



Barrier Coatings for Thin Film Solar Cells

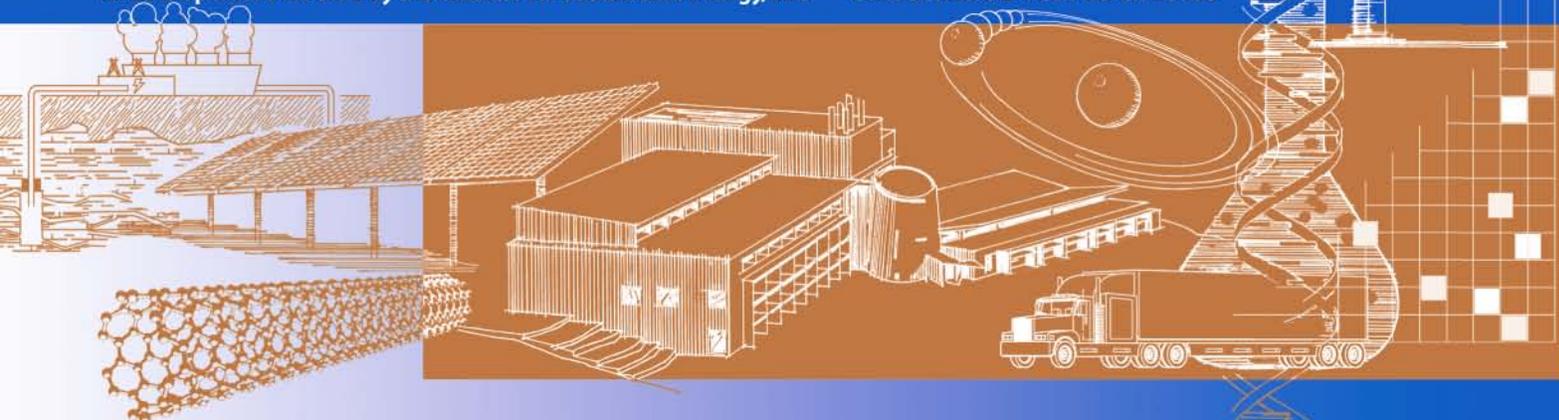
**Final Subcontract Report
September 1, 2002 – January 30, 2008**

L.C. Olsen
*Pacific Northwest National Laboratory
Richland, Washington*

**Subcontract Report
NREL/SR-520-47582
March 2010**

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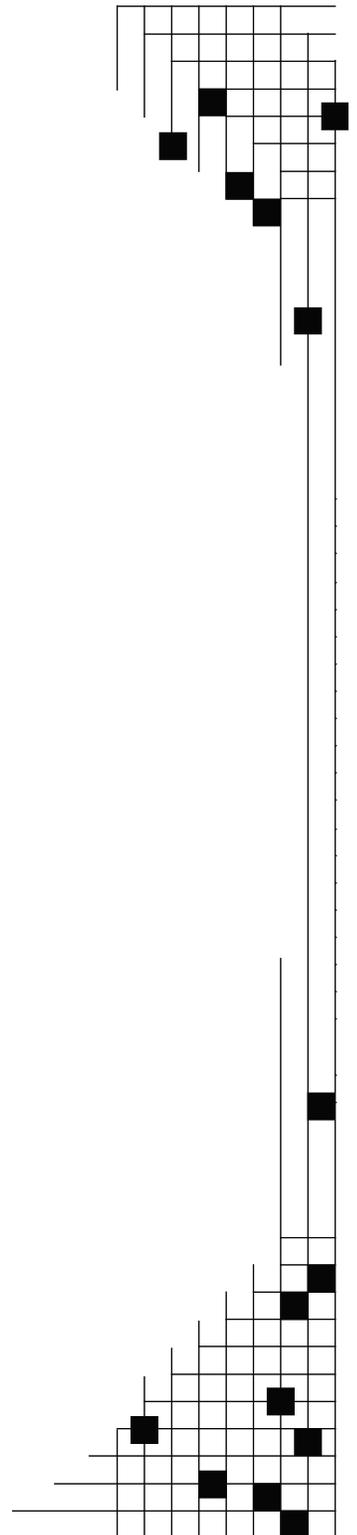
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ABSTRACT

This program has involved investigations of the stability of CdTe and copper-indium-gallium-diselenide (CIGS) solar cells under damp heat conditions and effects of barrier coatings. CdTe and CIGS cells were subjected to environmental conditions characterized by 60°C and 90% relative humidity (60/90), and to some extent 85°C and 85 % relative humidity (85/85). Barrier coating technology developed at PNNL for OLEDs was used to investigate approaches to encapsulation of the two types of thin film solar cells. Moisture barriers consisting of multi-layer coatings involving alternating layers of polymer and aluminum oxide were deposited directly onto the front surface of CIGS cells and the rear surface of CdTe devices, with the front surface defined by the light receiving side of the cell. Most of the studies were conducted with directly deposited barrier coatings. The CIGS cells were provided by Shell Solar, Industries (SSI) in the form of 10 cm x 10 cm and 5 cm x 5 cm mini-circuits, and by the Institute for Energy Conversion (IEC) in the form of small laboratory cells grown on a 2 in x 2 in glass substrate. The SSI devices were actually CIGSS cells since they contained sulfur as well as selenium, but they are referred to as CIGS cells in this report. CdTe cells were provided by Dr. Sampath at Colorado State University (CSU). Current voltage characteristics of cells were taken periodically when under damp heat stress. Photoluminescence studies were also utilized for characterizing the effect of damp heat stress. An approach to encapsulation by direct deposition was determined for each type of cell that allowed the device to survive 1000 hours in a 60/90 damp heat environment. SSI cells were also tested under 85/85 conditions. The efficiencies of SSI thin-film CIGS cells with directly deposited barrier coatings subjected to 85/85 stress were found to degrade to 60% of their beginning-of-life value. The decline in efficiency versus time was independent of the number dyads (polymer/alumina pairs) used to form the moisture barrier. The result suggests that moisture ingress was either occurring at the edges, or a directly deposited multi-layer barrier is inadequate for the SSI circuits under the 85/85 stress condition. IEC cells were encapsulated by directly deposited, five dyad coatings. One device survived 2000 hours in 85°C/85%RH without any degradation in efficiency. More recently, very good results were achieved with laminated SoloPower cells using PNNL coated PET. These results are briefly discussed. CdTe cells were tested with and without encapsulation. Uncapsulated CdTe degraded in an environment of 60°C/90%RH, but were found to be quite stable when encapsulated with PNNL barrier coatings.

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1. INTRODUCTION

A key issue facing thin film photovoltaic manufacturers is the need for an effective approach to module encapsulation. In order for photovoltaic modules to satisfy a goal of providing affordable power for more than twenty years with less than 10% degradation of power outputs, new low cost approaches to module encapsulation are required. The international standard IEC61646 requires that all modules survive 1000 hours in an environment of 85°C and 85% relative humidity. Meeting this requirement has been a major concern for thin film CdTe and CIGS cells, since both types of cells degrade under these conditions if they are not protected from moisture ingress. This report concerns studies of approaches to encapsulate these two thin film cells. The effort began in September, 2002. Initially, there was interest in barrier coatings for both of these cell types, but as time has passed CdTe is primarily being considered for flat plate modules with glass-to-glass construction. On the other hand, CIGS cells on flexible substrates are being considered seriously for building-integrated-photovoltaics (BIPV) as well as for flat plate module applications. Thus particular emphasis was given to studies of moisture barriers for CIGS. This program focused on the development of low cost barrier coatings that can be a component of an advanced, effective approach to module encapsulation.

