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MILESTONE REPORT #3

Project Title: **Cost-effective Pilot Line for Flexible PV Modules**		
Contract Number: RD3-53	**Milestone Number:** 3	**Report Date:** 3/22/2010
Reporting Period: October 22, 2009 to March 22, 2010		
Milestone Description: Scaled CIS Absorber		
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Congressional District: 24		

LEGAL NOTICE

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MILESTONE 3 SUMMARY REPORT

Executive Summary

The project is directed to achieving a cost-effective manufacturing-oriented design for pilot production of PV modules. It has been leveraging the results of InterPhases' RD-78 project to realize a commercially viable solar cell technology for large-scale renewable electricity generation.

The R&D continues to progress along a dual path of process scale-up and simultaneous optimization, aimed at building a strong base for the pilot production. Along with process scale-up and pilot line development, we have been investigating ways to enhance device performance. To make the next leap forward from the current level of performance, the research draws upon new developments in nanotechnology. Considering that the electronic and structural quality of the copper indium selenide (CIS) films is critical to the device performance, we continue to improve its deposition and recrystallization, taking advantage of the emerging annealing technologies to improve the crystallinity of CIS absorbers.

The scale-up research continues to simplify the fabrication, increase device stability and further reduce costs of large scale solar cell production. Fruitful relationships have been established with equipment vendors to develop roll-to-roll (R2R) deposition system and other necessary processing and characterization tools. A detailed characterization task has been launched through various collaborations in order to better correlate the material and electro-optical properties with the PV performance. Current period research has led to substantial technical advances for substrate/absorber processing, junction formation and characterization, window deposition, and R2R equipment development, in addition to accomplishing Milestone 3 goals.

Technical Progress

The project carried out further research on Tasks 1 – 4 including several subtasks. The research focused on achieving the following Milestone 3 objectives:

a) High rate electrodeposition of uniformly thick, shiny, *n*-CIS films.
b) Opto-electronic and structural properties of the absorber.
c) Efficient junction formation on scaled CIS/substrate.
d) Module assembly and encapsulation technology.

In the context of attaining objectives (a)–(c), we have been developing alternate device structures and associated deposition and recrystallization parameters for the various device components. To address objective (d) we investigated ♦ Interconnection method for optimal conductivity and adhesion, and ♦ Procedures for laminating PV module and contact application. In addition, a new task directed to achieving Milestone 4 for Pilot line design has been initiated via technical design for viable R2R processing equipment.

1. Absorber Re-crystallization

Having established the CIS deposition steps to produce high quality absorbers, we have been focusing on the second most crucial step of recrystallization with the dual objectives of (a) designing pilot scale annealing furnace, and (b) improving solar cell performance. We have been collaborating with a furnace equipment manufacturer to develop and fabricate annealing equipment for the CIS films. Alternate thermal processing methods, using various radiation sources were investigated. XRD and SEM analysis were used to assess the extent of crystallization and the effects on the grain structure.

The results on laser treated CIS films indicate that the grains melt and condense in a non-crystalline morphology. Thus the re-crystallization is insufficient to impact the absorber performance. Flash lamp annealing using various pulse programs led to coalescence of small grains into a layer-like structure. Annealing under vapor pressure led to significant crystallization, demonstrating that the electrodeposited films could achieve large crystalline columnar grains. Subsequent optimization of process parameters led to further improvements in crystallinity.

A new laboratory-scale sealed tube furnace was assembled to carry out thermal processing. Annealing experiments, carried out under various processing conditions that include varying vapor pressure, duration, temperature range and ramp rates, continue to generate highly crystallized CIS films. Specific conditions were established to produce large-grained CIS crystals. XRD analyses show very sharp and high intensity CIS peaks, Fig. 1a. The SEMs show different orientations of the annealed film that appears to be almost completely crystallized, Figs. 1b, 1c. Cross-sectional SEM, Fig. 1c shows large columnar grained CIS crystals across the entire height (thickness) of the CIS layer. In these films, the crystals seem to grow into each other, forming a very tight crystalline CIS layer. This would prevent pinholes even if any pinholes had existed in the as-deposited CIS layer.

