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Cost and Reliability Improvement for CIGS-Based PV on Flexible Substrate

Annual Technical Report
24 May 2006 – 25 September 2007

S. Wiedeman
Global Solar Energy, LLC
Tucson, Arizona

Subcontract Report
NREL/SR-520-43840
August 2008

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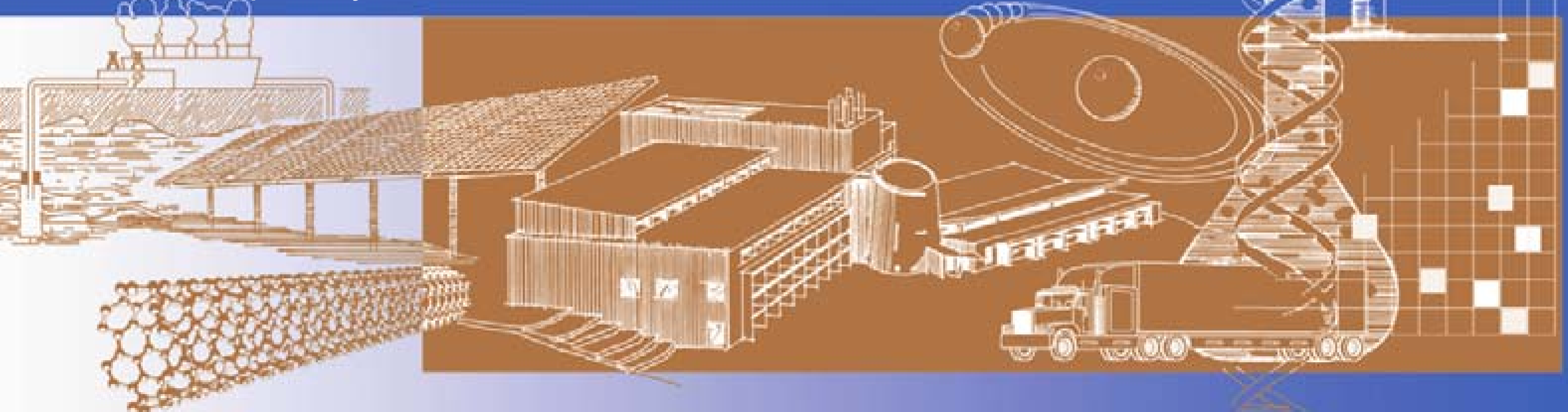

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Executive Summary

Global Solar Energy (GSE) has completed many of the tasks planned under the first phase of this subcontract while simultaneously executing a dramatic increase in production capacity in the planning and construction of two entirely new production facilities for thin film CIGS PV (in Tucson, AZ and Berlin, Germany).

GSE has made tangible progress, as detailed in the following pages, in quantifying and enhancing module reliability, reducing the cost and improving the performance of the CIGS deposition process, and in reducing the cost of the materials and processes used for the front and back contacts. Each of these areas is a major thrust of this Thin Film Photovoltaic Partnership Program subcontract, and an important opportunity to improve thin film PV product.

The largest share of the effort over the past months, however, has gone into the activities necessary to bring this countries' first large scale facilities for the production of CIGS PV into operation. A major endeavor, this effort entailed the selection, negotiation and purchase of a 120,000 sq. ft. facility on 22 acres in Tucson, and planning for another complete factory in a leased facility in Berlin. Both facilities entailed extensive architectural and design work to attain efficient, balanced production in all processes, in a fully facilitated, climate-controlled, state-of-the-art thin film manufacturing plant.

Simultaneously, lines of entirely new production tools for all processes were taken from concept, through design, vendor selection and into fabrication and installation for both plants. Previous experience gained by GSE in bringing the world's 1st generation of roll-to-roll CIGS processing equipment to 4 MWp/year production was fully leveraged in the design of the 2nd generation tools for the new plants in Tucson and Berlin. The 2nd generation thin film production tools are designed to run faster, longer, better and with greater flexibility, reproducibility, higher materials utilization, and less labor and maintenance cost.

Much of the design effort to attain these goals for the production equipment also represents progress toward the major thrusts of this TFPPP subcontract. For examples, we fully expect that the concepts incorporated into the 2nd generation CIGS deposition equipment will enable GSE to easily meet, and exceed, the "hi-bar" goal for CIGS processing rate in the TFPPP milestones. We fully expect that the flexibility and improved in-situ measurement capability built into the new machines will allow rapid progress toward TFPPP goals of thin absorber layers, improved uniformity, etc.

The 60 MWp/yr capacity of the 1st phase represents greater than an order of magnitude expansion for GSE. The 2nd phase expansion, already commenced, is to 140 MWp/yr capacity between Tucson and Berlin. Global Solar is committed to the successful large-scale manufacture of thin-film CIGS solar products.

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Task 1: Enhanced Module Reliability (Objectives)

1. Identify, characterize and quantify degradation and failure mechanisms in the PV stack and cell interconnect as well as encapsulation structure and complete module package.
2. Design meaningful stress tests for flexible and rigid thin film CIGS modules.
3. Develop a finite element model predicting mechanical post-lamination stresses at module operating conditions (daily and seasonal temperature cycles).
4. Explore solutions to eliminate failure & degradation mechanisms via process changes, advanced alternate encapsulation, protective coatings, structural elements and complete package.
5. Verify and optimize long-term product reliability.
6. Improve product appearance and cost.

1.1 Product Testing and Reliability

For rigid PV products intended for rooftop and commercial bulk power generation, long term reliability (20 – 30 years) is crucial. For flexible PV product in intermittent use, features such as durability, portability and appearance are valued over long term reliability. In either case, real-time and accelerated testing is important to determining reliability, durability, failure modes and their causes.

GSE uses multiple methods to evaluate suitability, including actual outdoor exposure testing, accelerated testing in dedicated chambers or heightened stresses, and specific, standardized tests.

1.2 Flexible Product

A battery of tests is shown below, which was devised in this example to pre-qualify flexible product for UL testing.

Table 1 - Pre-UL testing – a battery of tests run at GSE representing many of the procedures included in UL testing for 6 and 12 watt flex product.

Bonding Path resistance
Leakage Current
Dielectric Voltage Withstand
Water Spray
Leakage Current
Dielectric Voltage Withstand
Pull Test
Push Test
Wet Insulation Test
Dielectric Voltage Withstand

After continued improvement of procedures and materials used in product assembly, GSE product tested using the sequence above passed all tests.

For flex product a failure mode associated with lengthy cycles of folding and unfolding was observed. An evaluation of alternative wiring schemes (between sub-modules) for the portable foldable module product line was conducted with the objective of increasing the field durability of the modules against repeated deployment. Equipment was set up to accelerate and monitor failure in the fold zone. Microscopic analyses of the conductors in the folding areas after stressing were performed and the source of failure was determined to be metal wire fatigue and separation. An alternative wiring scheme was developed that increased the MTBF by over 5X. The alternative scheme was implemented for all models anticipated to require significant flexing in typical use.

Outdoor testing of flex modules for long term exposure under actual outdoor conditions has also been valuable in relative comparisons of product variations, and in identifying modes of failure. When a new failure mode is identified, specific tests are usually designed to isolate that failure mode under controlled conditions using quantitative means. Experience gained in identifying failure modes in outdoor testing and in accelerated testing has allowed GSE to establish protocols for test article submission for both modules and submodules of flexible and glass based products.

1.3 Glass-based Product

As an example, after early field observations in outdoor testing identified some failures relating to delamination in glass product, standardized “pull tests” were initiated to gauge adhesion strength as a function of the laminating materials and procedures used. The adhesion strength of several laminating materials to glass was tested versus several different cleaning methods. The cleaning method giving the best results was affirmed as the standard method, and used for all glass product.

