May 2004 • NREL/SR-520-36194

Subcontractor Report

Innovative Approaches to Low Cost Module Manufacturing of String Ribbon Si PV Modules

First Annual Report
27 September 2002–31 March 2003

J.I. Hanoka
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Marlboro, Massachusetts

NREL

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EXECUTIVE SUMMARY

This PV Manufacturing R&D subcontract is a three-year contract that began in September 2002. This report is a description of the first year's activities under this subcontract. The subcontract title is "Innovative Approaches to Low Cost Module Manufacturing of String Ribbon Si PV Modules". As such, the goal over its three year duration is the further development of Evergreen Solar's String Ribbon technology resulting in a virtually continuous, fully integrated manufacturing line. General objectives for this first year (or Phase I) are listed here, followed by the principal accomplishments for each of these objectives:

(1) Scale-up of a production worthy method for doping feedstock.
(2) Development of a multiple ribbon growth system (Project Gemini)
(3) Development of wrap-around contacts for making monolithic modules.
(4) Accelerated testing of small size (25 W) monolithic modules
(5) Development of an in-line production machine to form solar cell contacts using Evergreen's unique contact printing technology.

Scale-up of a production worthy method for doping feedstock. – A change in feedstock vendor policy necessitated the development of such a method. A new concept was tested first in the lab and then eventually introduced into the production line.

Development of a multiple ribbon growth system (Project Gemini) - Project Gemini is a method for producing two ribbons from a single crucible using the String Ribbon continuous ribbon growth technology. During this first year, the method was developed in the laboratory and successfully introduced into production by means of retrofitting 5 single ribbon growth furnaces. Given this dual ribbon output capability, the costs of a number of consumable items can be virtually halved. The success of this 5 furnace pilot line led to the decision to make Gemini the next technology platform for String Ribbon. The decision was also made to retrofit 15 more furnaces and to have 100 brand new Gemini furnaces built. This will lead to an ultimate capacity at Evergreen's present factory of between 10 and 14 MW/yr. Efficiencies of Gemini ribbon cells on the production line have continually improved. The best cell so far is 14.6% efficient, and the best production batch average is 13.7%.

Development of wrap-around contacts for making monolithic modules. - Considerable progress in making efficient wrap-around contacts on String Ribbon wafers was made this year. A method was developed that allowed the formation of cells with efficiencies as high as 13.6%.

Accelerated testing of monolithic modules - A method for making monolithic modules using wrap-around contacts along with printed conductive adhesive on Evergreen' proprietary backskin material was developed. Using thermal cycling as an accelerated environmental test for the efficacy of the contacts, it was found that 400 such cycles on small (25 W size) monolithic modules still resulted in negligible power loss. This indicated that the basic method and concept is very viable.

Development of an in-line production machine to form solar cell contacts using Evergreen's unique contact printing technology. - A new design for an in-line, web type contact application machine was completed. The machine was built and debugged on the production line. The result was a gain in yield at this step of at least 3% absolute, overall efficiency improvement of 0.3 absolute, and throughput increase of 70%.

Introduction – Goals of the Project

The objective of the PV Manufacturing R&D subcontract, "Innovative Approached to Low Cost Module Manufacturing of Sting Ribbon Si PV Modules," over its three-phase duration is to continue the development of Evergreen's String Ribbon Si PV technology resulting in an advanced generation of crystalline silicon PV module manufacturing technology applied to a virtually continuous, fully integrated manufacturing line. The final goal of this line will be the production of frameless modules using wrap-around contacts on String Ribbon solar cells and made in a monolithic module configuration. Specific objectives include methods for improving surface and bulk quality of as-grown ribbon, improving techniques for wrap-around solar cell efficiencies, extensive reliability testing under accelerated conditions, developing low cost manufacturing to make frameless modules in general and monolithic modules in particular, and in-line diagnostics throughout the production line.

During its first phase, the project involved five major areas of work:

(1) Scale-up of a production worthy method for doping feedstock.

(2) Development of a multiple ribbon growth system and pilot line introduction of same (Project Gemini)

(3) Development of wrap-around contacts for making monolithic modules, including a method for forming a monolithic module with satisfactory long term reliability.

