October 2004 • NREL/SR-520-36908

Subcontractor Report

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

Phase II, Annual Technical Progress Report
1 April 2003–31 May 2004

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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 second year's activities under this subcontract. The project title is "Innovative Approaches to Low Cost Module Manufacturing of String Ribbon Si PV Modules". 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. The original plan for the program was to focus on monolithic module development. A major development in String Ribbon technology began in the early part of the program and its success necessitated a change in the original plan. This development was the discovery of dual ribbon growth from a single crucible. Thus, in the second year of this program, it was decided to place most of the emphasis on the further development and implementation of dual ribbon growth from a single crucible (project Gemini) and to bring to a close the work on monolithic module development.

General objectives for this second year (or Phase II) are listed here, followed by the principal accomplishments for each of these objectives:

(1) Production implementation of multiple ribbon growth (Gemini -dual ribbon growth)

(2) Growth of surface oxide free Gemini ribbon

(3) In-line Diagnostics

(4) Monolithic module developments.

<u>(1) Production implementation of multiple ribbon growth (Gemini -dual ribbon growth)</u>
Gemini allows for the growth of two ribbons from a single crucible. This then results in a nearly halving of some of the consumables costs for ribbon growth. The final iteration of Gemini, termed Gemini II, has been introduced into production and by year end, 2004, will be capable of producing 15 MW/yr of String Ribbon. This project has become one of the most successful in Evergreen's history. Aggressive targets were set for it in terms of the usual production metrics such as yield and machine uptime and these have been met or exceeded. The ribbon so grown has also been the flattest ever produced in a production environment at Evergreen. All this has produced a net result of a very significant lowering of wafer costs.

<u>(2) Growth of surface oxide free Gemini ribbon</u>
Prior to the development of Gemini, a so-called no-etch process was developed. This process allowed for the direct movement of String Ribbon wafers from crystal growth to diffusion without any intervening wet chemistry or etch steps of any kind. Obviously, in order for the no-etch process to work, control of any as-grown surface is critical. With the introduction of Gemini, this became an issue once again. A redesign of the Gemini hot zone finally allowed for improved control of the as-grown surface. A finite amount of surface oxide is unavoidable in String Ribbon growth, but conditions were found that allowed this oxide layer to be thin enough and reproducible enough to be fully compatible with the no-etch process.

<u>(3) In-line Diagnostics</u>
For Gemini, a number of developments in the area of controls and instrumentation were introduced. These included a better method to measure and control ribbon thickness, a more accurate means of measuring melt depth, and an improved method to produce uniform thickness between the front and rear ribbons in a Gemini system.

<u>(4) Monolithic module developments</u>
The most significant development here was the demonstration that the bond between the conductive adhesive bars printed on the backskin material was so good that it could last to well over 1000 thermal cycles.

(1) Production implementation of multiple ribbon growth system (Gemini -dual ribbon growth)

The Gemini process in which two silicon ribbons are grown simultaneously from a single crucible is illustrated in Figure 1. The String Ribbon process is utilized, but now there are two sets of two strings each. As before, the process is virtually continuous, the ribbon is p-type, 2-3 ohm cm., and is grown in 2 m long strips that are then harvested off a growth machine without interrupting growth.

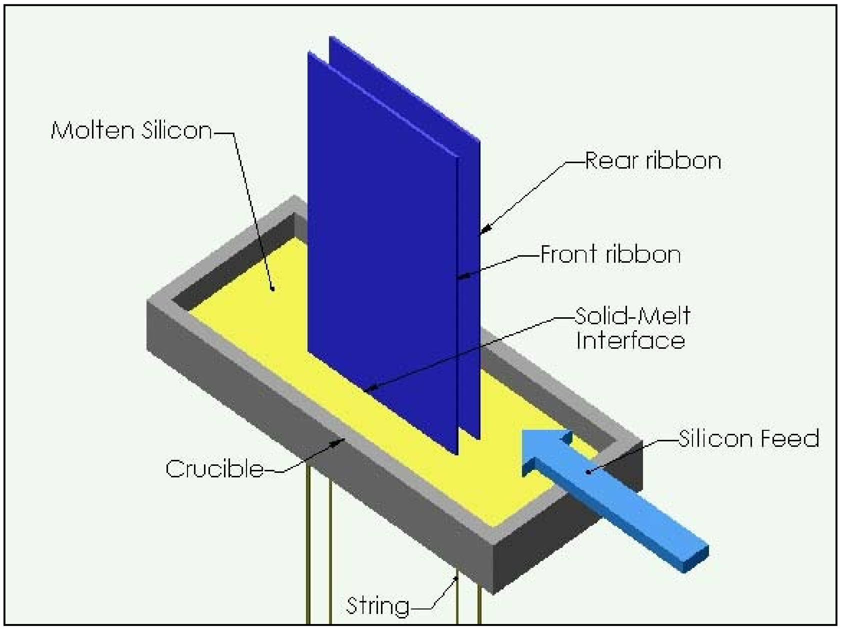


Figure 1 - Gemini - dual silicon ribbons are grown from a single crucible.

In the course of development of the Gemini process, several iterations of the hot zone were studied. The key requirements for a production worthy hot zone and process were these:

- Flat ribbon
- High yields and high machine uptime
- Ribbon surface free of surface layers
- Reduced part count
- Long run lengths.

In order to satisfy these criteria, a redesign of an earlier Gemini hot zone was undertaken. As will be shown further on in this report, the final hot zone chosen satisfied these criteria quite well. This new hot zone configuration was dubbed Gemini II, and all earlier configurations were lumped together under the designation Gemini I.

Regarding the second from last of the two criteria above, the number of parts was reduced by almost a factor of two over that of Gemini I. In addition to lowering the overall cost of the hot zone, this part reduction produced a far simpler structure that was much easier to assemble. With the redesign of the hot zone, a vastly improved capability in temperature measurement was also introduced and one important result of this enhanced capability coupled with some thermal design changes allowed for the longest run lengths ever seen for String Ribbon. Run length is defined as the time that a graphite crucible can be used before it is seriously eroded by the molten silicon. Increased run lengths translates directly into reduced consumable costs. Thus this development addressed the last of the above requirements. A major emphasis at Evergreen is the full implementation of Gemini into an ultimately 15 MW production line. Figure 2 shows an individual Gemini machine with two ribbons growing from it and Figure 3 shows a row of Gemini machines.

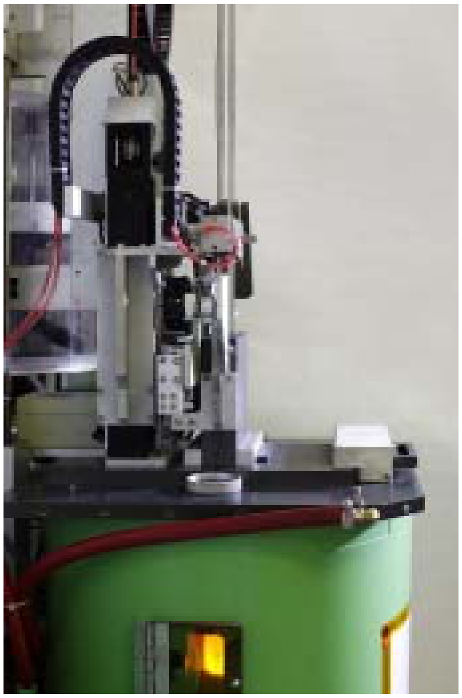


Figure 2 – An individual Gemini machine

Figure 3- Row of Gemini machines

In Figure 4, a production operator is shown removing two Gemini strips from a crystal growth furnace.

