determine the equivalent time at operating temperature at which degradation and failures of GaInNAs cells will occur, and to compare differences in degradation and failure between GaInNAs cells and GaAs cells included in the same test. By testing only a single junction these tests aimed to isolate failures to the GaInNAs material itself and identify and remedy any potential reliability problems before starting tests on the more complicated 3J cell. The GaAs cells act as a type of benchmark since it is a material used in many devices over many years.

Twelve GaInNAs cells and twenty GaAs cells were subjected to temperature step stress. The cells were stored unbiased in an air ambient at increasingly higher temperatures starting at 130C and ending at 215C. Prior to starting the test all cells were characterized by 1-sun light I-V measurement (LIV), Dark I-V measurements (DIV) and Flash I-V measurements at 500 suns concentration. At various times, the cells were removed from test and allowed to return to room temperature, at which point there I-V characteristics were measured under a 1-sun light source. Changes from starting values of open circuit voltage (V_{oc}) were used as an indication of cell degradation. If any change greater than 3% was found, all samples would get the full complement of LIV, DIV and concentrated flash test before moving to a higher temperature. Changes of greater than 10% in efficiency, V_{oc}, short circuit current (I_{sc}) and fill factor (FF) were considered a failure, and the cells would be removed from test.

The results of this milestone were successful in that they clearly show that dilute nitride cells have survived the equivalent of at least 100 years of on-sun operation (3285 sun hrs/yr) at a continuous operating temperature of 100 C with no failures. This is well in excess of what is needed for their use in CPV systems with 20 to 30 year operating life. In addition, the degradation of GaInNAs cells is no worse and likely less than that of GaAs cells subjected to same temperature stress test.

Reliability tests of solar cells rely on high temperature storage and temperature cycling to provide the stress for activating cell degradation and failures from which Mean Times Before Failure (MTBF) are extracted. There are other stress tests such as heat and humidity that gauge a cells response to a specific environment but don't predict its life in a standard CPV operation. However, there are no reports of reliability or stress testing of concentrator solar cells that mimic their actual conditions of operation – several hundred suns of concentrated light focus on the cell and high cell temperature.

Given the importance of reliability to CPV deployments and the long time scale of these deployments, the final objective of Task 3 was to design, build and characterize a system where cells can be stressed at increasingly higher temperatures while being under continual optical bias. The purpose of this system is to find the weak links in cell design, identify failure modes, and determine the true operating and destruct limits using repeatable testing techniques that more closely match the combined temperature and under sun environment encounter in real CPV operation. By subjecting the product to increasing levels of stress, long term failure modes that would show up under normal operating conditions in months or years can be revealed in just days or weeks.

The custom HALT environmental chamber is designed to measure the I-V characteristics of six packaged III-V solar cells simultaneously while subjecting them to rapid thermal transitions while under variable applied optical loads. A schematic of the system is shown in Figure 7. A vacuum chamber contains six independently temperature controlled stages, each holding one solar cell. A thermocouple close to the cell gives continuous temperature measurements and the I-V characteristics of each cell can also be continuously monitored. A closed loop temperature control system enables stage temperatures from -100C to +175C. Light from six independently controlled light sources mounted above the vacuum chamber is concentrated through a Fresnel lens and directed through a quartz window in the vacuum chamber onto the solar cell. A clipping aperture immediately above the chamber window controls the spot size on the cell. By controlling the vertical position of the Fresnel lens and the size of the aperture, the light concentration on the cell can be varied. Optical concentrations of 585 suns were demonstrated. The chamber can be pumped down to as low as 2.3×10^{-4} Torr or operated at atmospheric pressure with different environments such as dry Nitrogen or ambient air. The system has been characterized and met its design goals. Going forward there are opportunities to improve on the system and make it a more powerful tool for doing HALT in ways that more closely mimic CPV operating conditions.

