August 2001 • NREL/SR-520-30622

Subcontractor Report

Continuous, Automated Manufacturing of String Ribbon Si PV Modules

Final Report
21 May 1998 – 20 May 2001

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Marlboro, Massachusetts

National Renewable Energy Laboratory

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NREL Technical Monitor: Martha Symko-Davies

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EXECUTIVE SUMMARY

This report summarizes the work done under a three year PVMaT Phase 5A2 program. The overall goal was the attainment of a continuous, highly automated, fully integrated PV production line.

In crystal growth, advances were made which resulted in lower substrate costs, higher yields, and lower capital and labor costs. A new string material was developed and implemented. Following this development, better control of the edge meniscus was achieved. A completely new furnace design was accomplished and this became the standard platform in our new factory. Automation included ribbon thickness control and laser cutting of String Ribbon strips. Characterization of Evergreen's String Ribbon silicon was done with extensive help from the NREL laboratories, and this work provided a foundation for higher efficiency cells in the future.

Advances in cell manufacturing included the development of high-speed printing and drying methods for Evergreen's unique cell making method and the design and building of a completely automated cell line from the beginning of front contact application to the final tabbing of the cells. A so-called no-etch process whereby substrates from crystal growth go directly into p-n junction formation and emerge from this sequence without the requirement of going in and out of plastic carriers for any wet chemical processing was developed.

Process development as well as automation were brought to bear on improvements in soldering technology and cell interconnection in general.

Utiliizing state-of-the-art manufacturing science, the Fraunhofer USA Center for Manufacturing Innovation at Boston University facilitated layout and process flow for the operation of our new factory.

Evergreen Solar's new factory began operations in the second quarter of 2001. A good measure of the significant impact of this PVMaT subcontract is that virtually all of the manufacturing developments stemming from this project have been incorporated in this new factory.

Acknowledgements

A large number of Evergreen personnel have contributed to this work. In the crystal growth area, this includes Rob Janoch, Eric Gabaree, Dr. Andrew Anselmo, Mary Cretella, and Don Humphries. Our engineering work was headed by Jack McCaffrey and others who played a major role were Peter Kane, Sean Duffy, Peter Morse, Doug Miller, Marcos Benoni, Glen Bohling, Harry McDonald, Richard Burt, Keith Brooks, and Chris Mcleish. Cell process work was performed by Dr. Andrew Gabor, Paul Ciszek, Scott Danielson, Mike Ralli, and Joe Fava. Module processing projects were done by Bruce Newell, Bryn Lord, and Mark Mrowka.

Matthias Grossman has overseen the work done for us by the Fraunhofer Center.

NREL characterization work was done by Dr. John Webb, Lynn Gavrilas, and Dr. Bushan Sopori. Our contract monitor, Dr. Martha Symko-Davies, has been extremely helpful and supportive throughout this project.

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INTRODUCTION

This is a final report of a three year project whose overall objective was the development of continuous and automated manufacturing of String Ribbon silicon PV modules. String Ribbon refers to Evergreen Solar's method for forming continuous silicon ribbon. Two earlier reports were issued, following the first and second years of the project. This report summarizes all the work done over the course of these three years, including the last and third year. Evergreen Solar is a fully integrated manufacturer of PV modules with its own, unique technology in almost every aspect of making modules. For this project, the focus was primarily on the crystal growth and cell making areas. The scope of the project can conveniently be divided into four areas and will be discussed in what follows under these headings:

- **I. String Ribbon - Automation, Technology Advances, and Characterization**
- **II. Cell Making - Automation and Process Simplification**
- **III. Modules - Automation and Process Development**
- **IV. Factory Material Handling and Process Flow**

I. String Ribbon - Automation, Technology Advances, and Characterization

String Ribbon Growth Method – Evergreen's method for the continuous production of crystalline silicon substrates is termed String Ribbon and is illustrated in Figure 1.

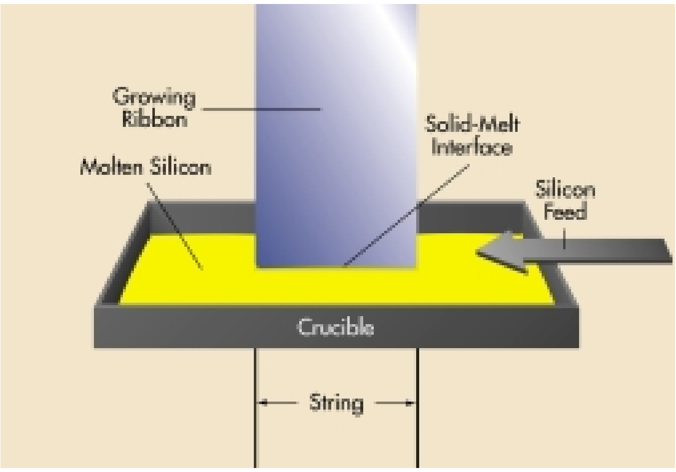


Figure 1 String Ribbon Growth Process.

Two high temperature string materials are brought up through a graphite crucible. The strings serve to stabilize the edges of the ribbon as it is grown. A seed is lowered into a shallow melt of silicon in the crucible, and a ribbon of 8 cm. width is then grown with the strings incorporated into the edges of the ribbon. The strings are non-conductive and left in the ribbon through cell making. The ribbon is grown in an Argon ambient.

The major effect of leaving the strings in the ribbon is the promotion of high angle grain boundaries for about 3 mm from the ribbon edge. The central portion of the ribbon consists of large grains (in some cases with areas> 15sq. cm.) and many coherent twin boundaries. The principal lifetime limiting defects are transition metal impurities and dislocations. Starting lifetimes are usually in the 1-5 microsecond range. The as-grown ribbon is p-type, bulk resistivity is about 2 ohm-cm, and the thickness at present is 300 microns.

The goals for this PVMaT project were to decrease the consumables' costs, to improve yield, machine up-time and productivity, and to reduce capital costs of the crystal growth furnaces. To attain these objectives, the principal projects were an increase in run length through the development of a new string material; a complete redesign of the crystal growth furnace itself; automation of the growth process- particularly thickness measurement and control; and automated laser cutting.

<u>Increasing Run Length</u> – The String Ribbon crystal growth process is designed to run continuously. Early on, a method to continuously replenish feed material and also a means of continually feeding string were developed and deployed. This allowed for a 24/7 operation. With this accomplishment of continuous operation, run length became a major driver of operating and consumables cost. A major factor here was the nature of the string material and an early goal of the project was the development of a better string material.

<u>New String Material</u> – The main criterion here was to find a material with a coefficient of thermal expansion (CTE) value close to that of silicon over the total temperature range of the melting temperature (1412 C) down to room temperature. The approach taken was this. First, various compounds were formulated and formed into short lengths. These short lengths were then used to grow a small amount of ribbon. Using as criteria the resulting ribbon edge quality and strength, as well as ease of growth, a number of possible candidate materials were tested and screened.

Following this screening, the few promising candidates were prepared in longer pieces of tens of feet for more extensive trials. Finally, from these trials, one composition was chosen and a much larger quantity of it was prepared for a full evaluation. The full evaluation proved to be very encouraging. We experienced more than a doubling of run length. After a full quarter of running all of production with this material, we saw some run lengths as high as four times greater than before the introduction of this new string material. While this was not typical, it did indicate the potential with this development.

The new string material also required a better control of the meniscus at the edges of the growing ribbon, close to where the strings are incorporated into the ribbon. Such a method for better control was found and soon thereafter made part of the standard operating procedure. A patent has been filed on this work.

