October 1999 • NREL/SR-520-26891

Subcontractor Report

Continuous, Automated Manufacturing of String Ribbon Si PV Modules

First Annual Report
21 May 1998 — 20 May 1999

J.I. Hanoka
Evergreen Solar, Inc.
Waltham, Massachusetts

National Renewable Energy Laboratory

1617 Cole Boulevard
Golden, Colorado 80401-3393

NREL is a U.S. Department of Energy Laboratory
Operated by Midwest Research Institute • Battelle • Bechtel

Contract No. DE-AC36-98-GO10337

October 1999 • NREL/SR-520-26891

Continuous, Automated Manufacturing of String Ribbon Si PV Modules

First Annual Report
21 May 1998 — 20 May 1999

J.I. Hanoka
Evergreen Solar, Inc.
Waltham, Massachusetts

NREL Technical Monitor: M. Symko-Davies

Prepared under Subcontract No. ZAX-8-17646-07

National Renewable Energy Laboratory

1617 Cole Boulevard
Golden, Colorado 80401-3393

NREL is a U.S. Department of Energy Laboratory
Operated by Midwest Research Institute • Battelle • Bechtel

Contract No. DE-AC36-98-GO10337

ACKNOWLEDGEMENTS

The following Evergreen employees have contributed to this work: Crystal Growth---Rob Janoch, Eric Gabaree, Rick Wallace, Dick Krauchune, Andrew Anselmo, and Jennifer Martz; Cell Manufacturing---Andrew Gabor, Xinfa Ma, Paul Ciszek, Mike Ralli, Bryn Lord, and Mark Mrowka; Modules---Bruce Newell and Joe Fava; and Factory Layout and Automation---Richard Chleboski, Peter Kane, and Lars Llorente.

NOTICE

This report was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or any agency thereof.

Available electronically at http://www.doe.gov/bridge

Available for a processing fee to U.S. Department of Energy
and its contractors, in paper, from:

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone: 865.576.8401
fax: 865.576.5728
email: reports@adonis.osti.gov

Available for sale to the public, in paper, from:
U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
phone: 800.553.6847
fax: 703.605.6900
email: orders@ntis.fedworld.gov
online ordering: http://www.ntis.gov/ordering.htm

♻ Printed on paper containing at least 50% wastepaper, including 20% postconsumer waste

TABLE OF CONTENTS

EXECUTIVE SUMMARY.. 3

INTRODUCTION... 4

TASK 1---Crystal Growth.. 4

- Increasing Run Length 5
- New String Material 5
- Edge Meniscus Control and Thin edges.................................. 6
- Reduced Consumable Costs.. 7
- Automated Thickness Control 7
- Lower Cost Furnace Design 8

TASK 2---Cell Manufacturing 9

- Elimination of the Pre-Diffusion Etch....................................... 9
- High Speed Drying 10
- High Speed Contact and AR Application Machine 10
- Automated Diffusant glass Etching 10

TASK 3---Module Lay-up 11

TASK 4---Factory Layout and Automation 11

- Manufacturing Process Analysis of the Pilot Line.................. 11
- Product and Process Improvements 12
- Factory Layout Alternatives for the Scaled-up Production 12

REFERENCES.. 24

LIST OF FIGURES

Figure 1 String Ribbon Growth Process 13

Figure 2 Production Crystal Growth Machine 14

Figure 3 Spools of the New String Material 15

Figure 4 Micrograph of As-grown Ribbon Edge 15

Figure 5 Micrograph of As-grown Ribbon Edge with Edge Meniscus Control 15

Figure 6 Typical Grain Structure and Example of Very large Grains 16

Figure 7 Automatic thickness Measurement 17

Figure 8 Prototype Installation of Automatic Thickness Measurement on a Production Machine 18

Figure 9 Reduced Crucible Size for Low Cost Hot Zone 19

Figure 10 Ribbon Growth Using the Low Cost Hot Zone 19

Figure 11 Dendrites on As-grown Surface 20

Figure 12 High Speed Drying Machine 21

Figure 13 High Speed Contact and AR Application Machine 22

Figure 14 Example of Patterned Backskin Material and Frameless Module 23

EXECUTIVE SUMMARY

This report describes the first year of a three-year PVMaT Phase 5A2 program. Evergreen Solar will soon be expanding into a multi-megawatt facility and the PVMaT work will be used to further the objective of a high-throughput automated production line in every aspect of PV module making from producing silicon ribbon to making a finished module.