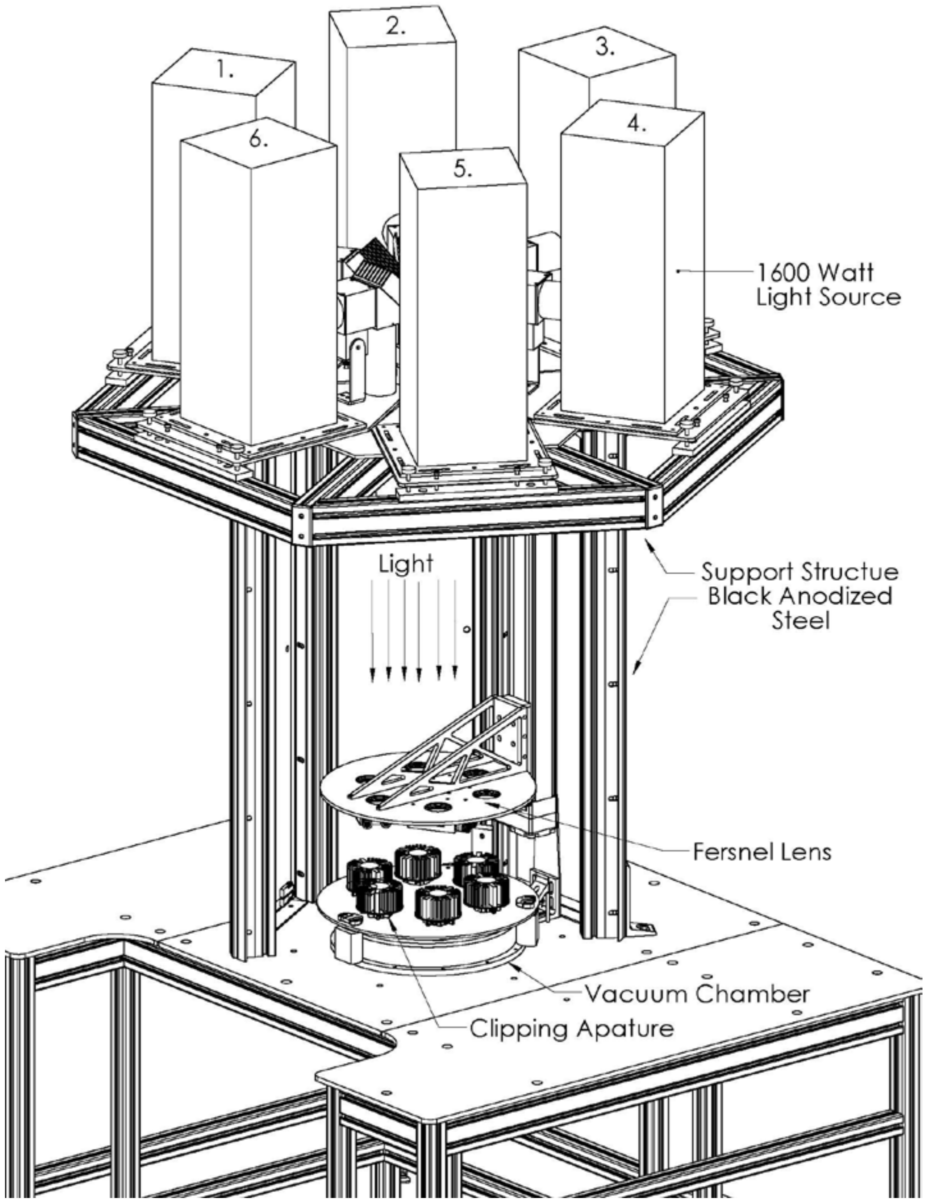

Figure 8: A schematic of the Light Bias Cell Reliability Test System

Phase 2 Scope of Work

The Phase 2 work plan was originally intended to continue the development started in Phase 1, but during Phase 1, the cell performance of milestones delivered, as well as the achievement of a World Record cell efficiency, exceed the Phase 2 milestones of the original SOW. Consequently after the Phase 1 Stage Gate review, new milestones were agreed to for Phase 2 that targeted cell performance under conditions likely to be experienced in operation rather than under standard test conditions. In addition, during Phase 1, a valuable improvement to the HALT system was identified. As a consequence the original Phase 2 reliability milestones were modified to incorporate this new design feature.

The objective of Phase II includes the development of deposition processes for integrating the three InGaP, GaAs, and GaInNAs sub-cells into a monolithic device that is optimized for the temperatures and concentrations typical of operating CPV systems, 60°C and $\geq$ 500 suns, and is coated with an ARC matched to glass, a requirement of the large majority of CPV system manufacturers. Additionally, process development of anti-reflective coatings will be continued as will the demonstration through HALT and accelerated life tests that cells developed under this program have lifetimes compatible with the anticipated 20-year lifetime of a CPV system. To achieve these objectives, the approach used in Phase I of statistical design of experiments combined with device characterization and modeling will be continued to find device deposition and processing parameters that result in cell efficiencies and anti-reflective coating reflectance that meet the program goals. In addition, the reliability testing focused on in Phase I will be expanded to verify device reliability suitable for CPV deployments.

The Phase 2 work plan is divided into 3 primary tasks that are organized such that work on them can be done in parallel. Phase 2 is expected to result in: a well defined process for making a triple-junction solar cell with a GaInNAs bottom cell that will have an efficiency $\geq$ 37% at >800-suns, measured at 60°C; a glass matched anti-reflective coating optimized for a triple-junction solar cell with a ~1eV bottom cell that has a Jsc $\geq$ 13.0mA/cm^2; a demonstration of a reliability of the developed cell that is compatible with current CPV system reliability.

Task 4 - Development of a Triple-Junction III-V Solar Cell Using GaInNAs as the Bottom Cell

The focus of this task is to better understand and control the design parameters and fabrication processes related to integration of all elements of a triple-junction cell that will lead to higher efficiencies for an integrated triple-junction cell with a GaInNAs bottom layer, but when operating with a glass-matched ARC and at 60°C and $\geq$ 500 suns concentration. The approach taken was to use the knowledge gained in Phase I to design a set of experiments, the results of which guided the development team to a device design and fabrication process meeting the Phase II goals.

Glass matched ARCs are commonly used in the CPV industry because a refractive secondary optical element is generally mated to the cell with a fluid indexed matched to glass. If a reflective secondary is used, then the cell is usually protected with a glass cover slip. In all cases the ARC on the cell needs to be matched to glass to prevent reflective light losses. The challenge from a cell test perspective is that cell efficiency measurements are done in air and the reflective mismatch between the glass ARC and air causes the efficiency measurement to be lower than would actually be the case in a matched system. Thus a cell with a glass ARC that measured 40% efficiency in an air test would give a higher efficiency if measured in a glass system. How much higher depends on the properties of the ARC. Likewise, as cell temperature is increased above 25C, cell efficiency decreases. Since cells are operating typically at temperatures of 50C to 60C or higher, good cell performance at these temperatures determine the module power output. Most CPV systems operate at a minimum concentration of 500 suns with many moving to concentrations around 1000 suns. While efficiency does increase with concentration when starting at 1-sun and going higher, at some point series resistance will negatively impact the electrical performance and efficiency will decrease as concentration increases. The crossover point depends on intrinsic cell properties and the grid design, making it possible to modify the cell to perform better at higher concentration.

The deliverables of the three milestones for Task 4 aim at evaluating the cell performance under conditions more typical of CPV cell environment rather than standard test conditions. One milestone is to supply cells with an aperture of 5.5 x 5.5 mm, and having an ARC matched to glass, that measures ≥40% efficiency at ≥500 suns concentration and at 25C. 10 cells with Solar Junction measured efficiencies ranging from 40.1% to 40.4% were submitted to NREL for test. Five cells were tested at NREL with efficiencies ranging from 40.7% to 41% at 500 suns. A second milestone had a target for cells with an Air matched ARC of ≥38% efficiency at ≥500 suns when the cell temperature is 60C. Eleven cells were submitted with 60C cell efficiencies ranging from 38.0% to 39.2% at 500 suns. NREL measurements confirmed these values. The final cell milestone was ≥37% efficiency at 800 suns and 60C for a cell with an air matched ARC. The 10 submitted samples ranged from 38.1% to 38.5% when measured at these conditions at Solar Junction. Samples measured at NREL at 60C ranged from 40.0% to 41.1% at about 900 suns concentration. This greatly exceeds the milestone target. The NREL result for this Milestone is shown in Figure 9.

Date: March 12, 2012
Manufacturer: Solar Junction
Structure: GaInP/GaAs/ GaInNAs triple junction
Wafer ID: C-553-4
Simulators: OSMSS, Spectrolab HIPSS
Temperatures: 25°C, 60°C
Spectrum: ASTM G173 Direct

Cell ID (map)	Area (cm^2)	Peak η (%) @ Conc. 25°C	Peak η (%) @ Conc. 60°C
7	0.3110	43.3 @ 492×	40.2 @ 627×
8	0.3098	43.5 @ 925×	41.1 @ 895×
9	0.3105	42.8 @ 720×	40.0 @ 903×
10	0.3117	42.4 @ 725×	40.5 @ 890×

Figure 9: NREL Report for Milestone D18, cell performance with an air ARC at 60C and >800 suns

Figures 10 and 11 represent the data from Milestone D16 of Task 4.

