668 Flinn Ave Unit 23, Moorpark, CA 93021
Tel/Fax: 1 805 530 1193
url: www.interphases.com

# FINAL REPORT

| | | |
|---|---|---|
| **Project Title:** **Cost-effective Pilot Line for Flexible PV Modules** | | |
| **Contract Number:** RD3-53 | **Milestone Number:** 7 | **Report Date:** 7/22/2012 |
| **Contract Period:** October 22, 2008 to July 22, 2012 | | |
| **Principal Investigator/Contract Contact:** Shalini Menezes, PhD | | **Telephone:** 805-530-1193 |
| **Congressional District:** 24 | | |



**PROJECT FUNDING WAS PROVIDED BY CUSTOMERS OF XCEL ENERGY THROUGH A GRANT FROM THE RENEWABLE DEVELOPMENT FUND**

# FINAL REPORT

## 1. Executive Summary

*InterPhases* originated new photovoltaic (PV) technology, based on copper indium selenide (CIS) thin-film absorber to realize commercially viable large-scale solar electricity generation. CIS PV offers potential for the highest thin-film PV efficiency, high reliability and excellent performance in Minnesota's cold and cloudy weather conditions. A previous RD2 project developed a novel lightweight, flexible CIS solar cell technology, specifically devised to provide subsidy-free solar electricity for Minnesota ratepayers. The RD3 project was launched to transition the RD2 results into cost-effective, environmentally benign, manufacturing-oriented production technology that could lead to affordable CIS based solar electricity.

The RD3 project focused on the deposition and scale-up the crucial component of the solar cell innovation – the CIS absorber. A new production-relevant roll-to-roll (R2R) process and tool were developed for inexpensive manufacture of flexible solar cells. Based on a novel design, a compact R2R system was constructed, installed and operated in-house for continuous deposition of CIS films. The R2R system works under ambient atmosphere, low temperature and environmentally benign conditions. Process parameters were identified to achieve large-area homogeneity and uniformity for CIS films on a continuously moving metal foil. The project thus met the objectives by satisfactorily establishing the scalability and R2R manufacturability of electrodeposited CIS solar absorbers.

The R&D effort pursued parallel development paths of (i) process scale-up, and (ii) device fabrication, in a manufacturing scenario. The dual path strategy led to multiple commercially viable outcomes: (a) a cutting edge R2R manufacturing system, (b) scalable atmospheric deposition process, and (c) new CIS based PV device structures, compatible with this manufacturing system. This strategy ensures device and process scalability and shortens the transition into mass production.

*InterPhases'* R2R technology offers many benefits over incumbent vacuum and non-vacuum R2R methods. It reduces the cost, complexity, process steps, footprint and lead time of state-of-the-art in order to increase productivity and ascertain near term commercialization of CIS PV. The next phase plans to integrate the R2R systems for CIS deposition with the systems being developed for the other components into a turnkey R2R line. This line will enable all-solution-based atmospheric fabrication of solar cells. It will be compact, easy to implement on site and replicable for future large scale manufacturing.

Designed for cost reduction and industrial scalability, the technical advances achieved under this RD3 project can transition successively into MW scale pilot line and GW level commercial PV production. Licensing the R2R technology to the PV industry and equipment manufacturers can lead to a robust local manufacturing base for Minnesota-made solar panels. Technology commercialization will provide affordable solar electricity for the Minnesota ratepayers without subsidies.

The RDF investment has enabled transformational PV technology that can prevail through the current collapse and consolidation of the PV industry. The CIS PV technology offers realistic potential to reduce manufacturing cost to below 40¢/W and PV-generated electricity cost to 5¢/kWh. Affordable solar devices can increase PV capacity in Minnesota, eliminate the need for subsidies, and increase PV market penetration in the Xcel service district. It will deliver the promise of PV — abundant electricity and a clean environment, along with many socio-economic benefits to MN ratepayers. Xcel Energy can reap large returns on its investment for the Minnesota economy through increased energy supply, job creation and tax revenues, and for its environment through lower $CO_2$ emission and fossil fuel use.