(4) Accelerated testing of 25 W size and 50 W size monolithic modules

(5) Development of a production machine to form solar cell contacts using Evergreen's unique contact printing technology.

As will be seen, significant advances were made in each of the five areas.

Accomplishments

(1) Scale-up of a production worthy method for doping feedstock.

As far as is known, all the vertical ribbon growth methods for silicon ribbon utilize as the feedstock, silicon pellets made by the thermal decomposition of silane in a fluidized bed reactor. The resulting feedstock materials are more or less spherically shaped silicon pellets on the order of a millimeter in size. The vendor for this silicon feedstock originally had offered boron doped material as well as undoped material. The vendor decided to discontinue making the doped silicon, and this required us at Evergreen to develop a method to dope this material that would eventually be suitable for production scale.

A number of possible concepts were considered and tested in the lab. From this work, one approach in particular was chosen for further consideration. The next step was to develop a process to make kilogram size batches in a reproducible manner. The results were tested by growing ribbon in the String Ribbon process (see next section) and then measuring the bulk resistivity as a function of length of the growth run. Following the successful outcome of this work, a design and equipment for a production size machine was then chosen. This equipment would allow for up to 300 kg to be doped at one time. Also, it was designed such that the only surfaces that came in contact with the silicon were fluoropolymers. The final piece of equipment had components that allowed for automatic transfer of the doped silicon into smaller containers that could eventually be handled by production operators.

Once the equipment was installed, extensive testing of the doping process was done to insure that the scale up in volume still produced a uniformly doped feedstock.

The net result was a very successful process that is now a standard production technique.

(2) Development of a multiple ribbon growth system and pilot line introduction of same (Project Gemini)

Project Gemini began this past year, first as an R&D concept and then into a pilot phase, and finally into production. The concept and the conventional, single ribbon growth of String Ribbon is illustrated in Figures 1a and 1b.

Figure 1a shows Evergreen's String Ribbon method as practiced for a single ribbon from a crucible. Two high temperature string materials are used to stabilize the edges of a ribbon grown vertically directly from the melt. The silicon melt is contained in a graphite crucible and the ambient gas is argon. The basic process is robust and virtually continuous. String Ribbon machines are run in production on a 24/7 basis.

In Gemini shown in Figure 1b, two ribbons are grown, back-to-back, out of a single crucible.

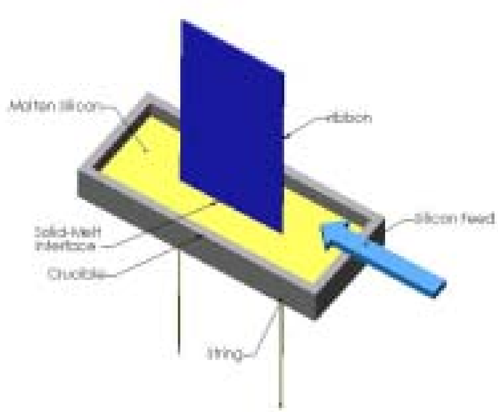


Figure 1a – Single ribbon growth in the String Ribbon process.

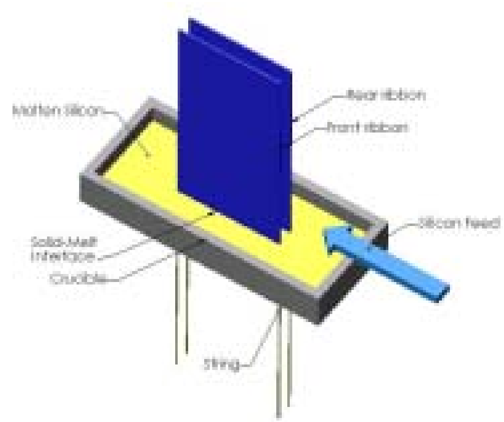


Figure 1b - Dual ribbon (Gemini) growth in the String Ribbon process

It can be seen that four strings are involved instead of two as needed for single ribbon growth. Thus, with most everything being equal except principally silicon costs, nearly twice as much ribbon is obtained from a single crucible and furnace for the same consumable, labor, and capital costs.