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

PV Cell & Module Performance Group

Concentrator Cell Test Report

Date: July 20, 2011
Manufacturer: Solar Junction
Structure: GaInP/GaAs/ GaInNAs triple junction
Wafer ID: C-444-4-A780
Simulators: Spectrolab X25, Spectrolab HIPSS
Temperature: 25°C
Spectrum: ASTM G173 Direct

Cell ID (map)	Area (cm^2)	η @ ~500× (%)	η @ ~1000× (%)
1	0.3120	40.8	39.8
2	0.3128	—	—
3	0.3128	—	—
4	0.3125	—	—
5	0.3118	40.8	40.8
6	0.3127	41.0	41.0
7	0.3128	40.9	41.1
8	0.3127	—	—
9	0.3129	40.7	40.6
10	0.3124	—	—

Figure 10: Data for Milestone D16 Showing the NREL Measured Efficiency for Cells with a Glass-Matched ARC

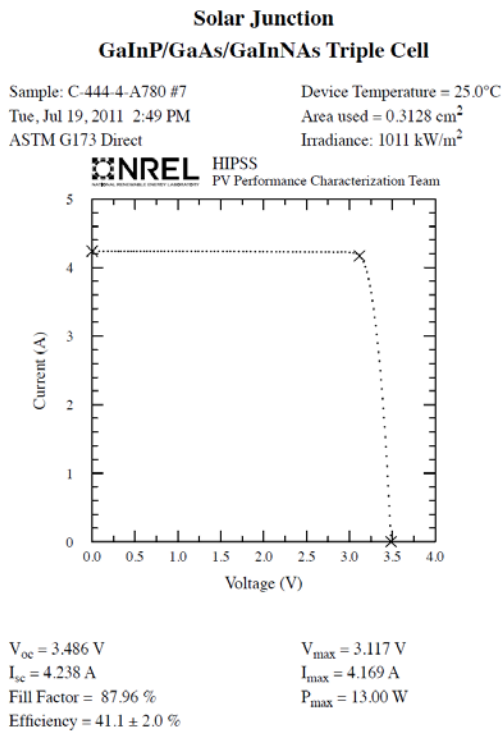

Figure 11: The I-V Curve from Sample 7 of Figure 9

Task 5 - Antireflective Coating Development for a Triple-Junction Cell with a GaInNAs Bottom Cell

Task 5 continues the development started in Phase I and further refines the design and processes for making an anti-reflective coating for a triple-junction cell having a ~1eV bottom cell but focus on ARCs that are matched to glass, as this is a requirement for almost all CPV system manufacturers. The device modeling developed in Phase 1 and the results of experiments were used to modify the antireflective coating design and/or the deposition processes to achieve good quality glass matched ARCs. Functionally this means that the ARC is designed to maximize the current from the cells. There were two milestones for Task 5, each with deliverables of 5 cells with a glass matched ARC and reflectivity data showing that the ARC was glass matched. . The first of these two milestones required a short circuit current (J_{sc}) of $\geq$ 12.0 mA/cm^2 and the second a J_{sc} of $\geq$ 13.0 mA/cm^2.

To meet the requirements for this Task, two different glass matched ARCs were developed, using the software model developed in Phase 1. The measured reflectivity of both ARCs agreed closely with the predictions of the model. This is shown in Figure 12 for the ARC of Milestone D19. Measurements by NREL showed that the milestone requirements were exceeded. Figure 13 is an I-V curve from a cell submitted for Milestone D20 showing a J_{sc} of 13.7 mA/cm^2, nearly 5% higher than the target value.

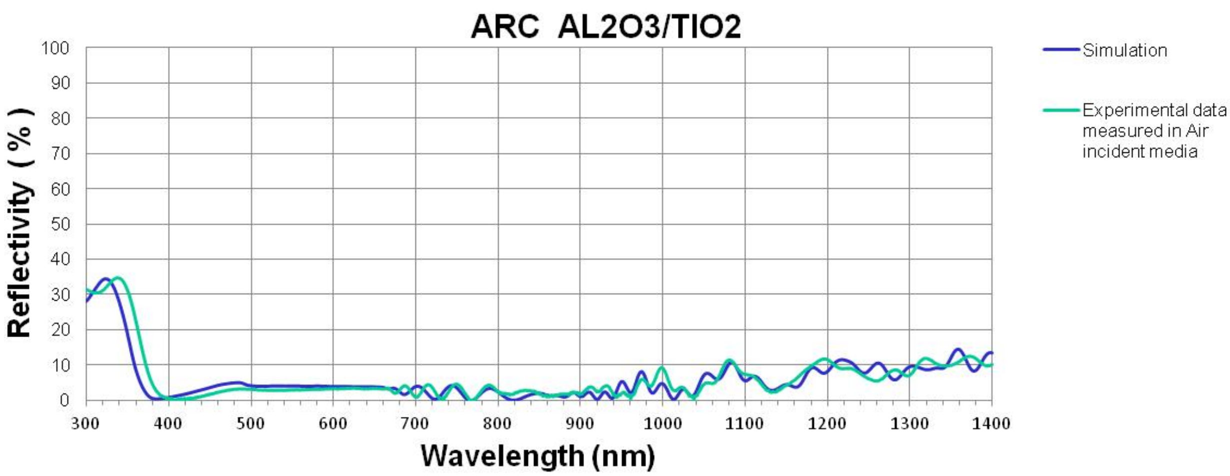

Figure 12: Comparison of the Predicated and Measured Reflectivity for a Glass-Matched ARC