Investigations have involved studies with CIGSS cells supplied by Shell Solar, Industries (SSI), CIGS cells provided by Dr. Shafarman at the Institute for Energy Conversion (IEC) and CdTe cells from Dr. Sampath at Colorado State University (CSU). This program has benefited greatly from the barrier coating technology developed at PNNL in the 1990s for organic light emitting diodes (OLEDs). Moisture barriers are based on a multi-layer coating comprised of alternating polymer/Al₂O₃ films. Battelle helped establish Vitex Systems in the year 2000 for purposes of commercializing the barrier technology. PNNL still carries out research and development concerning applications of the multi-layer coating technology.

The barrier coating technology is discussed in more detail in Section 2, followed by discussion of results obtained with CIGS cells in Section 3 and CdTe cells in Section 4. Finally, conclusions are presented in Section 5.

2. BARRIER COATING TECHNOLOGY

2.1 Multi-Layer Barrier Coatings

The barrier properties of multilayer, thin-film organic/inorganic barrier layers are treated in detail in Reference 1. Both transient and steady-state vapor permeation measurements were combined with classical Fickian diffusion models to interpret experimental data for water vapor transport through multilayer coatings. For example, data reported for multilayer coatings on polyethylene terephthalate substrates that indicated water vapor permeation rates of $< 10^{-5}$ g/m²/day at 25°C and 40%RH were utilized. Two key results of the work by Graff and coworkers are: (1) permeation through organic/inorganic multilayer coatings is controlled by the spatial density of defects and defect sizes in the vacuum deposited inorganic layers; and, (2) the long apparent diffusion path induced by the multilayer structure results in a long lag time, that is, the time required for a vapor molecule to pass through the barrier multilayer film.

The approach to deposit barrier coatings at PNNL involves a vacuum process for deposition of acrylate-based polymer films combined with sputter deposition of oxide layers to fabricate a multilayer barrier film structure. This approach is referred to as a Polymer Multi-Layer (or PML) process. These coatings are deposited either in an in-line coater or a vacuum web coater available at PNNL. These coatings are extremely effective in preventing oxygen and water penetration. This is a result of the inorganic layers providing the barrier properties, while the polymer layers planarize surface topography/defects, decouple defects/pinholes, and prevent damage (cracking) in adjacent inorganic layers. A tortuous path through the inorganic layers and polymer layers limits diffusion of gases and water vapor. Since physical vapor deposited layers replicate the surface topology of the substrate, high points in the underlying substrate cannot be smoothed by an oxide layer. These features are also subject to mechanical damage during a coating process, which lead to defects in the deposited coating.

Ideally, the initial polymer layer effectively covers defects and provides a smooth surface for inorganic film deposition (see Figure 1). The initial polymer layer (referred to as the P1-layer) provides a smooth surface for deposition of the adjacent inorganic layer with a minimum density of defects, which in turn increases the probability that the layer can effectively inhibit water or oxygen diffusion. The required initial polymer layer thickness will vary with the type of solar cell, depending on the roughness of the cell surface. Multilayer coatings generally have several polymer/inorganic film pairs (referred to as dyads), and are extremely effective in preventing oxygen and moisture penetration. This is a result of the inorganic layers providing the barrier properties, while the polymer layers planarize the surface topography, decouple defects/pinholes, and prevent damage (cracking) in adjacent inorganic layers. As depicted in Figure 1, a tortuous path through the inorganic layers and polymer layers limits diffusion and increases lag time of gases

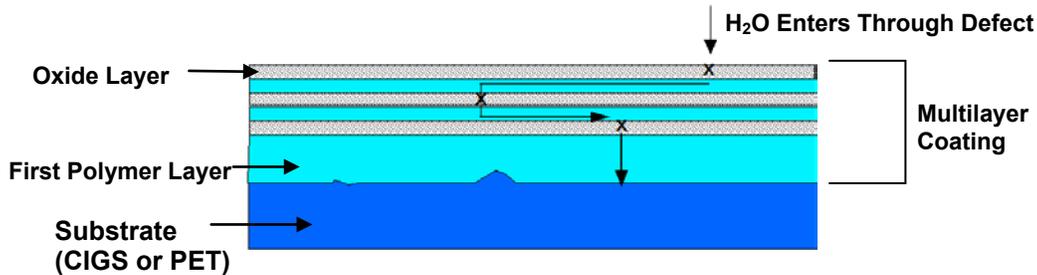


Figure 1. Basic approach to achieve an effective barrier coating with the ML process.

and water vapor passing through the multilayer structure. It is very difficult or impossible to deposit a single inorganic layer that can act as an effective barrier to water diffusion. Such a film replicates the surface defects which will provide entry points for water diffusion. Surface features will also introduce mechanical damage during the coating process, which leads to defects in the deposited inorganic layers.

As indicated in Figure 1, the substrate can either be a solar cell or a polymer sheet such as PET. If the coating is deposited directly onto a cell, we refer to the process as encapsulation by direct deposition. Barrier coated PET sheets, or other polymeric sheets, are used for lamination. Most of the studies discussed in this report involved barrier coatings directly deposited onto cell structures.

2.2 Barrier Coating Facilities

PNNL has two facilities for deposition of barrier coatings, a vacuum in-line coater (see Figure 2) and a vacuum roll-to-roll coater (see Figure 3). The in-line coater is a high quality batch coating system with sample size being as large as 8" x 12". Either rigid or flexible substrates can be used, and the substrate temperature remains below 60°C during film growth so that the film temperature is always significantly below the softening point of polymers. This system is used for directly depositing barrier coatings onto solar cells and also for coating polymer sheets to be used for lamination. Barrier coatings typically involve deposition of a relatively thick polymer layer (P1) followed by deposition of the first inorganic film to form the first dyad, and the growth of additional dyads to grow a multi-layer coating. After growing the first dyad with the in-line coater, the substrate is 'turned around' and returned to the polymer growth station to initiate growth of the second dyad. The process is repeated until the desired multi-layered moisture barrier is formed. Barrier coatings are currently made with an acrylate polymer and Al₂O₃ films. The polymer films are grown by first depositing a liquid, acrylate monomer followed by a curing step. Al₂O₃ films are grown by reactive sputtering.