Several technical hurdles had to be overcome before Gemini could be considered ready for production. These included: (a) being able to insure that the molten silicon menisci surrounding each of the two Gemini ribbons did not interfere with each other (discussed in more detail further on), (b) correcting for the expected difference in the radiative environment surrounding each ribbon, (c) developing robust mechanical means for harvesting two ribbons from a growth machine, and (d) suitable in-line diagnostics for such things as melt depth, ribbon thickness, and crucible temperature.

(a) Silicon Menisci - The problem that had to be solved here can be visualized from the following considerations: molten silicon wets the sides of a graphite crucible and also forms an angle of about 11^{o} with the growing ribbon. The result is that in a cross-sectional view of the molten silicon in the crucible, looking parallel to the ribbon edge, it will show a flattened "U" shape as seen in Figure 2. Similarly, if there were two ribbons growing near each other as in the Gemini configuration, there would be a U shaped molten silicon pattern between them as well.

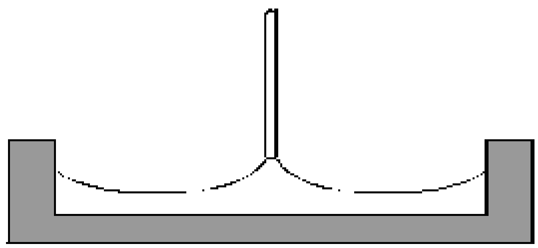


Figure 2 – Illustrating a meniscus shape for a single ribbon in a crucible. Shown is a cross section through a crucible where the ribbon is seen end on.

The ribbons as they grow are only pinned at their ends by the string material with the consequence that the ribbon centers can move. The driving force to reduce surface energy will result in the two ribbons trying to merge into each other at their centers. If this were to occur, the result would look, from the top, like an X with curved sides.

Another way to say this is that the highly curved meniscus between the two ribbons, can, in order to reduce surface energy, force the two Gemini ribbons together. Such an event then prevents the growth of two discrete ribbons.

An important development in the early Gemini work was a method to avoid this problem and control the shape of the meniscus surrounding each of the two ribbons in a Gemini configuration.

(b) Radiative Environment - One would naturally expect the radiative environment surrounding the two Gemini ribbons to be different and to show an asymmetry that could then affect the growing ribbon. Such an asymmetry would be expected to result from the obvious geometric asymmetry present in the Gemini configuration.

In this case, this problem was also successfully addressed by a suitable modification of the radiative environment surrounding each ribbon such that any possible thermal asymmetry could be minimized.

(c) Mechanical Harvesting - In a single ribbon configuration, after a 2 m long strip of ribbon has grown, it is diamond scribed at the top of the furnace and gently snapped to disconnect it from the ribbon still growing. Having two ribbons present in the Gemini configuration presented some mechanical issues with this procedure. In particular, following the scribing operation, it would now be necessary to remove both ribbons at the same time.

This then required that these ribbons be firmly gripped at their tops and also that this grip would release simultaneously for both ribbons. This required some careful mechanical design work on the part of Evergreen's engineering team. In the course of solving this problem, the ultimate design turned out to be an improvement on the original design used for the single ribbon machines. The net result has been that the production operators have found the new Gemini system even easier to use than the older, single ribbon system. A production operator can harvest two ribbons from a Gemini furnace quite easily.

<u>(d) In-line Diagnostics.</u> - A factor in yield loss for Gemini has been weaker wafer edges (this is the edge that contains the string, not the laser cut edge) resulting in what is termed "edge breakout". Weaker edges are due to thinner edges, non-uniform wafer thickness, and possible non-uniformities in the string material.

Several diagnostic techniques have been implemented as a means of reducing this as a source of yield loss. It has been demonstrated that keeping the melt depth within a certain range and also keeping the string tension within a particular range can significantly lower the level of edge breakout. The melt depth is controlled through a sensitive electrical circuit that includes the graphite crucible and the molten silicon and is able to measure melt depths down to fractions of a mil. An improvement in the thickness measurement and control has also helped in this area. This is the introduction of a dead band in the control algorithm that has the effect of reducing thickness variations.