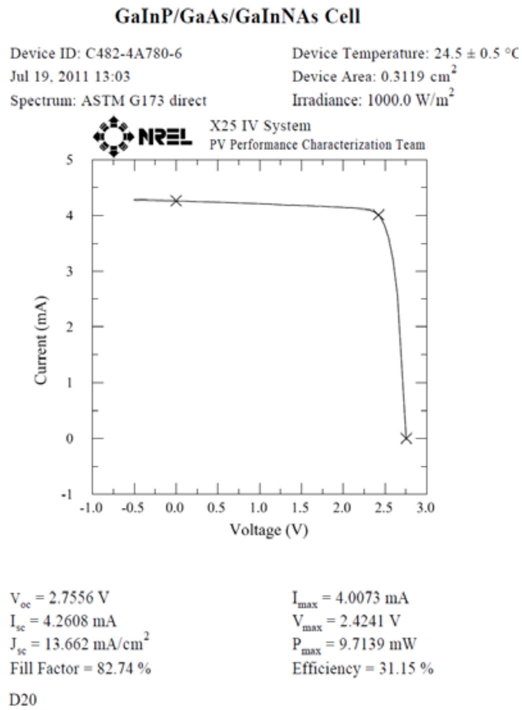

Figure 13: I-V Curve for Milestone D20 Showing a J_{sc} of 13.7 mA/cm^2

Task 6 - Reliability and HALT Testing of Triple-Junction Cells with a GaInNAs Bottom Cell

The goal of Task 6 is to determine whether or not the degradation and failure of 3J cells using dilute nitrides are consistent with CPV systems that expect a maximum power degradation of 20% over a 20-30 year system life, and to use HALT protocols to identify potential failure cell modes. This Task extends the work started in Task 3 of Phase 1 to included accelerated life test of completed 3J cell and use of the HALT system developed to identify modes of failure in a 3J cell. At the conclusion of Phase 1, it was decided to add a new feature to the HALT system, a shuttering system that enables light to be cell to be interrupted in a way that cell would experience when clouds block the sun or during sunrise and sunset when the sunlight suddenly goes away. The technical approach to meeting this goal is to apply a series of stress tests, ideally increasing the stress level until the cells fail, and to use the data to draw conclusions about the expected failure rate and failure modes of the cells over a 25-30 CPV system operating life. This information can then be used to try and eliminate or reduce the failures and thereby increase the reliability.

There were three Milestones for this Task, the first of which was to modify the HALT system to include a way of interrupting the light to the cell at least 10 times/second. The other two milestones were to report on the results of accelerated life tests and the HALT tests.

Modifications to the HALT system were made by inserting a graphite shutter after the light sources and before the chamber window over the cell. This can be seen in Figure 14 and compared to Figure 8. The graphite shutter has six holes adequate to pass the light in the open position and large enough solid areas to prevent light from hitting the cells. The shutter and its on/off rate were electronically controlled. Tests verified that shutter on/off could occur at least 10 times/second (100 Hz). Figure 15 is a picture looking up at the shutter.