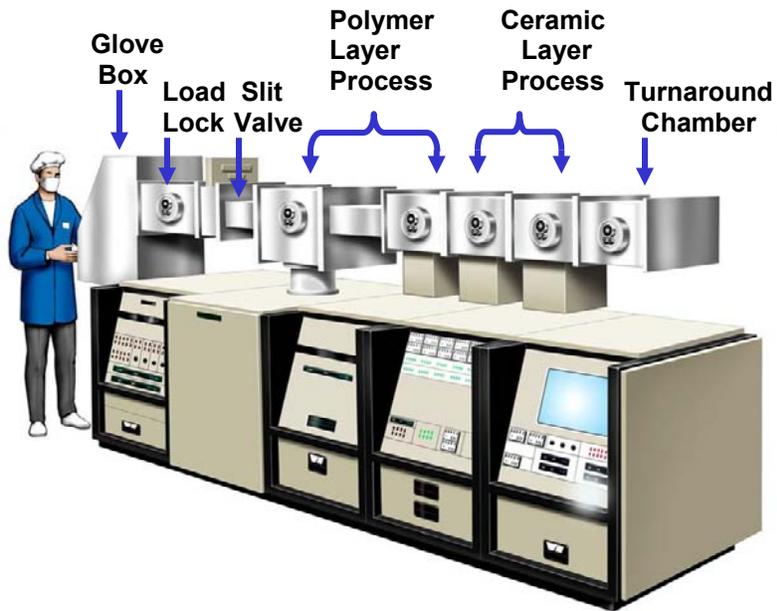


Figure 2. The PNNL in-line coater allows deposition of alternating layers of polymer and inorganic layers.

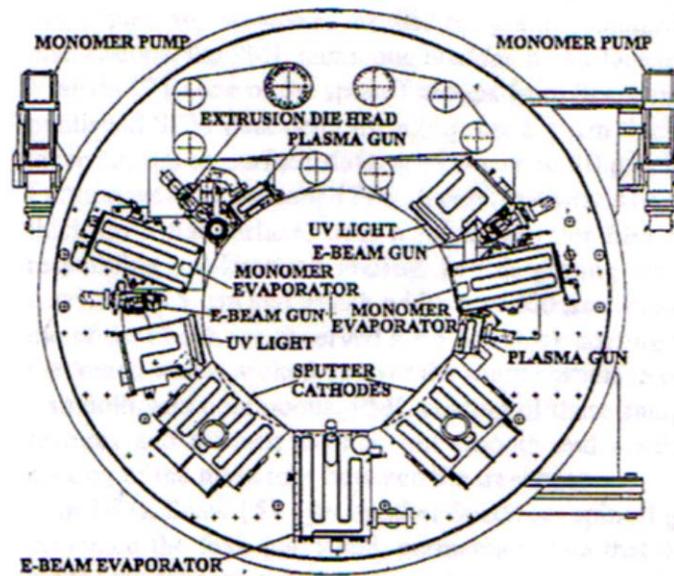


Figure 3. Vacuum roll coater at the Pacific Northwest National Laboratory. sputtering.

The PNNL vacuum roll coater accommodates 7-inch wide, 2000 meter long flexible substrates. Coatings can be grown at a speed of 2 to 3 meters/minute with reactive sputtering of aluminum being the limiting step. Although it is possible to utilize a roll of polymer 2000 meters long in the system, barrier coatings are currently grown on the roll coater system in a batch mode. For example, multi-layer barrier coatings are deposited onto 39 inch long, 7 inch wide straps of PET for use in a lamination process. The PET straps are placed on the cylindrical drum of the system and rotated through the deposition stations to form the multi-layer coatings. A barrier coated polymer sheet such as PET is referred to as 'Flexible Glass' (FG).

3. ENCAPSULATION STUDIES of CIGSS and CIGS Solar Cells

Thin-film solar cells based on CIGS are being considered for large scale power plants as well as building integrated photovoltaic (BIPV) applications. Since CIGS cells are very sensitive to moisture, they must be effectively encapsulated in order to satisfy the international standard IEC 61646 which requires the efficiency to degrade less than 10 % after 1000 hours in an environment of 85°C and 85% relative humidity (85/85). Beginning in 2002, we worked with Shell Solar Industries (SSI) to determine the effects of damp heat on their copper-indium-gallium-diselenide (CIGSS) solar cells. At that time, PNNL had one environmental chamber that was normally maintained at 60°C and 90% relative humidity for OLED applications. It was determined that testing at 60°C/90%RH would be adequate for the initial studies with SSI devices. Damp heat studies were carried out on uncoated and barrier-coated SSI mini-circuits. Towards the end of this program PNNL purchased another environmental chamber and damp heat studies were then conducted at 85°C/85%RH. Unfortunately, Shell Solar, Industries had been sold by that time, and we were only able to carry out studies at 85°C/85%RH with SSI devices that had been exposed to ambient conditions for several years. In the final stages of this program, CIGS cells supplied by the Institute for Energy Conversion were investigated. Results of damp heat studies with SSI mini-circuits and laboratory cells from IEC are presented in Sections 3.1 and 3.2.

PNNL continued to investigate damp heat studies with CIGS cells after the NREL program concluded. In particular, CIGS cells from SoloPower were laminated with PET coated with PNNL barrier coatings, and subjected to damp heat investigations in an environment of 85°C/85%RH. Results of these studies are discussed in Section 3.3.

3.1 Damp Heat Studies with SSI Mini-Circuits

A collaborative effort was carried out with SSI to develop barrier coatings for CIGSS circuits. This work resulted in an approach that allowed circuits to survive over 1500 hours in a 60°C/90%RH environment with less than 10% loss in efficiency. As noted above, at the time these studies were conducted it was necessary to test at 60°C instead of 85°C. SSI provided monolithically integrated thin-film CIGSS circuits, each of which consisted of ten cells connected in series on a 10 cm x 10 cm glass substrate as shown in Figure 4A. Each cell is approximately 0.69 cm x 8.3 cm. A border region of approximately 0.8 cm was depleted by SSI for the purpose of these studies to allow a smooth coating at the edge of the circuit. Before coating devices, the structures were cleaned since any debris on the surface may result in a pathway for water or oxygen diffusion after the coatings are applied. Since SSI cut the circuits out of larger modules, particles of glass constitute one type of debris. Shipping and handling the circuits can also lead to debris on the surface of these structures. These problems would not exist in a production process. Thus, prior to coating CIGSS circuits, the surfaces were cleaned to remove any loose debris. In addition to loose debris, however, we found that CIGSS surfaces contained relatively large nodules (see Figure 4B) which can penetrate coatings

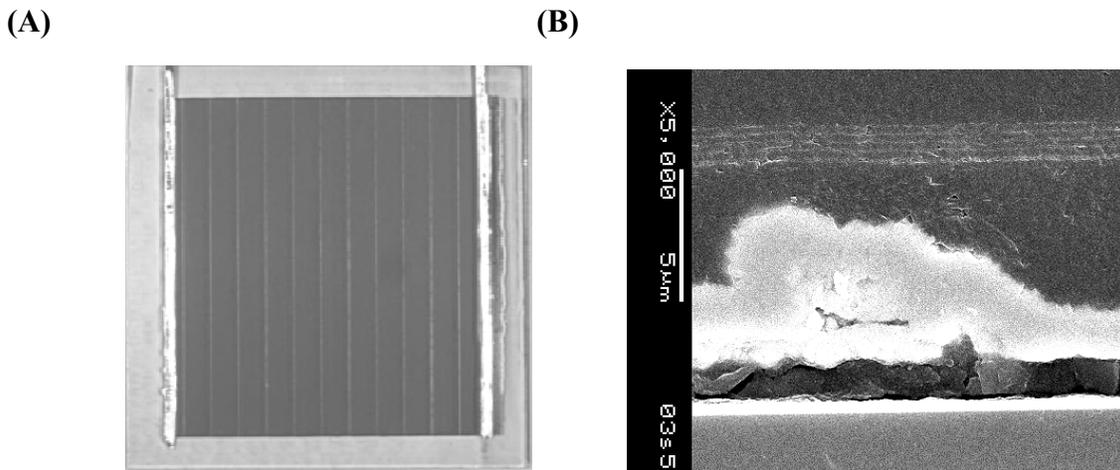


Figure 4. (A) A picture of 10 cm x 10 cm SSI CIGSS circuit described in the text. (B) Electron micrograph illustrates the effect of thick polymer planarizing layer (P-Layer).

and provide pathways for moisture ingress. It was determined that the first, polymer layer needed to be several microns in order to prevent nodules from causing problems with the barrier coatings. The electron micrograph in Figure 4B shows a typical nodule on CIGSS cells and also the effect of the thick polymer layer to planarize the surface.