## 2. Project Benefits

### 2.1 Appropriate PV technology for Minnesota

*InterPhases'* launched the CIS thin film PV project to provide affordable, subsidy-free PV electricity for Minnesota ratepayers. CIS thin film PV reveals increased interest due to its unlocked potential for highest thin film PV efficiency, reliability and low manufacturing costs. Besides these attributes, CIS PV offers potential for excellent performance under Minnesota's climate conditions: cooler temperature, dappled shading, cloudy weather and diffused light.

Minnesota is well-positioned for solar development. It ranks 15$^{th}$ in USA for solar production despite its location. In fact Minnesota receives higher insolation than both leading countries in solar capacity: Spain and Germany. The RD3 project outcomes: (a) fully operational R2R tool for CIS electrodeposition, and (b) extremely low cost flexible thin film PV panel design, are directed to meeting the goals for the utilities set by Renewable Electricity Standards for 2020 and the Solar advocates in Minnesota for 2030. Commercialization of project outcomes can contribute to the renewable/solar energy mix mandates for retail Xcel Energy electricity sales.

### 2.2 Technology Benefits

The RD3 project designed the CIS PV and the R2R manufacturing technologies to simplify manufacturing, lower costs and environmental impacts, and allow rapid scale-up of production volume as compared to conventional PV manufacturing processes. The end-products: (1) energy efficient R2R manufacturing system, and (2) low cost solar panels production technology, offer numerous benefits over the state-of-the-art. They can simplify high volume PV production for the Minnesota-based manufacturer, via:

- Cheaper, non-vacuum process for easy scale-up
- Single R2R line with small footprint to construct entire PV device
- 10 times lower capex, low energy usage relative to vacuum methods
- At least 3 times lower capital & manufacturing cost than competing R2R plating methods
- Conformal deposition on irregular surfaces for PV integration into non-planar products
- Higher flexibility in device structure, equipment and process choice
- Environmentally safer process that avoids hazardous gases, waste reactants, etc.
- Water-based, 90% cheaper atmospheric process with less stringent regulation of parameters
- Remarkable composition uniformity and excellent process control
- 99% material utilization, inexpensive precursors (metal salts).

The benefits of low cost CIS panels to end users, i.e. the ratepayers include:

- Affordable, long-lasting solar panels for green PV electricity
- Aesthetic roof tiles that blend with existing roof structures
- Panels of various sizes for use on residential, commercial and industrial structures
- Flexible modules for mobile applications, e.g. battery chargers for small electronics as well as automobiles, solar powered camping equipment, RV's, mobile clinics, boats, traffic signals, etc.

*InterPhases'* R2R technology averts the cost and practicability problems of incumbent methods. By reducing their cost, complexity, process steps, footprint and lead time, it offers potential for higher productivity and shorter term commercialization of CIS PV. It can lead to a robust local manufacturing base to generate Minnesota-made solar panels, for use in various consumer products.

### 2.3 Market Size

High volume manufacturing for thin film solar cells is the most direct and immediate application of the innovation. The end-products target 2 types of markets for: (1) CIS PV modules, and (2) R2R PV equipment.

The PV market increased from $71.2 billion in 2010 to a record $91.6 billion in 2011 and is projected to expand to $130.5 billion by 2021. While total market revenues were up 29%, installations climbed more than 69% to 26GW worldwide last year. This rapid growth, coupled with the loss of incentives led to production overcapacities and product inventories, causing the current PV industry and technology consolidation. Even so, the US market reached 1.7GW in the first 6 months of 2012, an over 120% increase over last year, projecting the US as the 3rd largest PV market in 2012. Commercialization of *InterPhases'* CIS PV modules will enable rapid penetration into the thin film PV panel market. It will partially help to meet the anticipated massive increase in US PV demand and capture 1-2% market share of the 7.5 GW US market.

The PV manufacturing equipment sector has also been a high-growth market. It has gone to $3.2 billion in 2010 and is projected to reach $4.3 billion in 2015 and $15.7 billion in 2020. Technology licensing will enable the R2R system to capture ~1% of the total equipment market.