New Furnace Design – The goal here was a redesign of the entire crystal growth system. Specific objectives were to reduce the capital cost of the system; make it more user-friendly and reliable; improve up-time and productivity; be more amenable to automation; and flexible enough to accommodate further technical advances.

Areas that were addressed included a redesign and simplification of the water cooled shell, a redesign of the frame with a smaller footprint, a more compact packaging of the electronics, an integration of all the control functions with a single Programmable Logic Controller (PLC), a much more tightly sealed system so as to reduce Argon consumption and oxygen ingress, a more accurate puller design, a complete redesign of the feeder to eliminate possible sources of metallic contamination, a vastly improved means of deploying the reels of string, and a more generic base plate that could accommodate further advances such as a lower cost hot zone and the growth of ribbon up to 10 cm in width.

Virtually all of the above items were achieved under this program. Figure 2 shows one of the new machines growing 8cm wide ribbon.

Figure 2 Newly Designed Crystal Growth Machines.

Another advantage of the new design was a far better set of viewing ports that made it easier for an operator to sight the hot zone. Some of these can also be seen in Figure 2. The capital cost of each machine was nearly 20% lower than our earlier machines so the overall cost goal was definitely met. A large number of these machines have already been installed in our new factory. Figure 3 shows a row of them.

Figure 3 Row of New Machines.

At present, ribbon of 8 cm width is grown routinely. The new machines are configured such that a change to 10 cm width ribbon can be done with minimal variation to the present design

The feeder was completely redesigned and is shown in Figure 4.

Figure 4 New Feeder.

For this, a number of metallic parts within the feeder chamber were eliminated and non-metallic components were used instead. A method of configuring the string reels was changed so that a much larger reel containing almost ten times as much string as before could now be used. This change alone resulted in a reduction in the number of times that an operator must change the string spools by a factor of ten. Figure 5 shows the new configuration for the string reels.

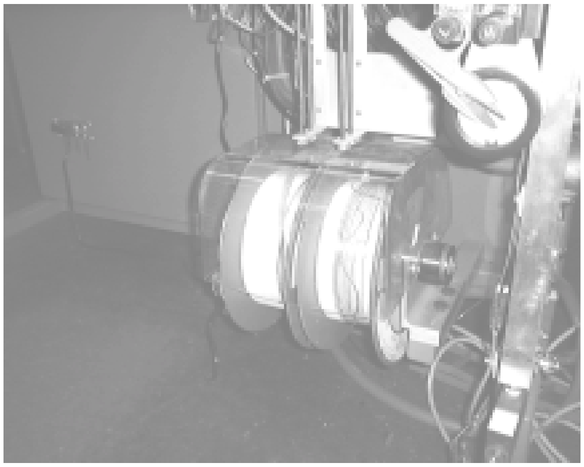


Figure 5 Configuration for Larger String Reels.

Automation of the New Crystal Growth Machines – A parameter that is important for downstream yields is ribbon thickness. The thickness must be uniform across the width of the ribbon and also along its length. Prior to this work, thickness measurement and control were done manually. This process was labor intensive and also posed the possible risk of contamination by excessive handling. Accordingly, we set out to develop a means of automatically measuring and controlling ribbon thickness.

Automatic Thickness Control – In the String Ribbon crystal growth method, thickness uniformity is achieved by adjustments to the melt temperature along the horizontal width of the growing ribbon. In earlier production systems, ribbon thickness was manually measured by the machine operator as the ribbon exited from the machine. If the thickness measurements warranted any thermal adjustments, these were made by the operator based on a few general rules of thumb.

In the first year of this PVMaT program the basic elements of an automatic method for thickness measurement were studied. In the second year, a complete system with feedback control was designed and built. Finally, in the third year, the method was implemented. Initially this was done on a few machines. After sufficient debug, it was ultimately introduced on every machine.

The first element developed was the automated measurement of ribbon thickness. A mechanical method was initially tried but found to be too complex, noisy, and unreliable. A non-contact method was then developed that was far simpler and reliable. This measurement method was found to be far more repeatable than operator measurement. It showed a standard deviation of 0.2 mils (5 microns) versus a standard deviation of 0.75 mils (19 microns) for the manual method. A typical plot of thickness measurement showing the difference in the automatic and manual methods can be seen in Figure 6.

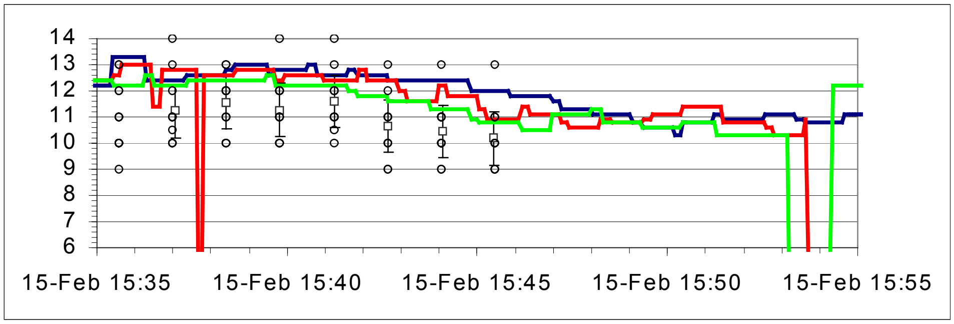


Figure 6 Manual vs. Automatic Thickness Measurement.

It also shows the wide differences in manual measurement among experienced operators, and the repeatability of the automatic method.

The next element to be developed was a model that could control the ribbon thickness. An objective function was created so that a quantitative measurement of ribbon thickness quality could be determined. The model for the control of ribbon thickness used four control inputs to adjust the thickness of the ribbon, with the so-called objective function as a performance metric. The objective function showed how well the system is being controlled as disturbances were introduced into the system (a lower value means the system is closer to optimum). The objective function was defined as = $(T - L)^2 + (T - M)^2 + (T - R)^2$ where T = Target, and L, M, and R are left, middle and right thicknesses.

Additional analysis of the process using DOE protocols showed that cross term effects from the inputs could be disregarded for the present. A series of experiments determined the coefficients for the model. Simulations of the control algorithm indicated that even if the calculated control coefficients were off by as much as 50%, there was little effect on the final converged solution.

Ribbon thickness measurement and control system were tied together using an upgraded PLC that was also used to control the rest of the crystal growth machine.

Additional hardware was added to the system to detect freezes of the ribbon to the growth interface. Freezes can be a consequence of both manual and automatic control systems, and must be detectable as soon as possible to minimize process downtime. Automatic freeze detection was achieved with a low-cost string reel motion detector.

Additional options were added to the control system as the system was developed. These options allowed a region of deadband (to prevent over-control), and to allow the modification of certain set control points to avoid oscillations if they were not in a controllable region. Since ribbon thickness is highly dependent on the height of the melt from which the ribbon was grown, steps were taken to ensure that the measurement and control of melt height was stable. Some PID tuning of other control loops was also investigated to eliminate naturally occurring variations in ribbon thickness. Typical results from the system in automatic mode are shown in Figure 7.