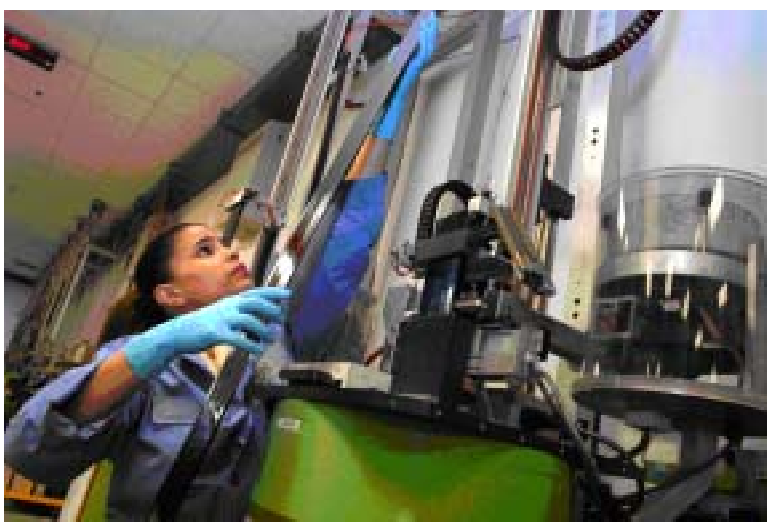


Figure 4 – A production operator removing two String Ribbon strips simultaneously

<u>Pilot Line Production Metrics - Yield and Machine Uptime</u> - One key metric for a new process being introduced into production is yield. As the project began, fairly aggressive yield goals were set for it. The Gemini II hot zone has shown excellent yield numbers. The series of figures following, figures 5,6, and 7, show the actually obtained yields (the red line) vs. the goals (in green), as a function of time. The vertical scale is the yield and the horizontal scale is time in weeks. The data represents approximately 3 months of running in 2004.

The figure below, Figure 5, shows the actual yield achieved in the crystal growth area and Figure 6 shows the yield against plan for cell making.

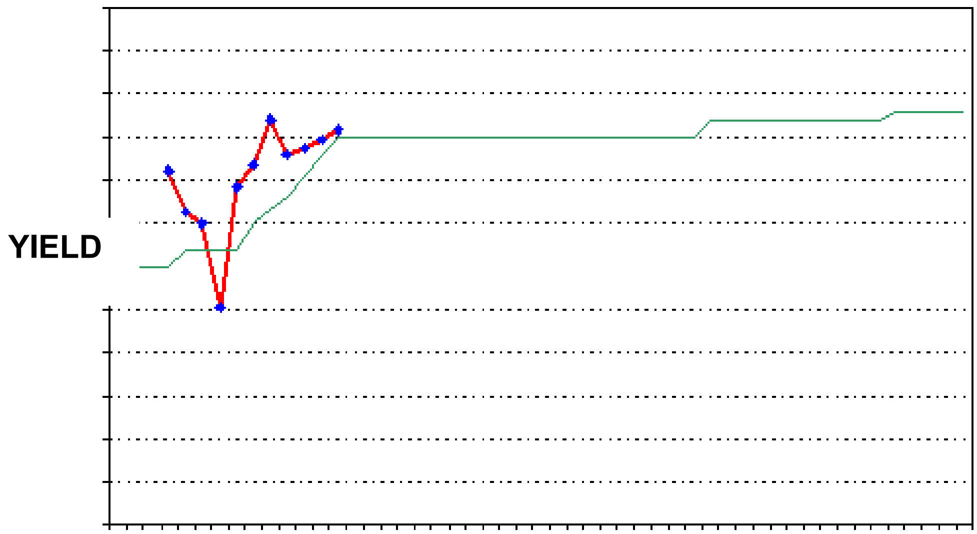


Figure 5, Pilot line crystal growth yield (in red) against plan (green) for Gemini II.

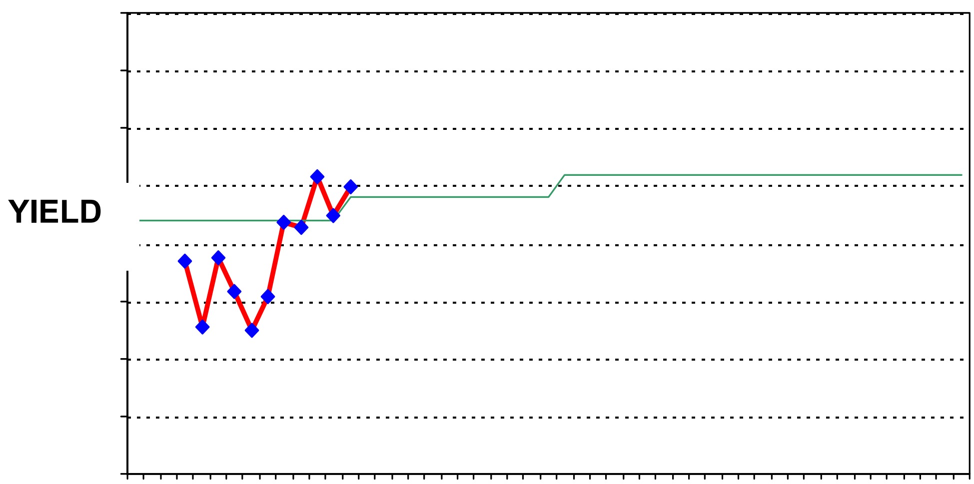


Figure 6 - Yield for cell making for Gemini II wafers against plan.

Finally, in Figure 7 below are shown the achieved and targeted yields for module making using Gemini II wafers. Again it can be seen that the key production metric of yield is either being met or even exceeded. In this latter case, the high level of flatness seen in the Gemini II wafers has undoubtedly been a major causal factor. The dip in yields for all three curves in Figures 5,6, and 7 was due to the various hot zone configurations (prior to Gemini II) that were under test during those earlier weeks.

In general, it can be stated that the recent overall factory yields so far obtained with Gemini II exceed anything obtained with earlier technologies at Evergreen Solar and represent a significant step towards the goal of low cost solar cell module manufacturing.

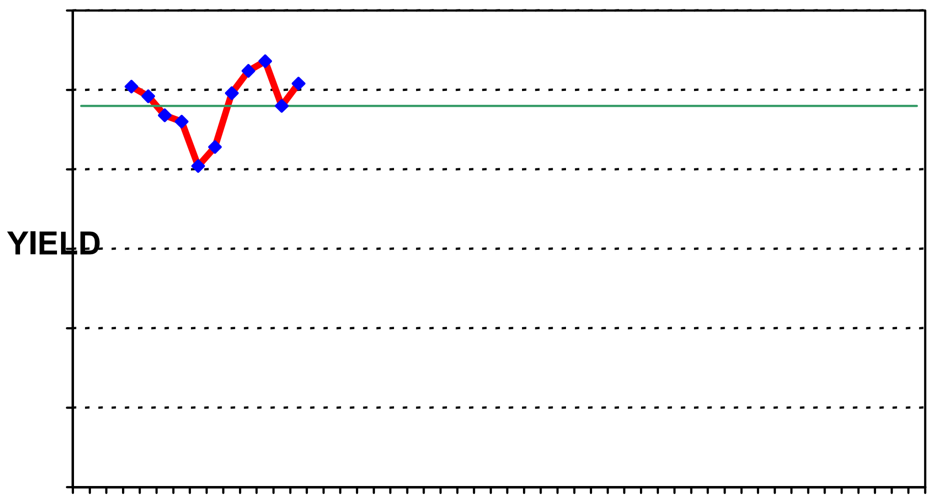


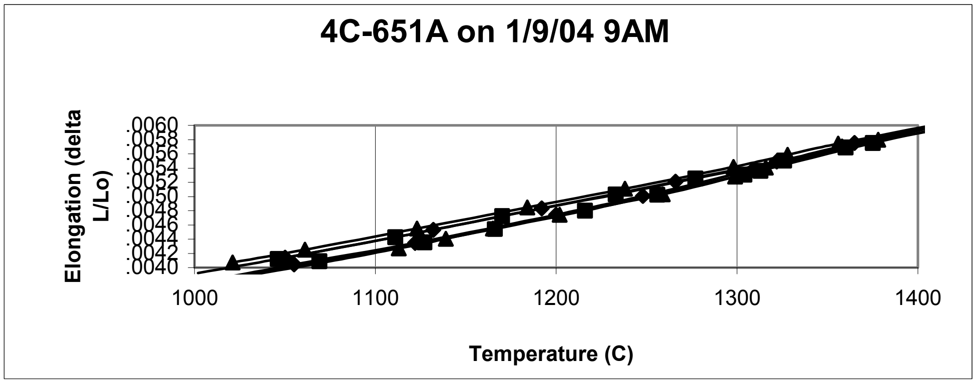
Figure 7 - Yield for module making vs. plan for Gemini II wafers.