### 2.4 Cost Effective Manufacture to reduce Solar Rebates

The extremely low manufacturing cost is the primary driver for CIS PV technology. The R2R deposition method is inherently low-cost, non-vacuum, repeatable and scalable for GW production. The project's economic benefits arise from reducing: (a) deposition cost of cell components, (b) capital and precursor costs, (c) operation temperature and energy usage, (e) processing steps and time, (f) equipment footprint and material needs. This approach drives the fundamental economics of future CIS-based PV systems to achieve grid parity for PV electricity. The manufacturing cost for 50MW/year plant is estimated at $\$58/m^2$. Thus 10% efficient CIS PV modules could be manufactured for 58¢/W. Higher efficiency of 15% would lower the cost to 39¢/W.

The Minnesota Solar Rebate Program provides ~ $2,000 for each kW system. With current cost for installed solar panels was between $7–$9/W, a 1kW system can cost around $8,000 ≡ $6,000 (consumer) +$2,000 (rebate). Typical Minnesota households need a 2–4kW roof-mounted system to provide 50–80% of electricity needs. Thus, rebates can range from $4,000–$8,000 per home.

The low cost of *InterPhases* CIS PV allows reducing the installed PV cost to $1.76/W. This value can provide a 1kW system for under $2,000 without the need for rebates. Under MN insolation (1,100 peak hours/year), the cost of electricity ≈ 5¢/kWh for 30 year PV system lifetime, well below the national average for electricity price. This price will enable successful deployment of PV power in the state.

### 2.5 Environmental and Economic Benefits of Outcomes

Atmospheric R2R electrodeposition conserves natural resources through environmentally safe manufacturing. The flexible thin film CIS solar cells can be directly integrated into various products or assembled into modules of various sizes and electrical outputs, thus reducing packaging costs and lowering field implementation costs. Project outcomes will lead to affordable, subsidy-free CIS PV modules. Their commercialization will:

- Accelerate the pursuit of PV electricity in Minnesota homes, schools, industry
- Enable robust and competitive PV manufacturing base in Minnesota
- Increase availability of peak time PV electricity for the ratepayers even in cold, cloudy weather
- Deliver the benefits of clean solar energy: energy security/ independence, reduced carbon emissions
- Save taxpayer money in the long-term with short-term solar investment.

### 2.6 Job Creation and Tax Revenues

Present growth rates indicate that hundreds of thousands of jobs will be created in the PV sector alone during the next decade, with about 20% of these in manufacturing (1MW PV production creates about 20 manufacturing and 13 installation jobs). A 50MW production plant can lead to 1,650 new jobs. Locating several 25MW plants in the Xcel Energy service territories will boost the local economy with high-quality solar manufacturing jobs. It will indirectly impact suppliers, vendors and PV installers. Market penetration can lead to an equal number of indirect job opportunities in the following fields:

- Device and system education, R&D
- Manufacturing, quality control and reliability
- Solar systems distribution & installation
- PV system design, modeling, integration, analysis, implementation, fault diagnosis, monitoring
- Policy, financing, marketing, management, consulting, training and education
- Solar architecture, energy efficient building design and sustainable energy.

Rate payers can derive fiscal benefits from tax revenues, from PV module production and sales. An average income of $50,000/year for the created jobs will generate over $100 million in income taxes. Sale of 100MW at $2.40 can generate $100 million in sales tax. Other tax revenues ensue from local, property and business taxes. Minnesota can be a national leader in creating PV manufacturing, installation and research jobs, while reducing dependence on imported energy and saving taxpayer money.

## 3. Project Lessons Learned

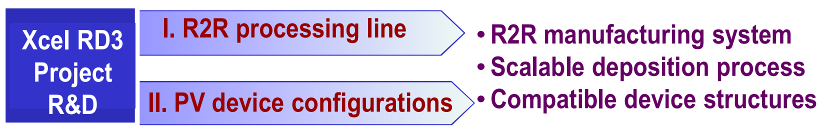



**Figure 1. Parallel pathways lead to practical outcomes**

Although CIS/CIGS thin film technologies have the best potential for high efficiency and lower costs, the complexity of the material, cell, module and manufacturing equipment and process level is rather high and a number of barriers must be overcome to realize its full potential. Thus the RD3 project pursued a new strategy of using parallel development paths for (i) the R2R manufacturing system, and (ii) creating new PV device structures, Fig. 1. This strategy allows optimizing device fabrication in a manufacturing scenario. It led to a new solar cell structure that is easier to scale up and is compatible with R2R production, generating multiple commercially viable outcomes. The dual path strategy ensures device and process scalability, avoids scale-up problems encountered by other thin film companies, and shortens the transition into mass production.