Another use of the same standardized adhesion “pull test” was to evaluate a method of chemical priming with current laminating materials for adhesion strength. Pull tests indicated consistently higher adhesion without using this priming compound.

Standard tests and patterns were also instituted for electrical performance measures. Curing profiles and multiple types of electrically conductive inks were iteratively tested to improve the resistance of printed cell grid patterns. Results of one test demonstrated an adjusted curing profile that resulted in a printed pattern resistance 55% lower than the “standard” curing profile.

Given the emphasis on glass-based product in the production plans, GSE has ramped up design and test efforts to develop compatible stringing materials and methods for glass product. Reliable stringing methods are required to avoid interconnection failures. Again, failure modes were identified, and experiments to evaluate stress effects were completed, resulting in a preliminary selection of compatible stringing materials for glass product.

Another change required for the expanded GSE production plan is the use of larger cell sizes, called “Gen2” (210mm x 100 mm, and 115 mm x 76 mm). The cell design and interconnect methodology developed for the Tucson 40MWp expansion line was evaluated. Gen2 cell strings were fabricated by a manual technique to define the specifications for an automated stringing tool. Materials were down-selected for string connection based on conductivity, mechanical stress, and capability of application in high speed equipment. The new generation strings (laminated into glass modules) demonstrated satisfactory performance under accelerated testing (Figure 1). Several modules have been placed outdoors for periodic measurement.

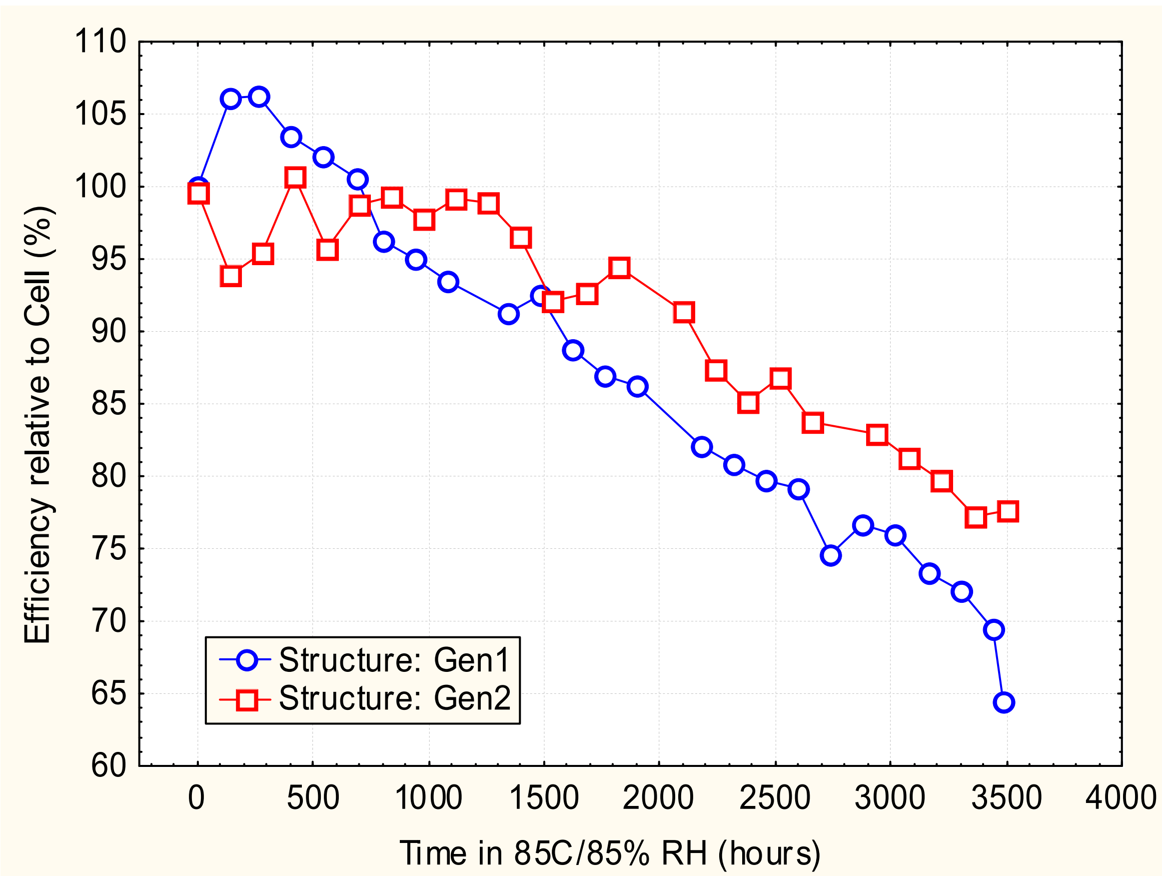


Fig. 1 *A comparison of glass module performance in damp heat between first and second-generation string technologies. The packaging is identical. The modules (15 and 10 in each group, res.) were light-soaked between 4 and 10 hours prior to each measurement.*

Because the "Damp Heat" test at 85°C and 85% relative humidity is one of the most demanding tests for module reliability, it is used frequently to gauge progress in reliability. Iterative testing of new materials and assembly techniques described in this section has improved the expected reliability of glass-based product. GSE has been able to demonstrate results that bode well in this regard (one example shown below in Fig. 2 for glass product).