Once the surface nodules became apparent, additional characterization studies were carried out. An electron micrograph of a nodule on an as-received mini-circuit is shown in Figure 5. Analysis of composition of the nodule indicated that the outer surface was ZnO resulting from the deposited ZnO TCO, but that interior contained Cu, In, Se and sulfur. Thus, the nodule apparently existed prior to ZnO deposition. We determined, therefore, that effective barrier coatings for the SSI mini-circuits required relatively thick P-layers.

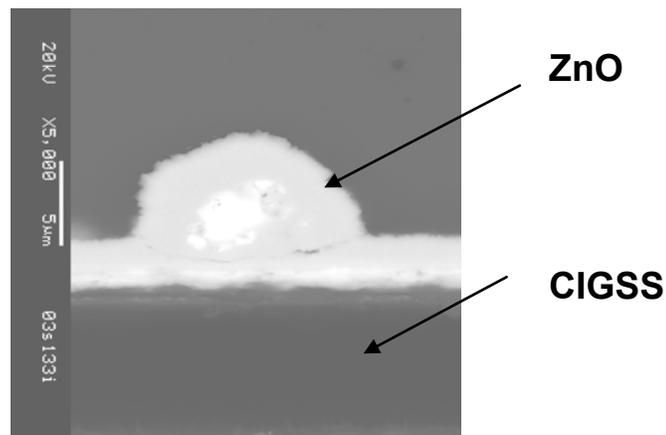


Figure 5. Electron micrograph showing nodule in as-received film surface.

Damp Heat Studies in 60°C/90%RH

The effects of multilayer coatings deposited onto SSI mini-modules were investigated by subjecting coated modules to temperature and humidity stress. In particular, current-voltage characteristics were taken periodically for coated mini-circuits stored in a Tenney environmental chamber at conditions of 60°C and 90% relative humidity. Efforts focused on the use of coatings consisting of five pairs (or dyads) of polymer/ Al_2O_3 films. The general structure of the barrier coatings was similar to that used by PNNL for OLED encapsulation. The first dyad consisted of a 3.5 μm polymer layer and a 1000 Å alumina layer, while the 2nd, 3rd, 4th and 5th dyads were comprised of 1000Å of polymer and 500Å of alumina. Results for coated mini-modules with two thicknesses for the P-layer and an uncoated module are shown in Figure 6. The efficiency of an uncoated circuit degrades very rapidly, becoming less than 1% within 400 hours. Moisture ingress affects all cell parameters. The main effects of moisture on CIGSS cells are to affect both the sheet conductance of the ZnO TCO and also to some degree the effective J_0 of the junction [2]. It is clear that a five dyad coating with a P-layer of several microns provides very good encapsulation for SSI circuits under 60°C/90%RH stress. If the P-layer is too thin water will penetrate the coating. In the extreme case, water spots will appear on the cell surface. The regions along mechanical cuts made as steps in the monolithic integration process are particularly important areas. It is imperative that the p-layer be relatively thick in order for the barrier coating to be effective.

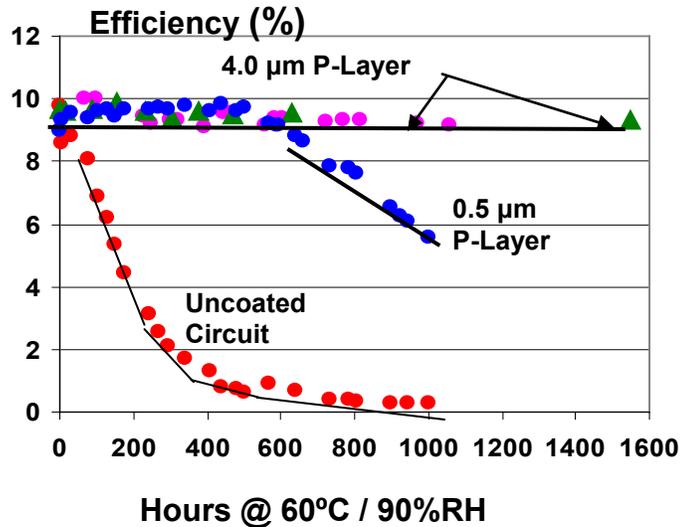


Figure 6. Efficiency versus time for three encapsulated circuits and an uncoated circuit stressed at 60°C/90%RH.

The effect of moisture on the ZnO TCO was investigated by measuring sheet resistance of the ZnO film on one of the single cells of the mini-circuit. Figure 7 indicates the location of applying a four point measurement. This measurement gives a reasonable approximation to the sheet resistance of ZnO since the underlying CIGSS/CdS junction would block current flow into the CIGSS. Table 1 gives results for the sheet resistance of a mini-circuit stressed at 60°C/90%RH. The sheet resistance increases as a result of the 60/90 stress.

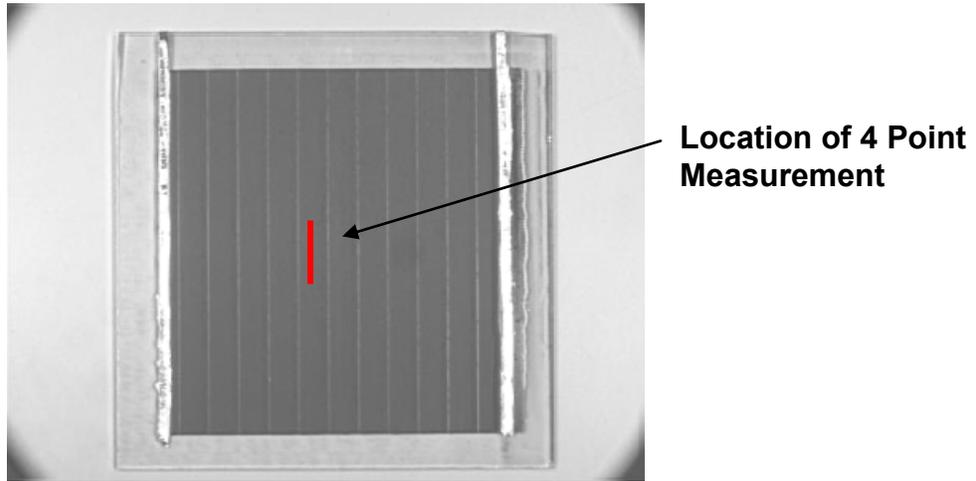


Figure 7. Picture of a 10 cm x 10 cm circuit and indication of the location of application of a 4 point measurement.