The process of R2R line construction imparted numerous technical lessons, summarized in various monthly reports. Importantly, it enabled the use of a simpler system and single-step process for CIS deposition. Our approach reduces the complexity and the tool footprint by at least 3 times as compared to the multi-step, multi-metal sequential deposition approach. The inadequacy of commercial R2R systems for our specific process led to the design and construction of an entirely new R2R deposition system. The testing phase provided many lessons in controlling the speed and synchronicity of the R2R processes.

Many innovations in thermal processing systems were achieved. They led to the design of 3 alternate versions of annealing systems, suitable for alternate CIS PV device configurations.

Investigations of alternate CIS device configurations provided useful insights into this unusual material. It highlighted the special advantages of each device type in terms of costs, material availability and performance potential. An opportune in-house development includes an NSF-funded R2R atmospheric spray pyrolysis deposition system. This system can be combined with the RD3 generated R2R system for CIS film, to provide a single low cost, all-solution-based R2R tool to fabricate complete solar cells.

## 4. Usefulness of Project Findings

The R2R manufacturing line can generate an endless PV roll that can be cut and assembled into lightweight, flexible solar panels for electricity generation. The specific benefits of electrodeposited CIS PV cells allow their deposition on curved, non-planar and irregular surfaces of a wide range of consumer and building products. They can be incorporated into the products for dual use applications, serving as parts of consumer products (laptop cases, backpacks) to building parts (façades, tiles) to generate power.

**Figure 2. Aesthetic PV tiles for rooftop solar power generation**

The technical advances from this RDF 3 project will transition initially into a pre-commercial 5MW turnkey line, and later will be scaled up for commercial CIS PV production at 50MW and then GW capacity. The R2R technology will also be licensed to the PV industry to generate additional jobs. At full production capacity this technology can create over 30,000 jobs in the manufacturing and installation sectors. It can lead to a robust Minnesota-based solar panel manufacturing industry.

Minnesota has vast solar energy potential, more so than Houston, TX and nearly as much as Miami, FL. Unlike Si PV, CIS PV provides excellent performance in cooler climates, cloudy weather and adverse environments. Its deployment can help Minnesota power needs in 3 market sectors:

1. The **grid-tied PV** market sector provides a clear advantage for market entry of *InterPhases'* CIS PV, as it uses existing power grids, thus reducing balance-of-system cost, and generates PV electricity at point of use, thus eliminating transmission expenses. CIS PV shingles can be used on rooftops of residences, schools, public & commercial buildings, and industrial buildings, Fig. 2.
2. CIS PV performance in adverse conditions is especially useful in **off-grid power** applications, for use in remote areas of Minnesota that are not connected to the grid. These include remote weather stations, state park residences, public area lighting at docks & parking lots, fire towers, traffic signals and battery charging stations for emergency and recreational vehicles, snow removal equipment, etc. Agricultural applications include powering water pumps, land aeration, fence chargers, etc.
3. Low cost, flexible CIS cells may be integrated into solar powered **portable consumer products** such as lighting, battery chargers, mobile clinics, automobiles, sail boats, recreational vehicles, etc.

Solar powered electricity will contribute to Minnesota's legendary standing as one of 'the most livable states in the nation'.

## 5. Technical Progress

The RD3 project constructed and installed a new in-house designed, R2R pilot line for CIS deposition. The effort focused on transitioning the critical steps for substrate preparation and absorber deposition to continuous R2R processing line. This pilot R2R system provides specifications and precise process parameters for advancing and refining the designs of the future large scale R2R production systems. This section summarizes the development and testing results for the R2R CIS processing line, and the subsequent steps for thermal annealing and device fabrication.