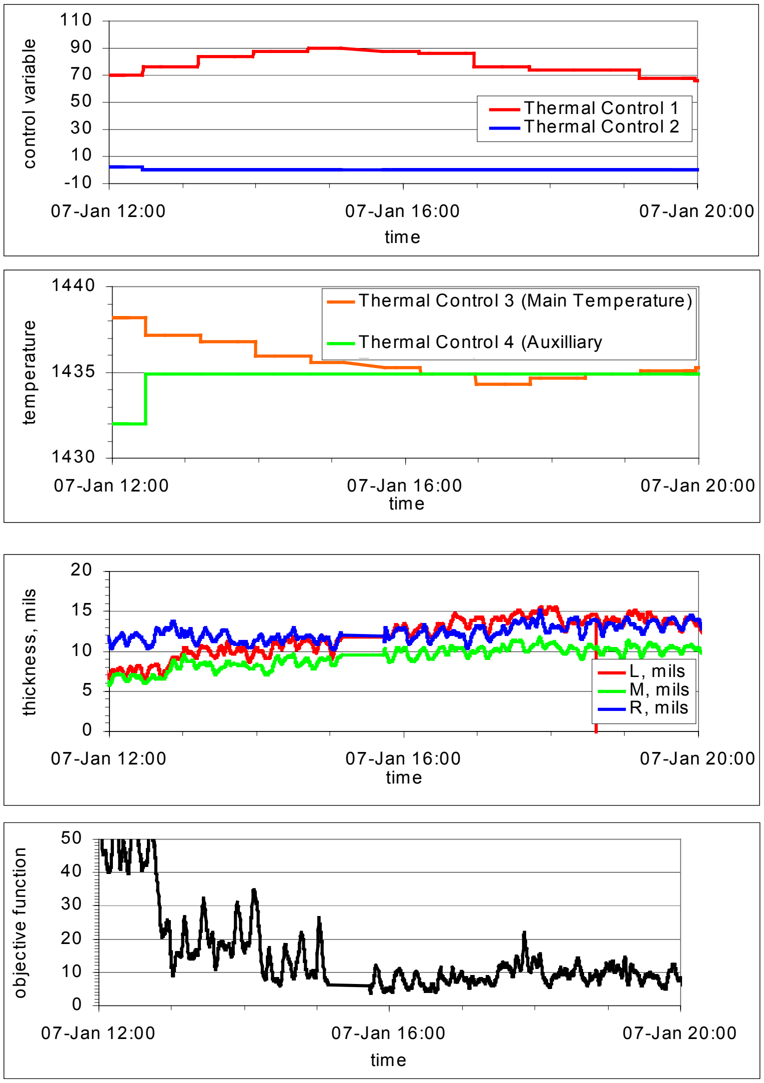


Figure 7 Typical Results of the Automatic Thickness System

The control values are given in the first two plots, the thickness values in the third plot, and the objective function in the last plot.

Efforts are continuing on further automation of these systems. In particular, this work is also being utilized to monitor various parameters that are then used as an additional training tool for the production operators. An example is shown in Figure 8. The left column of this figure displays data from furnace A02 and the right column shows

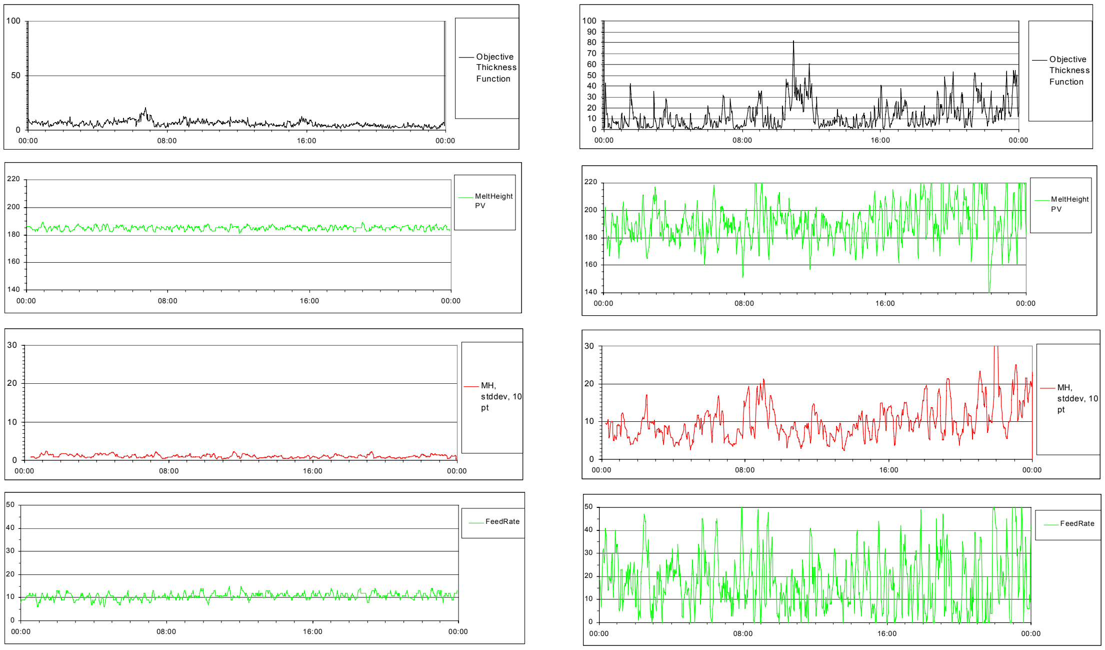


Figure 8 Automatic Thickness System as a Diagnostic Tool; A02 on left, A07 on right.

data from another furnace, A07. A02 was functioning well and producing ribbon at good yield. A07 was not showing good yield and uptime numbers. The horizontal scale for all 14 of the data sets is time over a 24 hour period. The various vertical scales will be explained further.

Examining each of the horizontal data sets in Figure 8 illuminates the reasons for this difference in performance. The top three data sets for each column are the three thickness values measured across the growing ribbon width using our automated thickness technique. The vertical scales are the thickness in mils. It is clear that the thickness is far more uniform for A02 than for A07. A summary of this difference can be seen in the plots of the objective function, plotted in the fourth set of horizontal data sets.

Finally, the reason for these thickness differences can be seen in the bottom three sets of data. The first set of these graphs plots melt depth, the second set the standard deviation of the melt depth from the set point and the bottommost sets of data gives the rate of feedstock addition. Thus fluctuations in the feedstock addition rate produce wide variations in the melt depth that then result in thickness variations. This type of information is being used to facilitate operator training as well as to serve as diagnostic tools in improving the performance metrics for these machines.

<u>Laser cutting</u> – One of the reasons that we have been able to eliminate any pre-diffusion etching (see below in the cell making discussion) is that the laser cutting method which has been developed at Evergreen Solar does not produce any microscopically visible cracks along the cut edges. Thus, an etching process to blunt microcracks is not needed here. For

this PVMaT project we have focused on a method that will allow us to automate the laser cutting process. In our factory we grow ribbon up to a length of about 2 meters, scribe it in-situ, and allow growth to continue. These 2 meter long strips are then cut by the laser into 15 cm long cell blanks.

An automated laser cutting machine has been designed, built, and is now running in our factory. Figure 9 shows the machine.

Figure 9 Automated Laser Cutting Machine.

Part of the automation effort here was to design a stackable plastic strip holder. A stack of these is shown Figure 10.

Figure 10 Stack of String Ribbon Strip Holders.

Such a stack is placed in the laser cutter machine. Strips of ribbon are automatically removed from such a stack, laser cut, and a series of 15 cm long cell blanks exits the machine, as shown in Figure 11.

