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Commercialization of High Efficiency Low Cost CIGS Technology Based on Electroplating

Final Technical Progress Report September 28, 2007 – June 30, 2009

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SoloPower, Inc.
San Jose, California

A Project Funded under the U.S. DOE Solar Energy Technologies Program's Photovoltaic Technology Incubator

Subcontract Report
NREL/SR-520-48590
August 2010

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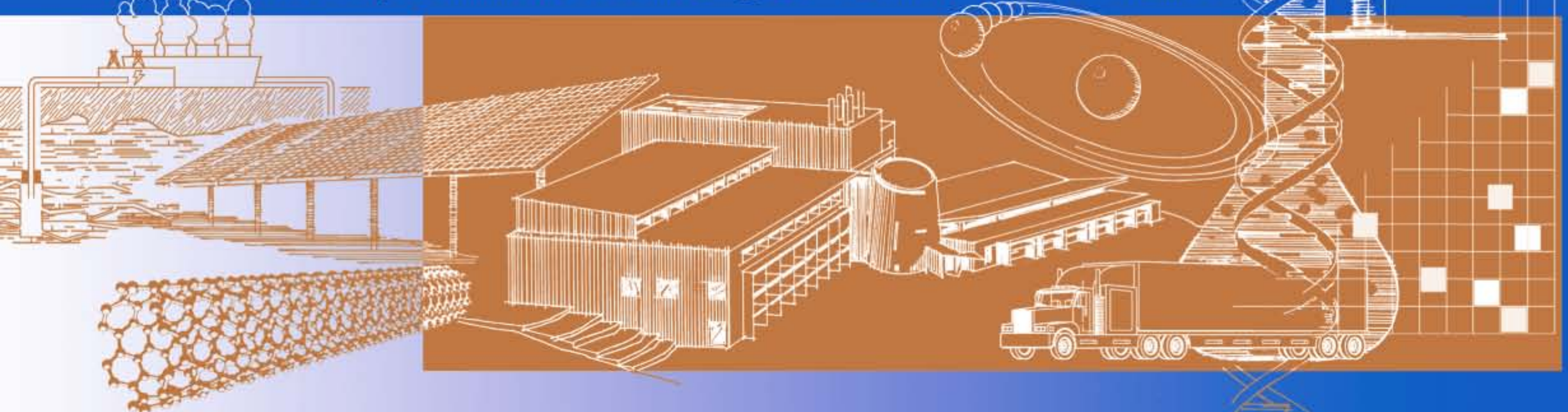

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NREL Technical Monitor: Richard L. Mitchell
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Executive Summary

This Photovoltaic Technology Incubator project was funded by the U.S. Department of Energy's (DOE's) Solar Energy Technologies Program. The focus was on research and development of SoloPower's electrodeposition-based copper indium gallium (di)selenide (CIGS) technology. The emphasis of the activities was designed to address and overcome possible barriers to manufacturing scale-up of large-area solar cells and modules. SoloPower reached all of its goals set under the project.

During the period of this project, SoloPower improved the quality of its flexible metal substrates, increased the size of its solar cells from 0.5 cm^2 to 120 cm^2, increased the small-area cell efficiencies from near 11% to near 14%, demonstrated large-area cells, and developed a module manufacturing process. During this period, SoloPower also more than tripled its workforce, moved from a small R&D laboratory to a large manufacturing facility, transferred its technology from bench-top/batch tools with capability to process 6-in. x 8-in. substrates to roll-to-roll manufacturing tools with capability to process about 1-ft -wide and over 1,000-ft-long substrates, and demonstrated a process flow that has a cap-ex of around $1/W.

SoloPower's novel roll-to-roll electrodeposition-based process includes the steps of substrate cleaning/preparation, electrodeposition, high-temperature annealing, cadmium-selenium (CdS) deposition, transparent conducting oxide (TCO) deposition, and finger pattern formation. These "front-end" process steps yield rolls of solar cells. Individual devices are then cut from the rolls and they are interconnected to form cell strings. The strings are integrated into module structures using processes similar to those of silicon solar cells.

The electrodeposition step of the SoloPower technology has the capability to control the Cu/(In+Ga) and Ga/(In+Ga) molar ratios of the deposited films across and along large-area (1,000-ft-long and 13.5-in.-wide) foil substrates. Such control allows processing of large-area solar cells. During the period of this program, over 100 cm^2 area solar cells with total area efficiencies as high as 12.25% have been demonstrated. A module-fabrication process flow was also developed yielding 1 m^2, 10% modules. SoloPower established an in-house safety/reliability laboratory for module package evaluation and developed a package that received certification under UL 1703 standard. A rooftop laboratory was also installed to collect real-time data from individual modules as well as from a complete system employing SoloPower modules.

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1. Objective

This PV Technology Incubator project was targeted at research and development of SoloPower's electrodeposition-based CIGS technology. The emphasis of the activities was designed to address and overcome possible barriers to manufacturing scale-up of large-area solar cells and modules. SoloPower reached all of its goals set under the project. Specifically, during the period of this project, SoloPower:

i. Increased the size of its solar cells from 0.5 cm^2 to 120 cm^2
ii. Increased small-area cell efficiencies from near-11% to near-14%
iii. Demonstrated large cells (102 cm^2) with efficiency over 12%
iv. Developed a module manufacturing process and demonstrated 1 m^2 modules with 10% efficiency
v. More than tripled its workforce
vi. Moved from a small R&D laboratory to a large manufacturing facility
vii. Transferred its technology from bench-top/batch tools with capability to process 6-in. x 8-in. substrates to roll-to-roll manufacturing tools with capability to process about 1-ft-wide and over 1,000-ft-long substrates
viii. Demonstrated a process flow that has a cap-ex of around $1/W.

The following sections of this final report will summarize the work carried out on most of the topics listed above.

2. Research and Development Activities

The tasks carried out to reach the ultimate objectives of the program included: work on the optimization of the metallic foil substrate, optimization of the absorber layers and other components of the solar cell structure, development and optimization of roll-to-roll electroplating and roll annealing tools and processes, development of a module manufacturing process flow, and understanding and optimization of the stability of cells and modules. Much effort during the Phase II program was spent on the improvement of the large-area cell and module efficiencies and establishment of the manufacturing line.

2.1. Optimization of Metal Foil Substrate

SoloPower's devices are fabricated on flexible metal substrates. Flexible metal surfaces, unlike glass surfaces, displayed considerable roughness and defectivity, especially at the time when the Phase I program was initiated. For stainless steel substrates, for example, the average roughness was in the order of 200-300 nm, with some defects having even larger peak-to-valley dimensions. Considering the fact that the CIGS films themselves have a thickness of about 1,000 nm, this surface roughness was not acceptable for processing large-area cells at high yield. The major goal of this task was the optimization of the metal foil substrate surface for electrodeposition of precursor layers.