Table 1. ZnO Sheet Resistance for Stress SSI Mini-circuit

| | |
|-----------------------------------|--------------|
| Beginning of Life | 18 ohms/sq. |
| After 1000 hours at 60°C/90%RH | 180 ohms/sq. |

Current voltage studies were also carried out for stressed SSI circuits [2]. We found that if one fits the I-V characteristics in the range of voltages greater than 0.3 volt with an expression given by

$$J = J_0 \exp (V/AkT) \quad \text{for } V \gg kT$$

the A-factor would change very little while the J_0 value increased by two orders of magnitude. The relatively constant A-factor suggests that the dominant recombination center is the same in both cases, but the increase in J_0 indicates the density of recombination centers increased by two orders of magnitude.

Two encapsulated circuits with appropriate P-Layers were returned to SSI for measurement with their simulator after being subjected to 1000 hours at 60°C/90%RH. I-V characteristics of these circuits were measured by SSI before sending them to PNNL. Barrier coatings were then applied to the circuits and then they were stressed in an environment of 60°C/90%RH for 1000 hours. The devices were then returned to SSI where they were characterized. In both cases, the circuit efficiencies increased, even after being stressed at 60°C/90%RH for 1000 hours (see Table 2). SSI also subjected these encapsulated circuits to UV testing. Although some blistering occurred, circuit 22-9 actually improved in performance as the power increased to 0.688 watts. The power produced by Circuit 22-4 decreased to 0.498 watts. More studies are required before we can characterize the effects of UV, but these results were very encouraging. However, the effect of light-induced transients has to be better characterized.

Table 2. Measurements By Shell Solar

| | Circuit | P_{max} (Watts) |
|--|----------------|--------------------------------|
| Bare Circuit | 22-4 | 0.525 |
| Encapsulated (and 1000 hrs @ 60/90) | 22-4 | 0.582 |
| Bare Circuit | 22-9 | 0.592 |
| Encapsulated (and 1000 hrs @ 60/90) | 22-9 | 0.631 |

Damp Heat Studies in 85C/85%RH

As this program progressed, it became clear that damp heat conditions defined by 85°C and 85 % relative humidity were being established as the appropriate stress conditions. In fact, the international standard IEC16646 includes the requirement that modules must survive 1000 hours at 85°C/85%RH (85/85) with less than 10% degradation in efficiency. However, the SSI CIGSS work had been transferred to Germany by this time. Thus, during the last two years of the NREL program, efforts were made to acquire 85/85 data on SSI mini-circuits. Unfortunately, the only SSI devices available were ones that had been provided early in the program, but had been stored in an uncontrolled environment. CIGS cells were also obtained from IEC for investigations of the effects of 85/85 stress conditions. Results for IEC cells are discussed in the next section.

SSI provided 5 cm x 5 cm mini-circuits early in the program. These 5x5 cm mini-circuits had unfortunately been stored under uncontrolled conditions for 3 years before we initiated 85/85 studies. Nevertheless, studies were carried out to acquire some data that might be of interest. Current-voltage characteristics plotted as current per unit area versus voltage are given in Figure 8 for a typical mini-circuit at beginning of life, after 3 years under ambient conditions, and after subjecting a circuit to 85/85. The SSI

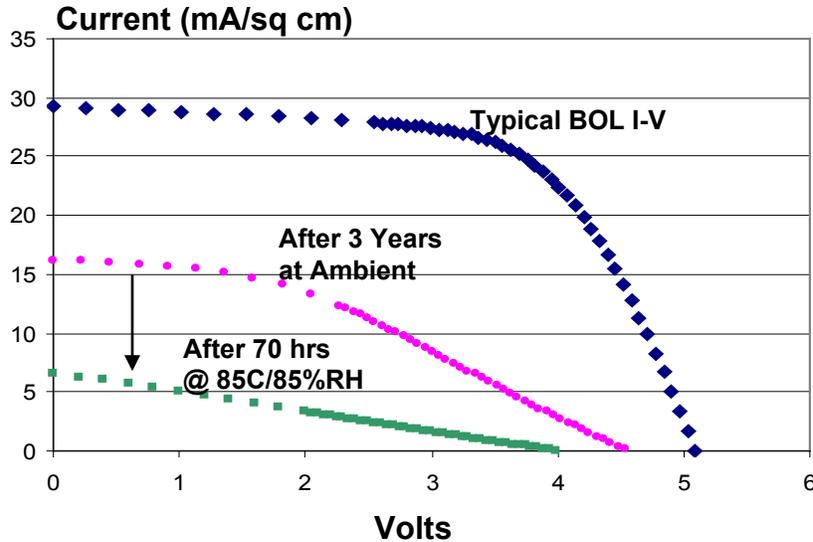


Figure 8. Current-Voltage characteristics of bare 5 cm x 5 cm SSI mini-circuits.

CIGSS cells utilized ZnO TCOs. Even though the ambient humidity was low during the 3 year period, and the temperature was only at room temperature, the cells degraded significantly during the 3 year period. Subjecting a bare device to 85/85 caused additional degradation as shown. Relative efficiency is plotted versus time for bare cells subjected to 60/90 and 85/85 conditions are shown in Figure 9. The 85/85 case is for one of the 5x5 cm SSI min-circuits which had already degraded as described in Figure 8. Even though the 5x5 cm devices had already degraded, it is apparent that the increase of temperature from 60°C to 85C has a very significant effect on the rate of degradation.

Even though the small mini-circuits had degraded, studies of the effects of 85/85 stress on coated devices were initiated. Four mini-circuits were coated with barrier coatings. The thickness of the P1 layer was varied for barrier coatings applied to the devices. Two of the circuits were coated with a relative thick multi-layer coating. One of those circuits was subjected to conditions of 85°C and dry conditions (see Figure 10), while the other circuit was subjected to 85/85 along with two other coated devices. Results for the device subjected to 85°C/ Dry conditions indicates that the increase in

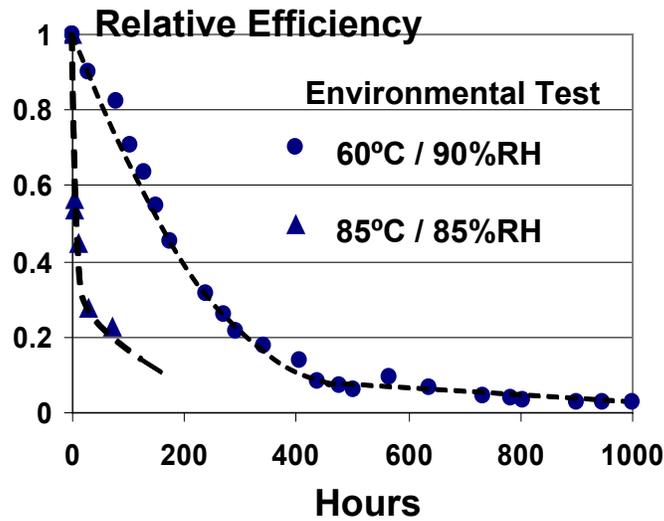


Figure 9. Relative efficiency for bare SSI mini-circuits.