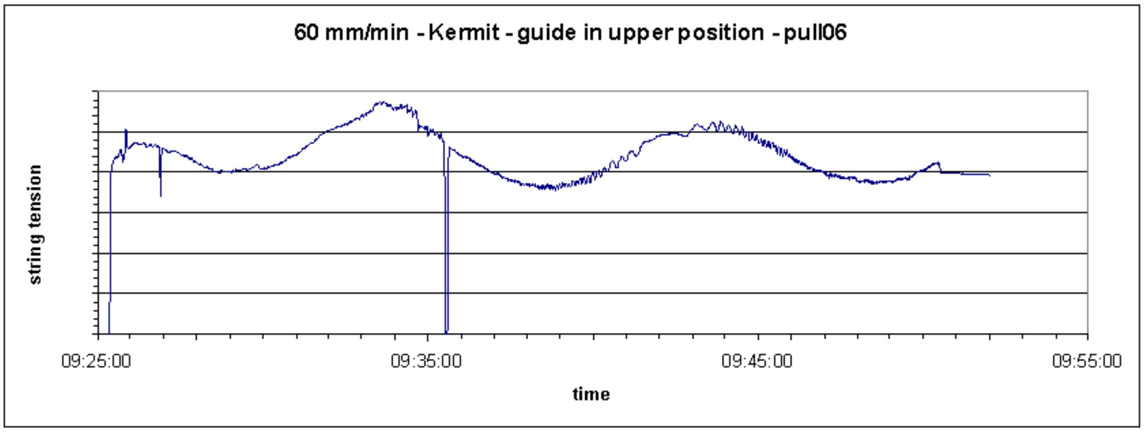
The string tension is now controlled by devices that are mechanical and not electronic. In order to determine accurate values of string tension, a diagnostic method using a load cell (range – 0 g to 150 g) with a resolution of 0.3 g was utilized. Data was taken at 1 s intervals and resulted in these findings:

- There is a significant variation (up to +/-20% of mean string tension) during a simulated pulling of a ribbon. Therefore, the existing string tension setup on current equipment (which is purely mechanical) may not be enough to ensure uniform string tension during ribbon growth.

- Electronically controlled equipment has a much smoother payout of string and is less likely to have dropouts in string tension.

- Some of the variation may be attenuated by at least a factor of two by modification of the string reels.

Figure 3 below shows two representative plots of string tension as a function of time from two experiments. The vertical scale is a measure of string tension. The top plot shows our present SOP system, with a variation of +/- 21% from mean string tension. The dropout that suggests an apparent glitch in signal is, in fact, real and due to the manner in which the string was wound on the reel. The lower plot shows a modified reel with improved equipment for string tension control. A variation of +/-9% from mean can now be achieved. Implementation of this has resulted in improvement of about 3% in yields.



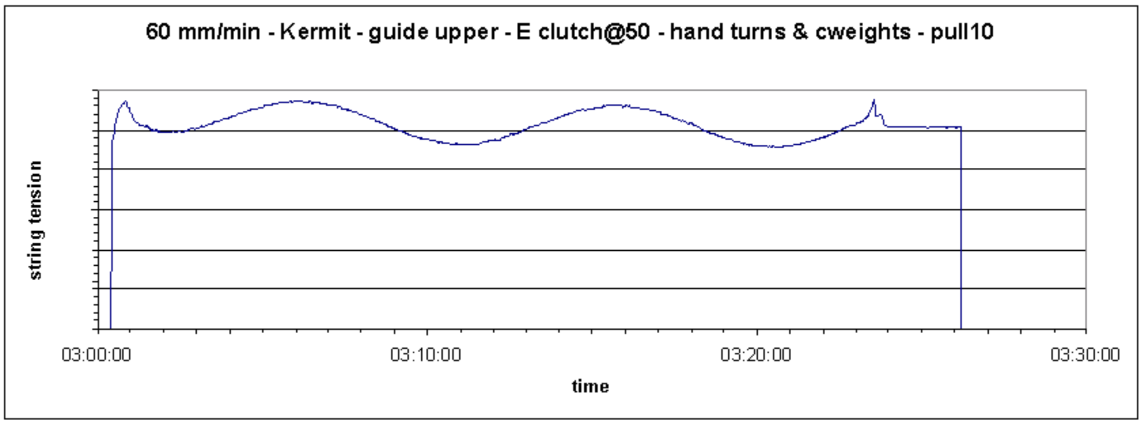


Figure 3 – Showing the variation in string tension with the older method (top) and the improvements using the newer method (bottom)