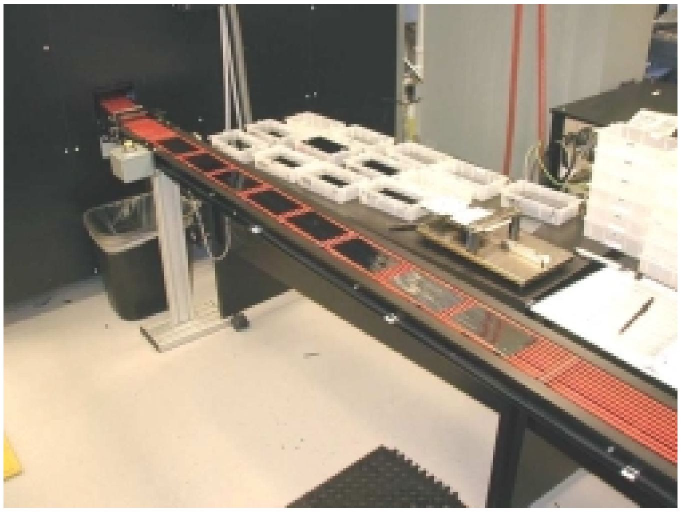


Figure 11 Laser Cut Blanks Emerging from the Laser Cutter.

When running well, this automated machine does exactly what we had expected it to do. Initially, we experienced a number of mechanical, optical, and software issues. The optical issues were due to manufacturing issues by the vendor and were fixed expediently. The software problems were connected with the vision system and its ability to find the cut blanks, and this was corrected. The mechanical issues are now being sorted out but they have not prevented us from routinely running the machine. The total cycle time of the machine is not as fast as our initial target. This is expected to improve after the mechanical questions are resolved.

Characterization of String Ribbon

Silicon Ribbon grown with the String Ribbon process is polycrystalline but with its own unique grain structure. The growth geometry imposes much of this structure. The grains are often wide single crystal grains, more or less in the growth direction and bounded by twins or bands of twins similarly oriented. Such grains can continue for considerable lengths on the order of tens of centimeters along the growth direction. Less frequently, there are grains bounded by high angle boundaries. At the edges of the ribbon, the incorporated strings nucleate high angle boundaries and these grow in for a few mm. Dislocation distribution can be very heterogeneous in this material as will be seen below.

<u>Dislocation Distributions</u> – Earlier evidence suggests that a principal limiting defect is that of dislocations. Two other earlier findings are relevant here. One is that String Ribbon responds well to hydrogen passivation [1] and the other is that the starting lifetime in the material varies considerably along the width of the ribbon but does not vary so much in the length (the growth direction). That is, a region that shows a high lifetime continues to do so along the growth direction and vice versa.

Dr.Bushan Sopori of NREL has done some dislocation scans on String Ribbon that illustrates some of the above points rather well. On the left side of Figure 12 is shown a dislocation scan, and on the right side is shown the corresponding distribution. The sample is a 5.6 cm wide piece of ribbon. The scan has gone nearly to the edge of the ribbon. The growth direction is vertically upwards in Figure 12. Note that the overall average of dislocation density is skewed towards the lower end.

It should be noted that in all these samples, there was no polishing. The samples were run with as-is surfaces. The lack of a flatter, polished surface precluded an accurate calibration of the dislocation densities, and the numbers shown could be too high by one or two orders of magnitude. Even with this, the comparative mapping here is very instructive. Note, for example, in Figure 12 the wide grain that has a very low dislocation density and that runs in a direction close to that of the growth direction. Also, it can be seen that closer to the ribbon edges, the dislocation density is clearly higher. Another sample that has a higher overall dislocation density is shown in Figure 13.

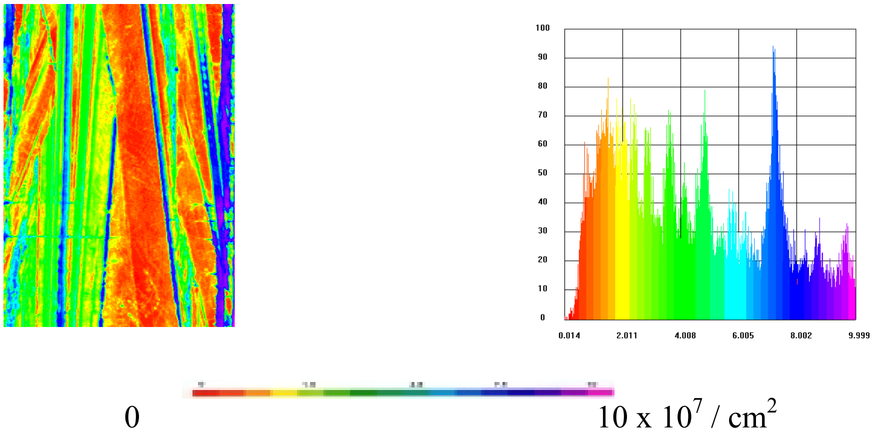


Figure 12 Dislocation Scan of String Ribbon with Low Dislocation Density

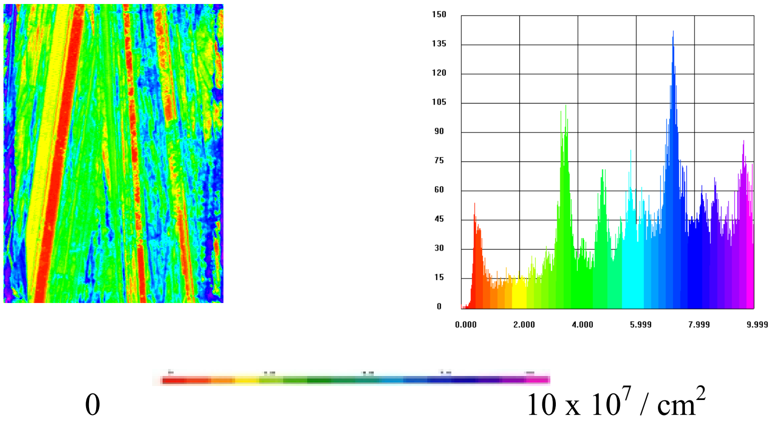


Figure 13 Dislocation Scan of String Ribbon with High Dislocation Density

Oxygen and Carbon Concentrations – A set of samples was forwarded to NREL for FTIR analysis. The goal was to determine oxygen and carbon concentrations and how they are distributed in the String Ribbon material as a function of growth system parameters and crystal structure. Analyses were through a 3 mm aperture and by difference-subtracting the spectrum of a float-zoned silicon wafer to yield the impurity absorbance spectrum of each sample.

The samples included material from a number of growth systems. This included standard production material, material grown at 50% higher speeds, and material from an experimental run that looked at the effects of a reducing ambient in order to suppress silicon oxide and silicon carbide formation and prolong the life of graphite/carbon compounds. In each case, samples were selected from two of the most commonly occurring grain structures: densely bundled twins covering as much as 1-3 cm across the width of the ribbon, and regions of large single crystal grains that can reach dimensions of 3 x 5 cm.

There are some indications that wafers with mostly densely bundled twins may display superior solar cell performance and that these regions can exhibit low dislocation densities. In the single crystal regions, it was thought that the oxygen and carbon concentrations might give an indication of the degree of dissolution of the graphite crucible and the extent of oxygen contamination. The latter has never been found to be at significant levels in String Ribbon material, at least based on FTIR measurements.

In the reducing ambient experiments the analyses were done to determine whether there were any significant effects on the carbon and oxygen concentrations due to this reducing atmosphere. These are the general observations:

- Almost no interstitial oxygen was found (1 x 10^{16});
- Substitutional carbon was generally in the mid, 5-6 x 10^{17}, range;
- The single crystal grains generally were at the low end of concentration for substitutional carbon;
- There was no significant difference in interstitial oxygen and substitutional carbon levels for the material grown at 50% higher speed vs. the ribbon grown under our present production speed.

Overall, it is interesting to note that the substitutional carbon levels may be lower than that found for EFG. This is generally in the 9 x 10^{17} – 1 x 10^{18} range. In general, the present results confirm an earlier analysis of String Ribbon done some four years ago at NREL, except that the carbon level was higher at a value of 7 – 9 x 10^{17}. Since our growth process has changed dramatically since then, it was felt to be worthwhile to again characterize the material and further to see if grain structure differences were measurable. So it may be real that the carbon level is somewhat lower now.

