NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Scale-Up of World Record 16.5% CdTe Cell Design for a 50 MWp Production Facility

September 27, 2007 — March 26, 2009

Fred H. Seymour
PrimeStar Solar
Arvada, Colorado

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Subcontract Report
NREL/SR-5200-51518
May 2011

Contract No. DE-AC36-08GO28308

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NREL Technical Monitor: Harin S. Ullal
Prepared under Subcontract No. NAT-7-77015-07

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Summary

This final report covers progress made on subcontract NAT-7-77015-07 by PrimeStar Solar Inc. for the 18 month period from September 27, 2007 through March 26, 2009.

The project objectives were to accelerate the commercialization of the world record 16.5% efficiency cadmium telluride photovoltaic technology. This was done by developing high performance 6”x6” prototype mini-modules and by designing and commissioning a pilot line for manufacturing of commercial sized 60cmx120cm modules.

The subcontract was structured in two nine month phases with a total of 6 quarters. The subcontract had the following five tasks:

1. Advanced Window Layer Films - one deliverable
2. Optimize cell performance on 6”x6” mini-module substrates - five deliverables
3. Optimize performance for 6”x6” interconnected mini-modules - four deliverables
4. Design pilot line to manufacture 60cmx120cm modules - one deliverable
5. Build pilot line equipment and commission pilot line - two deliverables

All deliverables to date have been submitted and have been accepted by NREL ahead of schedule. Work continues on one remaining high efficiency 6”x6” mini-module deliverable which is due May 25, 2009. This deliverable was originally due March 26, 2009 and the due date was rolled back to May 25, 2009 because of delays in authorizing phase II of this subcontract.

At this point PrimeStar Solar has accomplished the following:

- Produced working high performance 6”x6” mini-modules with cell interconnect and advanced window layers
- Built and commissioned pilot line for full sized 60cmx120cm commercial modules
- Produced working 60cmx120cm commercial grade modules

This contract aligns with the SAI program by accelerating the development of high efficiency low cost CdTe solar PV module manufacturing. This will contribute to the goal of PV grid parity by 2015. Progress with the deliverables and milestones in this subcontract constitutes progress towards the KPP and milestone objectives for the SAI program. The CdTe PV DOE 2015 roadmap objectives are listed in the table below and this subcontract contributes towards five of the seven objectives. These five objectives are highlighted and they are: module efficiency; module cost; installed cost; LCOE; and overall process yield.

Table 1. CdTe PV DOE 2015 Roadmap Objectives

Parameter	2007 Status	2015 Goal
Champion Device Efficiency	16.5%	18%-20%
Commercial Module Efficiency	**>9%**	**13%**
Module Cost ($/W)	**$1.25/W**	**$0.70/W**
$/W installed System Cost	**$4-$5/W**	**$2/W**
LCOE	**$0.18-$0.22/kWhr**	**$0.07-$0.08/kWhr**
Overall Process Yield	**80%**	**95%**
Annual Degradation Rate	1.2% per year	0.75% per year

The remainder of this report contains a more detailed description of the accomplishments achieved through this subcontract including:

- Subcontract schedule details
- Task 1 – uniform advanced window layer films
- Task 2 – optimizing cell performance
- Task 3 – optimizing mini-module performance
- Task 4 – pilot line design
- Task 5 – pilot line equipment build and startup
- Final comments

Most of the deliverables in this subcontract involved specific performance metrics including cell efficiencies, mini-module efficiencies, and module efficiencies. The actual performance of PrimeStar Solar devices are proprietary information. Because there is the possibility that this final report will be disclosed to the public, the performance values are not disclosed in this document.

Subcontract Schedule Details

The subcontract periods were organized into two phases of three quarters each for a total of six quarters.

Phase I. The first objective was to refine the high efficiency film stack deposition recipe. Using PrimeStar Solar prototype development equipment uniform semi-conductor films were produced on 6"x6" substrates. Over 600 6"x6" substrates with functional thin film CdTe PV solar cells were produced. The second objective was to design the pilot line production equipment for 60cmx120cm commercial scale modules. PrimeStar Solar's Thin Film Equipment Group completed this pilot line equipment design.