### 5.1 R2R line Construction, Installation and Testing

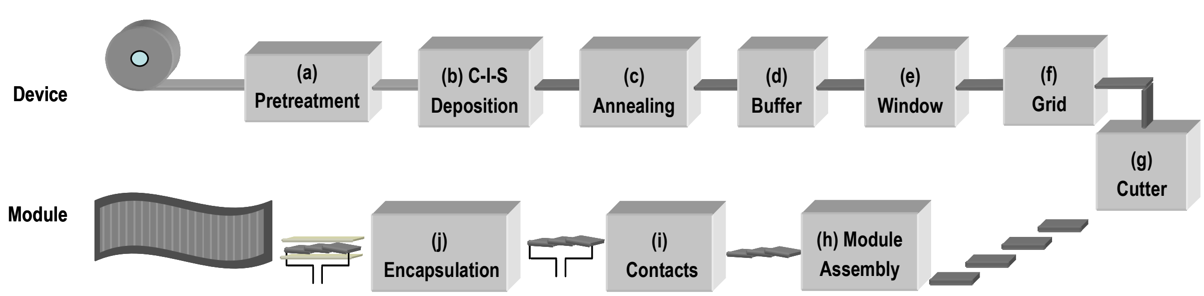



**Figure 3. R2R processing schematic shows (top) PV roll fabrication, and (bottom) module construction**

The pilot line layout designed for production of CIS solar modules comprises two sequential lines:

**Device R2R line** uses specific custom steps for *InterPhases* PV technology. The technical effort focused on providing the critical elements of this line. The project R&D developed detailed procedures, customized tools, equipment and process parameters for steps (a)–(e), Fig. 3, and installed these at our facilities:

1. R2R line for electrodeposition of the CIS absorber steps (a, b)
2. Thermal processing system for the CIS absorber (c)
3. PV device fabrication with the electrodeposited CIS films (d, e).

**Module Fabrication** steps of (f)–(j) use relatively standard industrial procedures that can be adapted for CIS solar modules. Thus, in the early stage we used batch processing tools in a sequence that was similar to future R2R fabrication.

### 5.1.1 R2R Electrodeposition System

Much of the R&D performed throughout the project has been integrated into the construction and optimization of the most innovative segment of the pilot line. Commercial R2R systems could not meet the specifications and budget for our process. So we custom designed and constructed a completely new R2R plating system in-house, specifically tailored for our CIS deposition process. It can also be used to deposit other device layers. To accommodate the new system, our laboratory facility was re-structured by installing utility lines for: water supply/drainage; electric power and multiple electrical outlets; various exhaust hoods; and lighting apparatus above the R2R plating tank.

The modular R2R system integrates steps (a, b), Fig. 3, into a single compact processing tool placed between unwinding and rewinding stations. It combines

1. *Mechanical system*, which includes an unwind station, a rewind station, multiple rollers and roller guides distributed along the line to allow foil transport.
2. *Solution pumping/heating* system which includes: An overflow tank, heater and pump to supply plating solution to the plating tank; water spray rinsing and air drying systems for the bare and plated foil.
3. *Electrochemical* system to regulate the deposition process.

The modular system design enabled testing and modifying key specifications for the individual system components to achieve the desired speed control, and better synchronicity and compatibility with the overall R2R processing line. The modules can be adapted for different substrate configurations and expanded to incorporate additional modular units for process steps (c–e), Fig. 3.

### 5.1.2 Process Parameters for R2R Synthesis of CIS films

The system operation of the installed modular R2R deposition system, Fig. 4, was tested by depositing CIS films. As the substrate roll unwinds, it goes through a series of steps for acid activation, spray-rinsing and air drying, before CIS deposition in the plating tank. As it exits the tank, the CIS coated substrate is rinsed and dried before rewinding into a finished roll.

