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MILESTONE REPORT #4

Project Title: Cost-effective Pilot Line for Flexible PV Modules		
Contract Number: RD3-53	Milestone Number: 4	Report Date: 7/22/2010
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Milestone Description: Pilot design for R2R components		
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MILESTONE 4 SUMMARY REPORT

Executive Summary

The project is directed to achieving a cost-effective manufacturing-oriented design for pilot production of PV modules. By leveraging the results of InterPhases' RD-78 project, the current effort seeks 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) absorbers is critical to the device performance, we continue to improve the critical deposition and recrystallization process steps.

The project is advancing to the stage of designing components for continuous roll-to-roll (R2R) processing line. Much of the R&D performed in the preceding months has been directed into designing and developing the most innovative portion of the pilot line, Fig. 1. The research has focused on process layout and equipment design as follows:

- (a) Technical design for substrate processing equipment
- (b) Technical design for absorber electrodeposition equipment
- (c) Technical design for continuous thermal processing equipment
- (d) Engineering design for surface processing and buffer layer deposition equipment.

The primary steps (a) – (d) are unprecedented and have been developed primarily for InterPhases' *n*-CIS PV technology. Thus substantial R&D was required to develop the processes and equipment for these steps. The research has been conducted in continuous iterative loop for optimizing the process parameters to achieve the high performance, low cost manufacturability goals. The steps (b) and (c) are especially crucial to the solar cell performance. Research for the steps has concentrated on refining the process parameters needed to design the R2R equipment for CIS electrodeposition and annealing. Significant interactions with the equipment manufacturers have led to fruitful relationships to develop R2R deposition system and other necessary processing and characterization tools.

Simultaneously, the research continues to simplify and scale-up the fabrication steps, increase device stability and further reduce costs of large scale solar cell production. Detailed characterization effort has been launched through various collaborations in order to better correlate the material and electro-optical properties with the PV performance. The research has generated a large database of new information on process parameters, deposition cell geometry and component configurations. These are being implemented in the design of scaled electrodeposition and annealing equipment for the R2R processing line. The research results also revealed new phenomena for this interesting CIS PV system, which we are exploiting for further advances in PV performance and process simplification.

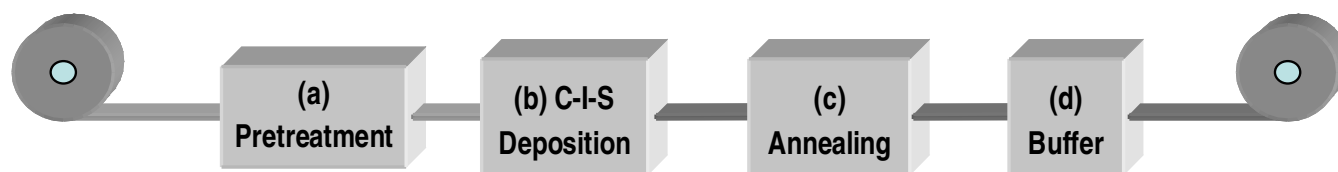


Figure 1. Principal components of the R2R pilot line for PV device fabrication

Technical Progress

To advance the process layout, and equipment design objectives, the project has carried out further research on Tasks 2–6, directed to attaining project Milestone 4. The research has focused on producing CIS devices on large substrates on the intermediary stage of scaling up the processes. The results have been integrated into technical designs for each of the components of the R2R system in Fig. 1.

1. Design considerations for continuous substrate preparation and CIS electrodeposition equipment

The deposition line includes cleaning, deposition, rinsing and drying operations. Steps (a) and (b) in Fig. 1, use multi-step R2R precleaning and electrodeposition systems. Step (a) includes sub-steps for (a1) soak cleaning, (a2) rinsing, (a3) activation, additional (a4) rinses and (a5) drying steps for the substrate. These steps have been effectively transitioned to process large foil substrates in batch mode.

The next step (b) constitutes the core of the *n*-CIS solar cell project. Substantial effort has been devoted to develop and optimize the parameters for this critical step of absorber layer deposition. Recent research has been evaluating the effects of process parameters and deposition tank configurations, focusing on generating engineering data to achieve large-area uniformity, optoelectronic quality and deposition rates. Clear understanding of the current distribution effects is necessary to developing a viable technical design for the CIS deposition equipment.

Current distribution is influenced by the geometries of the deposition cell and electrode, along with other parameters, e.g. solution flow patterns. Establishing optimum current distribution requires an intermediary scaling up step to replicate the results obtained for the small cell to a larger high speed flow cell (HSFC) set-up. This HSFC cell simulates high speed R2R plating by providing knife edge cathode agitation system, Fig. 2. This set-up was used for scaled CIS electrodeposition on 6" x 4" metal foil. The process variables considered include ♦ position of electrodes, ♦ flow patterns resulting from solution agitation, and ♦ location of electrical contact. The electrolyte composition was varied for each sample to obtain different CIS composition and dopant concentration. Other deposition conditions were maintained constant. An advantage derived from the much larger solution volume of the HSFC is minimum variation in the electrolyte composition and pH.