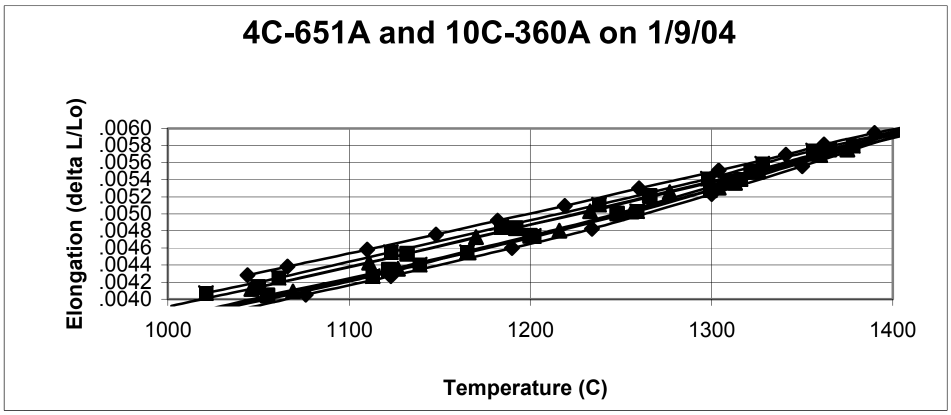
The major remaining issue with even higher production yields is that of thin ribbon edges. A detailed investigation of this effect and means to ameliorate it was undertaken. Two areas in particular were studied. One was that of possible changes in the Coefficient of Thermal Expansion (CTE) values of the string material and the other involved a detailed study of the thermal profile across the ribbon width.

CTE Characterization of string

The graphs below in Figure 8 are the first attempts at elongation measurements that would allow for CTE determinations of the string material. This is a difficult measurement as it must be made at rather high temperatures. All the measurements shown in Figure 8 are done up to 1400°C. Recall that the melting temperature of silicon is 1412°C and that silicon is not very plastic below about 1000°C

In all the cases shown in Figure 8 the upper curves represent the cooling curve and the lower curves are for the heating curve. These curves indicate that there may be a hysteresis effect. These curves also indicate a possible difference between two batches of string material. One batch did not result in significant edge breakout and the other batch did. More work will be needed to see if there are real differences here.





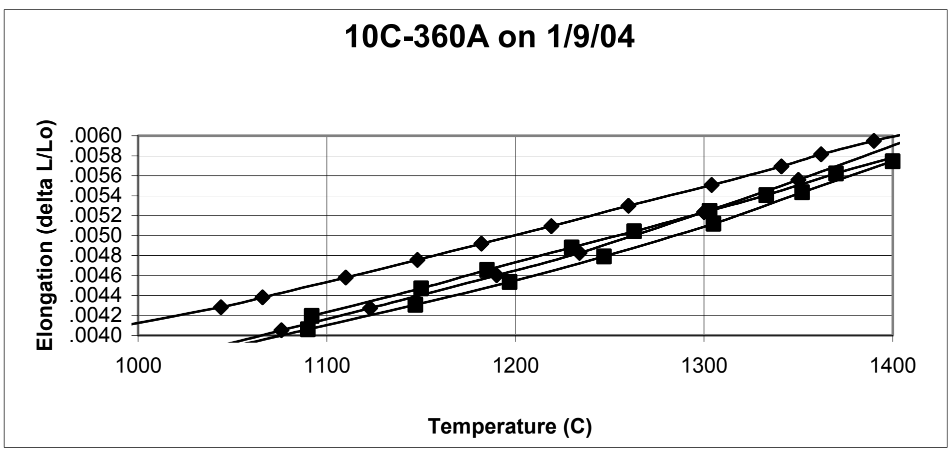


Figure 8 - Elongation measurements of string material.

Thermal Profiles - This was undertaken in order to explore some basic issues of the effects of measurement position, time, thermal regulator position, and gas flows on the thermal profiles in the afterheaters and in particular how this might affect growth at the edges of the ribbon. The afterheater used for this initial work was an earlier version of the overall redesigned hot zone – the so-called "Gemini II". These issues are expected to have similar effects on newer afterheater configurations, and thus can inform our thinking on any future design direction.

The thermal profiles were generated by hanging an unshielded thermocouple down from the furnace top over a crucible with silicon melt in a complete hot zone, but without any ribbons present. The ribbons are a very important element in the thermal performance of the after-heaters, by conducting heat up from the melt, radiating to and blocking radiation from the after heater elements, and engaging and directing gas flows. Thus the profiles do not show the ribbon temperature, but are only a representation of the thermal environment within which the ribbon cools. However, since the ribbons are thin, with high surface area and low thermal mass, their temperature profiles are expected to be similar to their environment except in areas of very high gradient.

Measurement Position - The first three profiles measured temperatures in the plane of the back ribbon, midway between the ribbons, and in the plane of the front ribbon, respectively, under nominally identical furnace conditions (thermal regulator position, gas flows, set point temperature). Subsequent profiles indicated that there is no difference between the front and back ribbon positions. They give the same profile, as expected.

Thermal Profile - All the thermal profiles show that at meniscus height the temperature seen by the thermocouple is hotter at the ribbon edges than at the ribbon center. However, the edges cool faster than the center, so that the edges of the ribbon are cooler than the center of the ribbon at a height of several cm. above the meniscus height. Cooling the ribbon in a "frowning" profile, with the edges colder than the center, works well for reducing stress and is used in the other crystal growth systems. Figure 9 shows a typical profile.