In a later experiment, SIMS was used to measure total carbon and total oxygen. The total [O] concentrations measured using SIMS were at least an order of magnitude higher that the [O_i] measured by FTIR. This must mean that all this oxygen is in the form of precipitates in the ribbon and not as interstitial oxygen. Finally, another interesting phenomenon is that the total carbon measured by these SIMS experiments is similar to that of the $[C]_s$ measured by FTIR indicating that all the carbon present is in the form of substitutional carbon. Also, the carbon level shows a near surface depletion in some cases. A similar effect was observed many years ago in EFG. Its significance is not yet clear.

II. Cell Making - Automation and Process Simplification

General Remarks – There were two complementary goals in this area. First, it was necessary to reduce the number of process steps and second, to reduce the amount of handling of the ribbon blanks as they were being made into cells. The latter could then be done through automation. The plan here was to develop a solar cell processing line where the cells or blanks are always horizontal. This meant the elimination of any steps that called for cell blanks to be put into plastic carriers so as to receive chemical etching procedures. Belt to belt type transfers were to be utilized wherever possible and handling of individual blanks by an operator was to be totally eliminated.

For the automation part of this program, a considerable amount of engineering was put into developing generic systems with similar basic components in every process step. This would make duplication of any of these systems simpler. Furthermore it would facilitate maintenance of the machines involved. The latter is particularly significant since many of the systems would be run on a continuous, 24/7 schedule except for scheduled maintenance times.

As examples, the same PLC was used in every machine. Where rotary tables were employed, these were also all the same. Similar gantry equipment used in various operations and generic vision systems for locating cells were also employed. Underlying all this was the effort at designing a high volume automated line with minimal handling and minimal processing steps.

Transport of Wafers and Wafer Size – With the move into the factory, some significant changes were implemented. One in particular is the cell size. We have changed from a 5.6 cm x 15 cm cell (area $\approx$ 84 cm^2) to an 8 cm x 15 cm cell (area $\approx$ 120 cm^2). Advances in our crystal growth technology have allowed us to do this with the increased productivity and reduced costs this would bring in its train.

Also, as described further, with the development of a so-called no-etch process, the conventional plastic carriers are eliminated, and a new method of wafer transport had to be developed. This method embodies the use of plastic boxes designed to hold at least fifty of the 120 cm^2 area cells or wafers in a horizontal stack. These boxes are made to be easily stacked, to be bar coded so that individual lots of wafers can be traced, and to be moved by robots, conveyors, and the like.

An example of these boxes is shown in Figure 14, along with a stack of the 8 cm wide ribbon substrates. This box will represent a volume density saving of about three times over that of the plastic carriers—an important consideration when designing the size needed for a buffer.

Figure 14 Example of Bar Coded Plastic Boxes.

Overall Cell Process Sequence – The following are the steps in the cell process which are discussed in detail further on in this report:

- Diffuse to form p-n junction
- Remove diffusant glass
- Hydrogen passivate via plasma nitride
- High speed contact printing and drying
- Apply front contact and dry
- Apply rear contact and dry
- Fire
- Test
- Tab fronts of cells

Diffusion and Automatic Diffusant Glass Removal – As already mentioned, a process has been developed whereby no etching is needed between wafer production in crystal growth and diffusion to form a p-n junction. In Figure 15 is shown an automated loading station prior to the diffusion step itself.

Figure 15 Automated Loader for Diffusion.

Here, boxes of wafer blanks directly received from crystal growth are automatically moved on the conveyor shown in Figure 15 and then are configured for the diffusion step (Figure 16).

Following this step, there is an automatic diffusant glass removal machine and this is shown in Figure 17.

Figure 16 Entire Diffusion Setup.

Figure 17 Diffusant Glass Removal Machine.

Accumulator and Hydrogen Passivation Load and Unload – Another type of accumulator for buffer storage will be employed following diffusant glass etch. At present the plan is that this machine will be the mirror image of the one shown in Figure 15. In this case, the diffused wafers will again be placed in boxes so as to reduce the amount of buffer volume needed. This machine has not yet been built. We have decided to defer this until it becomes clearer exactly what buffer requirements will be needed prior to hydrogen passivation.

Hydrogen Passivation and Cell Efficiencies – Evergreen is now developing a plasma nitride hydrogen passivation process. The process will lend itself readily to robotic load and unload of String Ribbon wafers. The process is still under development and not optimized, but the basic concepts underlying it have been demonstrated. At the time of this writing, passivated cell efficiencies were in the 12 –13% range. Figure 18 shows the distribution of cell efficiencies for a recent production batch.

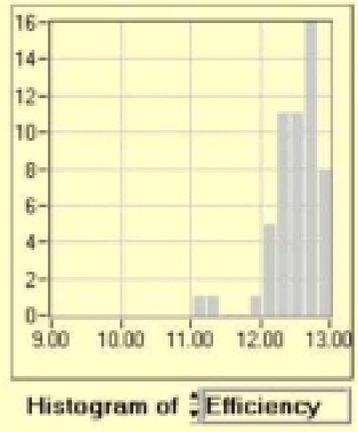


Figure 18 Distribution of Cell Efficiencies.

The best 120 cm^2 cell coming directly out of our production line had the following parameters: Jsc = 31.1 mA/cm^2; Voc = 590 mV; F.F. = 0.730; Eff = 13.3%.

In addition to the NREL characterization work detailed above, Prof. Rohatgi's group at Georgia Tech has done research on processing and efficiency of String Ribbon material. Some relevant findings are:

- Starting lifetimes will determine final efficiency to a significant degree, even given that certain processing steps in combination can produce final lifetimes [2] capable of resulting in cells between 15% and 16%

- If starting lifetimes are > 5 microseconds, then cells of 15% efficiency [3] have been made using processes which are close to that of production methods.

- Using laboratory processing, the best cell made on String Ribbon is 16.2% [4].

Thus, given our early production results and the Georgia Tech work, it is reasonable to expect efficiency increases in the near future.

High Speed Printing and Drying – This was a goal in connection with contact formation. In this case, we purchased commercially available equipment and then modified it to our particular needs. We have able to reach the high speed goal with no trouble at all. The equipment was obtained from industries that normally do not service the photovoltaics industry and so some modification was necessary. With this, we believe we have laid the foundation for even higher speeds in the future, as this equipment is used in an industry that is geared to very high speed printing and drying.

Overall Machine Sequence – As part of the goal of reduced handling, we have created a machine sequence whereby there is no operator handling at all. This does not yet include every portion of the cell making sequence but does include a significant part of it.

This sequence which has no operator handling comprises the front contact application machine, a drying tunnel to an accumulator/buffer, connection to the rear contact application machine, connection to a gantry machine with vision to align the cells on the dryer belt, the dryer, the firing furnace, a gantry system with vision to remove the finished cells from the metallization firing belt, an accumulator/buffer, connection to the automated tester, followed by binning, and finally the front tabbing machine. Initial batches of cells made in our new factory through this machine set have met our starting targets for yield and efficiency. Details follow.

Contact Application Machines – Evergreen has its own unique technology for forming contacts on solar cells and has designed machines that are specifically geared to this technology. The use of these machines alone has contributed to an increase in yield in our cell area on the order of 10%. In the factory, an additional machine—a so-called accumulator, is interposed between the front and rear contact machines. The accumulator in this case has two functions. One is to turn the cells over, and the other is to serve as a buffer or storage.