Phase II. The first objective was to produce complete working 6"x6" prototype CdTe PV mini-modules with scribing, interconnects, and encapsulation. Over 900 6"x6" working mini-modules were produced. The second objective was to build and commission a pilot line and to produce working 60cmx120cm modules. This was achieved and to date over 200 working 60cmx120cm modules have been produced.

There were five tasks in the subcontract and these were scheduled within quarterly time periods as shown in the table below.

Table 2. Subcontract Tasks and Schedule

	Phase I			Phase II		
	Q1	Q2	Q3	Q4	Q5	Q6
Start Date	9/27/2007	12/27/2007	3/27/2008	6/27/2008	9/27/2008	12/27/2008
1. Films						
2. Cells						
3. Mini-modules						
4. Pilot Line build						
5. Pilot Line Startup						

The thirteen technical deliverables for this subcontract are listed in the table below:

Table 3. Subcontract Technical Deliverables

	Deliverable	Due	Done
T1-D1	Advanced window layer films – demonstrate deposition uniformity	Q2	✓
T2-D1	Working solar cells on mini-module substrate	Q1	✓
T2-D2	Higher efficiency working solar cells on mini-module substrate	Q2	✓
T2-D3	Higher efficiency working solar cells on mini-module substrate	Q3	✓
T2-D4	Mini-module substrate with cells demonstrating efficiency uniformity	Q3	✓
T2-D5	Highest efficiency working solar cells on mini-module substrate	Q4	✓
T3-D1	Working interconnected 6"x6" mini-module	Q3	✓
T3-D2	Higher efficiency working interconnected 6"x6" mini-module	Q4	✓
T3-D3	Higher efficiency working interconnected 6"x6" mini-module	Q5	✓
T3-D4	Highest efficiency working interconnected 6"x6" mini-module	Q6	In progress
T4-D1	Complete pilot line design for 60cmx120cm modules	Q3	✓
T5-D1	Pilot line build complete	Q5	✓
T5-D2	Working full sized 60cmx120cm commercial module	Q6	✓

The subcontract budget and cost share by phase are listed in the table below. The PrimeStar Solar cost share was principally for completing the prototype 6”x6” equipment purchases in phase I, and for the pilot line equipment purchases in phase II.

Table 4. Subcontract Budget and Cost Share

	NREL	PrimeStar Solar	PrimeStar Solar % Cost Share
Phase I	$1,458,584.20	$ 625,000.00	30%
Phase II	$1,519,815.70	$8,000,000.00	84%
Total	**$2,978,399.90**	**$8,625,000.00**	**74%**

Task 1. Advanced Window Layer Films

The objective of this task was to produce advanced window layer films on 6”x6” glass with uniform thickness and appropriate electrical and optical properties.

Initial recipes for the advanced window layer source material specifications including compositions were obtained from NREL. These materials included a cadmium stannate (CTO) transparent conducting oxide (TCO) layer, a zinc tin oxide (ZTO) buffer layer, and an oxygenated cadmium sulphide (CdS:O) n-type p-n junction layer. Source materials were purchased from multiple vendors. A portion of the vacuum deposition equipment used with these advanced window layer materials was operational prior to the start of this subcontract. The remaining vacuum deposition equipment was completed and commissioned shortly after the start of this subcontract.

Initial testing was completed for all of the advanced window layers by the end of Q2 in this subcontract. Films were deposited under a range of conditions. The deliverable T1-D1, consisting of the advanced window layer films, CTO, ZTO, and CdS:O deposited on 6”x6” mini-module sized substrates meeting specified uniformity and performance characteristics, was completed, submitted and accepted by NREL ahead of schedule.

The feasibility and economic viability of incorporating these advanced window layers into the commercial production film stack bill of materials was investigated. Preliminary large volume source material price estimates were gathered from potential suppliers. Combined with film thickness and estimated production material utilization, preliminary source material cost estimates were made for each semiconductor layer. This economic cost modeling continues to be refined as further information is gathered.

Task 1 was completed ahead of schedule. Having access to NREL's film characterization equipment as well as the NREL scientists who helped with interpreting results was crucial to completing this task in a timely manner.

Task 2. Optimize Cell Performance

The goal of this task was to produce high performance CdTe PV solar cells on a 6"x6" substrate using the advanced CTO/ZTO/CdS:O window layers. There was an additional goal of achieving PV cell performance uniformity across the 6"x6" substrate. CdTe PV solar cell film stack development on mini-module scale substrates was underway prior to the start of this subcontract.