<u>Efficiency Improvements in Gemini Ribbon - Starting Lifetime Improvements</u>

In earlier work, it appeared likely that transition metal impurities were responsible for a depressed lifetime in the as-grown Gemini ribbon. Through working with a vendor, an enhanced graphite purification method was employed on some of the key parts used in the hot zone of the Gemini furnace. This enhanced purification has made a significant difference in the starting lifetime of Gemini ribbon and ultimately in the solar cell efficiency. The change in lifetime is illustrated in the graph below in Figure 4 where the improved purification parts were introduced and the starting lifetime immediately went up.

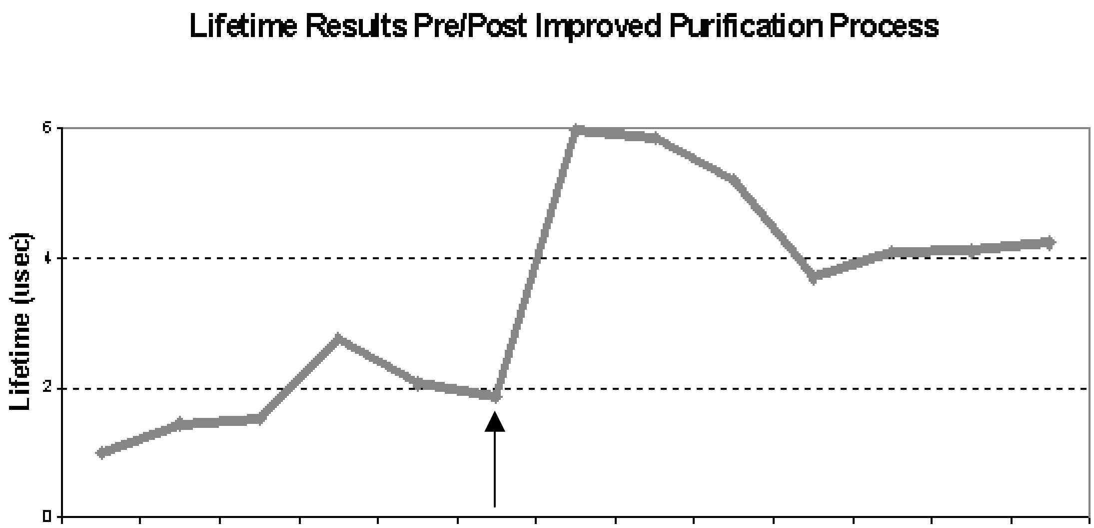


Figure 4 - Starting lifetime before and after improved graphite purification. The arrow indicates when the enhanced graphite purification was introduced.

There has been a corresponding increase in cell efficiency, to the point where the average of the best batch of Gemini cells to date equals that of the best batch seen for single ribbon cells. The histogram below in Figure 5 shows the distribution of the best Gemini batch to date. Note that the batch average is 13.67% and that the best cell is 14.55%.