Figure 19 shows a view of the contact application machines, a drying tunnel between them and the accumulator that is also placed between them. #1 in this figure is the front contact application machine, #2 is the drying tunnel, #3 is the accumulator/buffer, and #4 is the back contact application machine.

Figure 19 Contact Application Machines with Drying Tunnel.

In Figure 20 is shown a belt transfer system and the gantry system that is used to take cells from the rear contact application machine and place them on the belt for contact firing.

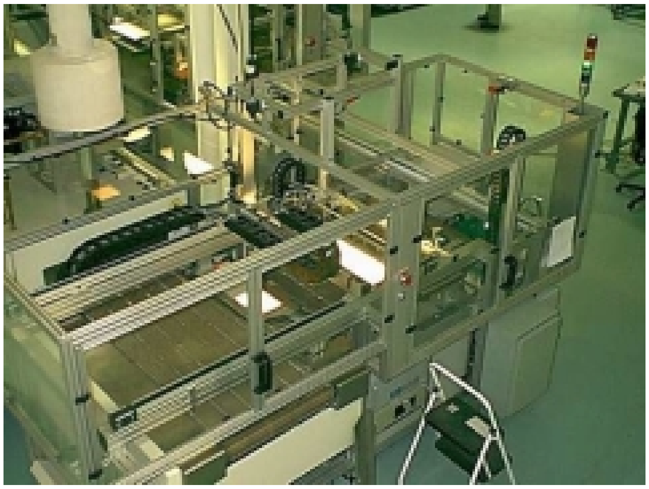
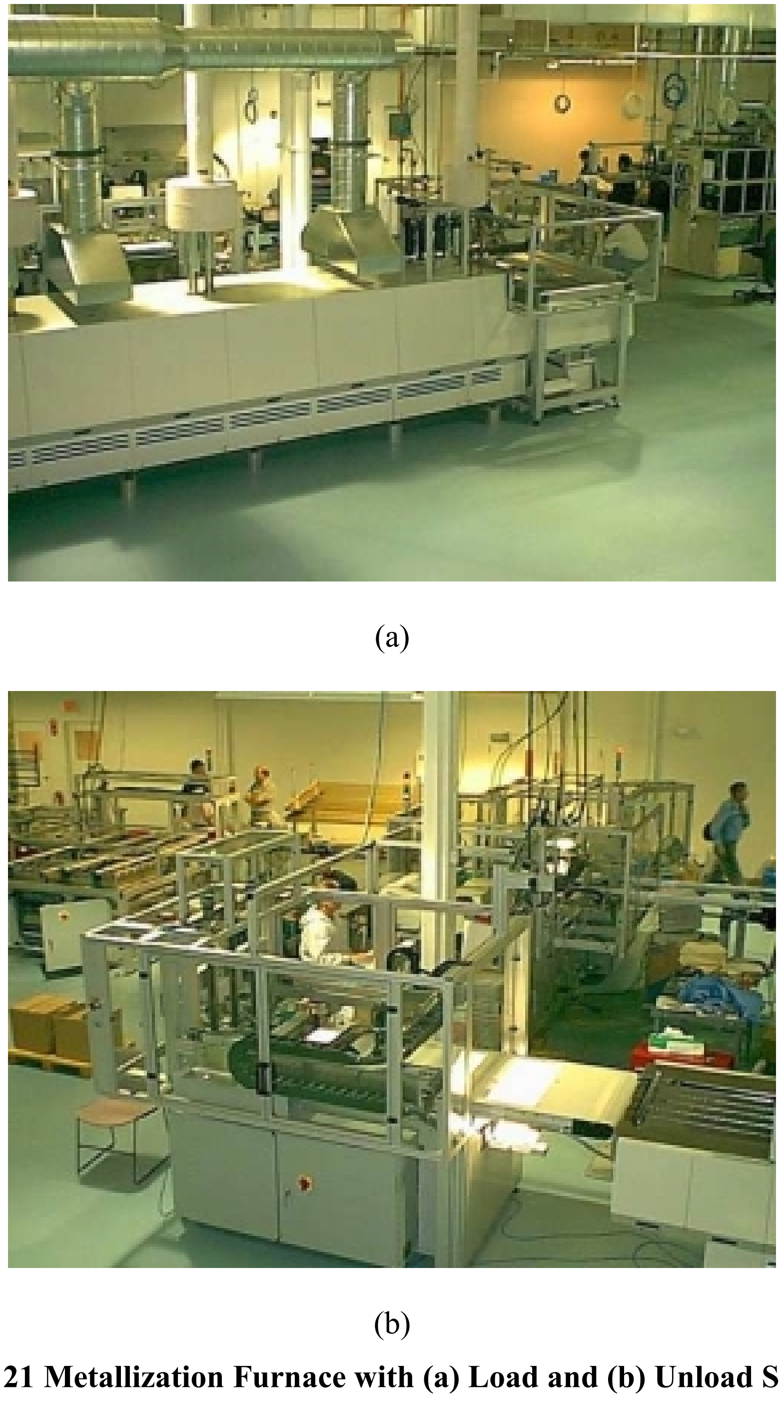


Figure 20 Automated Loader for Firing Furnace.

Figure 21 shows the metallization firing furnace along with the automatic load and unload machines on opposite ends of this furnace.



(a)

(b)

Figure 21 Metallization Furnace with (a) Load and (b) Unload Stations.

III. Modules - Automation and Process Development

General Comments on Process Flow – The division of manufacturing into three areas, crystal growth, cell making, and module manufacturing is done for convenience. In fact, underlying the theme of continuous manufacturing is the idea that transitions between these areas are seamless. A total achievement of this goal has not yet occurred. In order to do so, it would be necessary to eliminate all batch processing steps and have totally continuous processing. However, major steps towards such a goal have been made. The elimination of pre-diffusion etching is an excellent example of this. As grown wafers are kept horizontal throughout all subsequent cell and module processing steps and the distinction between crystal growth and subsequent process steps is significantly blurred.

Another example is in the interface between cell and module making. In this case, the end of the cell line and the beginning of the module line are indistinguishable from each other. In Figure 22, the automated machines for the sequential processing from the metallization unload station (1) to the front contact tabbing (4) is shown.

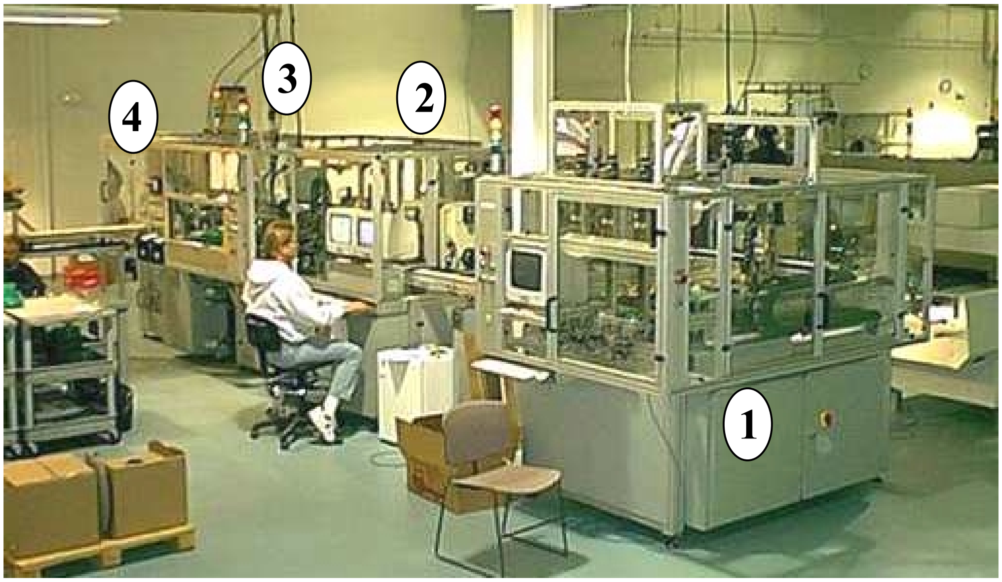


Figure 22 Integrated System for Unload, Test, and Tab.