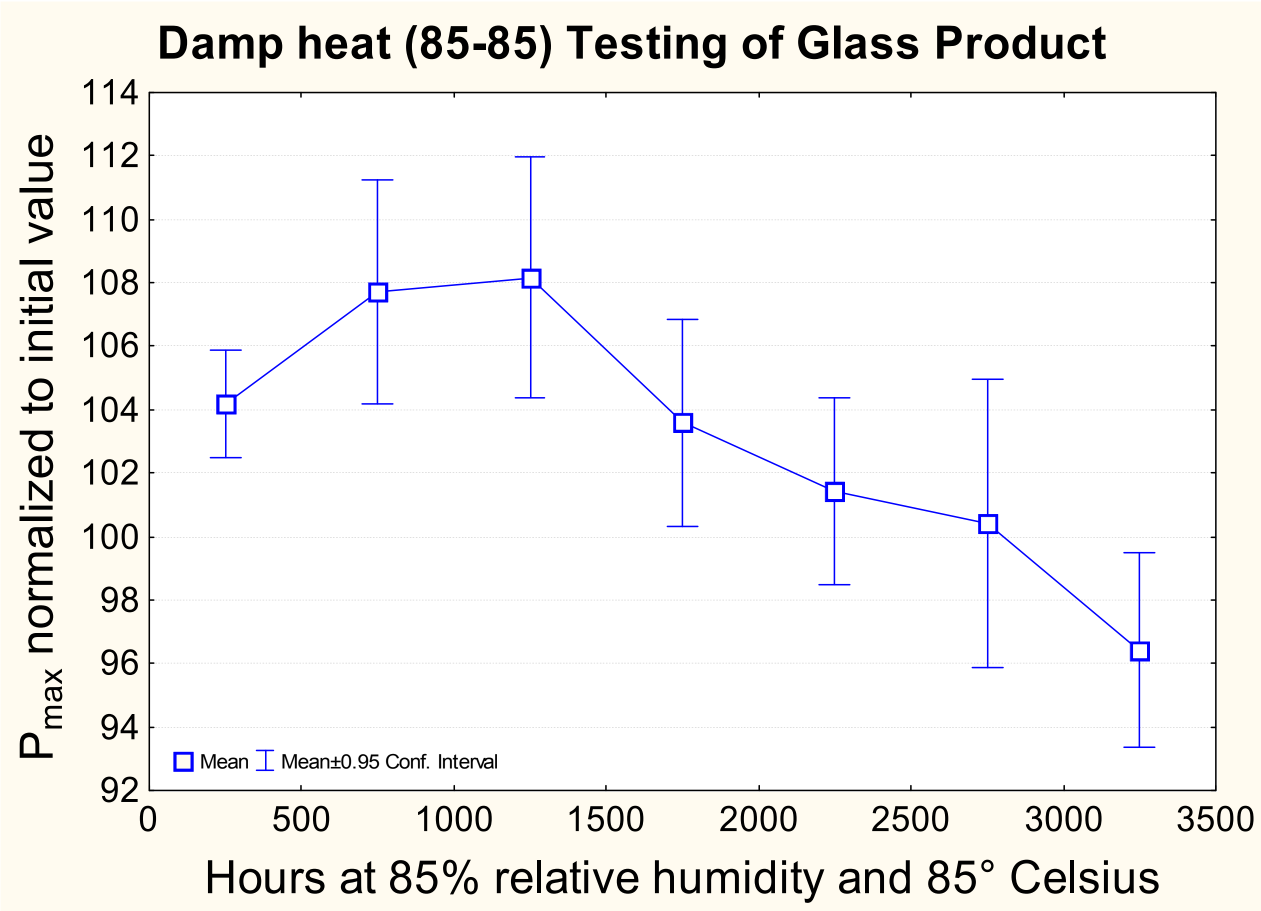


Fig. 2 *An example of accelerated testing in progress at GSE. Various product configuration and materials are tested in damp heat (85°C, 85% relative humidity) for extended time. Normalized power output greater than 100% are often observed due to "light soak" effects typical of CIGS PV.*

Extended testing of different product configurations and laminates continues in the damp heat (85°C, 85% relative humidity) to build accelerated test data. Glass-based product also continues in outdoor test deployment to gather performance data under actual conditions. Ultimately the data gathered using accelerated and real-time testing will allow stronger correlation between the two and accurate assignment of the acceleration factors in the accelerated tests.

Accumulated performance data for early glass-based product, deployed at Springerville, AZ for long-term outdoor testing continues to function with little degradation. This data, monitored daily, is shown in Fig. 3 below.

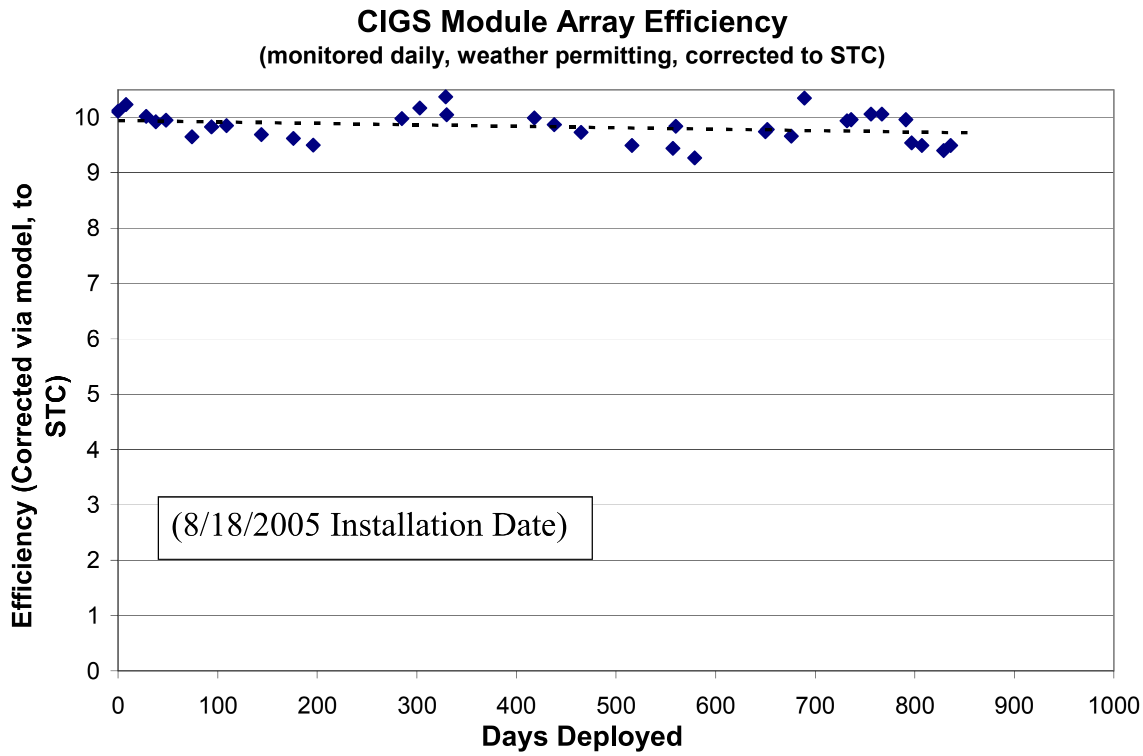


Fig.3 *Performance data taken over an extended time for GSE glass-based product in actual outdoor use. These modules are early versions of glass-based product, and thus did not incorporate many of the improvements developed under this program.*

1.4 Reliability and Performance – Related Tests

The reliability of two screen-printable Ag inks was compared to the standard production ink applied as the collection grid. Various formulations of conductive inks are constantly under consideration for cost reduction and to improve the printing characteristics (line definition, pot life). Reliability was evaluated by accelerated testing (85˚C/85% RH) of glass-laminated and flexible modules. No statistically significant difference between the inks was observed.

Inventory storage of finished large area cells in itself may introduce questions of stability. The electrical parameters of large area cells stored in a humidity-controlled environment up to 1024 hours were evaluated, to understand whether changes in the characteristics of inventoried solar cells can occur. The test was configured to eliminate light-soaking (during testing) from affecting the results. One lot from each of four CIGS deposition systems were evaluated. Over the duration of 1024 hours, three lots increased in efficiency (+3%, +3%, +11%), and one lot decreased (-12%). Further investigation will be performed to understand the differences observed.

Production control and analyses of reliability tests are frequently complicated by light-soaking effects. Conditioning outdoors is subject to the vagaries of weather and season. Various light sources were evaluated for their utility for light-soaking non-encapsulated solar cells and thereby bringing the cells to a reproducible state for testing. Emphasis was placed on light sources with strong UV and/or blue spectrum components. One of the wider spectrum sources was ultimately identified to meet the requirement for indoor light soaking required for accurate test measurements.

Task 2: CIGS Coating Cost Reduction (Objectives)

1. Increase processing rate for CIGS deposition by at least 25% with a high-bar goal of 50% (from 12-in/min to 15-in/min and potentially 18-in/min).
2. Modify effusion sources as necessary to ensure adequate cross-web uniformity at increased absorber formation speeds.
3. Reconfigure In and Ga sources to allow improved homogenization of In-Ga at the higher CIGS deposition rates and reduced time for mixing by diffusion.
4. Re-optimize CIGS process parameters for device efficiency at the high processing rates and altered In-Ga delivery.
5. Evaluate alternate sodium delivery, for efficiency, control and uniformity; and high process rates, implement if successful into the standard process.
6. Evaluate thinner CIGS layers. Reduce flux rates to achieve less than 1.0 μm CIGS thickness and re-optimize CIGS process conditions to maximize efficiency for thin absorber layers.

2.1 Production Scale-up (New Manufacturing Facilities)

The overall intent of this contract is to enable significant gains in cost and throughput for thin film PV. The specific process improvements to enable significant cost and throughput gains are listed in the objectives above (for the CIGS layer, and in the following sections for the front and back contact layers). However, the overall goal of this contract, and many of the specific process improvements are related to, or dependant on, the design and installation of improved plant and equipment. GSE has embarked, in earnest, on just such a massive expansion. For completeness, and because new plant and equipment is a prerequisite to implementation of many of the objectives in sections 2, 3 and 4, progress toward this endeavor will be summarized in this section.