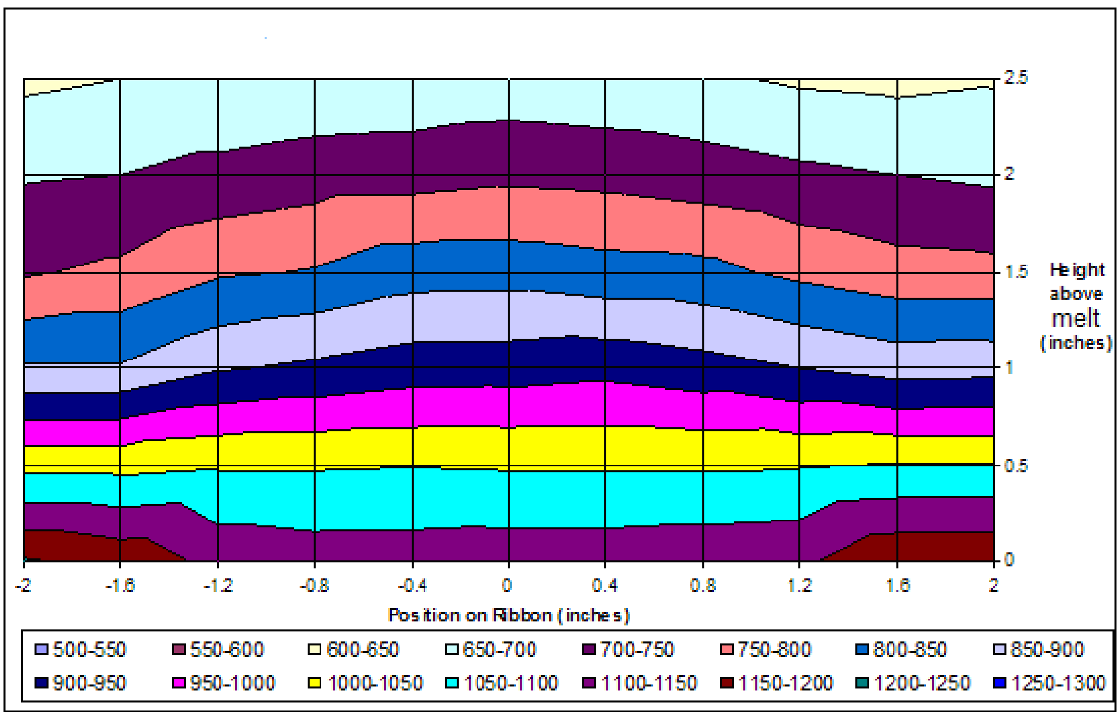
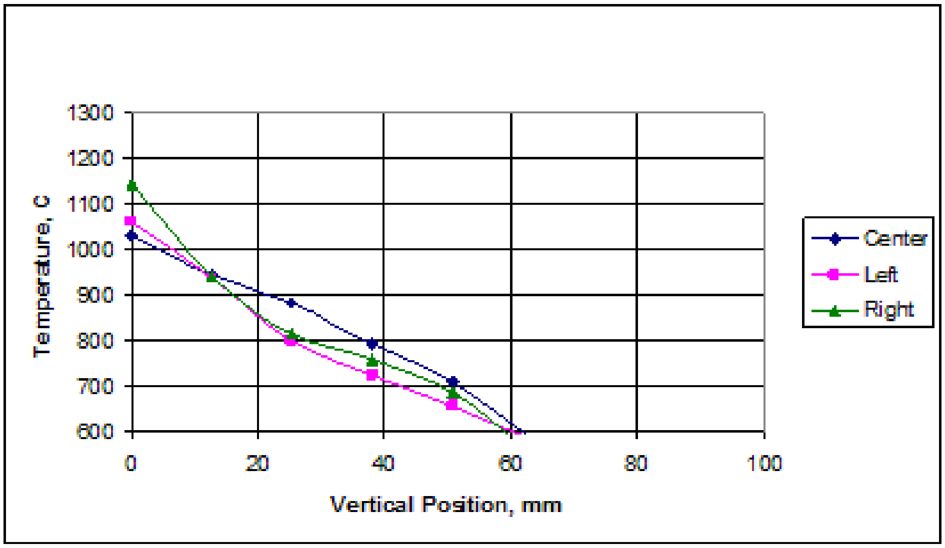


Figure 9 -Typical lateral thermal profile.

Gas Flow Effects – Not surprisingly, there were significant gas flow effects. Comparison profiles were taken using the present gas flows and with the ambient gas turned off so that natural convection would be operative. The temperature increased on the order of 50°C throughout the profile, and the fluctuation in temperature at each point increased from about +/- 5°C to roughly +/- 20°C, showing increased natural convection. However, in a parameter sensitivity study, it was found that the argon ambient gas flow setting could be changed by +/- 50% without any adverse effects on the yield or machine uptime of the growing ribbon. This indicated that the parameter space for these settings for gas flow is quite broad.

<u>Vertical Thermal Profile</u> - Incorporated into the overall hot zone design are devices that allow for thermal regulation at various points along the crucible. Figure 10 shows vertical profiles as a function of positions of the thermal regulators. The upper profile is with the regulators in the uppermost position and the lower profile is for the regulators in the lowermost position.



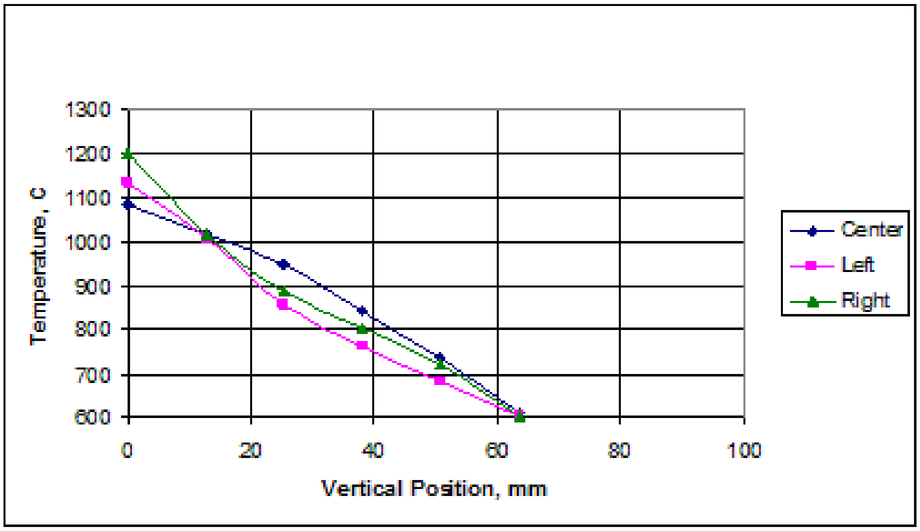


Figure 10– Vertical thermal profiles for various settings of the thermal regulators.

It can be seen that moving the thermal regulators to maximal positions can introduce major changes in the vertical thermal profile.

Machine Uptime
Machine uptime is a measure of how much time a machine that sits on the production floor actually produces usable ribbon. Figure 11 shows results obtained for the first quarter of 2004. The dip in the results is due to the effect of bringing on more crystal growth furnaces. In any case, it can be seen that the goal, while quite aggressive, is basically being met.