Included in this is the automated tester (2) and binning machine (3). Recall that the cells are automatically handled from front contact formation until this step of attaching the tabs on the front bus bars.

Development of Improved Soldering Techniques – As part of the above sequence and also very relevant for the formation of interconnected strings, an improved soldering method for applying tabs to the front bus bars was first developed along with an automatic machine that incorporated this process. It is the last machine in the above mentioned sequence and is shown again in Figure 23.

Figure 23 Front Contact Tabber.

Finally, this method was further developed so that it could be utilized for the soldering together of series connected strings of cells. A full-fledged machine to do this is being built at present and is expected to be completed about one month following the termination of this subcontract.

<u>Automated Layup Tables</u> – A method for doing automated layout of a module prior to lamination was developed and a machine for this was built. It is shown in Figure 24.

Figure 24 Automated Layup Machine.

IV. Factory Material Handling and Process Flow

Evergreen's New Factory – Figure 25 shows a picture of Evergreen's new factory.

Figure 25 New Factory Building.

As an important part of our overall PVMaT subcontract objectives, we have enlisted the help of the Fraunhofer USA Center for Manufacturing Innovation at Boston University. This Center is part of the worldwide Fraunhofer Gesellschaft, based in Munich, Germany. The Fraunhofer Center does contract research in manufacturing technology, and Boston University itself offers advanced degrees in this area. A Boston University graduate student spent considerable time doing motion studies on our production line.

This factory has a rectangular shape. Using extensive feedback from virtually all the senior technical personnel at Evergreen, the Fraunhofer group helped us to lay out a production line with a very efficient factory flow. At one end of the building incoming feedstock silicon is received, and at the other end of the building, finished modules are shipped out to customers. Figure 26 gives a schematic of the building layout.

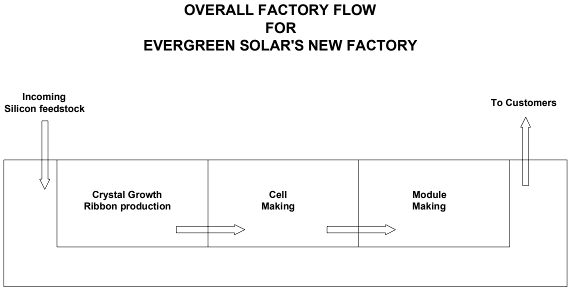


Figure 26 Schematic of Factory Flow.

Plant Layout and Process Flow – The basic model used by the Fraunhofer group is called the Taylor ED Simulation Model. This is a software package that allows for simulating process flow, buffer requirements, downtime, and efficient layout of equipment. The

Taylor ED Simulation Model is based on an "atom concept." The four dimensions of the atom are x, y, z, and time, t. These atoms can freely communicate with each other, can contain other atoms and be freely created and destroyed. Everything in the simulation package is an atom regardless of whether it is a resource, a product, a model, etc. The following are examples of the use of this simulation model in helping us to design the factory.

Power Outages and Continuous Operation – The String Ribbon crystal growth process is one that is designed to run continuously. In fact, the process and the associated crystal growth machines work best run in a fully continuous mode. By continuous here we mean seven days a week, twenty-four hours a day. The only reason for shutting down a furnace is erosion of the graphite crucible. A routine shutdown is scheduled for every furnace after a prescribed number of weeks of continuous operation.

Given both the need for, and the desirability of continuous operation, what happens when there is a power outage? An emergency generator large enough to handle the load would be the best answer but the capital investment required here is formidable. We had the Fraunhofer group run some simulations of possible downtimes for two outage scenarios of different lengths, 30 minutes and 24 hours. The idea here was to evaluate where the trade-off would occur for the large capital purchase of an emergency generator versus the lost production due to the outage. An example of the simulation results is shown in Figure 27.

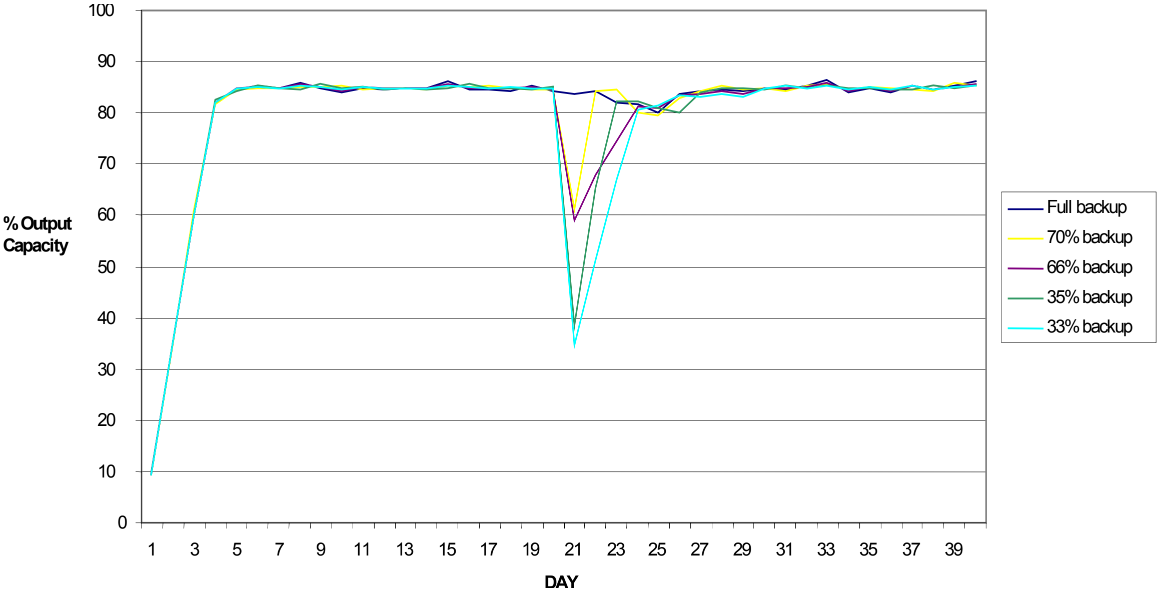


Figure 27 Simulation for Power Outage.

From the local utility we obtained historical data on the average times for outages over the last few years.

With this information, it first appeared that we could afford to defer the purchase of the emergency generator. However further studies of the amount of time that a crystal growth furnace could endure a power outage and still be started up again and the labor requirements to start up all the furnaces indicated that it could make economic sense to install an emergency generator. With this, we decided to buy and install an emergency generator.

Crystal Growth Layout "Cells" – We anticipate a large number of crystal growth machines for the factory—on the order of 120 for the full factory. The correct placement of such a large number of crystal growth machines was clearly an important challenge. Again here we first sought feedback from both R&D personnel and production personnel in the crystal growth area. This was then provided to the Fraunhofer people in an iterative process until a mutually satisfactory layout emerged. The result was a layout with a cellular concept. A single such "cell" would contain the number of crystal growth machines that a single production operator could be expected to run.

The cells themselves were in a "U" shape. Three such cells are shown in a simulation layout shown in Figure 28 along with the diffusion process line on the right hand side of the diagram and the laser cutter in the center of the cell.