In March of 2006, GSE was charged with expanding its manufacturing capability by more than an order of magnitude. GSE was expected to bring on line a new plant (in Tucson), with re-designed equipment for all processes within 12 months. Subsequent to this decision, another plant in Berlin, Germany having a capacity of 35 MW/year was planned in addition to the 40 MW/year capacity slated for the Tucson plant. These planned capacities are for the “phase 1” construction. A “phase 2” of the expansion is planned to increase the capacity of the Tucson location to 140 MW, in addition to a capacity increase in the Berlin plant. The “phase 2” expansion is slated for completion in 2010, with the required -facility improvements for phase 2 already complete in the Tucson plant, and additional deposition equipment already under contract for many process steps for the Berlin factory.

During phase 1 of this TFPPP subcontract GSE located and negotiated the purchase of a building and land (110,000 sq. ft., and 22 acres, resp.) in Tucson, and has made lease arrangements for the factory space in Berlin. The Tucson building was formerly one of the largest magnetic tape coating facilities in the world, so in this sense the new PV factory continues the thin film coating legacy of the original building. Other similarities are absent, and thus the interior of the former building was entirely demolished, and then rebuilt. All existing equipment was removed, an extensive volume that filled a 250,000 sq. ft. lot 3 times over. Industrial architects and contractors were engaged to plan all aspects of the new plant – renovation, distribution of utilities such as electrical power, compressed air, process gasses, chemical distribution and containment, process cooling water, heating, ventilation and air conditioning, humidity control, storage and office space. Figures 4-6 below show the Tucson facility in early stages of demolition.

Fig. 4 *One section of the GSE Tucson building under demolition.*

Fig. 5 *A northeast section of the GSE Tucson building under demolition.*

Fig. 6 *The building exterior for the Tucson facility before renovation.*

Fig. 7 *Interior structures, equipment chases and HVAC under renovation in the Tucson facility.*

Fig. 8 *Interior rooms, overhead lighting and HVAC under renovation in the Tucson facility.*

Simultaneously, subcontractors were engaged to design and build deposition and production equipment for all the processes required for large scale CIGS PV manufacture. Deposition equipment was built to GSE specifications and concepts, based on the actual manufacturing experience GSE had gained with the 1st generation equipment at the existing plant in Tucson. In all cases, the re-designed equipment embodied advancements, including:

- Deposition equipment built for higher deposition rates,
- Reduced product cost,
- Improved materials utilization,
- Enhanced process control and reproducibility,
- A high degree of automation, all processes are designed to run largely unattended,
- High throughput,
- Process flexibility.

Specifically for the CIGS process, the deposition equipment was designed to handle rolls of substrate 3x the length of the existing, 1st generation equipment, at 2x the speed, with better cross-web and down-web uniformity, improved In, Ga and Se utilization, and more process flexibility.

2.2 Enhanced CIGS Deposition Rates

The maximum rate possible for CIGS formation is hitherto unknown, being limited at some point by the time-at-temperature required for sufficient materials reaction and diffusion through the absorber layer thickness. Higher CIGS formation rates are desirable to maximize throughput for the CIGS deposition, and is one of the goals of this program. Feasibility trials for CIGS deposition speed were run under this TFPPP program, demonstrating that deposition speed can be increased from 12 to 15-in/min in the current reactors without any impact on performance or material characteristics. Absorber layer compositions evaluated with Auger electron spectroscopy indicated essentially no change in the desired profile at 15-in/min compared to 12-in/min in Fig. 9.

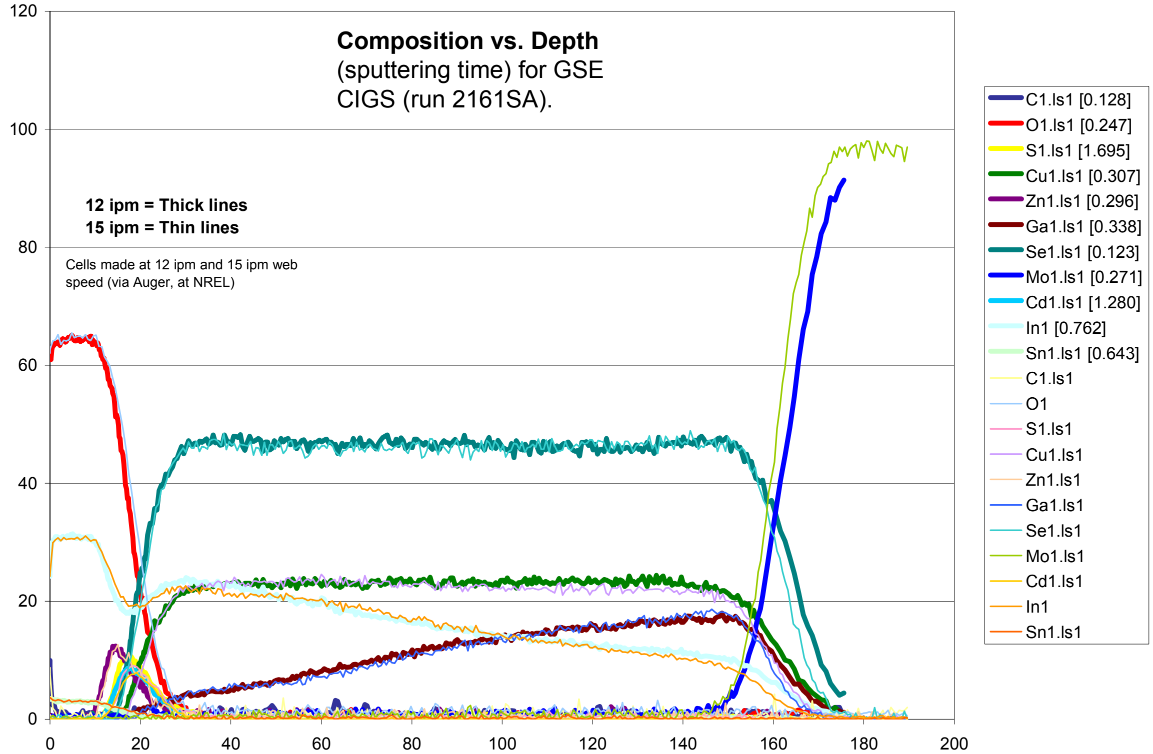


Fig. 9 *Auger electron spectroscopic analysis done at NREL comparing the composition of cells made at GSE at web speeds of 12 and 15-in/min.*

With proper control adjustments to flux rates at different stages of deposition, it is apparent from Fig. 9 that the deposition rate (and web speed) can be increased by at least 25% over the standard rate for the Gen 1 process at GSE while maintaining a virtually identical composition profile.

The equivalence of the CIGS material quality made at increased deposition rates is also evident in cell performance, as indicated by the large area (68 cm^2) sample cell efficiencies in Fig. 10. Both cells were deposited at different locations on the same roll of substrate, in the same run but with control adjustments made to flux rates to maintain material thickness and profile at the higher web speed. Fig. 11 shows the IV characteristic of a single large area cell, again, indicating that good performance can be maintained even at an increased CIGS deposition rate, in satisfaction of one of the deliverables under this program.