In this work, SoloPower utilized various analytical techniques to evaluate the surface roughness of the metal foil substrates, to understand the nature of the foil substrate defects, and to classify the defects according to their influence on the performance of finished devices. The analytical techniques used included SEM/EDX, optical microscopy, and laser beam induced current (LBIC) measurements. While the SEM/EDX and optical microscopy provided the physical properties (size, shape, etc.), chemical composition, and area density of the defects, LBIC maps of finished cells established correlation between the physical and chemical properties of the observed defects and their electrical influence on the solar cells. As a result of this work, we classified the substrate defects as “killer defects” (those that cause shunting), “nuisance defects” (those that may be only cosmetic), and others that may only lower the current density (such as insulating defects). SoloPower worked with metal foil suppliers and also internally developed approaches to flatten the surface of the foil substrates and to passivate and/or reduce the density of substrate defects that are identified as killer defects.

Early in the program, we identified two killer defects. One of these defects was found to be associated with the substrate cleaning procedures (see Figure 1), which caused extreme shorting. The other defect originated from the substrate surface itself. The source of the first failure was eliminated through changing the parameters and consumables in the substrate preparation process. The effect of the second defect, which was a “dimple” type defect on the surface of the foil, was reduced to a level that allowed large-area cell fabrication with good yield. After successful completion of this task, the solar cell area was gradually increased from 0.5 cm^2, to 10 cm^2, to 50 cm^2, to 100 cm^2 and eventually to 120 cm^2. During the April-June 2009 period, SoloPower also started to fabricate cells with an area of about 180 cm^2.

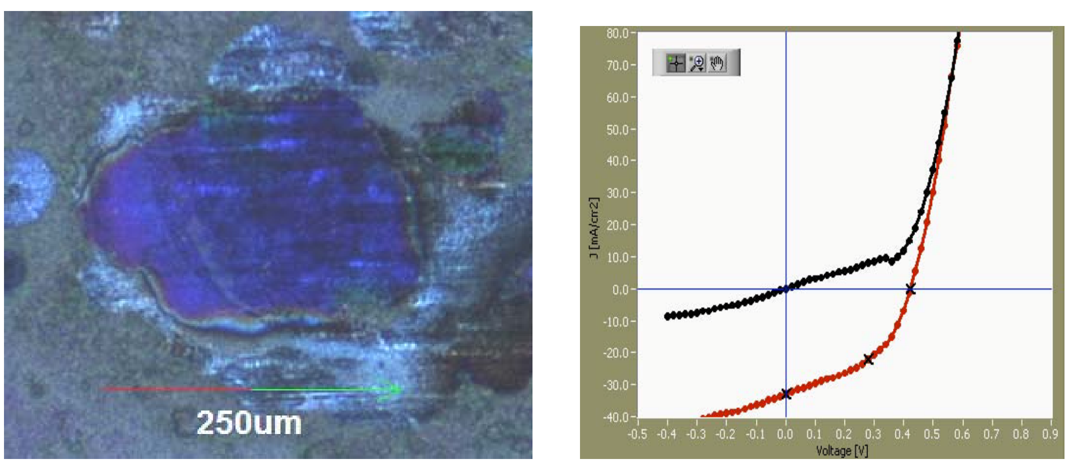


Figure 1. A killer defect associated with poor cleaning of the substrate causes extreme shunting in a solar cell. The relatively large area with debris does not get properly electroplated and thus forms a shunting path.

As a result of the work carried out under this task, the average surface roughness of the stainless steel foil substrates was reduced to <100 nm, which was the original goal of the task and which was found to be an acceptable value for high-yield solar cell fabrication. A roadmap was also established to reduce this average roughness value to below 50 nm.

2.2. CIGS Layer Growth

CIGS absorber layers were formed over the 50-µm-thick, flexible stainless steel foil substrates after deposition of a contact layer. The size of the substrates for the batch process line was 6 in. x 8 in. For the roll-to-roll processing line, the width of the foil substrates was 0.34 m (13.5 in.), and the length changed depending upon the experiment carried out.

After cleaning, the rolls were coated with a Mo-based contact layer using a roll-to-roll sputtering tool. The rolls were then transferred to the electrodeposition station where a Cu-In-Ga-Se precursor film containing the preselected composition was electrodeposited on the contact layer in a roll-to-roll electroplating machine.

The precursor layers in the roll form were subjected to an RTP-type annealing/crystallization process step to convert them into device-quality CIGS layers. The typical temperature range employed in this process step was 500°-550°C, although CIGS film formation could be achieved in a wider temperature range of 450°-600°C. The thickness of the CIGS layers was in the range of 1-2 µm, typically in the range of 1.1-1.3 µm. Compositional analysis of the precursor layers and the CIGS films was carried out by XRF measurements. Results were also confirmed by inductively coupled plasma (ICP) analysis after cutting coupons from various regions of the processed rolls and then chemically dissolving these coupons to prepare ICP samples.

2.2.1. Roll-to-Roll Electrodeposition

The electrodeposition step is the heart of the SoloPower technology. During this project period, the company developed and demonstrated the capability of its electrodeposition process to yield Cu-In-Ga-Se precursor layers with controlled and repeatable Cu/(In+Ga) and Ga/(In+Ga) molar ratios. After roll-to-roll plating hardware to process a 13.5-in.-wide web was installed, the capability of the tool to deposit films with uniform thickness was first demonstrated. Then the compositional control was shown through measurement of electrodeposited Cu-In-Ga-Se precursor layers.

One of the most important requirements for successful application of an electrodeposition technique to CIGS absorber formation is the demonstration of the ability of the technique to control the composition of the deposited films in a reliable and repeatable manner. Figure 2 shows the Ga/(Ga+In) molar ratio data collected from the electrodeposited layers by ICP measurements during a period of 95 days. The target in this experiment was a molar ratio of 0.3 in the deposited film. The electrolyte and the process conditions were kept unchanged during the whole test period.

The data of Figure 2 demonstrate that the electrodeposition process of this work has the capability to include Ga in the deposited films in a reliable and repeatable manner. Figure 3 shows the Cu/(Ga+In) molar ratio data collected from the same plated samples during the same 95-day period. The target ratio in this case was 0.8, and as can be seen from the data, this ratio was controlled between the values of 0.76 and 0.84 as measured by ICP. This is within the accuracy band of the measurement method, and therefore the results demonstrate a good ability for the technique to control composition. It should be noted that for the two excursion points in the data of Figure 3, the measurement instrument was found to be faulty. The data of Figures 2 and 3 were collected from the batch process line to evaluate the behavior and stability of the plating baths. As the above results demonstrated, even for baths with limited volume, the chemistry did not show any time-dependent instabilities.

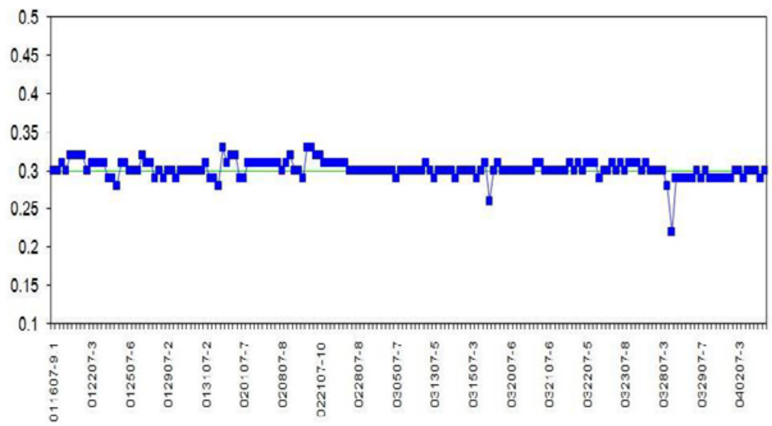


Figure 2. The Ga/(Ga+In) molar ratio data collected from samples electroplated during a period of 95 days. Experiment was carried out in the batch plater.