We have continued to modify the laboratory furnace to obtain the necessary processing parameters and optimize the re-crystallization conditions to produce uniform, columnar, large- grained crystals and good adhesion to the substrate. These results show almost perfect crystal structure that characterizes very high efficiency solar cells. The extraordinary crystallinity achieved for the first time for inexpensive electrodeposited CIS films affirms the validity of our low-cost approach to produce high efficiency solar cells.

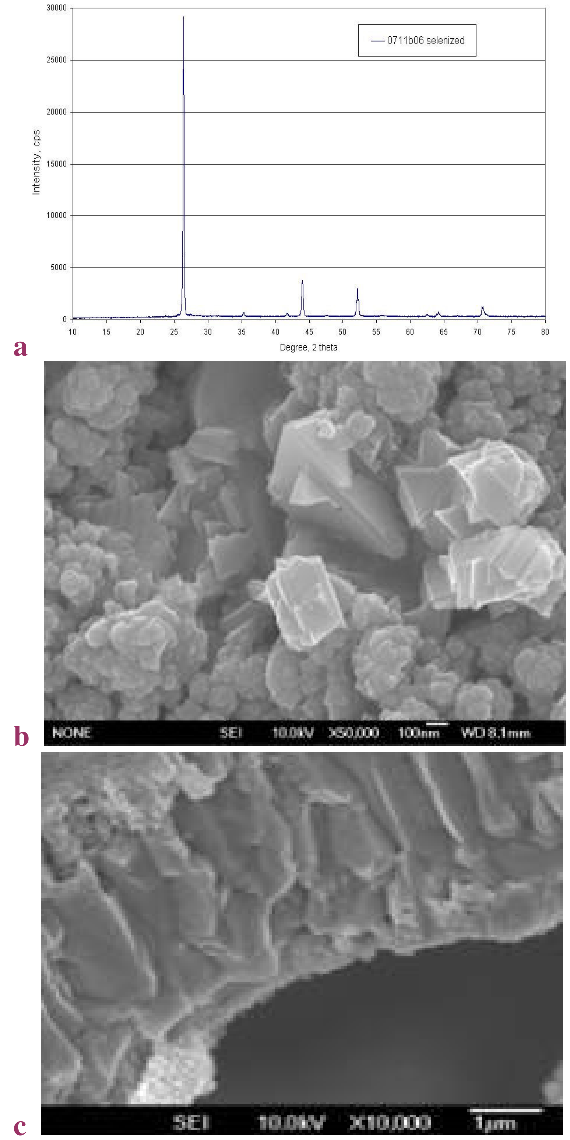

Figure 1. XRD and SEM views of re-crystallized CIS films

2. Pilot Line Annealing Equipment

We have been in discussion with an industrial furnace equipment manufacturer to design a high throughput R2R pilot annealing furnace based on the results of our batch annealing experiments. It was determined that the continuous R2R process also avoids the problems of a batch process, such as repeated loading and unloading, sealing to prevent leaks and maintaining high pressure inside the chamber, heating of the whole furnace to very high temperatures and then cooling to room temperature. The dynamics of the R2R processing avoids many of the issues encountered in a stationary furnace. Thus the scaled process will be even more commercially feasible, relative to the stationary laboratory scale process. Based on our laboratory results, subsequent discussions of thermal processing issues and exchange of equipment concepts, the collaboration with the furnace manufacturer has generated a conceptual design of R2R processing furnace. Many processing features for the new furnace design were derived from our current laboratory experiments. We are continuing discussions with the company, and use our laboratory results to modify and optimize the design.

3. Alternative Device Components and Configurations

The previously initiated task of exploring advanced device structures has been extended to take advantage of the special morphology for our electrodeposited CIS films. A number of device structures based on CIS are made with alternate configurations and components. Devices with both substrate and superstrate configuration were investigated. Alternate *p*-type junction partners were paired with CIS. Associated deposition approaches, including electrodeposition and re-crystallization parameters for these components were investigated. Remarkably, some of the new material combinations were able to tolerate the much longer anneal times that are needed for good crystallization, without decomposition. Sharp XRD peaks for CIS indicate substantial degree of re-crystallization, forming a bilayered structure. Lower annealing temperatures reduced the partial disruption or cracking of the top layer seen at high temperatures. The dark current I-V curves of solid state devices with metallic contacts typically show rectifying behavior.