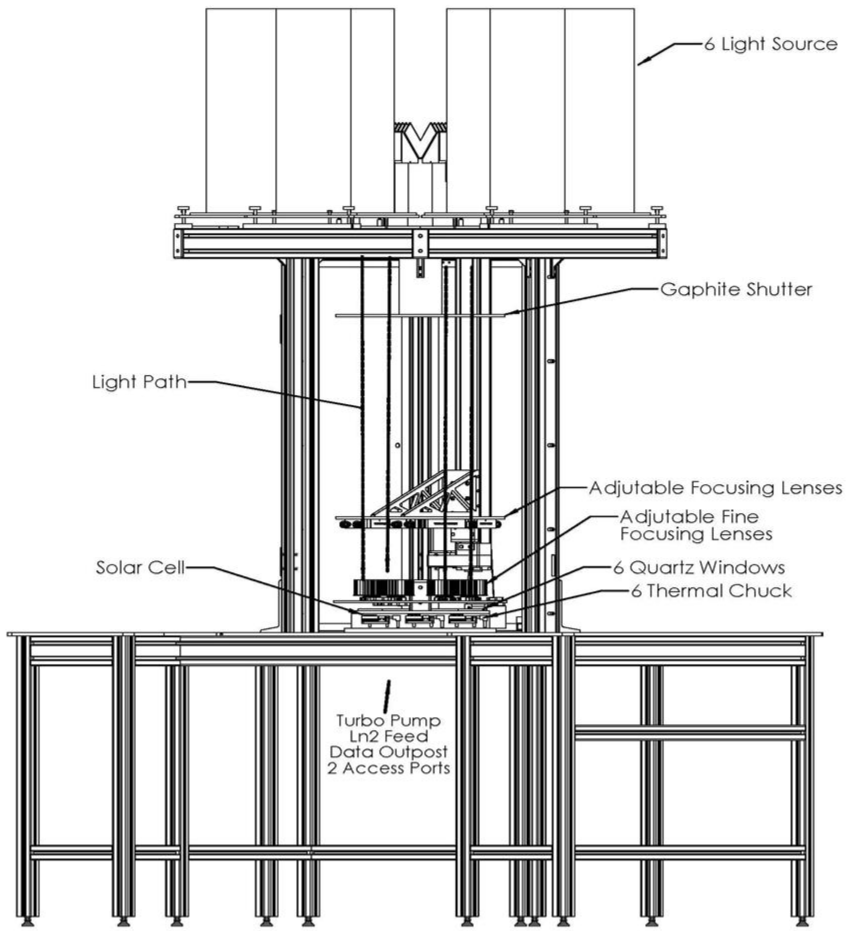

Figure 14: Schematic Side View of the HALT Chamber with the Graphite Shutter

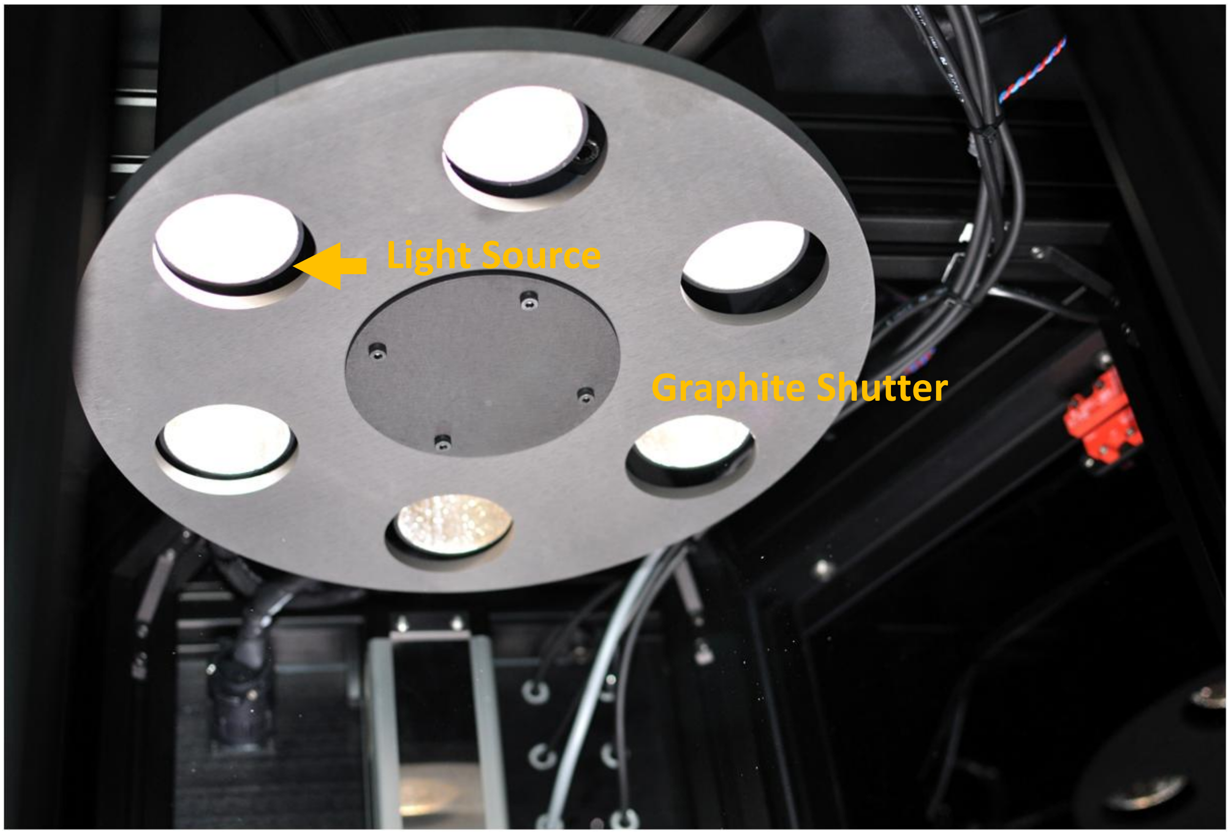

Figure 15: Picture of the Graphite Shutter in the HALT System

The final two milestones are reports on the ongoing HALT using the new system and the accelerated life test. In all these tests, cells were characterized by calibrated 1-sun I-V and 500 sun flash I-V at 25C, prior to starting the test and again at the termination of the test. Reference cells, kept at 25C, were measured at each test point along with the devices under test. In the case of the accelerated life test, the cells under test were removed periodically for calibrated measurement and then returned to test. For all of these tests, failure was defined as a decrease in efficiency of ≥10% from the starting value.

Two separate tests were done in the HALT system. Both tests were done with the shutter directing light on and off the cells once per minute, 30 seconds on then 30 seconds off, and with the cells held in a vacuum of < 200 Torr. In the first test, cells were controlled to a temperature of about 43C with 170 suns of light. After a period of time, the cells were raised to 180C, held there for several hours and then lowered to 43C. The cells were cycled a second time between 43C and 180 before the test was terminated. The cell I-V was measured once every 2 minutes, which enabled us to look for unusual changes in the electrical properties. Figure 16 shows the expected behavior of the Voc and Isc as the cell temperature changes from 180C to 40C. At the conclusion of the first test, six cells had experienced a total time at 180 C of 9 hours and 14 minutes with a total of 554 light cycles. The total time at 43 C was 106 hours and 17 minutes for a total of 6377 on/off cycles. All together, the cell saw a total of 6931 on/off cycles, the equivalent of 19 years (365 days/yr) of on/off operation in a CPV deployment experiencing no cloud cover. No significant change in flash efficiency was found at the conclusion of this test.

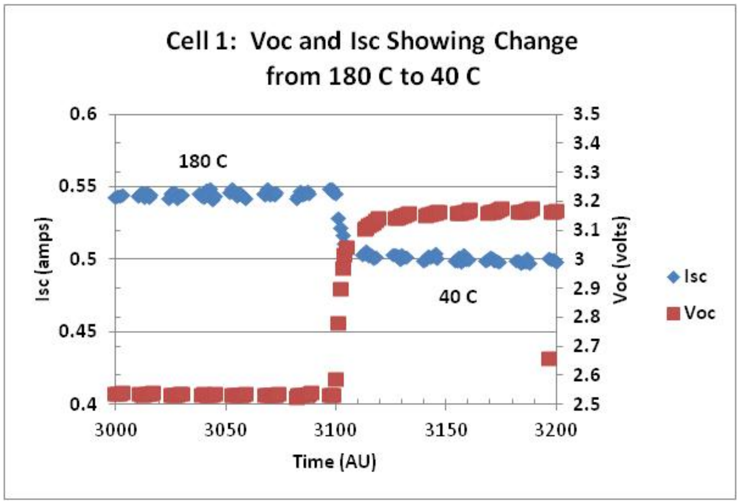

Figure 16: Graph Showing the Expected Change in Voc and Isc as Cell Temperature Changes

A second set of test in the HALT system was done on a different set of cells. In this case, the cell temperature was initially set to 110C, then increased to 160C after 169 hours. After312 hours at 160C, the temperature was increased to 180C and held there until the tests were concluded. The starting optical concentrations were 650-800 suns, depending on the specific test position, but these drifted down to 400-600 suns by the end of the test. The reason for the decrease in concentration was due to a carbon deposit on the inside of the window into the cell, which adsorbed some of the light directed to the cell. This is illustrated in Figure 17, which compares the reflectivity of a new quartz disk used as a window and a used window in the area of the dark spot. There is substantial loss in transmission in the UV/Vis region of the spectrum that effectively lowers the concentration of light on the cell.