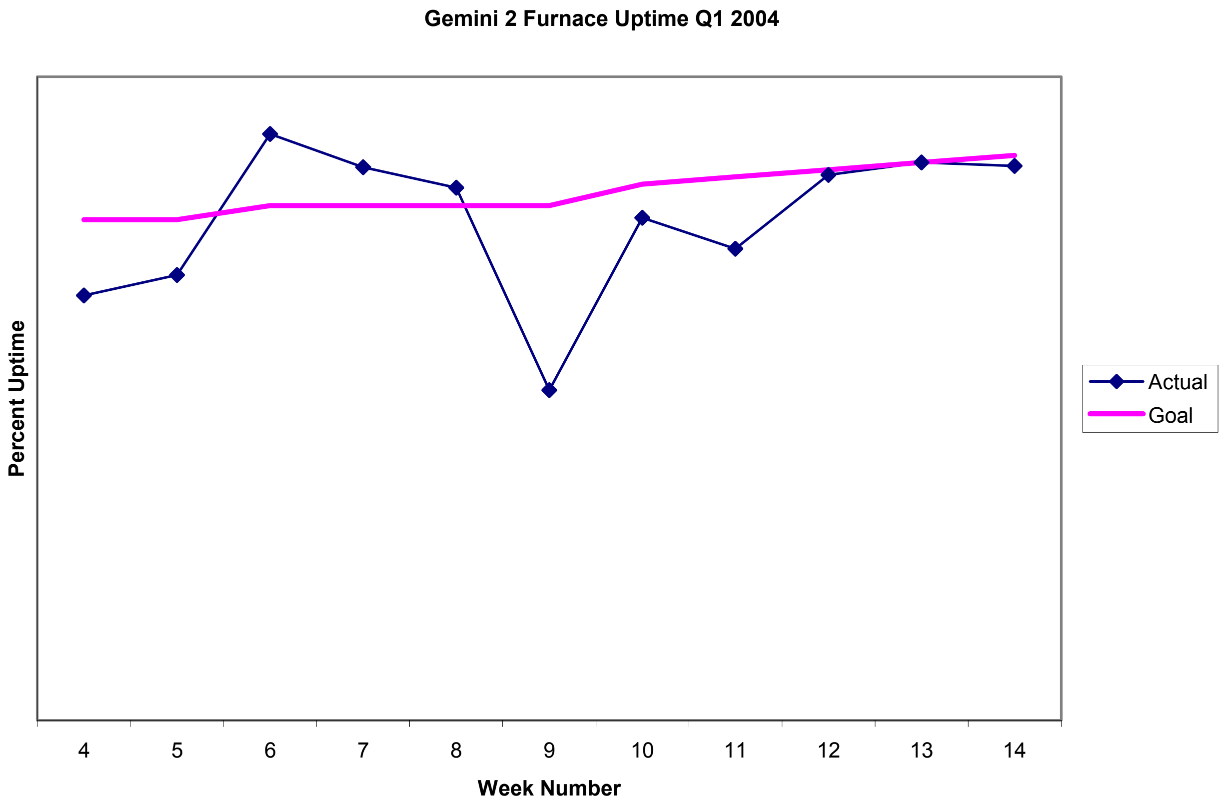


Figure 11 - Uptime vs. goal for Q1 , 2004

(2) Growth Of Surface Oxide Free Ribbon

An issue with the earlier iterations of the Gemini hot zone was that of the formation of an oxide stripe on the two inner surfaces of the growing ribbon. Since a continuous ribbon growth system must be open at the top to allow the ribbon to emerge, a finite amount of oxygen in the ambient is probably inevitable. The ambient contains Argon that is under some positive pressure, but not enough to prevent some entrainment of outside air. This oxide stripe was anywhere from one hundred to several hundred Angstroms thick. As will be shown further on, this is sufficient to inhibit or slow down phosphorus diffusion and create regions of very shallow junctions. Not surprisingly, cells made on wafers that contain such an oxide stripe can have very low fill factors due to low shunt resistance. Evergreen's production area did not want to have to keep track of the inside and the outside surfaces of a Gemini wafer as this would entail another handling step. Consequently it was necessary to find a method that would eliminate the formation of such an oxide stripe.

Several factors were brought together to address this problem. A redesign of the afterheater and other components in the hot zone was done along with further consideration to the ambient gas flow patterns in the machine. This iteration of the hot zone is now referred to as Gemini II. The result of deploying it has been an elimination of any significant surface oxide stripe, as will be shown below. Gemini II also provided for another significant benefit. The number of parts was reduced by almost a factor of two over that of its predecessor, Gemini I. The reduction in parts, in addition to lowering the overall cost of the hot zone, produced a far simpler structure that was much easier to assemble.

The importance of a thin and uniform oxide layer on an as grown Gemini surface is illustrated in Figure 12 that shows how oxide thickness affects diffused sheet rho. The blue horizontal band labeled optimal sheet rho only refers to present conditions – in future, the optimal value should be higher. This study of oxide thickness vs. diffused sheet rho indicated that above about 80 A, the oxide thickness can matter significantly in uniformity of the diffused layer.

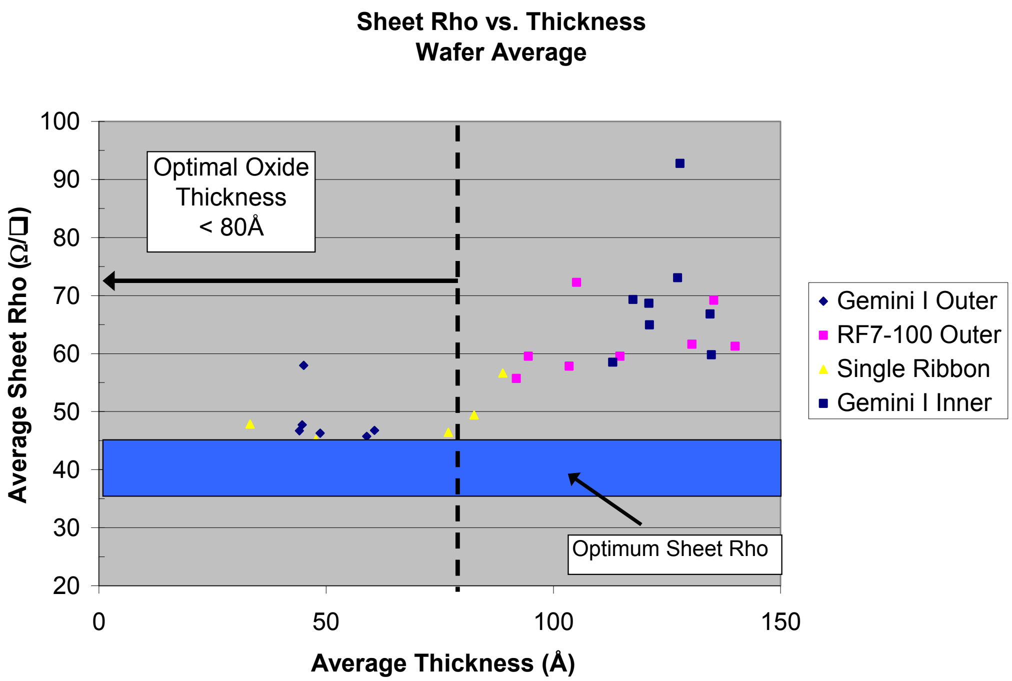


Figure 12 - Diffused sheet rho vs. oxide thickness on Gemini wafers.

Wafers with Re-grown Oxide

A second set of wafers was prepared with a slightly different procedure to compare the native oxide on as-grown Gemini wafers with a thermal oxide formed both on Gemini and on Cz wafers. The native oxide was removed using HF. The wafers were then heated in a furnace in a dry air ambient to re-grow oxides of varying thickness. Oxide thickness was measured only at the wafer center, but diffused sheet rho was measured over a nine-point grid. The sheet rho results for Gemini wafers with re-grown oxide are similar to those with as-grown oxide (see Figure 13). Results for Cz wafers are similar to those for Gemini wafers at low oxide thickness, but for thicker oxides, the Cz wafers do not show a more rapid increase in sheet rho as do the Gemini wafers.

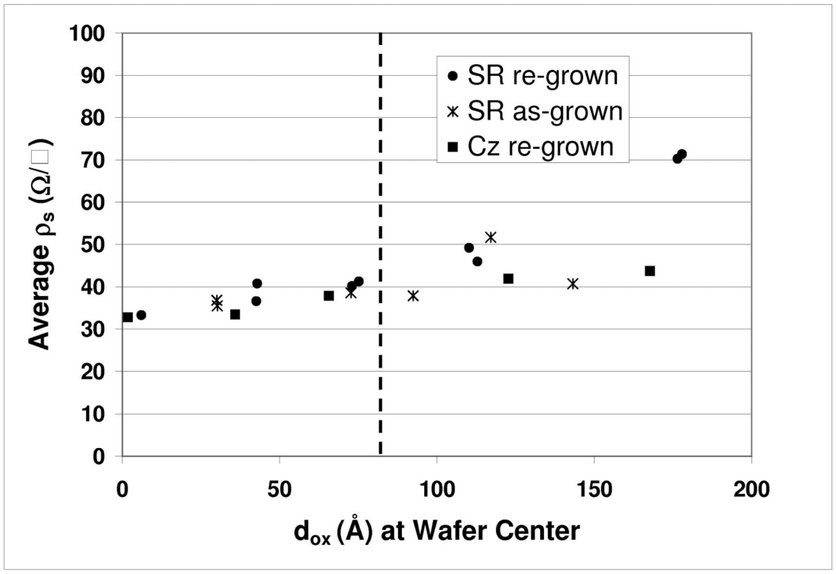


Figure 13 - Sheet resistance vs. oxide thickness for Gemini (SR) wafers with re-grown and as-grown oxides and for Cz with re-grown oxide.

Some of the wafers with re-grown oxide layers were also sent to NREL for SIMS analysis to obtain phosphorus doping profiles as shown in Figure 14. Note that the thicker oxide acts to reduce the overall diffusion concentration along the doping profile.