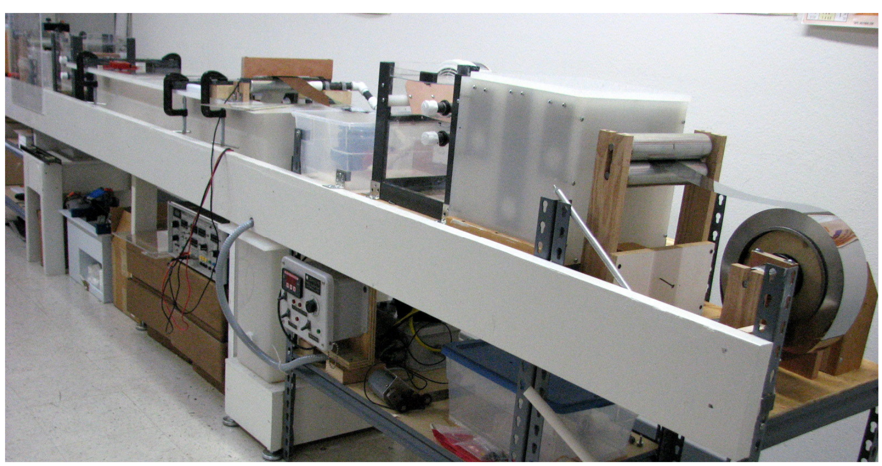


**Figure 4. Assembled R2R plating system**

We have successfully transitioned the batch process procedures for CIS to R2R processing on a continuously moving substrate. Several continuous R2R deposition runs were carried out. Process parameters were adjusted to produce CIS films with uniform composition and morphology. XRF analysis of the 5 ft. long CIS plated foil indicates high composition uniformity along the length and width of long foil. The results demonstrate smooth, shiny films with excellent composition and thickness uniformity on large substrates as was previously obtained on 5 $cm^2$ substrates, Fig. 5. Preliminary device data assures future high performance of CIS cells, based on previous efficiency milestones and the following achieved CIS properties metrics: (a) composition: uniform composition obtained across the width and length of a continuously moving foil, (b) type: *p*-, *i*- or *n*-type conductivity is obtained by controlling process parameters, and (c) grain size: 10-50 nm for as-deposited films and ~1µm after anneal, Fig. 6. The project thus met the RD3 objectives by satisfactorily establishing the scalability and R2R manufacturability of device quality electrodeposited CIS solar absorbers.

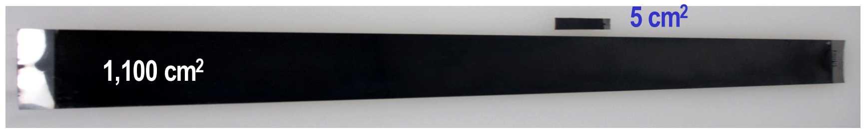
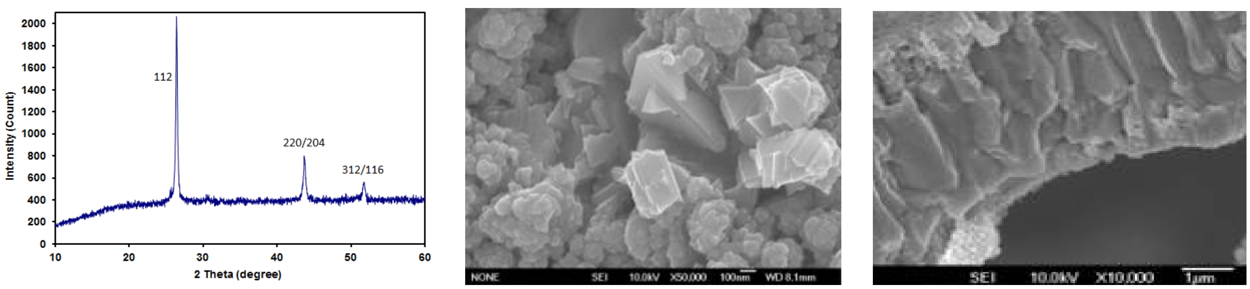



**Figure 5. Successful scaled replication of CIS absorber deposition on 5 $cm^2$ and 1,100 $cm^2$ foils**

## 5.2 Installation & testing of Thermal Processing System




*a* *b* *c*

**Figure 6. (a) XRD and (b, c) SEM views of re-crystallized CIS films**

In general, all CIS or CIGS PV technologies require a post deposition annealing step in selenium (Se, $H_2Se$), sulfur (S, $H_2S$, $H_6N_2O_4S$) or inert (Ar, $N_2$, air) gaseous atmosphere. While this essential and commonly used process step is technically achievable, it is desirable to use the least hazardous procedure and materials. RD3 project has extensively tested various alternate thermal processing methods, using various radiation sources and gas atmospheres to determine the most economical and safe methods to convert the electrodeposited CIS films into high quality absorbers. The critical parameters vary for each type of radiation which impacts the absorber performance.