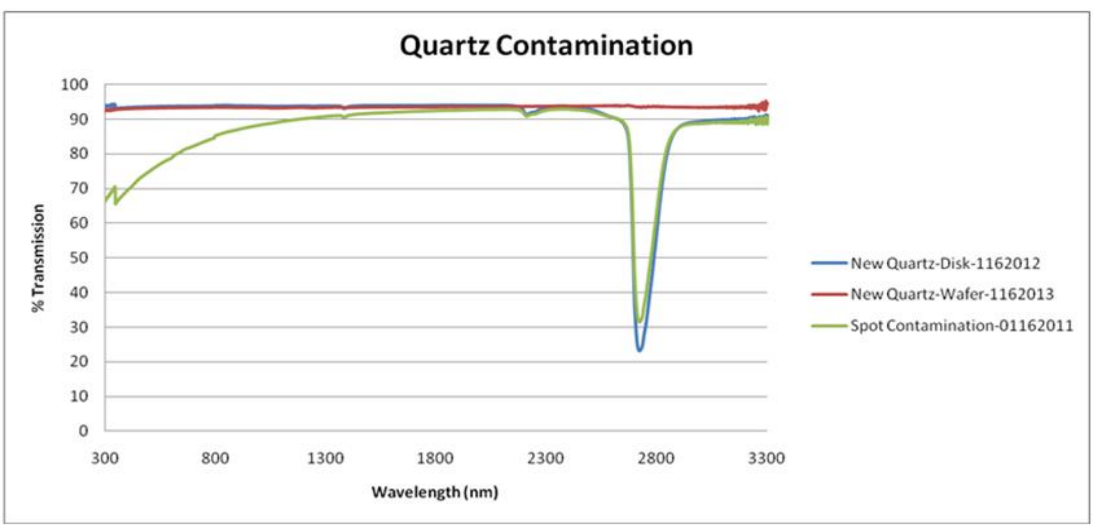

Figure 17: Reflectivity from the Quartz Window Showing the Adsorption of the Dark Spot

The source of the carbon is not known with certainty but is most likely from the cell package. At the conclusion of the test, the cells had been subjected to 650 hours at high temperature and 39,000 light cycles and showed no failures. Figure 18 shows the difference between the starting and final electrical parameters from a standard flash test. It seems likely that the cells themselves had gotten some level of carbon deposit if such was visible on the inside of the quartz window. This may explain the differences in current and efficiency that are observed in Figure 18.

	Difference Between Final and Starting Values						
	M1	B3	H9	D5	I10	J11	K- Reference
Voc (V)	-1.0%	-0.7%	-0.7%	-1.0%	-1.0%	-1.2%	0.3%
Isc (A)	-3.5%	-2.5%	-1.4%	-2.8%	-1.8%	-3.0%	-0.7%
Fill Factor	-0.7%	-0.7%	0.0%	-0.4%	-0.5%	-0.8%	-0.1%
Efficiency	-5.0%	-4.0%	-2.0%	-4.6%	-3.3%	-5.0%	0.0%

Figure 18: Change from the Starting Electrical Parameters of the Final HALT

The technical approach to estimating the expected reliability of Solar Junction's 3J cells was to use a high temperature storage test and, based on the results, infer with a reasonable level of confidence the probability of failure after 30 years of on-sun operation at a cell operating temperature representative of what could be expected in a high solar resource location. It was not planned for Task 6 to develop an activation energy for 1 or more failure modes. A minimum of three temperatures and long times on test are required to get a reasonable estimate of an activation energy, an effort beyond the scope and time frame of this program. Alternatively, activation energies for III-V devices including cells are reported in the literature and can be used to analyze the results.

For the high temperature storage tests 26 standard triple-junction solar cells with GaInNAs bottom layers were randomly selected for test from three different epitaxial growth wafers, each of which was processed in a different wafer processing lot. The cells all contained an anti-reflective coating matched to glass. All cells were characterized at 25C by calibrated 1-sun I-V and flash I-V at 500 suns prior to starting the tests. Twenty three cells were put in a temperature controlled oven at 180C in ambient air. There was no cell electrical bias during the temperature storage. The cells were removed periodically for calibrated electrical measurements at room temperature and returned to test. As with the HALT, failure was defined as a 10% reduction from the starting value of the room temperature 500 sun flash efficiency. The test was carried out for a total of 2028 hours at 180C. One failure was registered after 1240 hours of test and one more after 1720 hours of test. A standard Arrhenius relationship was used to extrapolate from the time at test temperatures to equivalent hours at anticipated cell operating temperatures. Since the mathematical expression assumes an activation energy, a range of activation energies were assumed to build a matrix of equivalent sun-years of operation at different operating temperatures. The results after 1,000 hours of test are shown in Figure 19. One sun-year is the equivalent of 3285 hours of sun per year, higher than all but a few candidate CPV deployment locations in the world. For comparison, Tucson, AZ has about 2600 peak sun hours/yr. For good solar cells, an activation energy of 1.0 eV is used and is characteristic of contact metal diffusion into the semiconductor. HBTs have even higher activation energies than 1.0 eV.

1 sun-year = 9 sun-hrs/day*365 days/yr = 3285 hrs

Operating Temp (^{o}C)	Activation Energy (eV)				
	0.7	0.8	0.9	1.0	1.1
70	2,107	4,791	10,894	24,774	42,822
80	1,077	2,225	4,598	9,501	19,630
90	571	1,078	2,035	3,841	7,249
100	314	543	941	1,630	2,824
110	178	284	453	724	1,156

Figure 19: Matrix of Equivalent Sun-Years of Operation for Different Activation Energies and Operating Temperatures after 1000 hrs of Test at 180C

The case of no failures is a particularly interesting point. With no failures, a simple form of the binomial probability distribution can used to infer minimum probability of failures at a certain confidence level. Since there were no failures at 1000 hours, the equivalent times at temperature shown in Figure 19 can be used to calculate a family of cell reliability at the expected end of a PV project, 30 sun-years. Figure 20 shows the minimum cell reliability (1- probability of failure) with 95% confidence at 30 sun-years of continuous operation at the temperatures shown. The probability is calculated for different operating temperatures and for a range of activation energies. Looking at the curve for 0.7 eV in Figure 7, this graph would say that after 30 sun-years of continuous operation at about 95C, the minimum reliability with 95% confidence is 99%. Stated another way, the probability of failure is no more than 1% under these conditions. In the case of an activation energy of 1.0 eV, which is characteristic of good solar cells, the reliability after 30 sun-years of continuous operation at 100 C is 99.5% of better. Currently, the maximum degradation of a PV power plant is no more than 20% over its expected