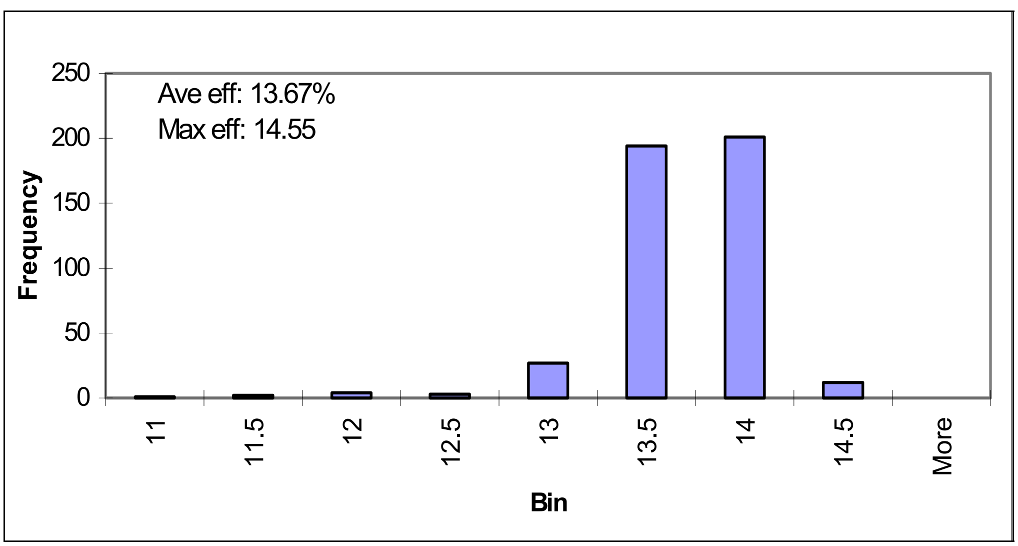


Figure 5 - Efficiency Histogram of Gemini cells

(3) Development of Wrap-around Contacts for Making Monolithic Modules

Wrap-around contacts mean that both the front and rear contacts of a cell are accessible from the back of the cell. To form a monolithic module, conductive adhesive bars are printed on a sheet of backskin material, and the wrap-around contacts are then bonded to these bars. The basic idea of wrap-around contacts is shown in Figure 6. Note that such a concept eliminates any wires between adjacent cells, and all the handling that is associated with forming front to back contacts using wires is now eliminated.

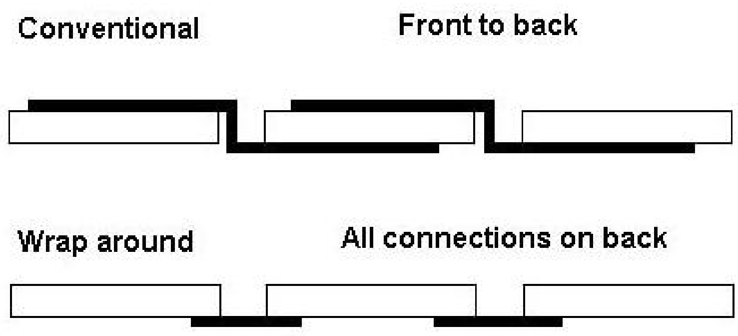


Figure 6 - Showing how a module made with wrap-around cells would differ in interconnection from a module made in the conventional way.

Figure 7 below shows how wrap-around contact cells would be used to form a monolithic module.

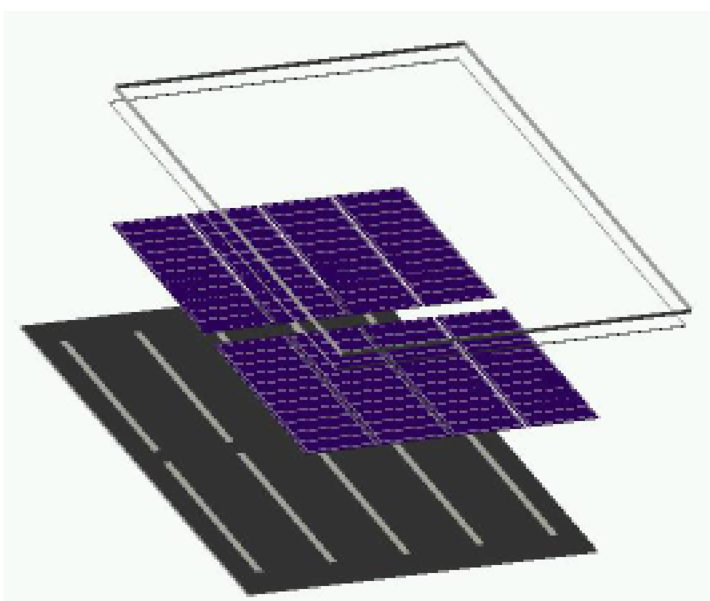


Figure 7 – Showing the layout of a monolithic module. The backskin material with the printed bars of conductive adhesive is at the bottom, the wrap-around cells are shown in blue, a transparent encapsulant layer and finally a superstrate of glass are shown.

Initially, it was planned to first make modules of 36 cells of 120 cm^2 size (50 - 58 W module size) and then eventually to make modules of 72 cells (115 W module size).