Using a laser scribing process sequence similar to that used for thin film module cell interconnects, the substrate films were divided into a 10x10 array of PV cells that were 0.71cmx0.71cm (0.5cm^2) each. An automated JV testing instrument was developed to facilitate the evaluation of each substrate. The picture below shows a 6"x6" substrate with a completed 10x10 array of CdTe PV solar cells.

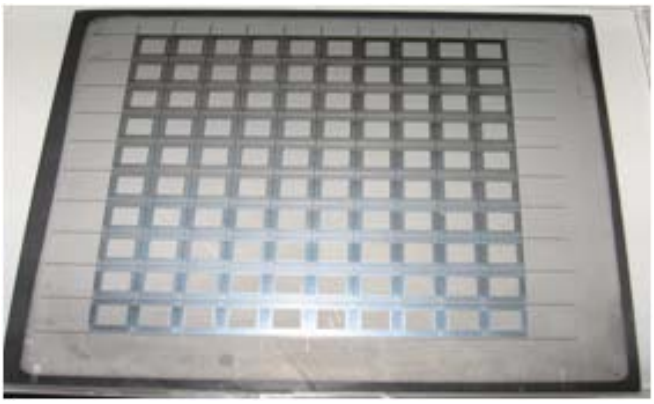

Figure 1. Array of CdTe PV cells on 6"x6" substrate

During the course of the subcontract the film deposition sequence recipes were refined including those for the advanced window layer films. The cell efficiencies were gradually improved. The cell efficiency uniformity deliverable T2-D4 was achieved February 19, 2008, ahead of the June 26, 2008 due date. Over 600 substrates were completed into arrays of working cells. Deliverables T2-D1, T2-D2, and T2-D3 having 6"x6" substrates with progressively higher cell efficiencies were achieved ahead of schedule. The culmination was deliverable T2-D5, consisting of three 6"x6" mini-module sized substrates with working cells above a given efficiency that were submitted and verified by NREL. These were the highest cell efficiency deliverables in this subcontract. Task 2 was completed in August, 2008, ahead of the September 26, 2008 due date.

Although complete, Task 2 work continues with high efficiency cell development to further improve cell performance. Four key performance metrics continue to be monitored. These are:

1. Peak cell efficiency
2. Cell efficiency uniformity across the substrate
3. Cell efficiency reproducibility from run to run
4. Cell efficiency stability following device completion

With metric #4 (stability), close collaboration with NREL continues in the design and the execution of experiments for device stability. NREL's expertise in this area has accelerated development of an appropriate Accelerated Life Test (ALT) protocol for our devices.

Task 3. Optimize Mini-Module Performance

The goal of this task was to produce high performance CdTe PV mini-modules on a 6"x6" substrate using the advanced CTO/ZTO/CdS:O window layers. These working modules were completed with laser scribed cell interconnects, busbar, taping, encapsulation, edge seal, and junction box to make the module suitable for use outdoors.

The laser scribing recipes and deposition interleave sequence was developed and refined to achieve performance objectives. This included scribes for P1 (anode isolation), P2 (interconnect), and P3 (cathode isolation). Refinements included laser pulse duration, frequency, and scan rate as well as minimizing scribe line widths, line separation zones, and the non-producing heat affected zones.

Completed working 6"x6" prototype mini-modules are shown in the two pictures below:

Figure 2. 6"x6" prototype mini-module (Front View)

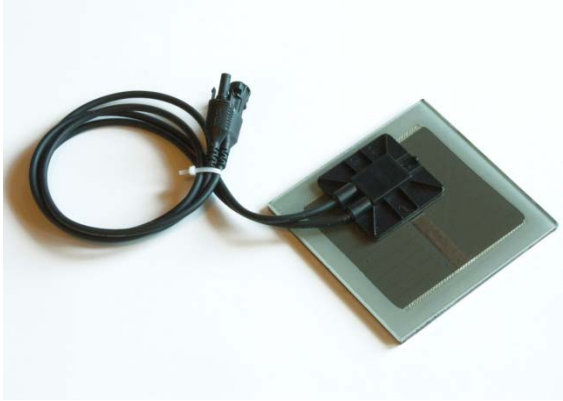

Figure 3. 6”x6” prototype mini-module (Back View)

Development work is ongoing to better understand and remedy the factors that limit module performance. The deliverables for this task, T3-D1, T3-D2 and T3-D3, working mini-modules with progressively higher efficiencies, were due June 26, 2008, September 26, 2008 and December 26, 2008 respectively. These were delivered and verified by NREL ahead of schedule on February 15, 2008, April 17, 2008 and August 14, 2008 respectively.