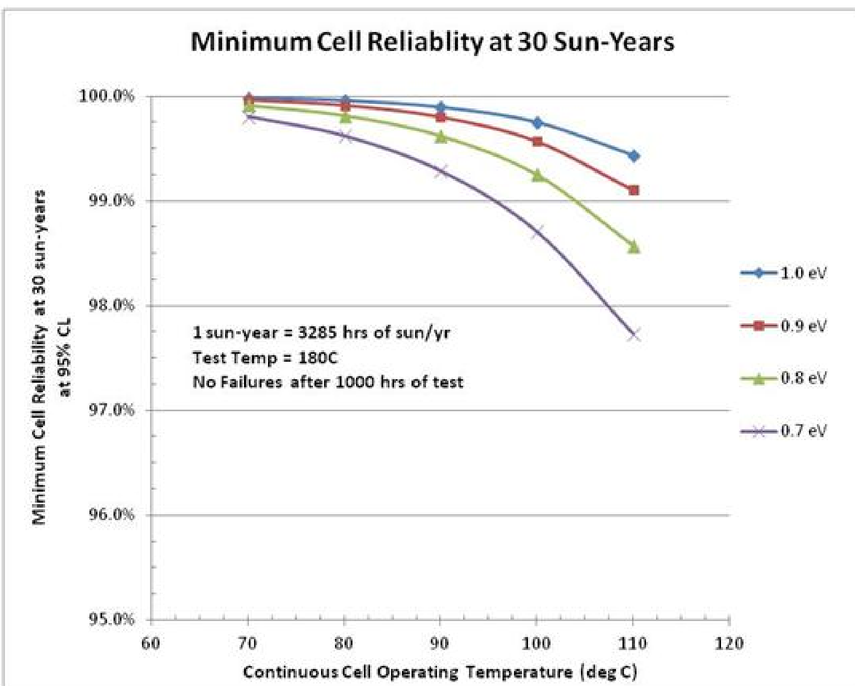

Figure 20: Cell Reliability at 95% Confidence Level for 30 sun-years of Operation

20 or 25 year life. Based on this data, 3J cells made with a GaInNAs bottom junction will not contribute in any significant way to the degradation budget.

Recognizing that cell degradation does occur and to include the failures, another way of looking at the data is in Figure 20, which plots the average change in efficiency of all active cells versus time calculated from the Arrhenius relationship. Active cell means those that have not failed. For Figure 22 failed cells are excluded from the calculation of efficiency change once they have reached the failure criterion. Assuming a 90C continuous operating temperature and an activation energy of 0.7 eV, lower than is typical of good cells, no degradation is seen in the test samples after the equivalent of 30 sun-years of continuous operation at 90C. Indeed, after the equivalent of 100 sun-years of operation at 90 C, less than 1% degradation is seen in the 23 samples.

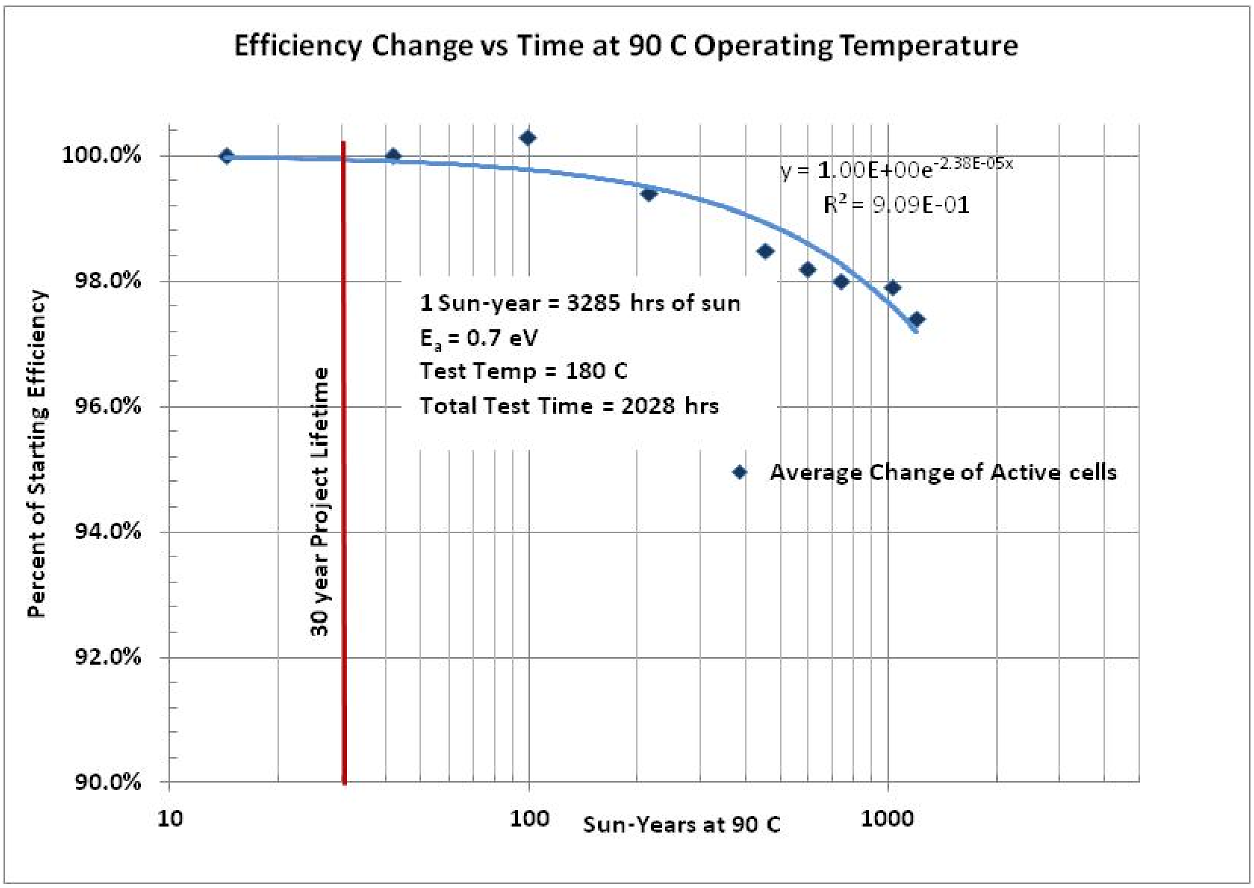

Figure 21: Percent Change in Efficiency vs Time

The degradation that is observed appears to be a result of agglomeration of the silver gridlines that occurs at extended time at high temperature. This phenomenon has been observed and reported on for silver films. Figure 22 is an SEM showing the blocky nature of the gridlines after 2028 hours at 180C. The morphological change that occurs with increased time at high temperatures results in increased electrical resistance in the gridlines. Increased resistance in the gridlines causes the fill factor (FF) of the cell to decrease, which causes the cell efficiency to drop. This is what is observed in the failed and degrading devices, lower FF and lowered cell efficiency almost totally accounted for by the drop in FF.