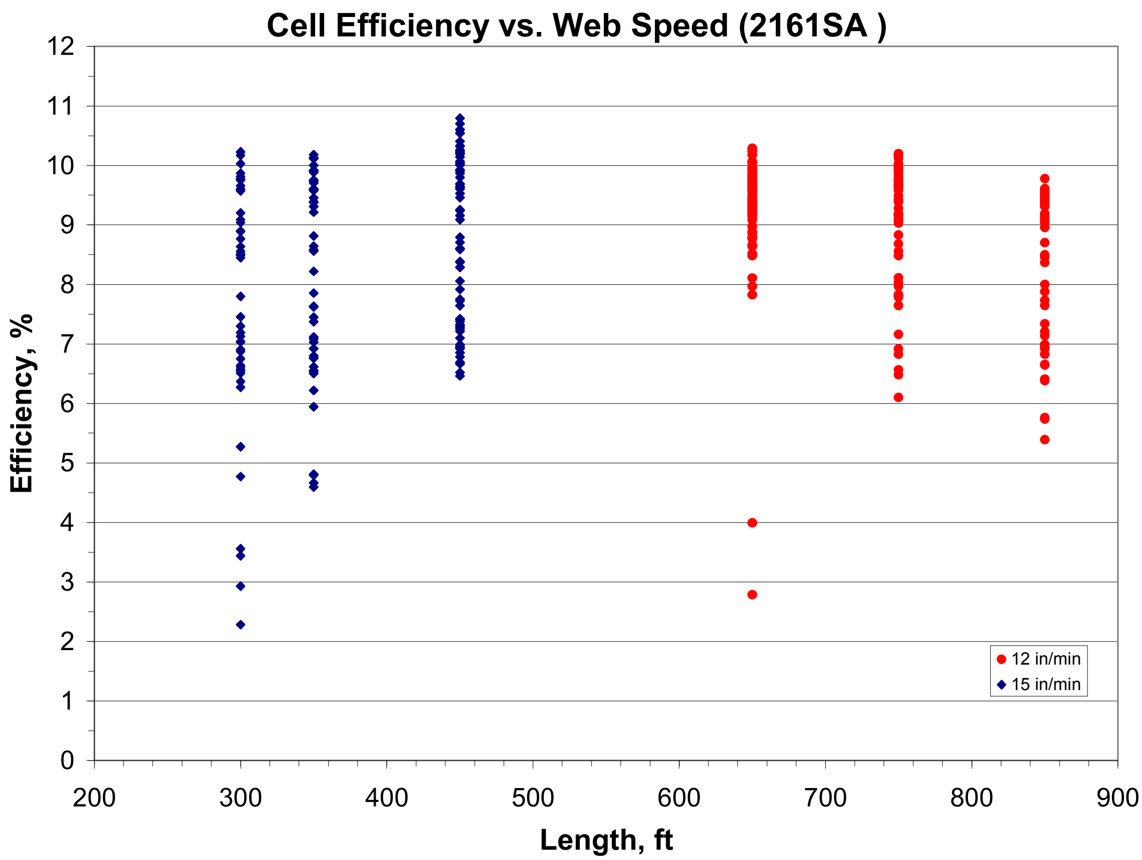


Fig. 10 *Cell efficiency results for a controlled study comparing CIGS material made at 15-in/min vs. 12 in/min.*

Further gains in maximum CIGS deposition rate are expected in the new Tucson and Berlin plants owing to the design of the 2nd generation CIGS deposition equipment. Based on experience with the earlier equipment, significant changes were instituted in the design phase of the 2nd generation equipment specifically to accommodate higher deposition rates without sacrificing material properties. In addition, the 2nd generation equipment was designed to allow more control and flexibility over the composition profile, further enhancing possibilities for achieving even higher deposition rates and/or performance. Fundamentally, even after the tests described here, the maximum deposition rate for the CIGS process is not known.

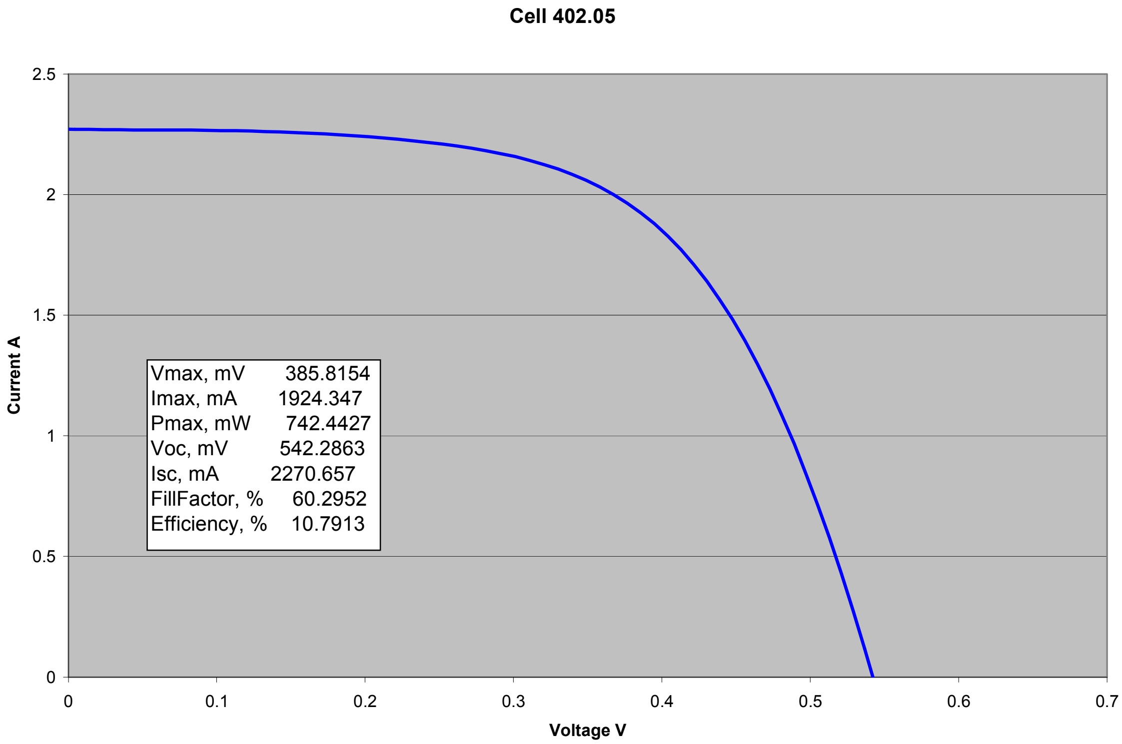


Fig. 11 A representative I-V characteristic for a large area c*ell made at an increased web speed of 15-in/min.*

Similarly, fundamental improvements have been made in the design phase for the 2nd generation equipment to address the 2nd, 3rd and 4th objectives listed in this task. Significant changes to the effusion source design used for CIGS deposition have been made to ensure adequate cross-web composition uniformity, in addition to improvements in materials utilization. The re-designed metals effusion sources have undergone preliminary testing during this reporting period, and so far perform well. Confirmation that the new design sources meet this objective is expected after they are fully installed and the 2nd generation equipment becomes operational in the new plant. This objective is complicated by concurrent demands for operation at higher deposition rates (discussed above) and greater capacity demanded by the planned introduction of much longer runs for up to 3x length webs in the 2nd generation equipment.

Improvements in In-Ga homogenization and compositional profile control, and performance improvements relating CIGS processing parameters (per the 3rd and 4th objectives) have been addressed in the design phase by instituting a scheme for more flexible delivery of CIGS reactants, but must be optimized and proven through designed experiments once the 2nd generation equipment is operational in the new plants.

Working toward ever-improving control over product quality, variables that are identified but have an unknown impact are evaluated as time and capability allow. In this regard, tests were conducted to determine the effect of humidity swings on the quality of CIGS deposited in the production coaters and the resulting effect on solar cell performance.