The final deliverables consisting of three encapsulated modules with the highest mini-module efficiency in this project are due at the end of Q6 (May 25, 2009). We expect to achieve this milestone on or ahead of schedule.

Although not a deliverable for this subcontract, ALT experiments are underway and we routinely stress test un-encapsulated 6”x6” mini-modules with 1000 hours exposure at one sun illumination at 65^{o}C in open air. This is designed to determine the intrinsic stability of our mini-module devices and it includes the laser scribes and interconnects. Open circuit, short circuit, and resistor load (to simulate max power point) conditions are tested. To date none of the modules have shown catastrophic degradation. As expected, the open circuit setting shows the most severe degradation followed by the resistor load and the short circuit setting shows the least degradation. As more data is collected, process design of experiments are continually refined and carried out to develop a process recipe that minimizes the intrinsic device degradation.

Task 4. Design Pilot Line Production Equipment for 60cmx120cm Modules

The goal of this task was to develop detailed designs, manufacturing drawings and cost estimates for a pilot line with a 3MW$_p$ nominal annual production capacity where the critical components are scalable to 50MW$_p$ per year.

Designing and building thin film deposition equipment is one of PrimeStar Solar’s core competencies. The PrimeStar Solar founders combined have nearly 100 years of hands-on engineering experience in designing, building, and operating large scale thin film deposition equipment for sputtering semiconductor layers. This capability allows PrimeStar Solar to quickly translate new thin film process development into commercial production. This key

competitive advantage is helping PrimeStar Solar accelerate the commercialization of the NREL world record CdTe technology.

Custom equipment has been designed for the deposition of all key semiconductor layers in these CdTe PV solar modules. Because this is proprietary information and there is the possibility that this final report will be disclosed to the public, no engineering details are disclosed in this document.

Three thin film deposition machines were designed and reviewed in detail by the NREL Technical Monitor to verify compliance with the deliverable. This review took place on May 29, 2008, ahead of the June 26, 2008 deliverable deadline. 3D images of the equipment along with the drawing books are shown in the picture below.