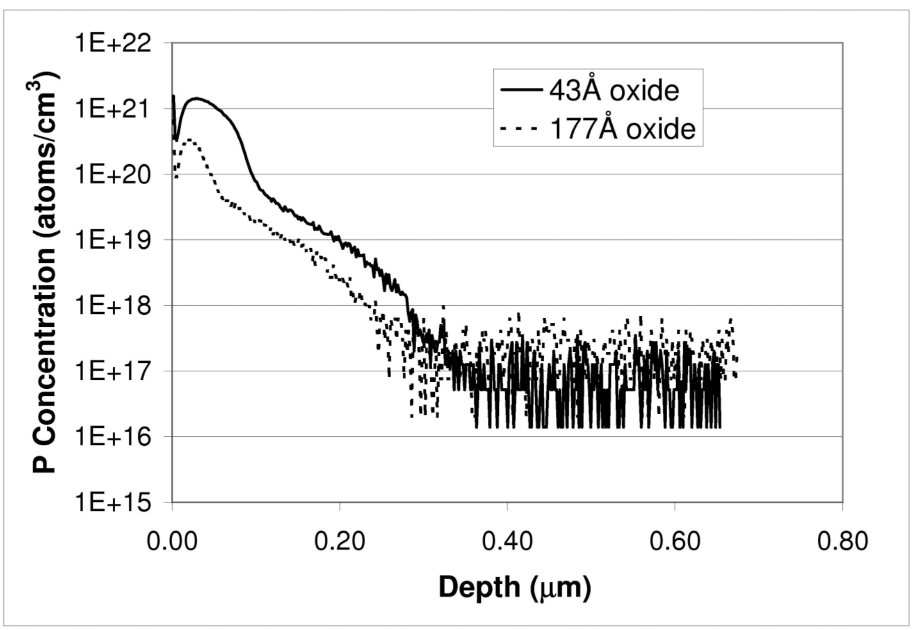


Figure 14 - Phosphorus depth profiles for two re-grown oxide layers on Gemini wafers.

Control of Oxide Thickness
Oxide thickness was tracked on several dual-ribbon production furnaces over a three month period to assess conformance with the process window defined above. Samples were measured at three to five points each on both sides of the wafer, including both front and back ribbons. The results are shown below with data points for the average and vertical error bars showing the within-wafer standard deviation for each measurement (see Figure 15). Each furnace is shown as a distinct data series.

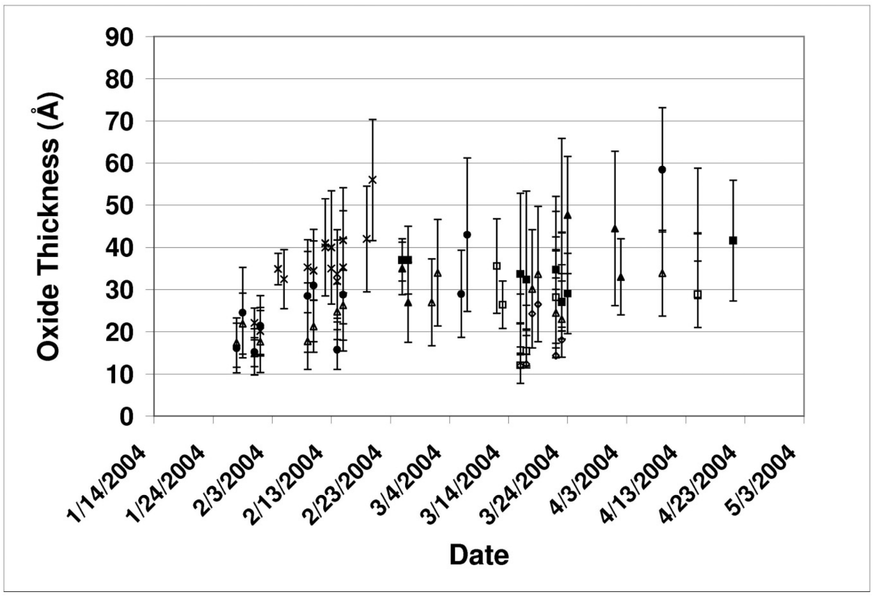


Figure 15 Oxide thickness vs. date for several dual-ribbon production furnaces.

All the results were well within the 80Å process window. The grand average of all measurements was 29.7Å, and the average of all within-wafer standard deviations was 10Å. Establishing this level of control for such thin layers while simultaneously satisfying other constraints necessary for high-yield Gemini crystal growth represents a significant achievement.

(3) In – Line Diagnostics

In the crystal growth area there were several advances made under the general goal of in-line processing. On the Gemini machines themselves, the ultimate goal is a machine that is automated and not requiring operator intervention. Of course this is an ideal- crystal growth still retains some aspects of art as well as science. However, considerable progress towards such a goal has been made and these advances have contributed to the high machine uptimes and yields shown earlier in this report.

Controls and instrumentation for Gemini

Individual Ribbon thickness uniformity - Early in the Gemini work, there were indications that the continuous feeder used on the Gemini machines, along with the appropriate thermal conditions could help the thickness uniformity question. It should be recalled that the feedstock material used is in the form of small spherical shaped silicon on the order of one mm in diameter. An immediate question with the continuous feeder was the uniformity in distribution of the feedstock particle sizes. Although there was considerable variability here, it was felt that it still might be possible to utilize the feeder to help foster a constant volume of silicon melt and uniform thickness. To this end, a redesigned feeder was built and successfully tested in the lab under accelerated conditions that would simulate about a total of 6 months to a year of actual growth. A number of these improved feeders were then installed on the pilot line. The feed rate was measured for several furnaces as a function of the set point for each particular feeder. The results are shown in the graph below, Figure 16.

It has been discovered that the use of an improved feeder mount while definitely helpful, is insufficient to insure uniform ribbon thickness in Gemini II ribbon. It has been determined that the variation in the distribution of particle sizes in the silicon feedstock precludes the use of only the feeder as a means of controlling thickness of the grown ribbon by means of controlling the feeder rate.

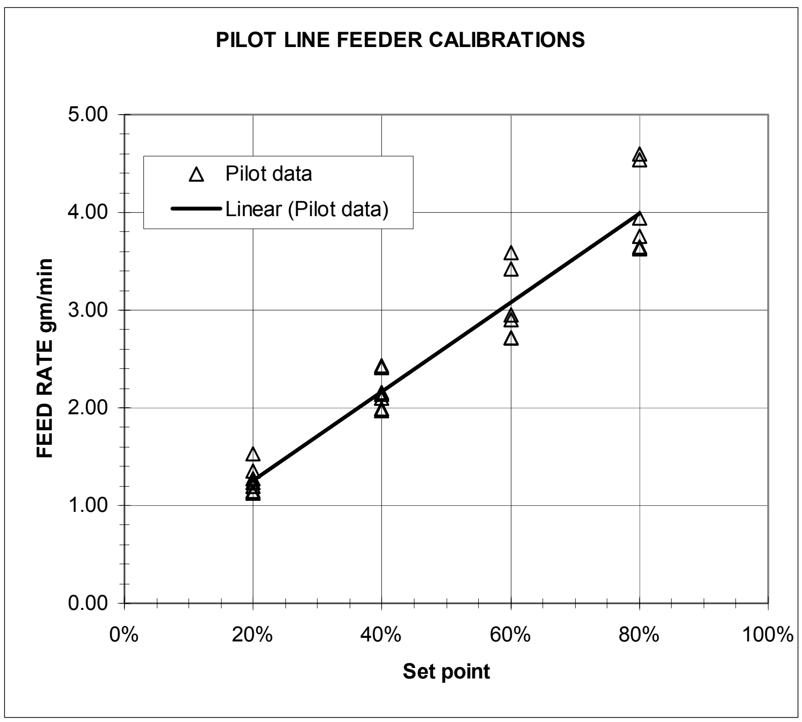


Figure 16- Feed rate as a function of set point.

The scatter around each particular point represents the difference in feed rate in going from one furnace to another and not differences within a particular feeder. These results indicate a scatter of +/- 8%, a number that is too high. The motor speed on the feeder was checked and found to be consistent, so this was not the source of the variation. Some offline tests were then done that indicated that the feedstock hopper may be misaligned and that such misalignment could produce as much as a 26% change in feed rate. This was corrected as part of a new feeder design.