Early indications of an issue with String Ribbon edges precluded the pursuit of this plan. It was learned that to make a successful monolithic module with full area 120 cm^2 cells required that the cell edges, where the wrap was taking place, be uniform in thickness and shape – preferably to be flat. If this edge was not sufficiently flat, then it was possible for encapsulant to flow around the edge of the cell and disrupt the bond of the contact (for the front contact) to the conductive adhesive bar printed on the backskin.

In practice, the String Ribbon edges that contain the string are not as uniform as, say, a saw cut wafer. In fact, it was demonstrated that using saw-cut, cast poly wafers, a monolithic module of 36 cells could be made fairly readily. Two such modules were made and were tested in an environmental chamber for thermal cycling. They showed negligible power drop after 400 thermal cycles. To put this into some context, the standard qualification tests require that no more than a 10% power drop in a module is seen following 200 thermal cycles. This test and further tests described below showed that the conductive adhesive used for the monolithic module concept will hold up well in accelerated testing.

Given the somewhat variable nature of string edges on ribbon blanks, wrapping the fingers around this edge and then forming a good contact with the conductive adhesive bars printed on the backskin proved to be problematic. Since the ribbon cell blanks are laser cut, the laser cut edge on a half cell size was used instead. This proved to be a better means to obtaining more uniform performance, but it did require that the usual cells of 120 cm^2 be cut in half to 60 cm^2.

Consequently, experiments with using the laser cut edge instead of the string edge have been conducted. This has the following important advantages:

1. The cut edge is generally flatter than the string edge, which will minimize encapsulant flow between the cell and the conductive ink on the backskin.
2. If and when a cell cracks, it almost always cracks parallel to the string edge and usually close to one of the string edges. If the cells wrap on the string edge, this effectively kills the module but has a much smaller effect on cells wrapped on the cut edge.

Efficiency of Wrap-around Contact Cells.

Initial results showed efficiency and yield to be comparable to the cells having the wrap-around contact on the string edges, and recent efficiencies on wrap-around (WA) contact cells have shown improvements so that the ultimate project goal of 14% cells now appears within reach.

The table in Figure 8 has results that indicate this. The cells in this table were fired using a new production firing profile. Half of the cells were cut after firing and the other half were cut before application of the contacts. In addition, the contacts were formed in a way that allowed for more silver to be printed on each finger. This undoubtedly helped to reduce the series resistance and improve the fill factors. The cells test quite well, and there is a new record WA cell of 13.57%. The cells are all 60 cm^2 in area.

		Voc	Jsc	Vmax	Imax	Pmax	FF	Eff.	Weight
Cut after firing									
Average	18	0.587	31.98	0.462	1.683	0.778	0.690	12.96%	4.48
St. dev.		0.003	0.23	0.004	0.017	0.012	0.008	0.20%	0.50
Cut before contacts applied									
Average	17	0.585	31.73	0.462	1.687	0.779	0.698	12.98%	5.22
St. dev.		0.004	0.47	0.005	0.029	0.020	0.010	0.34%	0.44

Record Cell 7-3AF

Voc	Jsc	Vmax	Imax	Pmax	FF	Eff.
0.590	32.11	0.469	1.737	0.814	0.717	13.57%

Figure 8 – Table showing cell results for wrap-around contact cells on String Ribbon.

(4) Accelerated Testing of Monolithic Modules

Following the discussion above, modules with 60 cm^2 size cells were made that would have a power output of about 25 W. The construction of these modules was this: the wrap-around cells were placed on the backskin material that contained the printed bars of conductive adhesive, an encapsulant sheet was placed over the cells on the backskin and then a glass superstrate was placed over all this. The encapsulant used was the proprietary one developed by Evergreen. This assembly was placed in the laminator. In order to minimize cell cracking, the bladder pressure in the laminator was kept about half that of the usual pressure. These modules were laminated and then tested in an environmental chamber without any particular edging placed on them – i.e. the module edges were bare in these tests. Thermal cycling data out to 400 cycles is shown in Figure 9 for a number of 25 W size modules. The data again indicates that the fundamental scheme works very well.