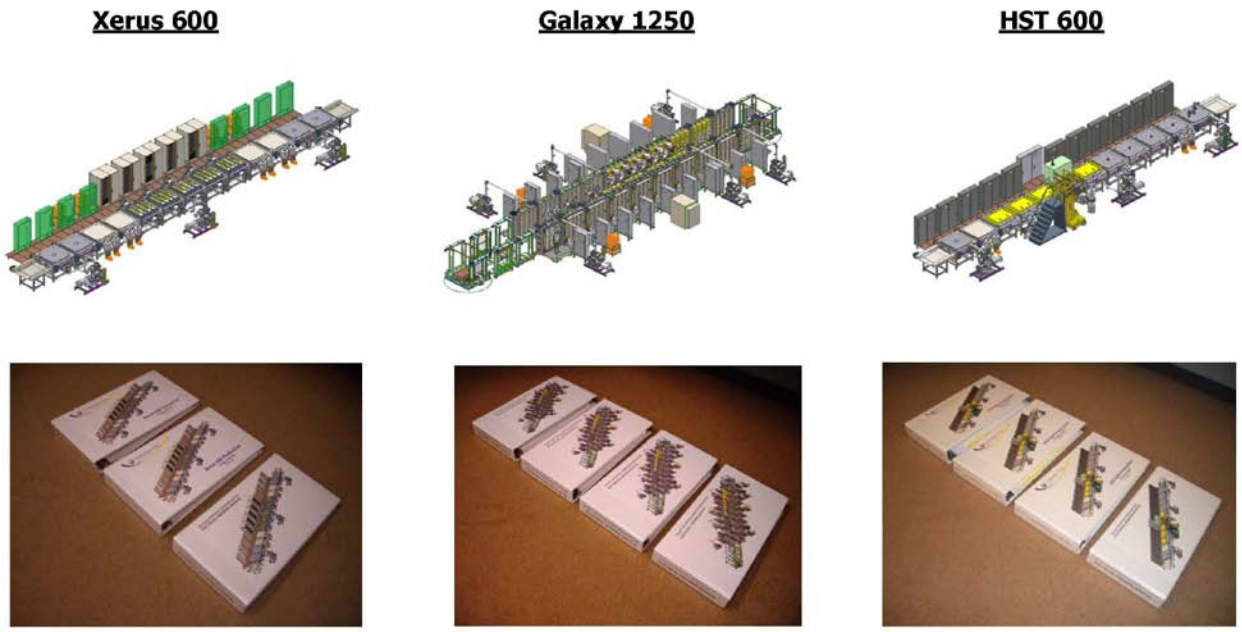

Figure 4. 3D images of the equipment along with the drawing books.

Task 5. Commission Pilot Line for Production of 60cmx120cm Modules

The goal of this task was to build, install, commission, and operate the pilot line equipment as well as produce working 60cmx120cm modules. The PrimeStar Solar capital expenditure for the pilot line equipment provided the cost share component of this subcontract.

PrimeStar Solar's pilot facility equipment was installed and commissioned during Q5 of this subcontract. This included equipment for glass washing, semi-conductor deposition, post deposition back contact treatment, laser scribing, encapsulation, and characterization. The

commissioned pilot line was verified by Harin Ullal, NREL Technical Monitor, during a visit to the pilot facility, November 6, 2008. This deliverable T5-D1 was completed ahead of the December 26, 2008 deliverable deadline. Pictures of the CdTe process equipment exit and a completed module in J-V testing are shown below.

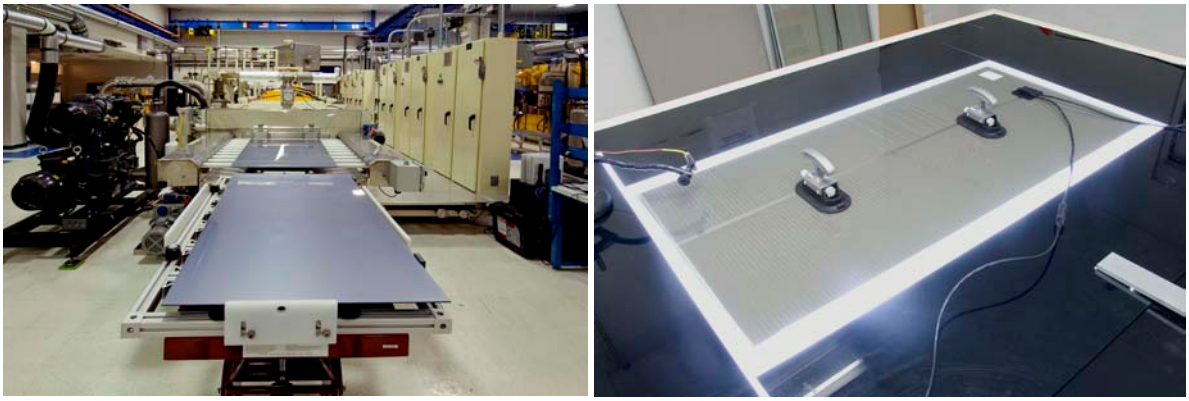

Figure 5. CdTe process equipment exit and a completed module in J-V testing.

Deliverable T5-D2, two working 60cmx120cm modules of a given efficiency were submitted to NREL February 2, 2009 and following performance verification were accepted as having met the milestone. This was ahead of the May 25, 2009 deliverable deadline. Pictures of the 60cmx120cm pilot module product are shown below.

Figure 6. 60cmx120cm pilot module product.

Final Comments

Beyond the scope of this subcontract, equipment and process refinements continue in order to enhance the performance of these commercial scale modules. Moving towards commercial production, module reliability testing is underway, module certification testing is underway, and construction of equipment and facilities for commercial volume manufacturing are underway.

PrimeStar Solar has been pleased to be able to conduct this work under this SAI-Incubator subcontract. This subcontract award in combination with the continuing support from NREL and its people has significantly accelerated the commercialization of this CdTe technology and it is helping to achieve the SAI KPP milestones and objectives.

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