The test for the efficacy of this new feeder in determining thickness uniformity was to weigh each 2m long x 8 cm wide strip of ribbon before it is laser cut into 15 cm long wafers and compare this weight to that theoretically expected, based on the target thickness of the wafers of 12 mils (300 microns). The optimum weight per strip for a 300 micron thickness is 104 grams. The table below in Figure 17 shows the weight variation for 12 furnaces in the pilot area. The next to last column on the right is calculated from thickness measurements derived from the thickness measurement device on the Gemini machine and this is then divided by the thickness suggested by the ribbon strip weight. The very last column is the number of strips for each furnace.

Furnace	Avg Wt (g)	Sigma Wt	Avg Wt (g)	Sigma Wt	Theory/True (Back)	N
E01	107.9	4.4	96.9	7.3	1.004	7
E02	101.6	3.8	102.0	3.8	0.953	8
E03	107.6	6.2	101.5	5.4	0.953	1
E04	107.2	3.2	100.9	4.1	0.980	8
E05	104.4	3.9	101.8	5.2	0.996	8
E06	104.3	5.5	112.4	6.9	0.894	6
E07	101.5	4.5	103.1	5.8	0.944	6
E08	110.1	6.2	99.6	7.0	0.990	7
E10	115.2	5.3	91.5	4.6	0.933	1
E11	98.6	6.6	99.3	3.9	0.965	5
E12	105.4	6.4	86.7	6.0	0.969	3
E13	94.3	6.9	89.4	6.4	0.929	4
AVE	104.8	5.2	98.8	5.5	0.959;	7

Figure 17 – Gemini ribbon thickness variation as determined by strip weight.

<u>Reduced Variation in Front to Back Thickness</u>

With the Gemini hot zone, there was a significant issue with a variation in thickness between the front and rear ribbons in a particular furnace. Several things have been done to address this. The first was the modified gas flow as introduced in the Gemini II hot zone. Another was improvements in controlling the feedstock feed rate. Thickness measurement was improved as described next.

<u>Improved in-situ Diagnostics</u>

Methods for measuring temperature accurate to +/-0.4^{o}C were developed. The technique to measure melt depth was refined to the point where fractions of a mil could be measured. However, one issue that arose in this connection was the finding that the melt surface was curved everywhere, due to the small size of the crucible (cf. -1st annual report). In-situ ribbon thickness was developed to allow for a reproducible reading of +/- 0.3 mils.

(4) Monolithic Module Development

As already mentioned, at the outset of this three year subcontract, a major focus was on the development of monolithic module technology. During this second year, the Gemini project became a far more dominant project and the decision was made to concentrate on it and to phase out the monolithic module work. The following will summarize the status of this work by the end of this second year. In the first year report, the method for forming a monolithic module was illustrated. In the interest of clarity for the discussion following, this method is shown again in Figures 18 and 19 below. Figure 18 shows the concept of wrap-around cells that are used in a monolithic module. The dark lines indicate a conductive adhesive that is printed on the backskin material.

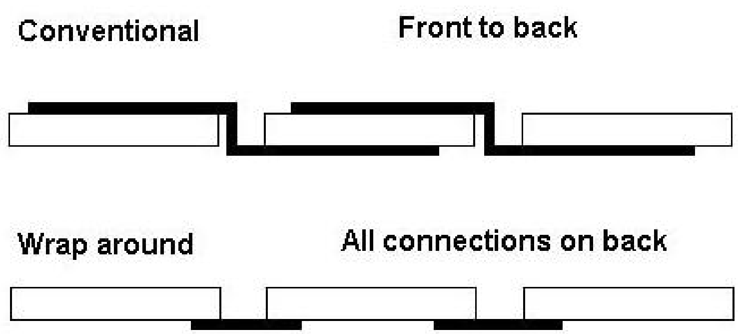


Figure 18 - Showing how a module made with wrap-around cells would differ in interconnection from a module made in the conventional way.

Figure 19 below shows the overall layout for a monolithic module using wrap-around cells. A particularly noteworthy feature is that there is no encapsulant layer behind the cells, they bond directly to the backskin and to the conductive adhesive bars printed on the backskin sheet.

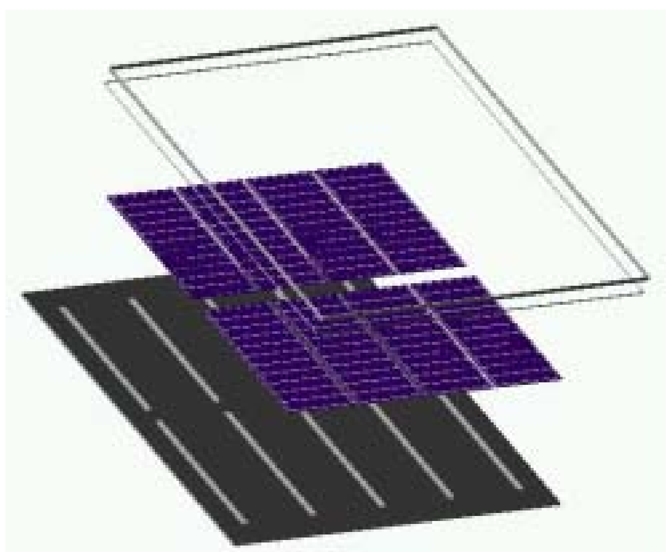


Figure 19 – Showing the layout of a monolithic module. The backskin material with the printed bars of conductive adhesive is at the bottom, the wrap-around cells are shown in blue, a transparent encapsulant layer and finally a superstrate of glass are shown.

The method to make monolithic modules involved three principal areas broken down into the following steps:

1. Wrap-around contact cells
    a. Form wrap-around contacts using in-line metallization application machine to apply front contacts first.
    b. Apply the rear contact using in-line metallizaton application machine.
    c. Fire cells.
    d. Test and bin cells.

2. Backskin
    a. Cut backskin sheets to size and pre-shrink.
    b. Print conductive adhesive bars.

3. Monolithic module construction
    a. Place wrap-around contact cells onto backskin.
    b. Form external contacts and module edging.
    c. Laminate
    d. Trim
    e. Module test.

An in-line machine for forming wrap-around contacts was modified and used as the basis for a production machine to form contacts on conventional (not wrap-around) String Ribbon cells. This machine is now capable of forming contacts at a 10 MW/yr rate, operates on an in-line basis, and is a key element in Evergreen's overall expansion plans.

The backskin material used for forming monolithic modules is the proprietary material originally developed under the first PVMaT project at Evergreen. For use in a monolithic module, an issue that emerged with its use was that of shrinkage. As shown in Figure 19, a series of conductive adhesive bars are printed onto this backskin material. Given this, it is important that the spacing between the bars is maintained – that is, dimensional stability is needed here. Sheet extruded polymers can exhibit shrinkage in the extrusion direction. The shrinkage occurs when the polymer is heated and the polymer chains that were stretched in the extrusion direction tend to relax. This can result in shrinkage in the extruded direction.

The easiest way to handle this problem is to heat the backskin before the conductive adhesive contacts are printed on it. Some work was done on a roll to roll method to do this with I.R. heaters between the two sets of rolls. The speed of the rollers following the heated was adjusted to allow for the shrinkage of the polymer. A production type machine for this, was, in the end, not built. This was partly due to the fact that the close-out of this particular project was already a likely possibility. Instead, a batch type process was used and was found to be satisfactory for the smaller quantity of modules that were made.

An issue with forming the monolithic module was that of the external leads and the sealing of these to the polymer edging. Some of the early accelerated tests, particularly thermal cycling indicated that an electrical failure could occur in this portion of the module. Figures 20 and 21 show the front and rear of such a region.

Figure 20 – Top front of a monolithic module showing the region where the leads emerge from the module.