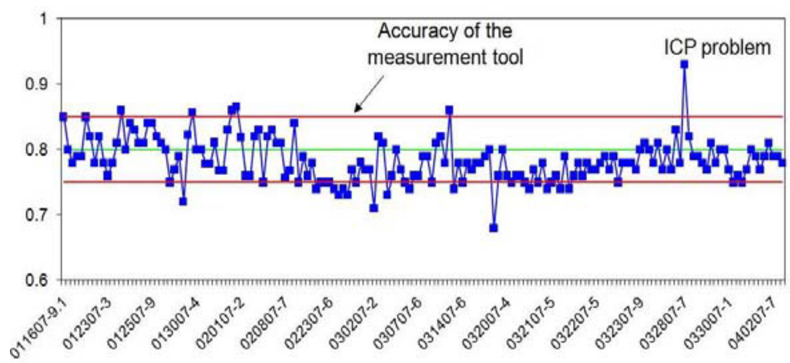


Figure 3. The Cu/(Ga+In) molar ratio data collected from samples electroplated during a period of 95 days.

In addition to the repeatability and robustness of the electrodeposition process in terms of its compositional control, experiments were also carried out with the roll-to-roll electroplating tool to demonstrate that the film thickness and the stoichiometry were uniform throughout a large-area substrate. In one early experiment during the Phase I program, a 13.5-in.-wide and 400-ft-long foil substrate was continuously processed through the roll-to-roll electroplating system and then the deposited film thickness, the Cu/(Ga+In) ratio, and the Ga/(Ga+In) molar ratio were measured across the 12.5-in.-wide section of the web as well as along the web, at 100-ft intervals. The thickness of the deposit was found to be within 10% of the target value.

Figure 4 shows the Cu/(Ga+In) molar ratio data collected across the width of the foil substrate, at the beginning of the web, and at the location 300 ft away from the beginning of the web. Although the data for the Ga/(Ga+In) molar ratio are not presented here, both the Cu/(Ga+In) molar ratio and the Ga/(Ga+In) molar ratio were found to be within +/- 8% of their respective target values throughout the 400-ft-long substrate.

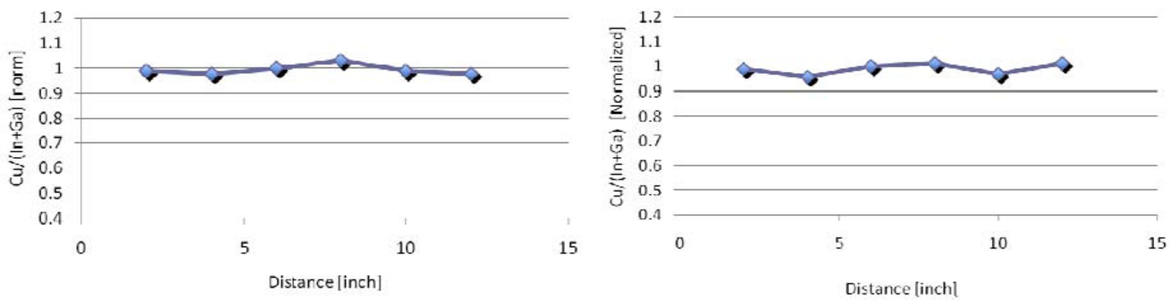


Figure 4. The Cu/(Ga+In) molar ratios measured across a 13.5-in.-wide and 400-ft-long foil substrate at a location near the beginning (left) and 300 ft from the beginning (right) of the web.

Experiments were also carried out to demonstrate that compositional control in the electrodeposition technique is reliable and repeatable for longer substrates. Figures 5 and 6 show the results of an experiment carried out to demonstrate such ability for SoloPower's roll-to-roll electrodeposition process. In this experiment, a 240-m-long roll was processed through the roll-to-roll electrodeposition tool and the targeted Cu/(In+Ga) ratio was changed in the middle of the roll, during processing, while keeping the Ga/(In+Ga) ratio constant. The change was accomplished through the controls available in the plating process.

As can be seen from Figure 5, the measured Cu/(In+Ga) molar ratio responded very fast (within a few meters) to the change made in the process parameters after running the first 120 m of the web under the first process condition (condition 1). Furthermore, after switching to the new condition, the process kept the new Cu/(In+Ga) molar ratio (condition 2) very stable until the end of the roll.

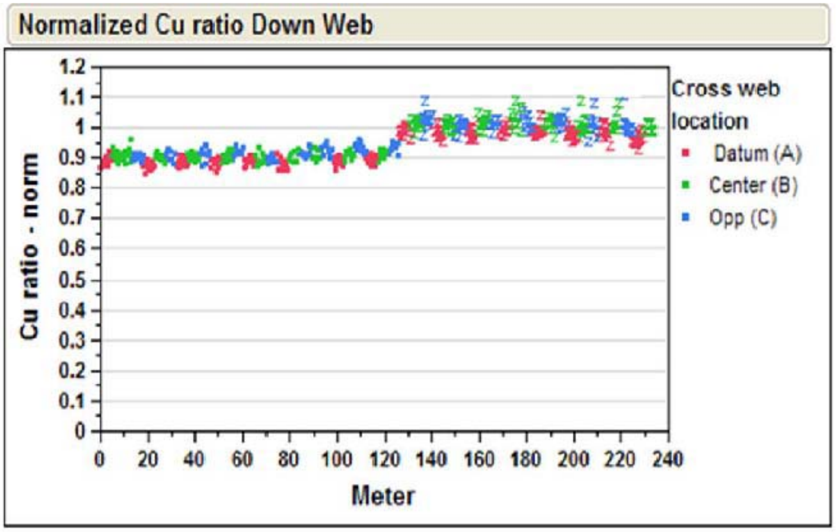


Figure 5. The Cu/(In+Ga) molar ratio measured on an electrodeposited precursor layer formed on a 240-m-long, 0.33 m-wide web. Process parameters were changed to increase the ratio after running the first 120-m portion of the web.

Figure 6 shows the measured Ga/(In+Ga) molar ratio for the same web. As can be seen from these data, the Ga composition is stable throughout the 240 m of the web as dictated by the process parameters of the roll-to-roll electrodeposition tool. These results demonstrate the ability of the technique to independently adjust and control the two important metals ratios in CIGS processing. It should be noted that the cross web-uniformity of the two ratios was also demonstrated in the above data that show measurements from the center of the web (labeled as Center-green) as well as the two sections along the two edges of the web (labeled as Datum-red and Opp-blue).