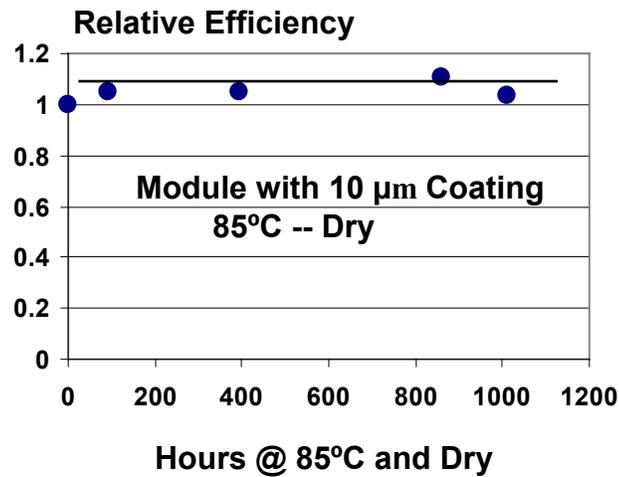


Figure 10. Relative efficiency versus time for a coated circuit in 85°C/Dry stress.

temperature from 60°C to 85°C is not by itself the cause of degradation. The results plotted in Figure 11, however, indicate that the directly deposited barrier coatings on these particular SSI mini-circuits are not adequate to completely prevent degradation. Note the linear behavior of the decrease in relative efficiency, regardless of the thickness of the P1 layer. This type of behavior could suggest that the moisture ingress is occurring at the edges. Additional studies would be required to develop an adequate direct deposited barrier coating for the SSI mini-circuits to meet the IEC61646 requirements.

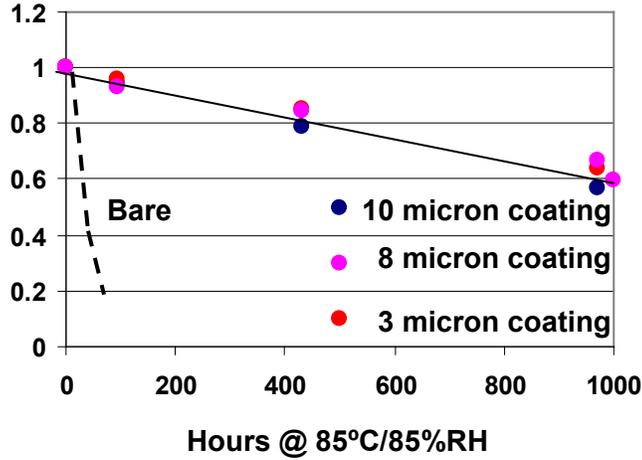


Figure 11. Circuits with varied P1 layers in 85/85 stress.

3.2 Damp Heat Studies with IEC CIGS Solar Cells

IEC provided arrays of six 0.5 cm x 0.9 cm cells defined on 1"x1" glass substrates for encapsulation studies [3]. The cell structure is based on the following: Glass/Mo/CIGS/CdS/ZnO/ITO/(NiAl Grid). These cells are grown by multiple source, film deposition on glass substrates. As a result, the cells are relatively 'smooth.' To establish a baseline performance, uncoated cells were subjected to the 85/85 environment. Figure 12 gives results for two uncoated cells that represent the range of observed cell performance. The results are very unusual. We are accustomed to observing very rapid degradation in CIGS cell performance when they are not encapsulated. One of the bare IEC cells devices survived almost 1000 hours before

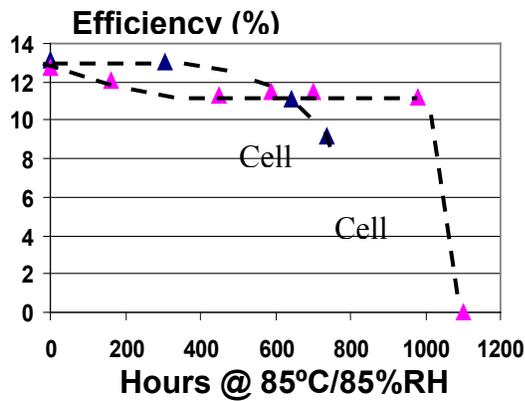


Figure 12. Estimated AM1 efficiency of bare IEC cells.

degrading very rapidly. These exceptional results are apparently due to the ITO coating deposited on a very smooth surface. We surmise that when the bare cell did degrade abruptly, water may have penetrated the ITO layer and began to react with ZnO.

Properties of the second bare IEC cell (referred to as Cell #2) that began to degrade at 400 to 500 hours changed in a typical manner for CIGS cells – but much more slowly. Cell parameters vs time are tabulated in Table 3. Initially, the fill factor degrades followed by the V_{oc} , and then J_{sc} . In previous studies of SSI cells, I-V analyses indicated that initially the sheet resistance of ZnO increased followed by an increase in J_o , apparently due to water penetrating the junction region. In the case of Cell #2, it appears that moisture passes through the ITO layer sooner than for Cell #1 causing an increase in ZnO sheet resistance and also begins to penetrate the junction region.

Table 3 – Properties of bare IEC Cell #2

| J_{sc} (mA/cm ²) | V_{oc} (Volts) | FF (%) | Est AM1 Efficiency | Hours @ 85/85 |
|-----------------------------------|---------------------|-----------|-----------------------|------------------|
| 28.7 | 0.632 | 71.8 | 13.1 | 0 |
| 29.8 | 0.627 | 69.6 | 13.0 | 306 |
| 28.3 | 0.617 | 63.6 | 11.1 | 642 |
| 27.3 | 0.615 | 55.0 | 9.22 | 738 |

IEC cells were also encapsulated and tested in an 85°C/85%RH environment. Cells were encapsulated with five dyad multilayer coatings, and using the advanced polymer formulation. Figure 13 shows a picture of a substrate with critical features that are required for the tests identified. In order to contact cell collector grids, a polymer bridge was first deposited followed by the deposition of silver leads as shown, and then the complete structure is encapsulated with a PML coating. Points for contacting the silver leads are protected so that they are not covered by the PML coating. During exposure to 85/85 the points for probing the collector grids are protected with vacuum grease to

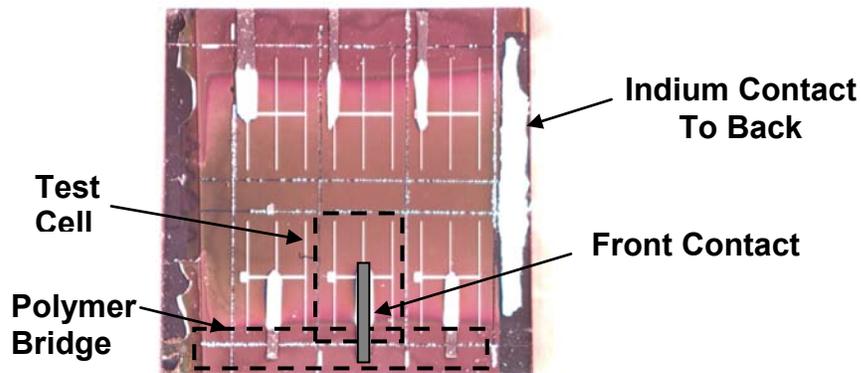


Figure 13. Picture of coated IEC cell with contacts for I-V measurement.