Based on our CIS recrystallization results, *InterPhases* engineers designed at least 3 different versions of thermal processing systems. Version 1, designed in collaboration with equipment manufacturers provided an advanced R2R recrystallization system, but the large expense of constructing this customized furnace and sequestering the toxic gases was beyond the scope of the current project.

Version 2 was constructed in-house for batch processing sections of the R2R electrodeposited CIS/foil. Experiments carried out under specific processing conditions led to highly crystallized CIS films. XRD analyses show very sharp and high intensity CIS peaks, Fig. 6a. The SEMs show different orientations of the annealed film that appears to be almost completely crystallized, Figs. 6b, 6c. Cross-sectional SEM, Fig. 6c shows large columnar grained CIS crystals across the entire height (thickness) of the CIS layer. In these films, the crystals grow into each other, forming a very tight crystalline CIS layer. These results show almost perfect crystal structure and grain size > 1micron that characterizes very high efficiency solar cells. The extraordinary crystallinity achieved for inexpensive electrodeposited CIS films affirms the validity of our low-cost approach to produce high efficiency solar cells. These results provide the bases for constructing a more manageable version of a R2R furnace system. We have designed this version 3 with features that can be synchronized with the CIS electrodeposition rate. It will be constructed and incorporated into the R2R line during the next project Phase.

### 5.3 Buffer/Window Equipment Installation & Testing

The R2R line for buffer deposition uses a smaller processing tank than the plating tank, followed by rinse and dry modules, as in Fig. 4. However, since the CIS film roll required cutting for the preceding (c) thermal processing step, the subsequent steps of (d) buffer and (e) window deposition steps in Fig. 3 were batch processed.

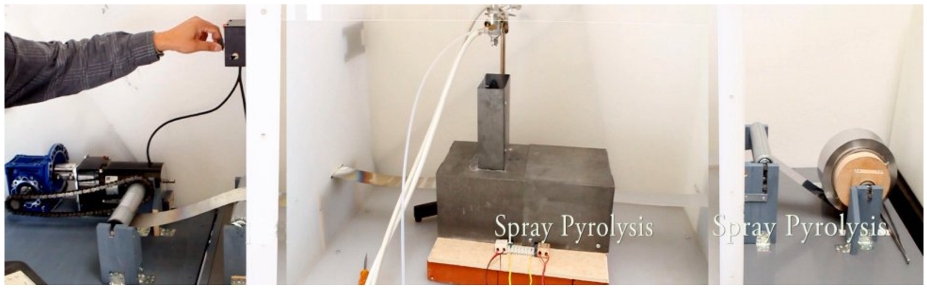



**Figure 7. R2R-ASP system**

Transparent conducting oxide (TCO) window deposition, step (e) currently uses a low temperature sputtering with a PVD 75 sputtering system. System parameters have been optimized to produce *i*-ZnO, *n*-ZnO, ITO and other TCO layers. At the same time we have developed an alternate economical non-vacuum method with NSF support. A R2R atomized spray pyrolysis (ASP) deposition system has been custom designed, constructed and implemented, Fig. 7. This simple solution-based, atmospheric deposition method offers excellent process control, generating uniform TCO films at seven times lower cost than the sputtering method. Its modular configuration is suitable for continuous in-line production in conjunction with the R2R systems developed for the CIS absorber and buffer layers. We plan to integrate the 2 systems into a turnkey line.

### 5.4 Module Fabrication

Solar cell combinations with series and parallel connections can be adapted for different output voltage, current or power, shape or size.

Individual cells cut from large PV foil were assembled into prototype modules. Silver metal grid contact was applied to the solar cells. These were assembled into modules via monolithic series interconnection and encapsulated, Fig. 8a. Fig. 8b shows the side view schematic of the cell interconnections and encapsulation.