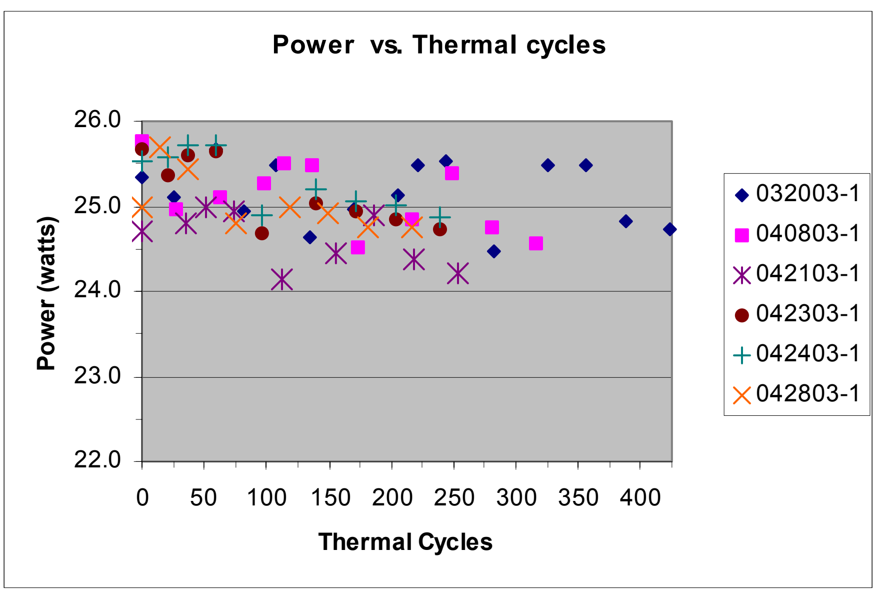


Figure 9 – Thermal cycling data for 25 W size monolithic modules.

(5) Development of a Production Machine to Form Solar Cell Contacts Using Evergreen's Unique Contact Printing Technology

Evergreen Solar has a unique contact application method based on a transfer technique that readily lends itself to String Ribbon in general and to wrap-around contacts and thin wafers in particular. Initially a prototype machine was made in the R&D lab to test the concept of an in-line machine to form contacts. Following the successful deployment of this prototype machine, a production sized machine was designed, built, and debugged. A summary of the results on this machine includes:

1) Transfer of contacts to the wafers. Transfer has been quite good with problems on < 1% of the cells, and we believe that most of the remaining poor transfers are due to inconsistent placement prior to the transfer stage. Design changes to improve placement have been made, and these are being implemented.

2) Damage to front contacts during back contact application. As a result of improvements to our cycle time, the front contacts now have less time to dry and become fixed to the Si before back contact application occurs. Front contacts that are not well fixed to the Si are more prone to forming bubbles when suction cups engage the front side of the cells during back contact application. These bubbles result in small regions of broken or missing front fingers. To achieve better drying, the addition of extra heating capacity in a buffer region between front and rear contact application has been done. In addition, it was observed that many of the suction cup bubbles occurred in a particular region of the cell, and it was found that by modifying the method used to fix the front contacts to the cells, a large percentage of the suction cup bubbles have been eliminated.

3) Transport of wafers between front and rear contact application: In transferring wafers from the front contact application machine to the dryer and then to the buffer, it was found that good wafer placement accuracy was being lost and wafers were not being loaded properly into the buffer. The addition of some sensors and a wafer-adjust stage have greatly improved the transport and placement accuracy of the wafers.

The net result of this work on the in-line contact machine is a machine and process that can now have a rate of 5 MW/yr and can easily be modified to do 10 MW/yr. Furthermore, the more accurate placement of contacts now has resulted in efficiency gains on the order of 0.2 absolute.

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13. ABSTRACT (Maximum 200 words): This report describes Evergreen Solar, Inc., String Ribbon Si PV technology resulting in an advanced generation of crystalline silicon PV module manufacturing technology applied to a virtually continuous, fully integrated manufacturing line. General objectives for this first year (or Phase I) are listed here, followed by the principal accomplishments for each of these objectives: (1) scale-up of a production-worthy method for doping feedstock; (2) development of a multiple-ribbon growth system (Project Gemini); (3) development of wrap-around contacts for making monolithic modules; (4) accelerated testing of small-size (25 W) monolithic modules; (5) development of an in-line production machine to form solar cell contacts using Evergreen's unique contact printing technology.

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