4. PV Device Fabrication and Characterization

A typical CIS based PV device, Fig. 2(L), was fabricated by depositing a thin *p*-type layer and a transparent conducting oxide contact to the SS/*n*-CIS samples. PV performance for several subcell devices illustrated in Fig. 2(R), was assessed by comparing the quantum efficiency (QE) spectra. A control sample consisting of an 18% efficient co-evaporated CIGS device was used for comparative QE assessment. Remarkably, our *n*-CIS device shows similar spectral response in the 500-600 nm range and only about 20% lower response at longer wavelengths, Fig. 3. This is an exceptional result that elevates the performance of our inexpensively electrodeposited film to that of a stringently controlled, high-end co-evaporated CIGS film.

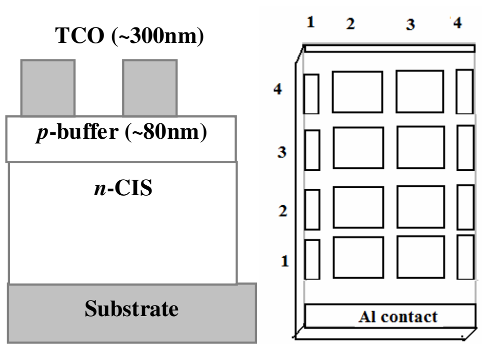

Figure 2. (L) Cell configuration and (R) pattern of ZnO:Ga contacts.

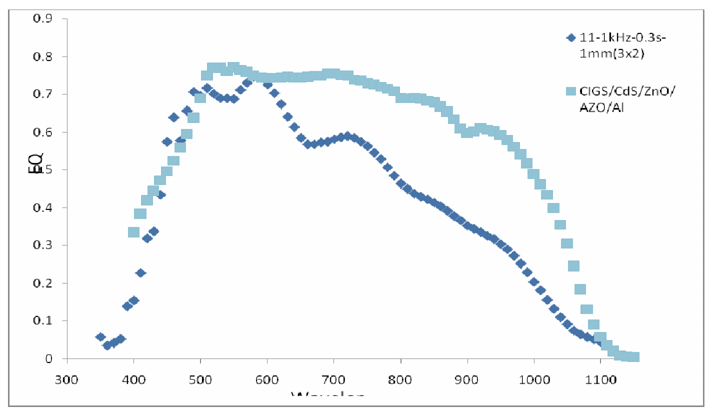

Figure 3. External quantum efficiencies of a *n*-CIS/*p*-buffer subcell and a high (18%) efficiency *p*-CIGS/*n*-CdS device.

5. Module Fabrication, Interconnection, and Lamination

Procedures have been devised and partially tested for deposition of metal contacts in certain patterns on SS/*n*-CIS/*p*-buffer/ZnO devices, monolithic series interconnection of solar cells into module, and encapsulation of the solar cell modules. Fig. 4 shows the design of 1ft^2 module assembly of CIS cells. Similar design can be used to produce 1m^2 modules.

In this task, small individual 6” x 3” cells are cut from large area PV foil and assembled into small prototype modules, Fig. 4. Assuming solar cell parameters of Voc = 0.5V, Isc = 35mA/cm^2 and efficiency =10%, a module having an area of 348.4cm^2 can provide output of

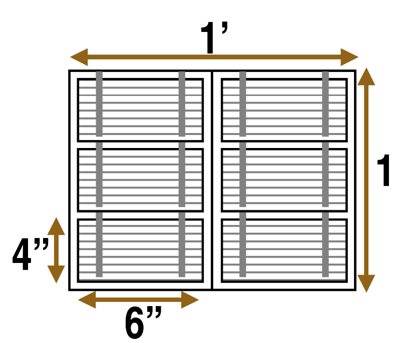

Figure 4. Square foot Module Design

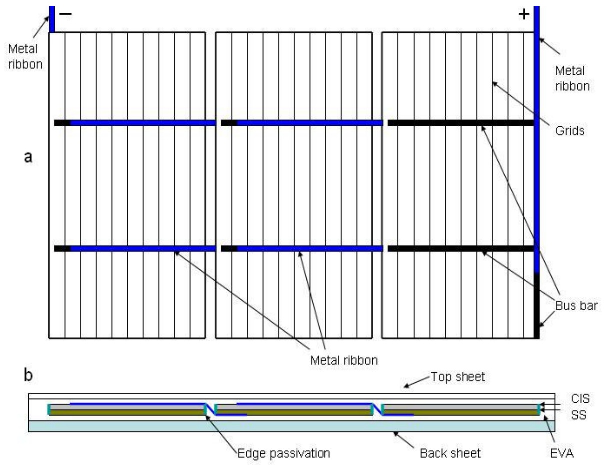

Figure 5. Schematics of solar modules: (a) contact grid, bus bars, and ribbon contacts; (b) monolithic series interconnection of solar cells and module encapsulation