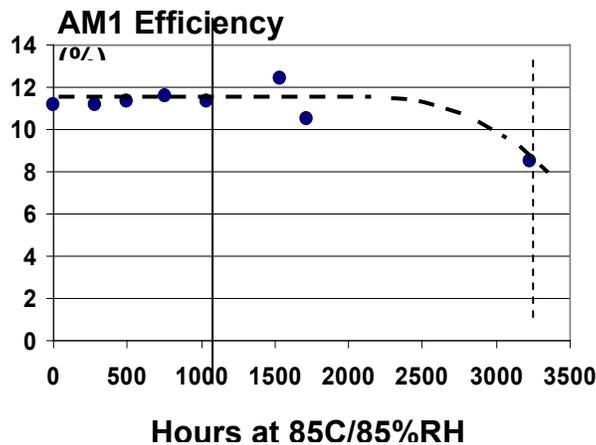


Figure 14. Estimated AM1 efficiency vs hours at 85C/85%RH.

prevent corrosion. Figure 14 gives results for encapsulated IEC cells subjected to 85/85 for 3250 hours. The results are extraordinary. The coated devices are essentially stable in the 85/85 environment for much longer than 1000 hours. In fact, no degradation was evident at 1500 hours. After 3200 hours in the 85/85 environment moisture began to penetrate at the coating edges and causing the efficiency to decline to 8.2 %.

Results obtained for encapsulated IEC cells represent a benchmark for encapsulated CIGS cells by direct deposition. The encapsulated IEC cells are stable for more than 1500 hours. The encapsulated IEC cells have three key features:

- ITO top layer
- Smooth surface
- PNNL multi-layer barrier coating

All of these features contribute to this outstanding result.

3.3 Damp Heat Studies in 85C/85%RH with Laminated CIGS Cells

Approaches to encapsulation of flexible CIGS cells from SoloPower by lamination were investigated subsequent to the NREL program [4]. The SoloPower cells were grown on metal foil. Barrier coatings were deposited on PET with the PNNL roll coater and supplied to SoloPower for lamination. Damp heat studies were carried out with laminated SoloPower cells at both PNNL and SoloPower. In all cases the laminated cells passed the IEC16461 requirement. The results clearly demonstrated that lamination with PNNL barrier-coated PET allows SoloPower CIGS cells to survive an environment of 85C/85%RH for 1000 hours with less than 10% change in efficiency. Results for one cell stressed at PNNL are shown in Table 4.

Table 4 - Encapsulated SoloPower Flexible, CIGS Cells

| Cell | Substrate | Area (cm ²) | TCO | Encapsulation | Efficiency (%) | |
|-----------|-----------|-------------------------|-----|--|------------------|-------------------------|
| | | | | | BOL ¹ | 1000 Hours @ 85°C/85%RH |
| SoloPower | Foil | 102 | ZnO | Laminated with PNNL Coating on PET by SoloPower ² | 8.8 | 8.8 |

1. BOL refers to beginning-of-life.
2. The Barrier Film used for lamination was grown with the PNNL Roll Coater.

4. ENCAPSULATION STUDIES of THIN-FILM CdTe SOLAR CELLS

A collaborative investigation of barrier coatings for CdTe cells was carried out with Dr. Sampath at Colorado State University. The CSU CdTe cells are fabricated with a superstrate configuration [5]. CSU used a Ni-C contact that is deposited as a slurry, and then cured. This contact is relatively thick as described in Figure 15. The back contact is also very rough as shown by the SEM micrograph in Figure 16. Cells received from CSU have back contacts and an indium pad in the corner of the square glass substrate for contacting the TCO as depicted in Figure 17. The glass substrates are typically 2 x 2 in.

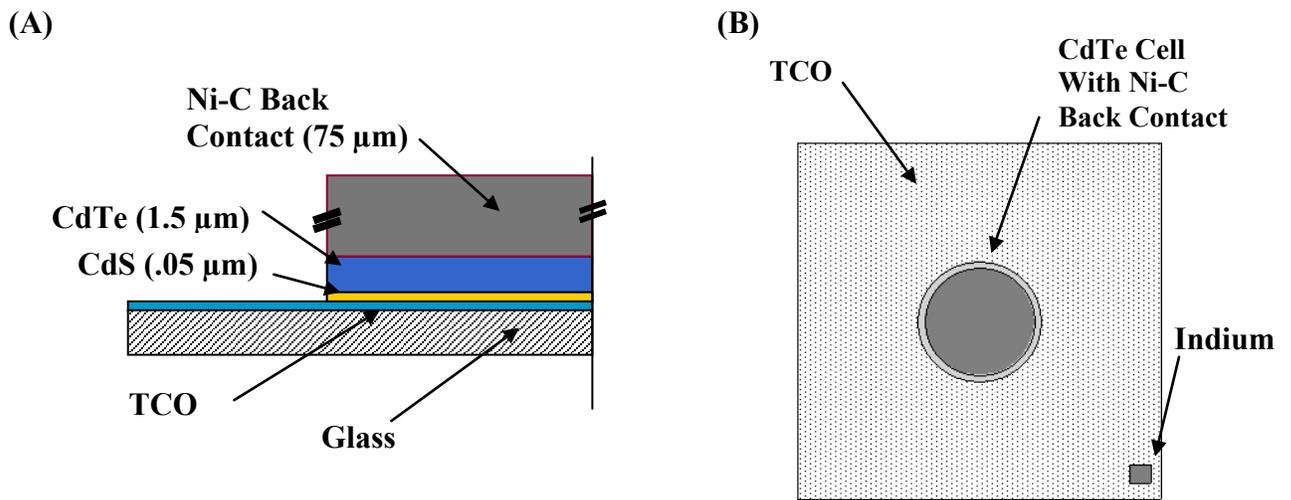


Figure 15. Description of CSU cell as received by PNNL: (A) Cross-section; (B) Top view.

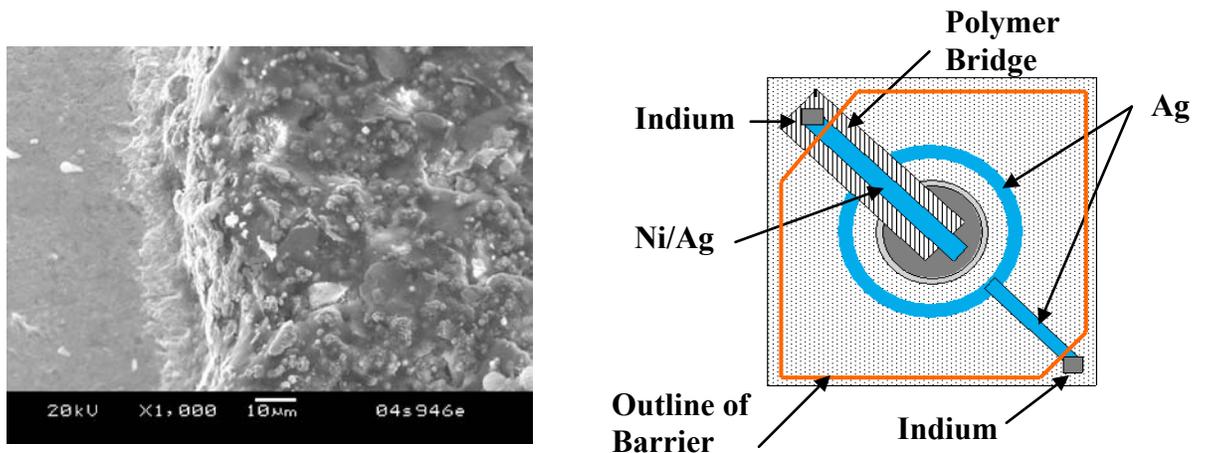


Figure 16. SEM micrograph showing the surface boundary of the CSU Ni/Carbon contact.