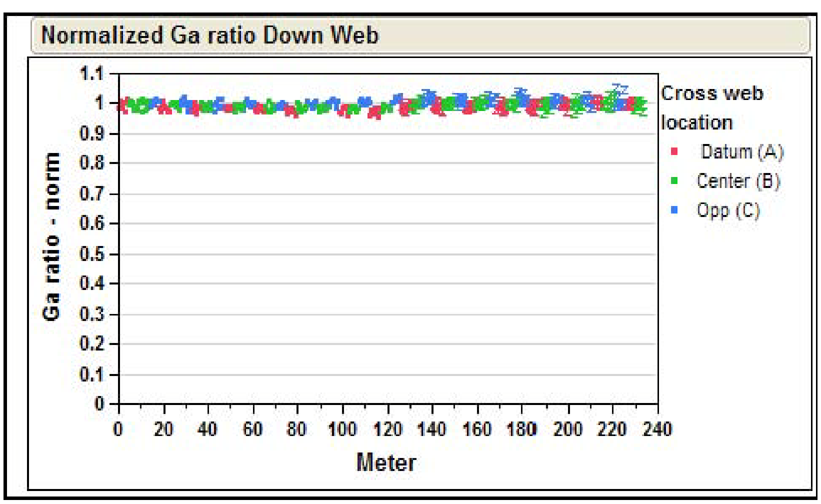


Figure 6. The Ga/(In+Ga) molar ratio data collected from the web of Figure 5.

2.2.2. Annealing Step and the CIGS Layers

SoloPower developed a novel annealing hardware and process for converting the electroplated Cu-In-Ga-Se precursor layers into device-quality CIGS absorbers. The tool has the capabilities to heat the substrate up to about 600°C at controlled rates and temperature profiles. After installation, during the Phase I program, several films were processed using this tool and the resulting CIGS layers were converted into solar cells using standard CdS, TCO, and contact deposition processes to test the uniformity of the process. In early experiments, processed web was cut into smaller sections and these sections were processed through the process of record in the batch line to complete the solar cells. This way, the individual process step of annealing could be evaluated without possible interference from the rest of the cell processing steps. Results of such experiments showed that the annealing process was quite uniform.

CIGS layers grown by SoloPower's technique are of good crystalline quality and display a preferred <112> orientation. The grain size is typically a strong function of the Ga content (increased Ga reduces grain size) as well as the details of the annealing process step. Figure 7 is a top-view scanning electron microscopy (SEM) image taken from a CIGS layer, and it shows well-formed grains larger than 1 μm. The cross-sectional SEM of Figure 8 was taken from a film formed at the high end of the temperature process window, and it shows a grain structure that is large and columnar.

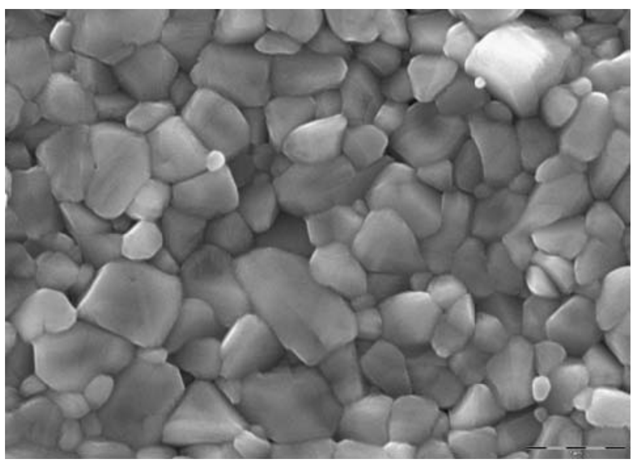


Figure 7. Top-view SEM of a CIGS layer grown on a metal foil substrate.

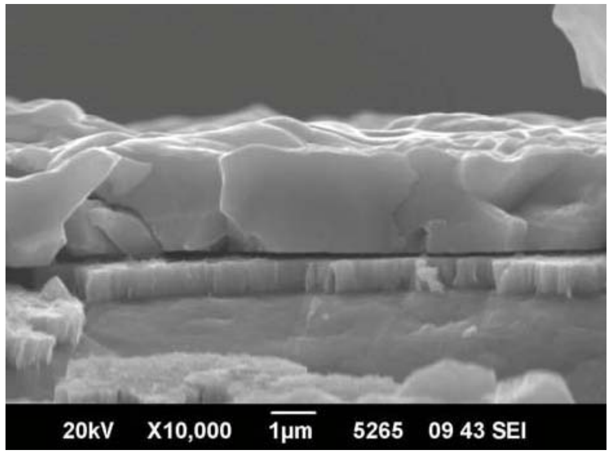


Figure 8. Cross-sectional SEM of a CIGS layer grown on a metal foil substrate at high temperature.

2.3. Solar Cells

Standard solar cell processing approaches were employed for device fabrication. The milestone of developing a TCO stack with <60 ohms/square resistance and >85% transmission in a repeatable manner was achieved early in the program during Phase I efforts. As can be seen from the sample data of Figure 9, the average sheet resistance of our stack is about 50 ohms/square and the transmission is above 90% in a repeatable manner. The data of Figure 9 were obtained from our batch tools at the time. These results have been later repeated for the roll-to-roll processing approach.

For roll-to-roll processing, a nominally 100-nm-thick CdS layer was first deposited on the CIGS film using the chemical bath deposition (CBD) method. A TCO layer was then sputter deposited over the CdS film. The roll of the solar cell stack obtained after the TCO sputtering step was coated with a large number of silver-based finger patterns using a roll-to-roll screen printing tool, which employed a low-temperature ink that can be cured below 250°C. As a result of this process step, a roll containing thousands of solar cells was obtained. Figure 10 shows the re-wind port of the finger deposition tool where the web with solar cells and a paper interleaf are being wrapped around the re-wind spool.