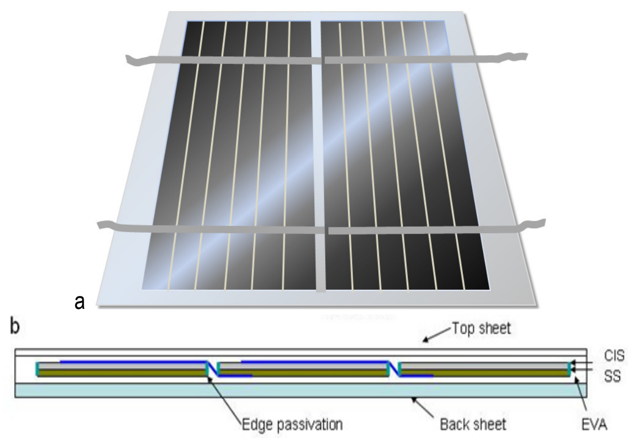



**Figure 8. (a) Finished module, (b) Monolithic series interconnection and encapsulation**

In manufacturing, the module cutting and assembly processes are automated in a commercially available turnkey line. This system uses robotic machines to cut a long roll of finished PV device, assemble and laminate the cut cells into modules.

### 5.5 Performance and Reliability

In parallel to developing the R2R line, the project investigated new ways to enhance device performance. The R2R system and process can electrodeposit high quality CIS absorbers on a moving foil. Furthermore, it can produce CIS films with either *p*-, *i*- or *n*-type conductivity that are amenable to new device configurations. Thus, in parallel to the pilot line development we have investigated different avenues to take advantage of these opportune results to fabricate CIS solar cells with alternate configurations, using compatible junction partners and window materials, each holding special advantages.

The performance potential of CIS device is the same as that of the incumbent CIGS PV without the associated expense. Unfortunately, the high cost factor led to the current demise of several large CIGS corporations. Knowing that we can achieve the same high efficiency with further optimization, the RD3 project focused on reducing the manufacturing cost (section 2.4). Our new R2R line provides the drastic cost reduction factor required to ensure the commercial future of CIS or CIGS PV. It eliminates expensive materials, equipment and processes, and the environmental impacts. Ongoing studies with new materials for other components of the CIS cell aim to maximize performance and minimize cost.

Unlike most other PV devices, CIGS device performance does not degrade in harsh atmosphere. We have confirmed this special reliability feature for our CIS cells and further verified the results through external independent assessment at cell level. An interesting result indicates that the device performance improves after air anneal. The PV output drops at high temperatures; but the devices recover, exhibiting ~37% increase in the short circuit current ($I_{SC}$) and 6% increase in open circuit voltage ($V_{OC}$) relative to the pre anneal performance. As observed for CIGS cells, prolonged 60°C/90%RH and 85°C/85%RH tests reveal that the damp heat tends to degrade the performance of un-encapsulated cells by lowering the $V_{OC}$ but not the $I_{SC}$. Light soaking at AM1.5 illumination has no significant effect on performance except for some dependence on the type of TCO used for the device. Encapsulation of cells offers considerable protection against the degradation from damp heat.

## 6. Conclusions

The RD3 project has met the objectives by satisfactorily establishing the scalability and R2R manufacturability of electrodeposited CIS solar absorbers. The outcomes delineate a viable pathway to realize affordable, efficient solar cells based on the CIS absorber. The R2R deposition technology averts the cost and practicability problems of state-of-the-art vacuum and non-vacuum R2R methods.

The project aptly focused on the deposition and scale-up of the most important part of the solar cell – the CIS absorber, because its electronic and structural qualities control the device performance and cost. Besides providing the highest thin film PV efficiency and reliability, CIS offers potential for excellent performance under Minnesota's climate conditions. Project's main outcomes: (a) energy-efficient R2R manufacturing line, and (b) energy-generating CIS solar panels, provide numerous cost and environmental benefits. They can reduce solar cell manufacturing cost to provide affordable PV electricity at 5¢/kWh for Minnesota ratepayers. Cost-effective solar electricity will eliminate the need for subsidies, increase solar market penetration in the Xcel service district, and contribute to the state's socio-economic welfare and a clean environment.

The project's technical benefits have far reaching implications to public acceptance of thin film PV technology. By reducing cost, complexity, process steps, footprint and lead time of current processes, the R2R electrodeposition process can increase productivity for near-term CIS PV commercialization. It is important to take the project's opportune results to the next stage on the path to the market. The next stage will exploit RD3 outcomes to:

1. Improve the operation and application range of the R2R system, and
2. Expand the line into a turnkey system for R2R solar cell production.

It will create a commercially viable PV technology that accrues benefits to Minnesota and its ratepayers. We look forward to continue the partnership with Xcel Energy, to commercialize the technology and generate ample returns to Minnesota taxpayers.