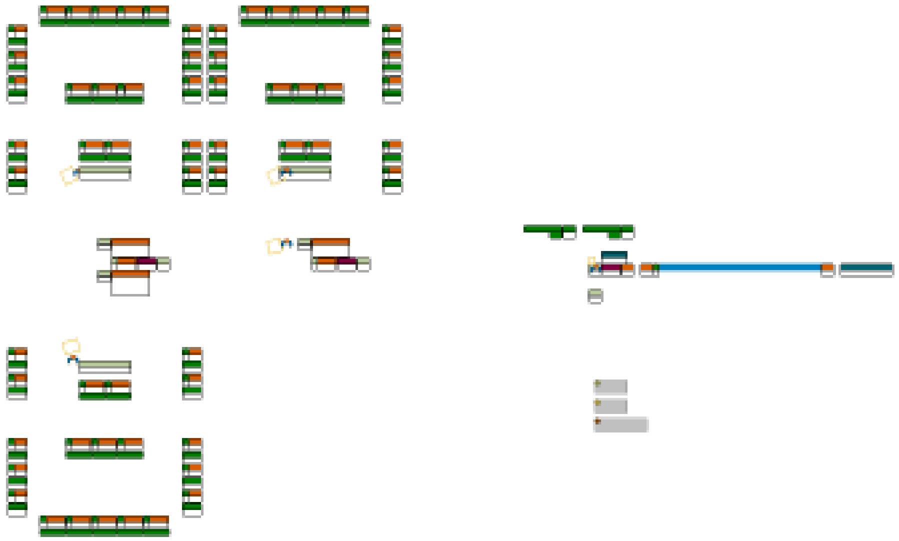


Figure 28 "Cells" for Crystal Growth Layout.

In Figure 3 (Page 9) is shown a row of new crystal growth machines in a single such cell.

New Products – Stemming from all the developments listed above, Evergreen has introduced a new product line, the Cedar Line. These will be the principal products emerging from our new factory beginning at the time of the termination of this contract. The first such product is a 50 watt module and the second one will be a 100 watt module. Examples of each are shown in Figure 29.

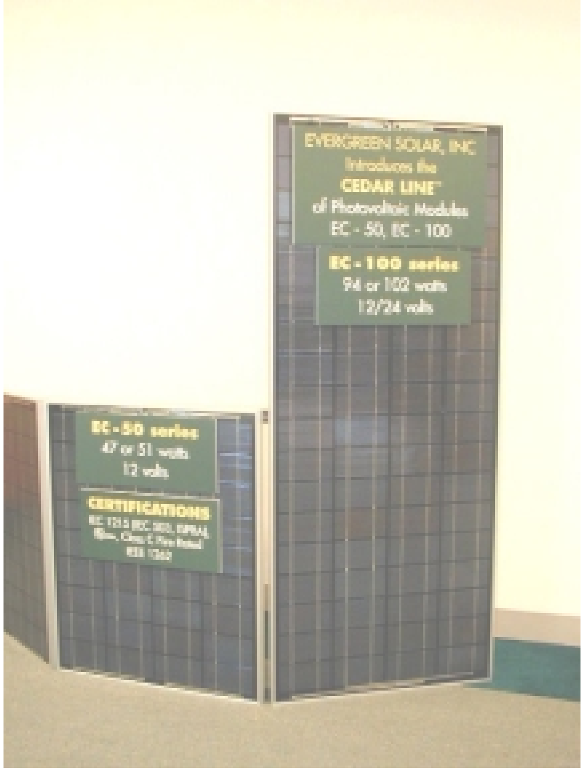


Figure 29 Evergreen's New Products

V. SUMMARY

A three year PVMaT project has resulted in major developments in PV module manufacturing technology. The most significant have been in the particular areas of silicon ribbon growth and cell processing. Extensive engineering and process development have been combined and represent important steps towards the goal of continuous and automated PV module manufacturing. Evergreen has opened a multi-megawatt factory that has incorporated these advances. Several patent applications and a number of technical papers have also resulted from this project.

VI. PAPERS AND PATENTS

Papers

1. R.E. Janoch, A.P. Anselmo, and J.I. Hanoka, Automation of the String Ribbon Process, 16th NCPV Program Review meeting, March, 2000 ,Denver, CO.

2. J.I. Hanoka, An Overview of Silicon Ribbon Growth Technology, PVSEC meeting, Sapporo, Japan Sept. 1999, to be published in Solar Energy Materials and Solar Cells.

3. R.E. Janoch, R.L. Wallace, A.P. Anselmo, and J.I. Hanoka, Advances in String Ribbon Crystal Growth, 9th Workshop on Crystalline Silicon Solar Cell Materials and Processes, August, 1999, Breckenridge, CO.

4 .R.E. Janoch, A.P. Anselmo, R.L. Wallace, J. Martz, B.E. Lord, and J. I. Hanoka, PVMaT Funded Manufacturing Advances in String Ribbon Technology, 28th IEEE PVSC, Anchorage, Alaska, Sept 2000.

5. A. P. Anselmo, R.L. Wallace, R.E. Janoch, J. Martz, and J.I. Hanoka, Automation of the String Ribbon Process, 10th Workshop on Crystalline Silicon Solar Cell Materials and Processes, August, 2000, Copper Mountain, CO.

Patents

A patent on edge meniscus control has been filed and two others are under preparation.

VII. REFERENCES

[1] D.S. Ruby, W.L. Wilbanks, C.B. Fleddermann, and J.I.Hanoka, 13th European PV Solar Energy Conf., Nice, 1995, 1412-1414.

[2] V.Yelundur, A. Rohatgi, A.M. Gabor, J.I. Hanoka, and R.L. Wallace, PECVD SiNx Induced Hydrogen Passivation in String Ribbon Silicon, 28th IEEE PVSC, Anchorage, Alaska, Sept., 2000.

[3] Private communication from Prof. Rohatgi, Georgia Tech.

[4] Work done at Georgia Tech, see p.511 of the Sandia Report SAND2001-0833; History of the Crystalline Silicon Photovoltaic Cell Research Program at Sandia National Laboratories, by D.Ruby and J. Gee, printed in April, 2001.

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13. ABSTRACT *(Maximum 200 words)* This report summarizes the work done under a three-year PVMaT Phase 5A2 program. The overall goal was to attain a continuous, highly automated, fully integrated PV production line. In crystal growth, advances were made that resulted in lower substrate costs, higher yields, and lower capital and labor costs. A new string material was developed and implemented. Following this development, better control of the edge meniscus was achieved. A completely new furnace design was accomplished, and this became the standard platform in our new factory. Automation included ribbon thickness control and laser cutting of String Ribbon strips. Characterization of Evergreen's String Ribbon silicon was done with extensive help from the NREL laboratories, and this work provided a foundation for higher efficiency cells in the future.

Advances in cell manufacturing included the development of high-speed printing and drying methods for Evergreen's unique cell making method and the design and building of a completely automated cell line from the beginning of front-contact application to the final tabbing of the cells. A so-called no-etch process whereby substrates from crystal growth go directly into p-n junction formation and emerge from this sequence without needing to go in and out of plastic carriers for any wet-chemical processing was developed. Process development as well as automation were brought to bear on improvements in soldering technology and cell interconnection in general. Using state-of-the-art manufacturing science, the Fraunhofer USA Center for Manufacturing Innovation at Boston University facilitated layout and process flow for the operation of our new factory. Evergreen Solar's new factory began operations in the second quarter of 2001. A good measure of the significant impact of this PVMaT subcontract is that virtually all of the manufacturing developments stemming from this project have been incorporated in this new factory.

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