The impact of this factor was important to the architects responsible for the plant design, and to assure adequate environmental controls for the new plants. It was determined that significant quantities of water in the deposition chambers were required before process control difficulties were encountered.

Task 3: Front Contact Cost Reduction (Objectives)

1. Develop a low-cost process for the transparent front contact TCO coating.
2. Improve deposition rate of the TCO process, while re-optimizing the process to maintain large-area cell efficiency above 12.5%.

A parallel approach using two paths has been taken for this task; a low-risk pursuit of marginal improvements using the present sputtered methodology, and a high risk pursuit of a novel TCO deposition process potentially offering very large reductions in cost. Cost reduction is important, as the TCO process is currently the single, most expensive thin film layer in the device stack.

3.1 Incremental Improvement of the Existing TCO Process

Lower cost ceramic targets were evaluated in first-cut experiments to reduce the cost of the TCO process. Arcing problems were pervasive, and thought to result from excessive clearance under the dark space shields coupled with excessive flake and debris generation. However further experiments revealed that the actual cause of the variation in sputter voltage was intermittent plasma extinction due to a weak magnetic field at the target surface.

In spite of this problem, generation of production solar cells was attempted for measurement and reliability testing. Compared to the baseline top contact process, solar cells fabricated with the alternative TCO material had significantly lower yield, and maximum conversion efficiency was 8.6% compared to the maximum 11% for the control cells. The yield and quality of the solar cells generated was deemed insufficient for reliability evaluation. Further deposition experiments were planned using stronger cathode magnet arrays to stabilize the plasma.

Four new magnetic cathode arrays were installed to better evaluate the alternative TCO which had been evaluated previously. The improved magnetics resulted in a 640% improvement in voltage standard deviation. Once process control was achieved, coatings of the new TCO were applied to create solar cells for first reliability testing. The flexible modules produced were found to degrade more quickly than ITO control modules under accelerated testing (85˚C/85%RH). Further effort is planned using the lower cost TCO targets, however, it is clear that the TCO deposited from these low cost targets must be modified to achieve better resistance to degradation in the “damp heat” (85˚C/85%RH) test.

The TCO thickness has been modified in the current production process and documented to give slightly better I-V performance concurrent with thinner TCO. Improved I-V performance arose due to a controlled shift of optical transmittance maxima to more desirable ranges of the solar spectrum, giving an Isc gain (shown in Fig. 12).

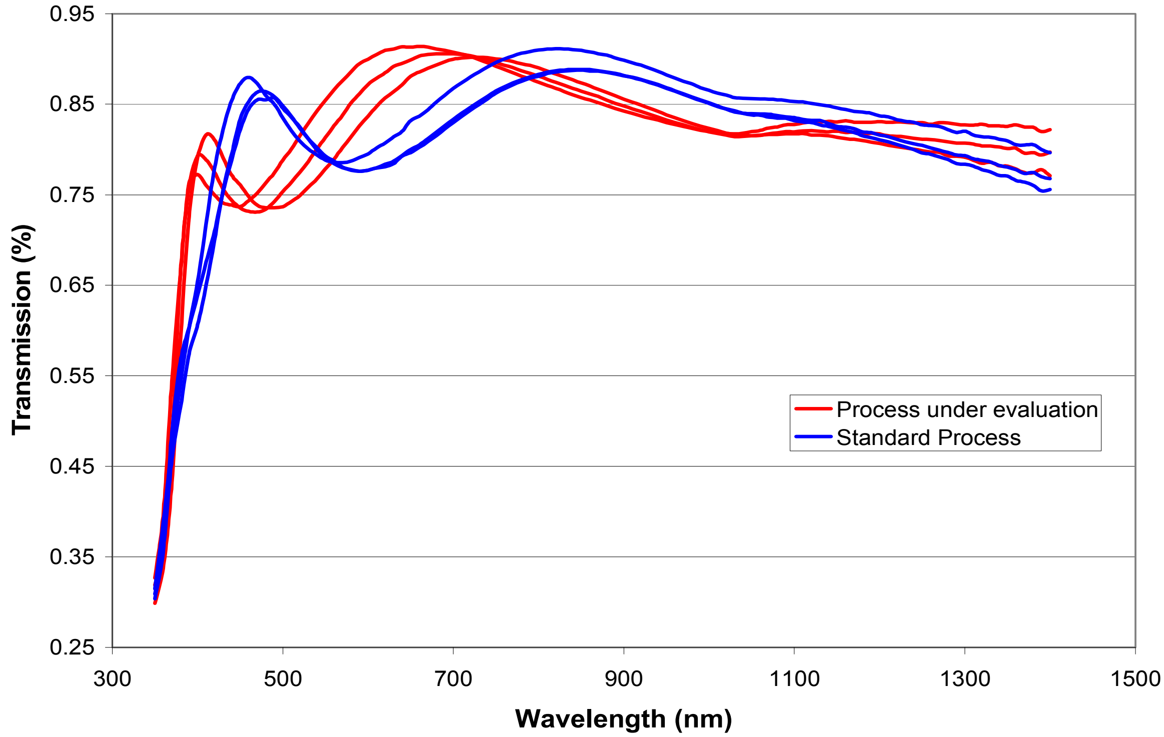
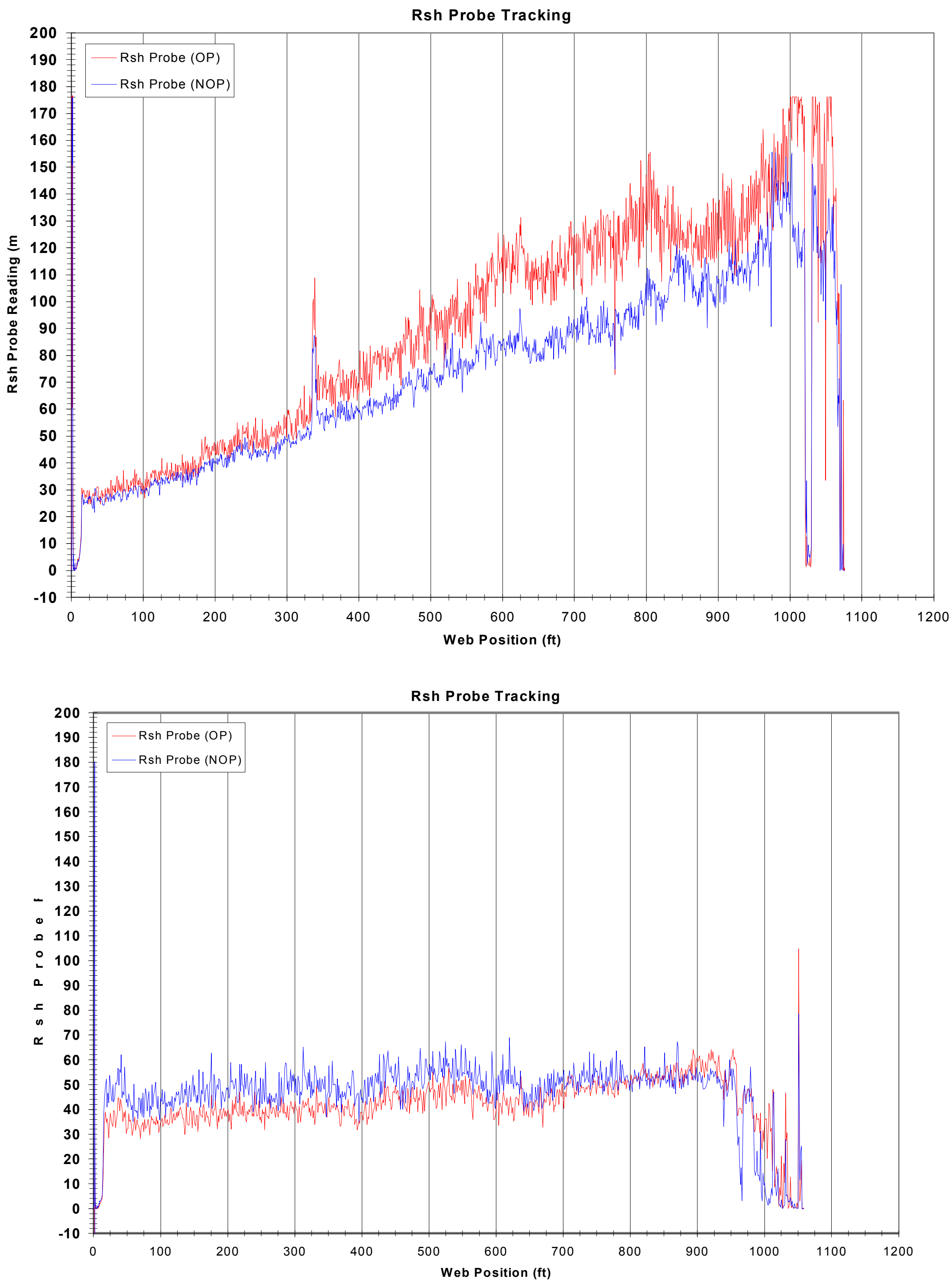