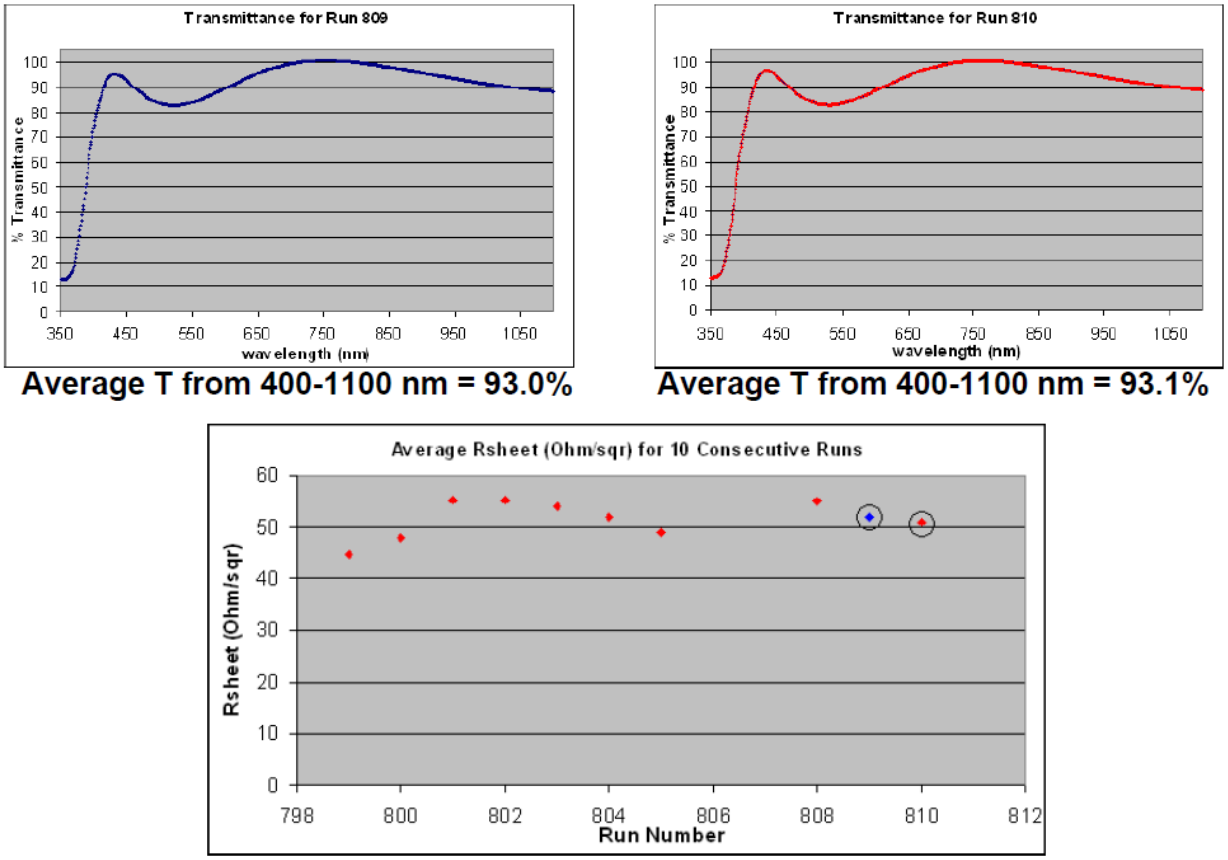


Figure 9. Sheet resistance and transmission of TCO stack for 10 consecutive runs.

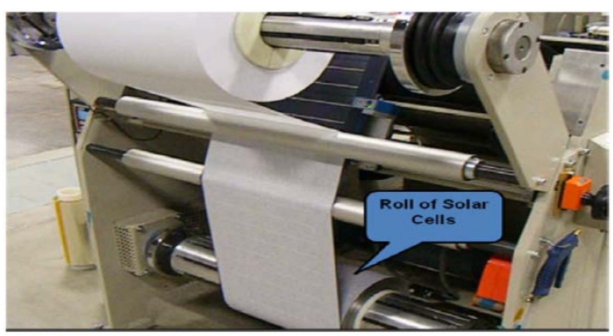
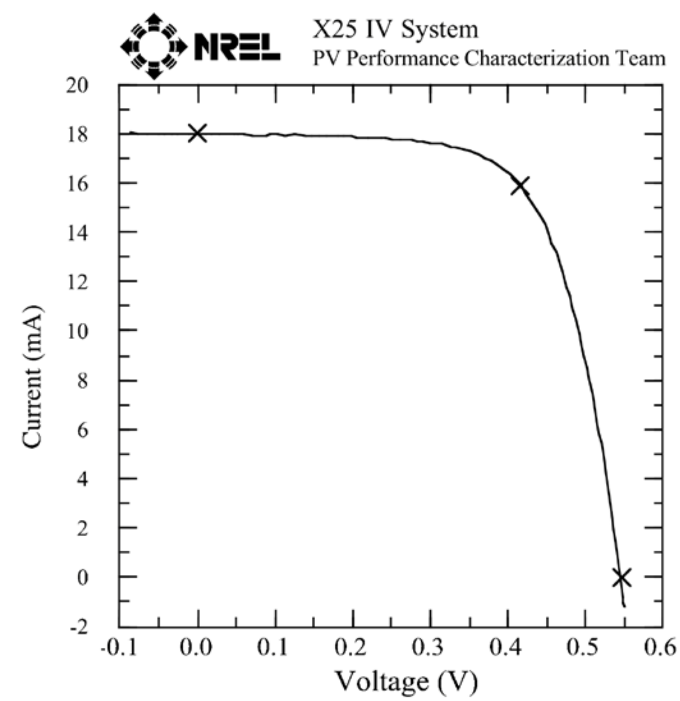


Figure 10. The last step of the solar cell fabrication process flow is the grid pattern application that forms a roll of solar cells at the re-wind port of the roll-to-roll screen printing tool. Photo credit: SoloPower

It should be noted that the grid patterns deposited on the roll of solar cell structure define the shape and the size of the devices that are later cut from the roll. We used three different finger patterns and three different cell sizes (nominal areas of 100 cm^2, 120 cm^2, and 180 cm^2) in our roll-to-roll development efforts. An automated roll-to-roll cutter was utilized to cut the cells from the rolls, based on the pre-selected sizes of the devices. Cut cells were sorted and binned according to their current and efficiency values, using an automated testing/sorting tool. Sorted and binned flexible cells were then interconnected using standard copper ribbons to form cell strings. The stringing method used low temperature solders or conductive adhesives that cured at temperatures below 250°C.

The solar cell efficiency deliverables during the course of this program increased from 7% (50 cm^2) to 12% (120 cm^2). In addition, work was also carried out on smaller-area devices to evaluate the practical efficiencies reachable by the processing techniques utilized. The illuminated I-V characteristics of a 0.48-cm^2-area solar cell fabricated on a stainless steel foil substrate is shown in Figure 11. The Al/Ni grid pattern was evaporated through a shadow mask on this device. The total-area efficiency is 13.76% with an open-circuit voltage value near 550 mV.



V_{oc} = 0.5463 V	I_{max} = 15.876 mA
I_{sc} = 17.987 mA	V_{max} = 0.4161 V
J_{sc} = 37.473 mA/cm^2	P_{max} = 6.6063 mW
Fill Factor = 67.23 %	Efficiency = 13.76 %

After 10 minute soak at P_{max}, 5 minute cool.

Figure 11. Illuminated I-V characteristics of a 0.48-cm^2-area device.

As stated before, large-area devices employed a screen-printed grid pattern. SoloPower delivered multiple large-area devices with efficiencies in the 11%-12% range to NREL for confirmation. Figure 12 shows the illuminated I-V characteristics of a 102-cm^2-area solar cell measured at NREL. The total-area efficiency of this device is 12.25%. The V_{oc}, J_{sc}, and FF values are 0.54 V, 34.4 mA/cm^2, and 65.7 %, respectively.