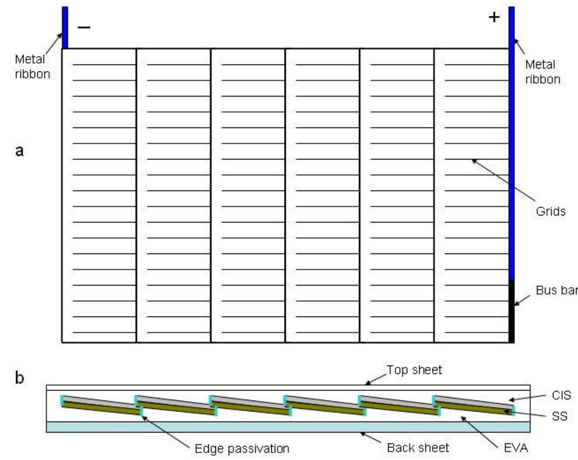

Figure 6. (a) Contact grid and roof-tile type interconnection of cells, and (b) Encapsulation of roof-tiled cells

1.5V, 12.2A and 3.5W. Connecting 2 modules in series will double the voltage output to 3V, while connecting 2 modules in parallel will double the current to 24.4A. Solar cell combinations with series and parallel connections can be adapted for different output voltage, current or power, shape or size.

Al/Ni or Ag paste metal contacts were applied to the solar cells. Fig. 5a shows the pattern of metal contacts on the cells and Fig. 5b shows the monolithic series interconnection with metal ribbons (blue) between cells, and the module encapsulation. For module manufacturing, the module cutting and assembly processes are automated. The cells are automatically cut from a long roll of finished PV device, are handled by a robotic module assembling machine, and then laminated using a laminator.

An alternative approach also under consideration is illustrated in Fig. 6. The modules are made by monolithically interconnecting cells in roof-tile fashion. This approach eliminates the issues of using metal ribbon for cell connection shown in Fig. 5. In this case, the cells are cut into 6” x 1.5” in size. Metal contact fingers of 1.4” in length are printed on the cells and one 6” long bus bar is deposited at one edge on each cell, Fig. 6a. The bus bar on each cell is overlapped and connected in roof-tile fashion to the next cell, thus using six cells for the roof-tile modules, Fig. 6b. As in the other approach, the cell assembly is encapsulated between top and back plastic sheets using EVA, Fig. 6b. Since the cells are very thin and flexible, and less than 0.06mm thick, the roof-tile modules still appear flat and bending the modules will not lead to detachment at the roof-tiled joints. Assuming that the solar cells have Voc = 0.5V, Isc = 35mA/cm^2 and 10% efficiency, the module (six 6” x 1.5” cells) will have an area of about 348.4cm^2 and produce 3.0V, 12.2A and 3.5W.

Other Activities

The 2009 Solar Power International Convention at Anaheim, CA, presented many opportunities for interactions with the various exhibitors focusing on equipment, production lines, turnkey lines, module fabrication and system level components. Business activities this period included: Visits to California NanoSystems Institute (CNSI) at UCLA and interactions with the scientists for potential collaborations; Visits from potential industry partners for development of a turnkey system for solar module manufacturing; Visits from a potential investor (CEO of an energy production company) for joint development of a manufacturing plant.

Milestone	Name	% Completed
1	Scaled fabrication for absorber CIS and cell	100%. Research continues to optimize and scale up the deposition and post thermal treatments for CIS films.
2	Scaled strip cell	100%. Research on alternate materials and device configurations.
3	Absorber, junction and module assembly	100%. Advances of absorber, device processing, and module design.
4	Pilot equipment design	10%. Technical design parameters for continuous RTP equipment.

Project Status

Pilot development tasks for achieving low cost PV electricity with CIS solar cells are progressing on schedule.