Fig. 12 *A comparison of the optical transmission as a function of wavelength for the standard production TCO process and a new process under evaluation.*

Further optimization of the baseline production TCO process was conducted in this time period. One goal was to improve bulk resistivity and thus enable a reduction in thickness. This has two key advantages; reduced cost by thickness reduction and increased optical transmission at higher energy wavelengths. Process variables including the composition of the sputtering gas, pulsing frequency, and pressure were systematically varied in designed experiments. The resulting process enabled a 50% increase in line speed with an equivalent sheet resistance and integrated transmission. Optical measurements of coatings produced by the new process show reduced thickness shifting the transmission peak closer the 550nm. Large area cells were produced to demonstrate equivalence with the baseline process.

The modifications made to the gas composition and pressure results in 100% higher bulk conductivity. Moreover, the improved process also exhibits a better controlled sheet resistance over the course of a run (Figs.13a,b). Sheet resistance regulation of the new process is ± 32% absolute with a standard deviation of 14%.



Figs. 13a,b *A comparison of the sheet resistance behavior over the course of single runs for the previous process (upper plot) and the improved process (lower plot).*

The improved TCO process optimization nets GSE significant cost savings. Higher bulk conductivity enables the process to run 50% faster, enhancing throughput. Sputter power is reduced by 33%. Higher bulk conductivity also reduces the coating thickness required, increasing target material utilization.

3.2 Novel TCO Deposition Process

The novel TCO deposition process is intended to avoid the requirement for sputtering targets, and those attendant costs with expensive target fabrication, limited target utilization and lifetime, maintenance and turnover labor thus yielding a cost improvement of an order of magnitude or more. An internal effort at GSE was initiated, as well as an effort carried out at a lower-tier subcontractor.

Toward that end in this period, a dedicated web coating chamber has been re-commissioned and made operational for development of the low cost TCO. The chamber has been fit with specialized mass flow control for two vapor-phase precursors, as well as up to 3 conventional gas feedstocks. Provisions were made for the addition of dopant in the dedicated chamber at GSE (called the “PE” chamber). Required ancillary provisions for a substrate heater and other monitoring instruments have also been installed in this roll-roll development chamber. A thermal decomposition reactor has been designed and fabricated to safely dispose of gas effluent expected of the process.

Exploratory experiments were completed depositing the low cost TCO on polyimide and stainless test webs. Sample TCO films (without any dopant) were also deposited on glass substrates for optical and electrical characterization. Some of the conditions yielded TCO films that were dense, uniform and well-adherent. The sheet resistivity of all films to date is high, as may be expected without any dopant.

Exploratory runs introducing varying levels of Al as a dopant to ZnO films were started. A first round of tests results show some reduction in sheet resistance, but still not approaching the low resistivity desired for TCO in films that are transparent and well adherent. Test depositions were primarily on glass witness slides.

A 2nd round of statistically designed experiments have been completed in the “PE” chamber at GSE, showing some additional reduction in sheet resistivity while maintaining high transparency and adhesion, however a sheet resistivity in the desired range has still not been attained. Although reasonable growth rates have been attained in the “PE” chamber, the resistivity must be reduced by at least another factor of 4x, with reproducibility demonstrated.

Work at the lower-tier subcontractor to GSE with a specialized deposition method that may potentially be suitable for low cost TCO was also started, referred to as the “ECS” method. The ECS method for deposition of ZnO has produced high resistivity films with good transparency and adhesion in a first round of experiments. Hall-effect mobility was low (1.2 cm^2/V-sec), and examination indicated the films typically had a large amorphous volume content. All films were done at low substrate temperatures and showed good uniformity of deposition in one dimension.

A further round of experiments with the ECS method gave reproducible results for the conductive ZnO, having improved carrier mobility in the range of 10-20 cm^2/V-sec, sheet resistivity of ~ 20 ohms/square and good optical transmission (shown in Fig. 14).

Several factors remain to be proven regarding the ECS approach for TCO based on ZnO, including adequate deposition rate and controllability, stability of the ZnO properties, and compatibility of the ECS approach for ZnO deposition on actual device material. The lower-tier subcontractor is confident of spatial uniformity with the approach, and is modifying the apparatus to allow the introduction of extrinsic doping.