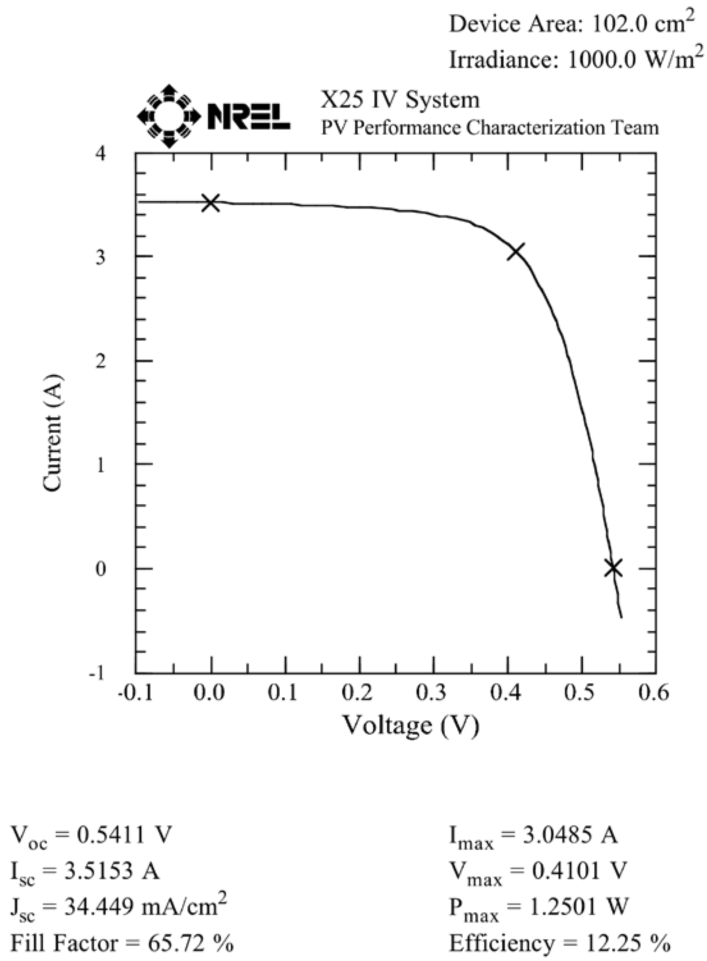


Figure 12. Illuminated I-V characteristics of a 102-cm^2-area flexible CIGS solar cell with 12.25% efficiency.

Dependence of the solar cell efficiencies on the Cu/(In+Ga) and Ga/(In+Ga) metal ratios of the precursor layers and the distribution of the efficiency values along and across the long flexible substrates were also studied. Data in Figure 13 show the relative efficiency distribution of nominally 180-cm^2-area solar cells made on the experimental roll of Figures 5 and 6. It should be noted that about 60-m-long sections from the beginning and the end of this roll were cut to carry out other experiments. The rest of the roll was then taken through the complete process flow to finish the devices. Therefore, the data of Figure 13 were collected from only the middle 110-m-long section of the roll.

As can be seen from the data of Figure 13, the solar cell efficiencies obtained from the section of the web run under “condition 1” in the electroplating tool are 50%-80% of the values obtained from the section of the web run under “condition 2.” Furthermore, the amount of the cross-web scatter in the device efficiency values from the portion processed under “condition 1,” which corresponds to a lower-than-ideal Cu/(In+Ga) ratio, is much larger than the scatter in the region of the roll that was processed under “condition 2.” The data of Figure 13 demonstrate the importance of compositional control for device efficiency and the ability of the electrodeposition method to yield solar cells with consistent conversion efficiency once the composition is fixed within the established process window.

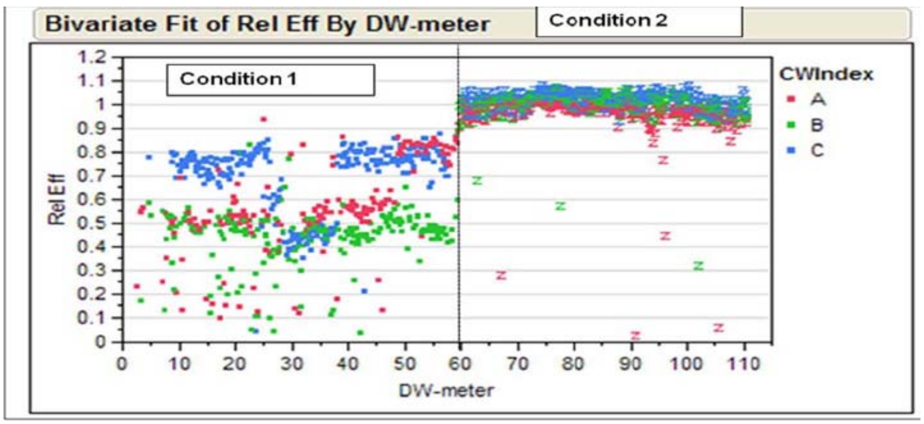


Figure 13. Relative distribution of the efficiencies of nominally 180-cm^2-area solar cells fabricated along and across a 110-m-long section of the web cut from the middle portion of the 240-m-long web of Figures 5 and 6.

During optimization of device efficiencies, various components of the solar cell were studied to understand their influence on the efficiency. In this activity, we identified the back contact to the solar cell as one important variable that affected the device efficiency and found that the contact-specific resistivity varied in a wide range of values. Figure 14 shows this variation for various types of contacts fabricated in different ways (labeled as A, B, C, D, etc.). Furthermore, we also studied the long-term stability of the contact resistivity when the device structure was annealed at elevated temperatures in dry air for times up to 728 h. These data are also shown in the figure below. As can be seen from the data, while the contact resistance generally increased with time and temperature, under specific process conditions it was very stable. The contact-formation approaches labeled as G, H, I, J, K, and L were found to be superior in terms of both the contact resistance and long-term stability, and one of these approaches was adapted as the “process of record.”

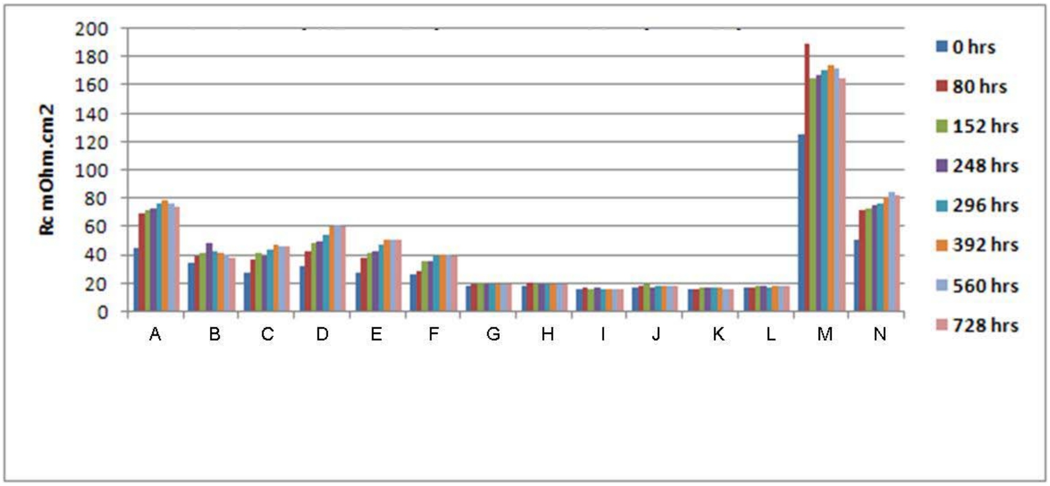
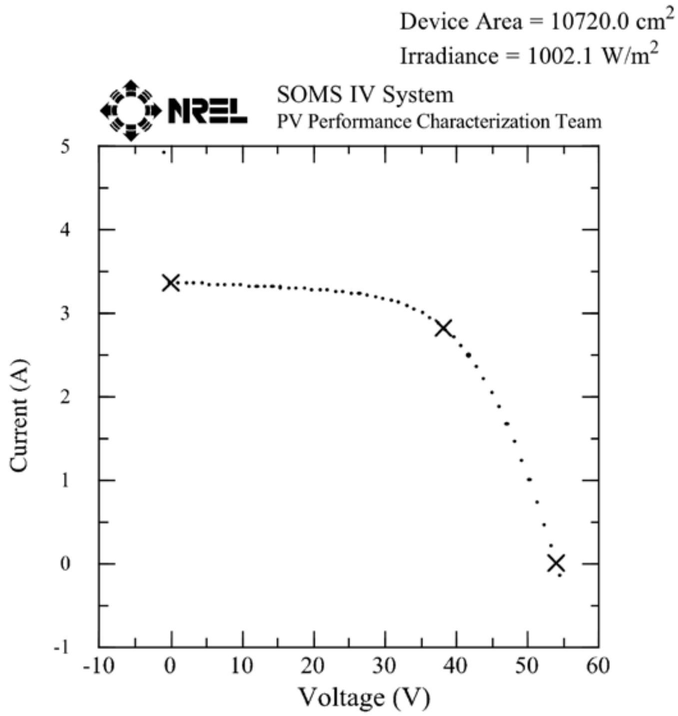


Figure 14. Back-contact resistivity for different types of contacts and the stability of the contact resistance at elevated temperature for up to 728 h.