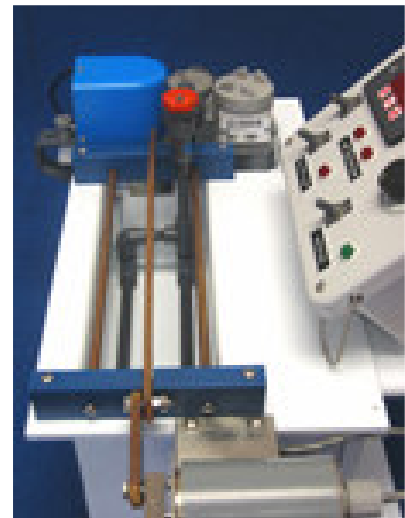


Figure 2. High Speed Flow Cell setup for scaled CIS deposition

The research aimed to reproduce high quality, small In rich *n*-CIS films by using the HSFC under the above conditions. This was accomplished. The CIS films had the same shiny, compact, smooth and uniform appearance as the small samples. Compositions and film thickness were measured using XRF at 5 fixed spots on the samples, Fig. 3, for all the samples. The CIS composition was relatively uniform in the horizontal direction. The results show some variation in film composition in the vertical direction, consistent with the vertical orientation of the substrates during electrodeposition. A higher Cu/In ratio was found closer to the electrically-contacted top edge (areas 1, 4) of the foil. The Cu/In ratio decreased from top to bottom leading to stoichiometric ODC compositions at the bottom (areas 5, 3).

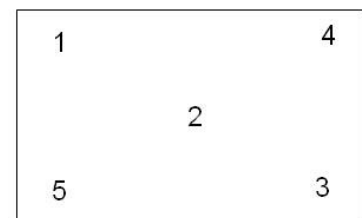


Figure 3. Spots on sample for XRF composition measurements

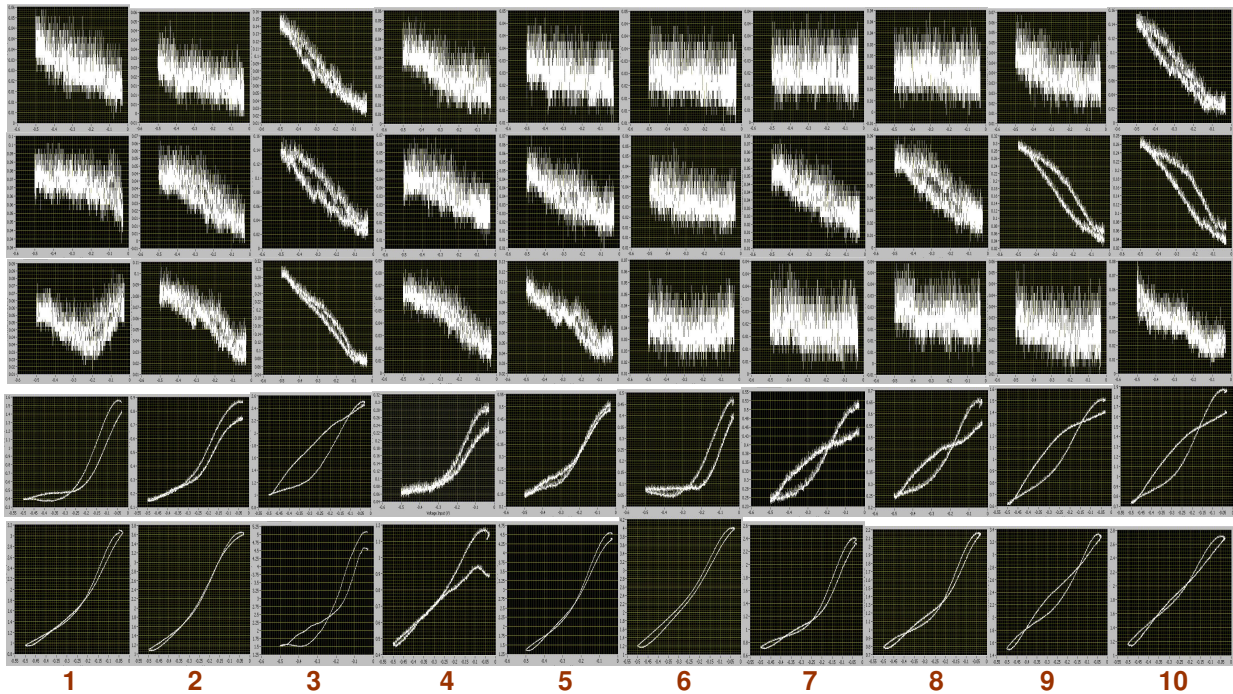


Figure 4. Photocurrents obtained on 50 spots located on the 6"x4" sample HS0301b.

is generation of large Se excess near the top edge. This also affects the Cu/In ratio and the photoactivity of the film.