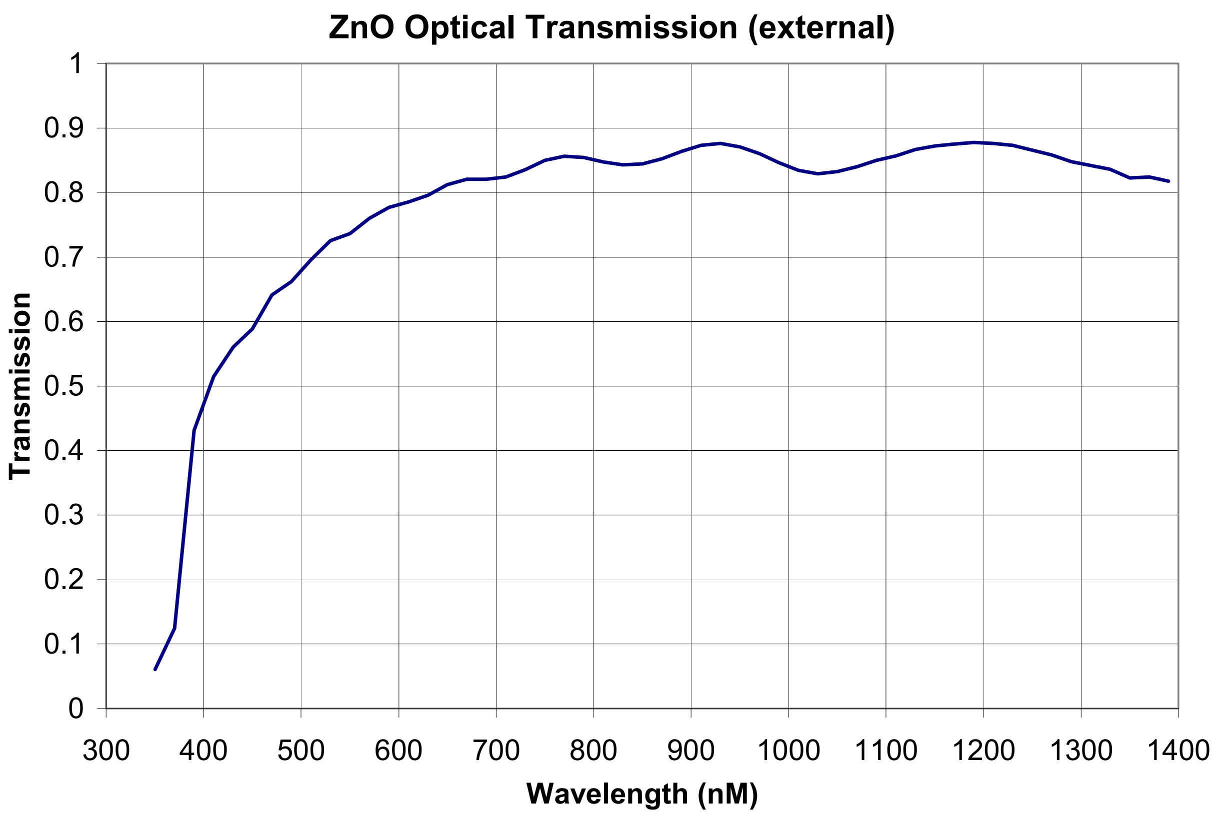


Fig. 14 *The external optical transmission of a ZnO film on glass deposited using the "ECS" method at a lower-tier subcontractor to GSE. This film had a sheet resistivity of 22 ohms/square.*

Task 4: Back Contact Cost Reduction and Efficiency Improvement
(Objectives)

1. Evaluate substrate properties and analyze resulting impacts on device performance.
2. Quantify impacts of reduced Mo thickness and correlate to device performance.
3. Examine low-cost alternate back contact materials for partial substitution of Mo and compare device performance and other properties against the established baseline.
4. Demonstrate increased device efficiencies and reduced process costs through material savings and increased process speeds.
5. Integrate alternate sodium delivery to maximize adhesion and efficiency at the higher CIGS web processing rate.

4.1 Back Contact Process Improvements

A first round of designed experiments using large-area cells indicated that cell performance is unchanged despite a reduction in the thickness of the back contact interface material of up to 50%, presenting an opportunity for reducing materials costs and process time. However, thickness changes in the molybdenum layer itself from the standard value resulted in a loss in cell performance. It may be possible, however, to change other process conditions to allow the use of thinner Mo. This prospect will be evaluated in upcoming tests.

Another series of experiments were conducted to study the effects of deposition parameters on the morphology of the Mo layer and the subsequent effects on cell performance. Parameters included were temperature, pressure, and gas partial pressures. We evaluated morphology by SEM, adhesion of the Mo/CIGS interface by pull testing and cell performance. We observed improved cell performance at distinct points in the Mo process, and this improved understanding led to changes in processing parameters that yielded better process control and homogeneity over the length of the web.

Prior to starting the back contact deposition, the chamber is run through a “conditioning” procedure. The conditioning procedure was changed in systematic experiments to improve deposition consistency. The results indicated no benefit to actual material consistency or quality, however the process reliability was improved due to reduced arcing over the course of production runs. Further tests to improve back contact quality and consistency are planned.

Modifications to the start-up sequence and pump-down requirements were also investigated to increase throughput in the Mo sputter process. Several modifications were successfully implemented that reduced the time required between depositions.

Flaking of deposited molybdenum during deposition shed from deposition shielding was observed to introduce defects on the web. Modifications were made to the deposition shields and process in the production coaters to minimize shedding. Other web defects caused by uneven tension of the metal foil during deposition were also identified. Interactions between web tension, deposition temperature, roller alignment in the chamber and shape of the foil (camber) were investigated as a possible cause for the tension-related defects.

4.2 Alternate Substrate Vendors and Materials

Testing of the stainless steel foil used for substrate material supplied by alternate vendors to GSE has started. As the pricing and quality of the incoming substrate material vary significantly, this effort has fairly large potential impact on total cost. Sample steel coils were received from 3 alternate vendors, and orders placed for sample coils from another two during this period. Substrate cleaning methods are also important apart from surface and mechanical properties or chemical composition, however, and must be evaluated concurrently with the material from other manufacturers. Evaluation of the incoming substrate material from different vendors is ongoing.

The experience in comparative evaluation of substrate from different vendors identified a need for a standardized battery of tests for incoming metal foil. A survey of applicable techniques and equipment to characterize the important properties of the incoming substrate material has been put together. As a result, GSE has identified optical surface profilometry as a primary measurement capable of giving quantitative information about important properties of incoming metal foil. Several optical profilers were evaluated, with one selected for purchase.

New vendors were also tested and successfully qualified for sputtering targets of Mo and other required back contact materials, giving multiple redundancy in vendors and a cost savings in some cases.

Additionally, a method was tested to join web sections in the roll-to-roll process established at GSE. The technique will facilitate more reliable and efficient testing and experimentation. A web can be split at any process and with each section undergoing separate treatment. After that step, the web can be joined together to complete identical processing for all other process steps.

Summary

GSE has embarked on a program to further improve module reliability, reduce the cost and time of CIGS coating, and for both the front contact and back contact deposition processes and materials. Simultaneously GSE has executed on an aggressive plan to build and equip two new CIGS PV manufacturing plants (in Tucson, AZ and Berlin, Germany) with a capacity approaching 200 MWp at the end of the planned phase 2 construction. Plant construction is well underway at both sites. Equipment for all processes is operational at the Tucson site and presently starting process adjustment and ramp-up. Phase 2 is scheduled for completion in 2010. Under this TFPPP subcontract from NREL, GSE has used standardized accelerated testing methods to evaluate alternative materials and methods of assembly to improve the reliability of both flexible and rigid (glass-based) product. CIGS coating process speed in GSE's roll-roll process has been improved per the subcontract plan, reducing labor and capital costs for that critical step. The front contact has been subject to improvements in cost, quality and control/reproducibility under a low-risk program using the existing deposition technology. The part of the proposed front contact program using higher-risk approach offering dramatically lower costs has shown good material properties for the TCO, although more work is needed to demonstrate satisfactory rates and device results. Back contact studies under this subcontract have resulted in a better understanding and control of that process, along with viable reductions in the thickness of an interface layer, garnering modest cost improvement. Overall, this phase is characterized at GSE as a period of rapid change in plant, equipment and production capability along with continued process improvement in key areas for thin film CIGS PV.

Future Plans

The new deposition equipment and processes have been designed to enable, and make full use of the improvements proposed under this NREL TFPPP program. For example, the new CIGS deposition equipment at both plants will begin running immediately at the high process speeds (100% above previous standard rates) as set out as goals in the subcontract. Speed and cost improvements in the front and back contact layers are already enabled by the design of the new equipment for those processes at the new plant, as planned under the TFPPP contract. Cost reduction through materials substitution in the front contact layer remain as key areas of focus in this program, as well as efficiency enhancement. Improved materials utilization and reduced absorber thickness for the CIGS absorber layer will be pursued as near and longer-term efforts, respectively, under the program. The new production CIGS deposition equipment has been designed for more flexibility in the composition profile and control than ever before, partially with the intent to facilitate viable absorber thickness reduction. Foremost among the activities planned at GSE is completion and ramp-up of the largest roll-roll CIGS PV manufacturing plants in the world at the Tucson and Berlin locations.

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14. ABSTRACT *(Maximum 200 Words)*
Global Solar Energy (GSE) describes its progress in quantifying and enhancing module reliability, reducing the cost and improving the performance of its CIGS deposition process, and reducing the cost of materials and processes for front and back contacts. GSE has been bringing its Tucson, Arizona, CIGS production plant into operation and planning another plant in Berlin, Germany. Much of the design effort to reach the goals for the production equipment also represent progress toward the major thrusts of this subcontract.

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