Figure 17. Contact configuration and approach to encapsulation of CSU cell.

After receiving cells from CSU, encapsulation involved the following steps: (1) deposit a silver ring contact onto the TCO coated glass; (2) deposit a polymer bridge; (3) deposit a Ni strip for contacting the back of the CdTe cell; (4) deposit a multi-layer coating (ML) coating over the complete structure (see Figure 15). Initial emphasis was placed on determining the effectiveness of multilayer layer coatings. Since the CdTe cells and modules fabricated by companies such as First Solar are based on a superstrate structure, barrier coatings on the back side need not be transparent. Thus, we also investigated barrier coatings based on an aluminum film combined with a single dyad. If an effective approach is developed to encapsulate the back surface of thin film CdTe cells based on a superstrate structure, the back glass sheet can be eliminated.

Data for cell efficiencies vs time are given in Figure 18 for bare CSU devices and encapsulated CSU cells subjected an environment of 60°C and 90% relative humidity (60/90). The three bare cells were all grown in the same run. These cells were grown at a time when CSU was adjusting process parameters, which explains the variation in properties. One of the encapsulated cells was actually exposed to 60°C and dry conditions to establish the effect of a stress of 60°C. The performance of the bare cells in the 60/90 environment is actually very impressive compared to results we have obtained for other thin film devices that have no encapsulation. However, it is clear that encapsulation is required. Data for two encapsulated CSU CdTe cells subjected to 60/90 are given in Figure 18B. One cell was encapsulated with a five dyad coating and the other with the aluminum based coating. The decline in efficiency is due almost entirely

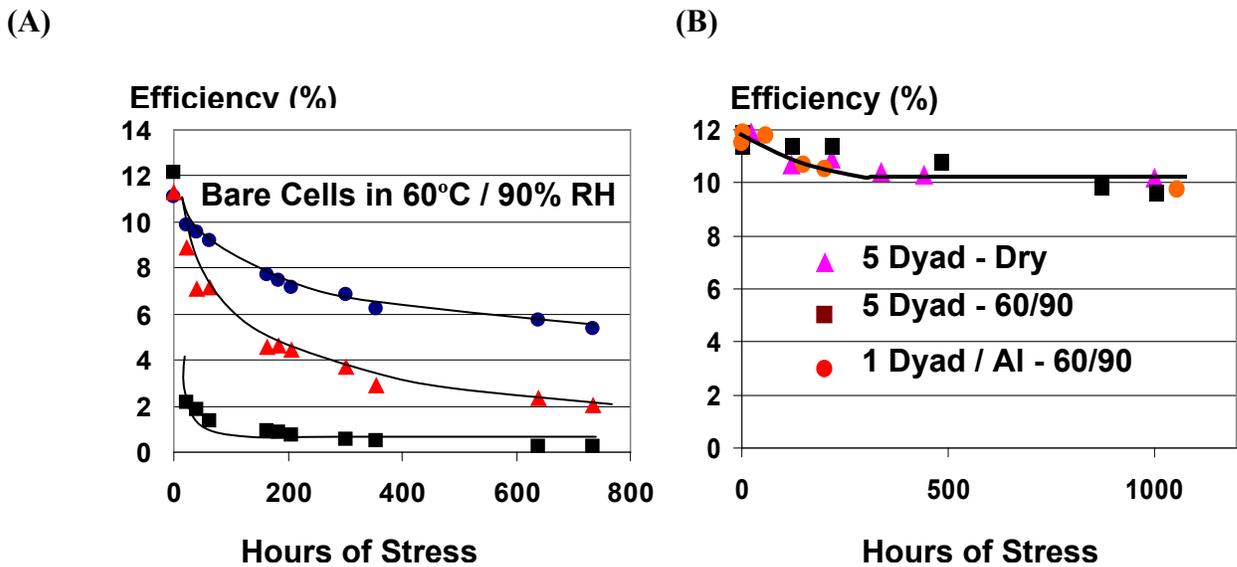


Figure 18. Efficiency vs Hours of Stress for Bare CSU cells and for devices fabricated as described by Figure 10.

to a decrease in the fill factor, or specifically, to increased series resistance. It appears clear that the degradation is due to the effect of 60°C. Since the bare cells degrade very rapidly in the 60/90 environment, one can conclude that both types of barrier coating are effectively preventing moisture ingress under 60/90 conditions. The primary motivation for this effort was to provide an alternative for the back surface glass sheet for superstrate CdTe modules. However, according to Dr. Sampath, effects of the back sheet on mechanical strength must also be considered.

5. CONCLUSIONS

The barrier coating technology developed at PNNL for OLEDs and other devices sensitive to moisture and oxygen has been considered for approaches to encapsulation of thin film solar cells. The PNNL multi-layer technology can be used to encapsulate cells by direct deposition and by lamination. In the case of lamination, the coatings are deposited onto a polymer sheet such as PET and the coated sheet is used for lamination. This program focused on studies involving directly deposited barrier coatings. Studies were carried out for CIGSS cells from Shell Solar, CIGS cells from IEC and CdTe devices from Colorado State University.

An approach was developed for encapsulating SSI mini-circuits by direct deposition that allowed cells to survive 1000 hours in an environment of 60°C and 90%RH with minimal degradation. Due to Shell Solar being sold, which ended the availability of appropriate devices, an approach to encapsulation to allow survival in 85C/85%RH was not developed. However, studies in 85C/85%RH were carried out on CIGS provide by the Institute for Energy Conversion. Uncoated IEC cells exhibited significantly more tolerance to 85/85 environmental conditions than typical CIGS cells. For example, one cell remained stable for nearly 1000 hours before decreasing rather abruptly to essentially zero efficiency. Typical behavior of IEC cells resulted in gradual decrease in efficiency beginning between 500 to 700 hours. It is hypothesized that the top TCO structure and the fact that the IEC cells are grown by multiple source deposition on glass substrates resulting in a very 'smooth' surface accounts for the behavior of bare IEC devices. The TCO structure involves a thin layer of ZnO and an ITO layer as the top surface film. We suggest that the ITO layer is acting as a very good barrier layer, but when it is penetrated by moisture the ZnO layer rapidly increases in resistivity, and junction properties deteriorate as well. Encapsulated IEC cells exhibited extraordinary stability. One IEC cell with a directly deposited barrier coating survived > 1700 hours in an 85°C/85%RH environment with very little decrease in efficiency.

Finally, investigations were also conducted with CdTe cells supplied by Dr Sampath at Colorado State University. These studies only involved stress at 60°C/90%RH. The CSU cell structure like most CdTe cells is based on a superstrate configuration. The back contact is a relatively thick Ni/C layer. Bare CSU cells were determined to degrade in 60°C/90%RH. However, they were stable for 1000 hours in the 60°C/90%RH environment when coated with a 5 dyad coating. The devices were also stable for 1000

hours when encapsulated with an aluminum film and one dyad of PNNL coating. No testing was done at 85C/85%RH. It should be noted that First Solar as well as new companies planning to produce CdTe modules utilize a glass to glass package, and therefore would apparently not be interested in using barrier coatings as studied in this work. However, if interest in eliminating the back glass sheet were to develop, an effective approach to encapsulating the back contact side of the module will become important.

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