2.4. Module Fabrication and Reliability Studies

Modules with front glass sheets were fabricated in a vacuum laminator using the cell strings. The back sheet was either a flexible polymeric foil or a glass sheet. Module deliverables of this project ranged from 0.5 m^2-7% to 1 m^2-10% module. Figure 15 shows the illuminated I-V characteristics of a module fabricated by bussing and packaging 10 cell strings. Each string contained 10 interconnected cells. The total aperture area of the module is 1.07 m^2. As can be seen from the data in the figure, the total power output was measured to be 107.5 W with V_m, I_m, and efficiency values of about 38.2 V, 2.8 A, and 10%, respectively.



V_{oc} = 54.04 V
I_{sc} = 3.350 A
Fill Factor = 59.4%
Efficiency = 10.0%

V_{max} = 38.22 V
I_{max} = 2.812 A
P_{max} = 107.5 W

Figure 15. The illuminated I-V characteristics of a 1.07-m^2-area module with 10% conversion efficiency.

For module testing and reliability, SoloPower established an in-house testing facility with capability to carry out UL and IEC test sequences, including damp heat testing, temperature cycling, humidity freeze testing, dry and wet hi-pot testing, mechanical loading, and hail testing. A large-area pulsed simulator for large-area module measurement has also been acquired and installed.

An outside Roof Lab was established at the roof of the SoloPower facility. The Roof Lab is a platform to collect real-life performance data from solar modules. It consists of three elements: a weather station, a single module measurement system, and a grid-tied system. All the system modules are inclined at latitude (37 deg) and face south. The weather station collects the data on irradiance (horizontal and POA), ambient temperature, wind speed/direction, relative humidity, and precipitation. Data on these properties are measured around the clock every 5 seconds and the averages for each 5-minute interval are stored into a database.

The single module measurement system is able to measure individual I-V curves using a 4-point-kelvin-contact and a Keithley pulsed source-meter. The system is able to monitor 64 individual modules using a 4PDT relay system. The system measures I-V curves at 5-minute intervals and saves them into the database along with the weather data. The I-V system wakes up automatically everyday when the sun is higher than 10 deg elevation and goes to sleep when the sun dips below 10 deg.

A daily computation of the PV system performance is carried out for each module at midnight and included into the database. These performance data include energy yield, system yield, reference yield, performance index, and PVUSA performance index. These indexes will allow SoloPower to measure performance degradation of different modules using the best-known methods in the industry. Figure 16 shows a photograph of the lab with various modules deployed.

Figure 16. A view of SoloPower's rooftop testing facility with CIGS modules manufactured by SoloPower's electrodeposition-based technology. Photo credit: SoloPower

The CIGS device structure is known to be sensitive to moisture at elevated temperatures. Therefore, it is essential that the module structure provide hermetic sealing to the solar cells packaged within it. In the absence of moisture the device is stable, as exemplified by the data of Figure 17, which show the results of a stability test carried out on a group of five solar cells. The devices were unprotected and were kept in an air oven at 85°C for 1,000 h. As can be seen from the data, the device structure is very stable under these dry conditions. When similar experiments were repeated under 85% relative humidity conditions, the unprotected cell efficiencies went down in an irreversible manner.

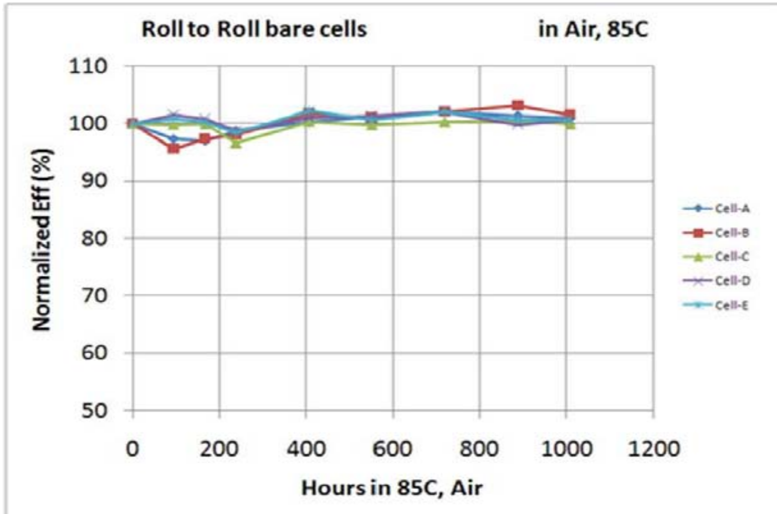


Figure 17. Normalized efficiencies of five different cells annealed at 85°C for 1,000 h, demonstrating the stability of the CIGS cells under dry heat conditions.

Studies carried out to identify the component(s) of the solar cell most affected by the damp heat conditions included testing of each of the components individually under damp heat conditions. These components included the substrate/CIGS/CdS structure, the TCO layer, the TCO/grid interface, and the front and back contacts made to the solar cell.

Figure 18 shows the results of a study carried out on the back-contact quality and reliability. The study compared four different contacting processes, some using different contacting materials. After measuring the initial contact resistance, the samples were subjected to damp heat conditions (85°C/85% RH) in an environmental chamber for a period of 456 h without any protection. Variation in the contact resistance values was monitored at intervals. As can be seen from these data, the back-contact resistance values for "process-2" and "process-4" are much lower than "process-1," and they are relatively stable under damp heat conditions. In the case of "process-3," although the starting contact resistance is low, it deteriorates fast through the 456 h of testing. These results demonstrate the importance of carrying out highly accelerated damp heat tests on each component of the CIGS solar cell structure to evaluate its sensitivity to damp heat so that the stability of these components may be optimized, yielding a more robust and moisture-resistant solar cell.

The above-mentioned sensitivity of the CIGS cell structure to moisture is the primary reason for the failure of modules that are not properly sealed. Figure 18 exemplifies the evolution of the module packaging activity at SoloPower through evaluation of various packaging materials and procedures to attain stable operation for modules under damp heat conditions. Figure 19 displays two sets of efficiency stability data obtained from two modules that were subjected to 1,200-1,300 h of testing in an environmental chamber kept at 85°C and 85% relative humidity. One data set belongs to module SP8928, which was packaged in a glass/film structure using materials and procedures that we identify as "rev-3." The other data set belongs to the module SP10231, which was fabricated using "rev-4" materials and procedures.