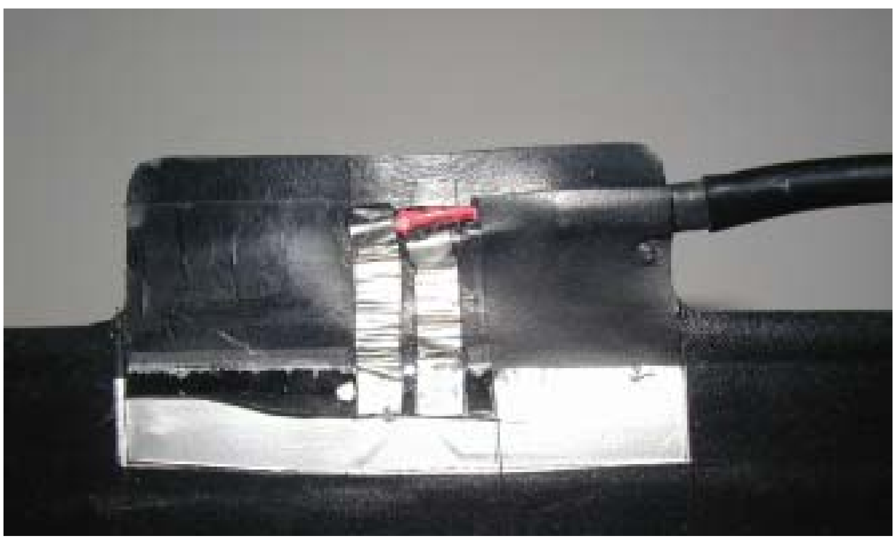


Figure 21 – Rear of the top front of the module shown in Figure 18, with the backskin covering cut away to reveal the connections to the external wire.

These photographs show detail of the leads emerging from a monolithic module with a polymer frame and sealed leads. In Figure 21, the back covering to seal the leads has been removed to show how the leads from the module connect into the wire that becomes the external wire of the module. A long term failure mode can be seen in the leads coming from the module. They show severe crimping – a result of thermal cycling. This crimping can result in a short and a module failure. The issue of crimpling was successfully addressed by using the appropriate polymers in the region of the connection to the external wire and ensuring that the crimpling shown in Figure 21 above would not then occur. A method to incorporate the placement of these polymers in some sort of automated machine and procedure was not developed but it was felt that this could be done when required.

Accelerated Testing

One of the earliest concerns with the overall monolithic module scheme is that of the long term integrity of the wrap-around contacts to the conductive adhesive bars printed on the backskin. As the data in Figure 22 shows, this is not an issue at all. The data in Figure 22 was generated from small (25 W size) monolithic modules that were subjected to thermal cycles until failure. These modules did not have a polymer edging or any edge protection at all. Instead, they had just a bare edge. As a result, the only failure mode seen was delam after the very large number of thermal cycles. As can be seen, a number of modules went out to over 1600 cycles without any power changes greater than +/- 8%.

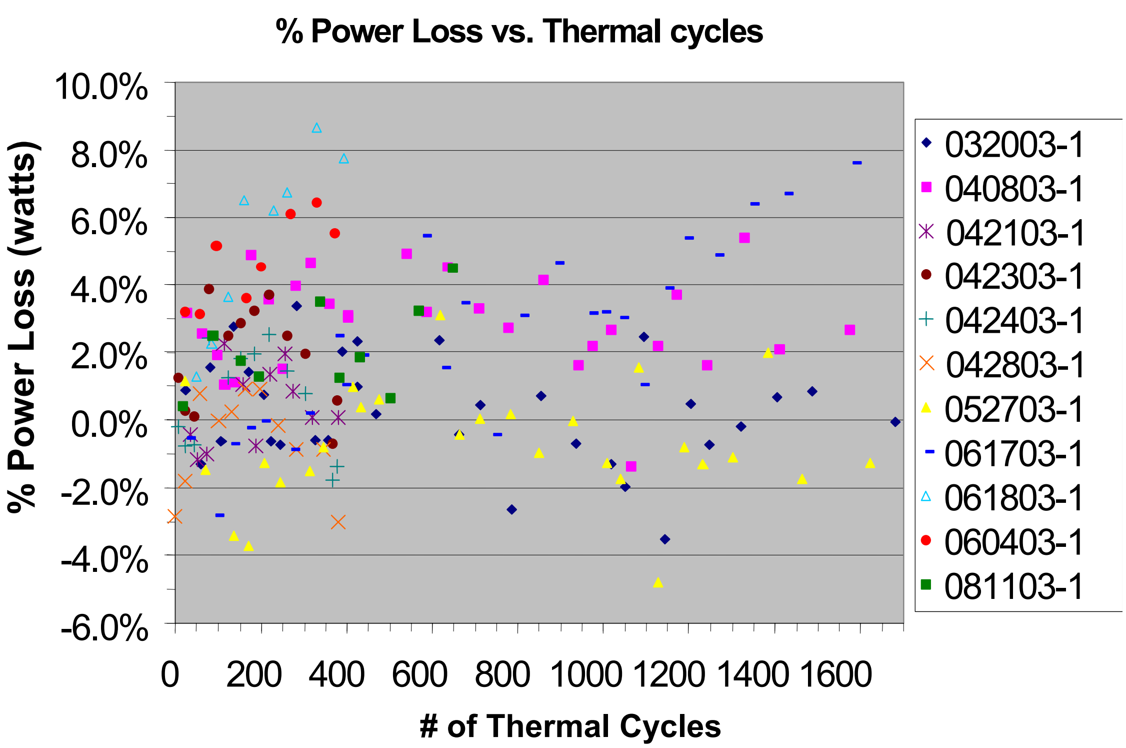


Figure 22 – Thermal cycle data for monolithic modules

SUMMARY

The second year of a three year Photovoltaic Manufacturing Research and Development subcontract resulted in a number of important advances for Evergreen. Foremost amongst these is the production implementation of dual ribbon growth from a single crucible (Gemini) using the String Ribbon continuous ribbon technology. This project has resulted in the flattest ribbon and the highest yields and machine uptime ever seen at Evergreen Solar. This then has resulted in significantly lowered consumables costs and lower overall direct manufacturing costs. In addition, methods to control the as-grown surface of Gemini ribbon have permitted the usage of the so-called no-etch process that allows for direct transfer of as-grown ribbon to diffusion without any intermediate etching step. In line diagnostics for Gemini were further developed – these included more accurate methods for measuring and controlling melt depth and more accurate means to measure and control ribbon thickness.

Earlier in the project, the focus was on monolithic module development. With the Gemini advances described above, monolithic module work was brought to a close during this second year of the overall three year project. A significant advance in this technology was the development of a conductive adhesive in combination with Evergreen's proprietary backskin and encapsulant. 25 W size experimental monolithic modules have been tested and found to able to withstand up to 1400 thermal cycles.

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14. ABSTRACT *(Maximum 200 Words)*
This subcontract resulted in a number of important advances for Evergreen Solar Inc. Foremost amongst these is the production implementation of dual ribbon growth from a single crucible (Gemini) using the String Ribbon continuous ribbon technology. This project has resulted in the flattest ribbon and the highest yields and machine uptime ever seen at Evergreen Solar. This then has resulted in significantly lowered consumables costs and lower overall direct manufacturing costs. In addition, methods to control the as-grown surface of Gemini ribbon have permitted the usage of the so-called no-etch process that allows for direct transfer of as-grown ribbon to diffusion without any intermediate etching step. In-line diagnostics for Gemini were further developed – these included more accurate methods for measuring and controlling melt depth and more accurate means to measure and control ribbon thickness. Earlier in the project, the focus was on monolithic module development. With the Gemini advances described above, monolithic module work was brought to a close during this second year of the overall three year project. A significant advance in this technology was the development of a conductive adhesive in combination with Evergreen's proprietary backskin and encapsulant. 25-W size experimental monolithic modules have been tested and found to be able to withstand up to 1400 thermal cycles.

15. SUBJECT TERMS
PV; module; manufacturer; string ribbon; Gemini-dual ribbon growth; no-etch process; monolithic; conductive adhesive; backskin; encapsulant; coefficient of thermal expansion (CTE); oxide thickness; in-situ diagnostics; thermal cycles.

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