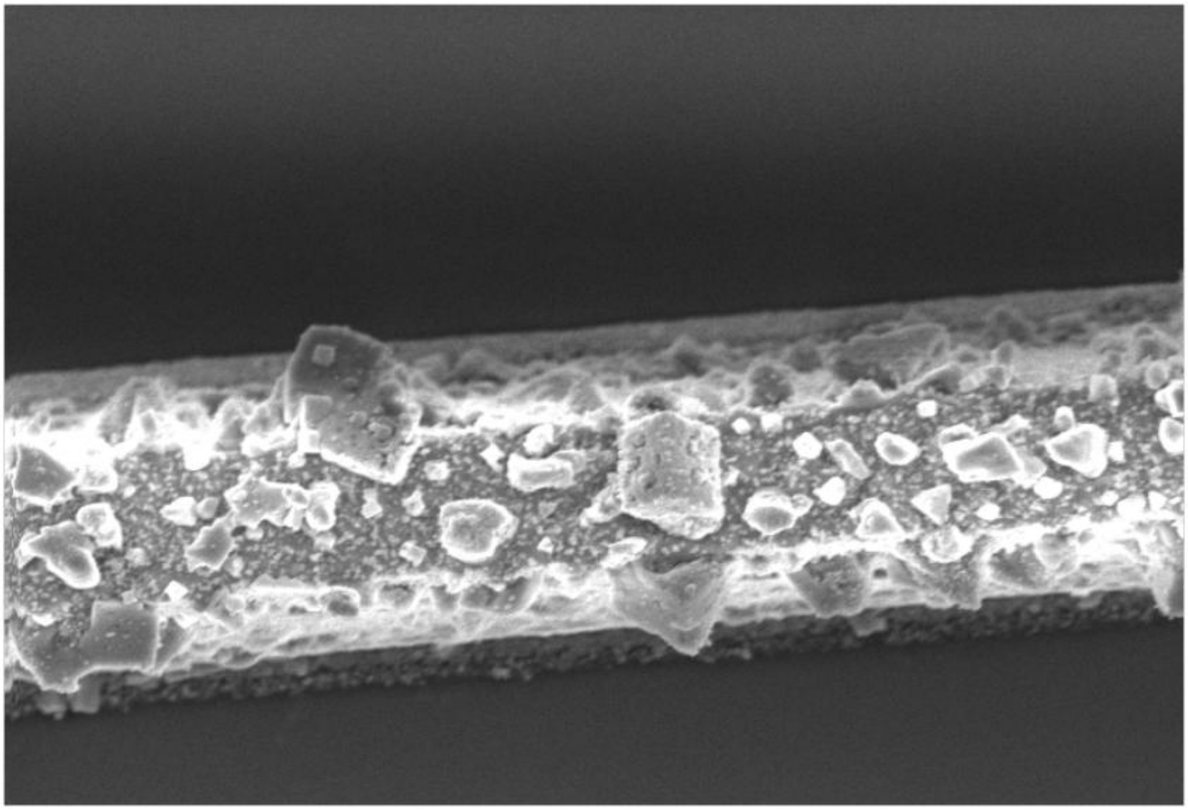

Figure 22: SEM of a Silver Gridline after 2028 hours at 180C

By contrast, Figure 23 shows a SEM of a gridline from reference cell that was kept at 25C throughout the test. The lumpiness in Figure 23 is characteristic of as deposited films and does not show the blocky morphology of the gridline in Figure 22. Regardless of the mechanism, the observed degradation is sufficiently slow that the probability of cell failure during the 20-30 year expected PV project lifetime is very low.

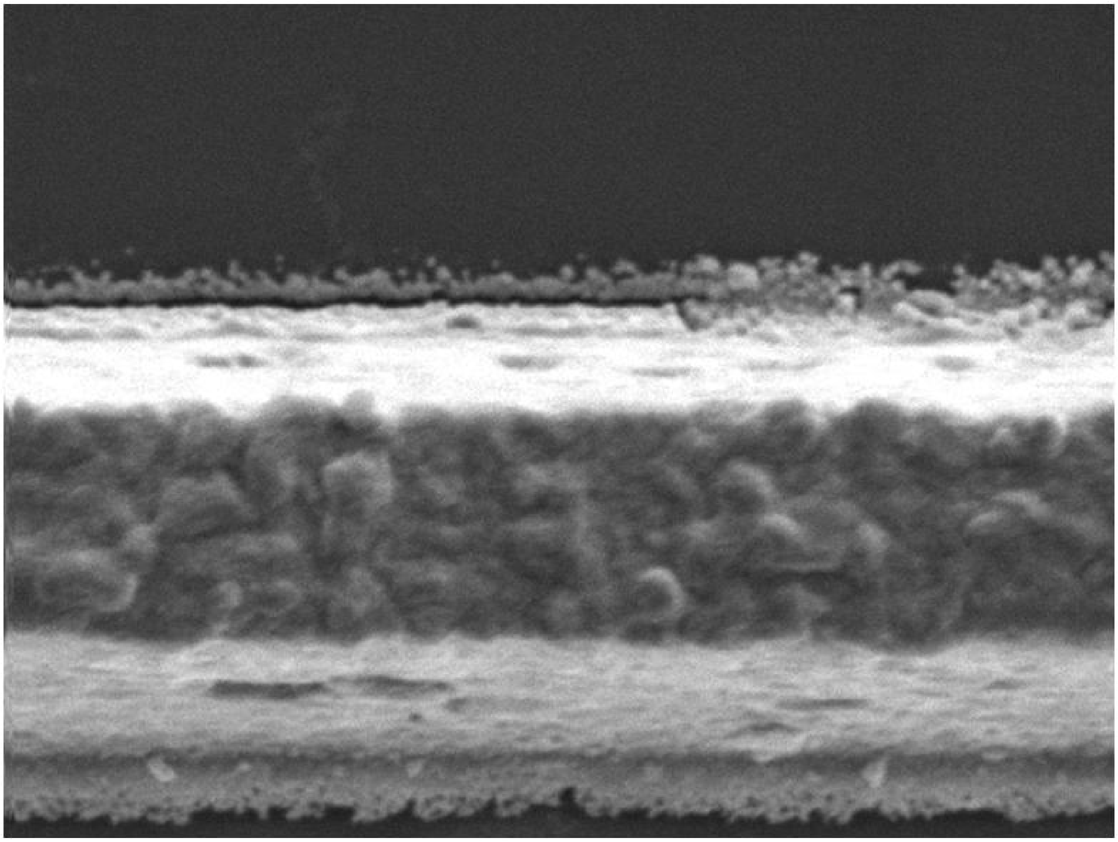

Figure 23: SEM of a Gridline from a Reference Cell Stored at 25C for 2028 hours