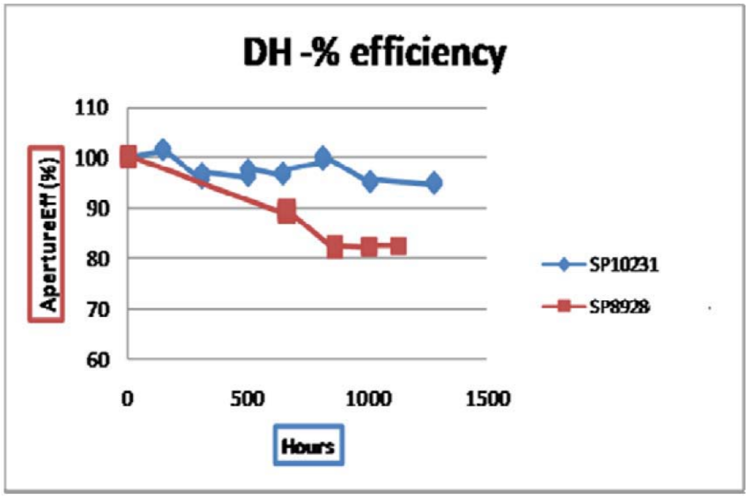


Figure 18. Variation of the back-contact resistance of flexible CIGS solar cells as the cells are aged unprotected in a damp heat environment. Four different types of contacting approaches were evaluated.

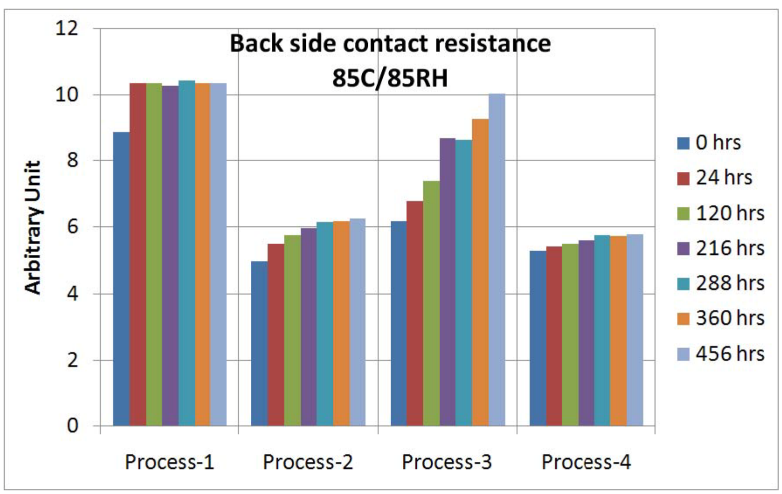


Figure 19. Efficiency data collected from two modules tested in an environmental chamber under damp heat conditions. Packaging of module SP8928 was defective, allowing the water vapor to enter the package.

As can be seen from these data, the stabilities of the two modules are drastically different under damp heat conditions. The post-mortem analysis of the module SP8928 clearly demonstrated that the culprit for its failure was moisture digression into the module through the junction box location on the back sheet of the module. Figure 20 shows a picture of that location taken through the front glass sheet. As can be seen from this photo, moisture entering through the back sheet and the junction box discolored the sections (circled) of the solar cells across from the junction box.

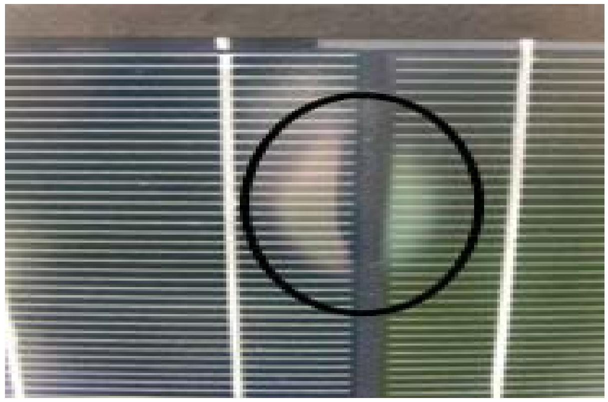


Figure 20. Photograph of the section of module SP8928 (see Figure 18) discolored (circled) due to moisture digression into the structure through the junction box. Photo credit: SoloPower

In-house module structure reliability studies included passing groups of modules through the IEC61730/IEC61646/UL1703 test sequences, which include dry and wet hi-pot tests, temperature cycling, damp heat testing, humidity freeze, and UV exposure tests.

On June 17, 2009, SoloPower announced that its CIGS-based modules have been certified under the ANSI/UL 1703 standard. ETL certification was granted following rigorous testing by Intertek, an independent product safety certification organization. The product was tested to ANSI/UL 1703, the standard for Safety Flat-Plate Photovoltaic Modules and Panels. The ETL Listed Mark covers SoloPower's products sold in the United States and Canada.

2.5. Building of Manufacturing Line

After initiation of the Phase I program, SoloPower relocated its operation from its R&D laboratory in Milpitas, California, to San Jose, California, into the 110,000-ft^2 manufacturing building ("Optical Court" factory) shown in Figure 21.

Figure 21. SoloPower's Optical Court factory. Photo credit: SoloPower

During the Phase II program, SoloPower completed its roll-to-roll manufacturing equipment set to be able to:

i. Fabricate rolls of solar cells
ii. Cut, test, and sort the cells from the rolls
iii. String the cells
iv. Encapsulate the strings to manufacture complete modules.

The tool set to carry out these process steps includes flexible substrate cleaning tools, contact deposition tools, electrodeposition tools, annealing tools, buffer layer deposition tools, TCO deposition tools, top contact deposition tool, cutting tool to cut the cells, testing/sorting tool, a set of cell stringing tools, and a complete manufacturing line for module making.

At the present time, the Optical Court factory is operational, manufacturing rigid, glass-based CIGS modules with 1.2 m^2 area. In addition, development work is continuing for a flexible product employing flexible and transparent barrier films as the front sheet of the module.

3. Conclusions

All of the goals of this Incubator project were reached. SoloPower was successful in transferring its novel electrodeposition-based CIGS technology from the concept and feasibility phase, through a batch-pilot phase, and into roll-to-roll manufacturing phase. Large-area solar cells with over 100 cm^2 area and over 12% efficiency have been demonstrated. Modules of 1 m^2 area with 10% efficiency have also been built. At the time of writing of this report, SoloPower is operating a full manufacturing line complete with front end operations to fabricate rolls of solar cells and back end operations to fabricate modules in a 110,000-ft^2 facility.

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14. ABSTRACT *(Maximum 200 Words)*
This report describes SoloPower's work as a Photovoltaic Technology Incubator awardee within the U.S. Department of Energy's Solar Energy Technologies Program. The term of this subcontract with the National Renewable Energy Laboratory was two years. The project focused on SoloPower's electrodeposition-based copper indium gallium (di)selenide (CIGS) technology. Under this subcontract, SoloPower improved the quality of its flexible metal substrates, increased the size of its solar cells from 0.5 cm2 to 120 cm2, increased the small-area cell efficiencies from near 11% to near 14%, demonstrated large-area cells, and developed a module manufacturing process.

15. SUBJECT TERMS
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