Photocurrent uniformity was evaluated for large CIS samples that were electrodeposited in HSFC and RTP annealed. As shown in Fig. 4, the photocurrent variation across the large sample is consistent with composition variation along the vertical axis with Cu/In ratio. The photocurrent changes from *p*-type at the top (areas 1, 4), to *n*-type towards the bottom edge (areas 5, 3), which had the highest *n*-type photocurrent. The middle (area 2) part tends to show mixed *n*- and *p*-type photocurrent.

These results indicate that the originally proposed vertical electrode configuration may not be appropriate for R2R production on large area substrates. An alternate geometry and equipment design have been developed to provide uniform film composition for the R2R pilot scale electrodeposition. The design details, equipment specification are company's proprietary technology. To produce uniform deposition and opto-electronic quality, specific design considerations are given to the cathode and anode contacts, deposition tank configuration, solution circulation, agitation, heating, etc.

2. Design considerations for continuous thermal processing of large-area CIS samples

Substantial research carried out in recent months has been channeled into developing the technical design for thermal processing apparatus for process step (c) in Fig. 1. A variety of processing conditions were investigated in order to derive optimum conditions and design features for an annealing furnace that can appropriately recrystallize the CIS films into large grains, and also maintain an optimum composition and conductivity type after the step (c). The large area electrodeposited CIS films were annealed at high temperatures in a standard muffle furnace, Fig. 5. Various annealing temperatures and durations were explored to identify the best annealing conditions. Annealing sequences

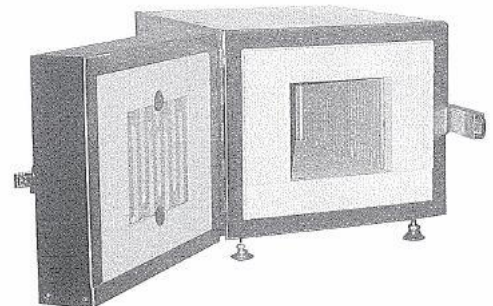


Figure 5. Thermal processing furnace

were tested in both open and closed systems. Different measures were devised to contain the gases, minimize decomposition and promote recrystallization of the CIS film. Experimental conditions were correlated to the compositions and visual appearance of the films before and after annealing. The high temperature annealing results indicate that a number of gas phase reactions for Se vaporization, condensation and CIS decomposition take place in a continuous cycle. Adequate Se vapor pressure is necessary to regulate the reaction equilibrium during recrystallization in order to retain the stoichiometry of CIS and avoid excess Se.

Annealing the large-area electrodeposited CIS samples at low temperature and shorter time avoids CIS film decomposition. Experiments were conducted to identify the optimum conditions that prevent CIS decomposition while removing excess Se in the samples. The data led to new annealing conditions to produce stoichiometric CIS compositions for the large area samples using the muffle furnace. Based on these results we have designed an annealing furnace to maintain the Se vapor under moderately high temperature in order to re-crystallize the large electrodeposited CIS samples. In conjunction with furnace developers we have developed new furnace designs and specifications that can meet these requirements. The system design includes pressure, temperature and gas flow controls. Technical designs have been developed for annealing large samples in batch mode as well as for continuous R2R thermal processing. The intermediary batch furnace will be extensively tested to further refine the specifications and customize the RTP design.

3. Design scaled apparatus for continuous surface treatment and buffer layer deposition

The results of Task 2 provide parameters for designing the R2R components for surface treatment, Fig. 1(d). The junction partner/buffer deposition includes two sequential processing steps (d1) and (d3) along with the (d2, d4) rinse and (d5) dry steps. The R2R system uses deposition tanks similar to that for substrate and absorber deposition steps (a) and (b). The system for surface treatment step (d1) has dimensions similar to the activation step (a3). It will create an n/p junction. It will be monitored by using in-situ PEC methods. The next step (d3) uses an electroplating system similar to that for step (c) but of shorter in length to accommodate depositing the thin buffer layer. The dimensions for systems (d1) and (d3) will be synchronized with the preceding steps (a) – (c). The PV foil can be rolled back or cut up into small cells for further processing steps that lead to PV modules.

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	100%. Technical design for R2R line components.

Project Status

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