The project has four task areas for this first year: crystal growth; cell manufacturing; modules; and factory layout and automation. The vast majority of the work this first year has been in the crystal growth and cell manufacturing areas. Evergreen Solar has its own unique technology in each of these areas.

In crystal growth, a key goal of this PVMaT project has been the development and deployment of an improved string material. The high-temperature string materials are used to stabilize the edges of the growing silicon ribbon in our String Ribbon silicon sheet growth. The result has been one of the major successes of this first year. Significant cost reductions and yield improvements have emerged from this improved string material developed under this subcontract. In addition, some of the groundwork for automation of the String Ribbon crystal growth process has been laid and shows much promise. A method for controlling the edge meniscus height was developed and a patent has been filed based on this discovery.

In the cell manufacturing area the focus has been on reducing the number of processing steps and on design and construction of high-speed processing equipment. The possibility of eliminating all pre-diffusion etching and going directly from growth into diffusion has been demonstrated on an R&D scale. Unique designs for high-speed drying equipment and for a high-speed contact and AR coating application machine have been developed. In the latter case, the basic concepts underlying various aspects of the machine design have been successfully tested for viability. The integration of the different components of this machine into a smoothly working whole is now well under way. In addition, non-vacuum methods of hydrogen passivation have been investigated but no production viable process has emerged from this work.

In the module area, initial work has shown that the unique properties of the backskin developed under Evergreen's earlier PVMaT Phase 4A1 contract can be expected to make the lay-up process simpler and involve less labor.

For factory layout and automation we have enlisted the help of the Fraunhofer Manufacturing Institute at Boston University in aiding us with the layout and process flow of our new factory.

In general, the project is on schedule with no significant technical barriers to reach our ultimate objectives.

INTRODUCTION

This report covers the first-year activities of a three-year PVMaT Phase 4A1 subcontract. The project has been divided into four tasks for this initial year:

Task 1—Crystal Growth

Task 2—Cell Manufacturing

Task 3—Module Lay-up

Task 4—Factory Layout and Automation

As the name of the project suggests, the final goal at the end of the entire three years is a highly automated, nearly continuous manufacturing line for PV modules. In the latter part of 1999, Evergreen is planning to move to a new site where a multi-megawatt factory will be operated. Much of what has been done in this first year of this subcontract will figure prominently in this scale-up.

In this first year, work was done in all four of the above tasks and progress was significant in all. The most difficult technical challenges were in crystal growth and cell manufacturing. Consequently they received the largest effort.

Task 1—Crystal Growth

Evergreen's method for the continuous production of crystalline silicon substrates is termed String Ribbon [1,2] and is illustrated in Figure 1. (All Figures are at the end of the text.) Two high-temperature string materials are brought up through a graphite crucible. A seed is lowered into a shallow melt of silicon in the crucible, and a ribbon of 5.6 cm width is then grown with the strings incorporated into the edges of the ribbon. No serious deleterious effects of leaving the strings in the ribbon have been found. So far, the only effects of incorporating the strings into the growing ribbon is that they can promote the formation of higher angle grain boundaries in a region a few mm wide adjacent to the ribbon edges and that they can result in thinner edges. As will be seen further on, each of these issues have been addressed under this subcontract. The central portion of the grown ribbon consists mainly of coherent twin boundaries and large grains. The material as grown is p-type, with bulk resistivity of about 2 ohm-cm, and is nominally 300 μm thick.

Under the general rubric of lowering manufacturing costs in the crystal growth area, the central issues addressed during this first year were these:

1. Increasing run length;

2. Reducing consumable costs; and

3. Reducing the capital costs of a crystal growth furnace.

Increasing Run Length—The String Ribbon crystal growth process is designed to be run continuously. Early on, at Evergreen a method to continuously replenish feed material and also a means of continually feeding string material was developed and deployed. As a result, the crystal growth machines can be run 24 hours a day, 7 days a week. Figure 2 shows a production crystal growth machine with the silicon feeder and the string reels. With the accomplishment of continuous operation, run length becomes a major driver of operating and consumables cost.

Initially, it was clear that the two most significant factors for determining run length are the nature of the string material and the dissolution of the graphite crucible. Both are discussed below.

New String Material—After a considerable amount of actual running experience, it became clear that the string material was a principal factor in reducing run lengths. The string material was a high-temperature material, especially formulated for us by the vendor. Also, some in-house modification of this material was done.

After establishing the string material as the major culprit in producing shorter run lengths, we embarked on a major program to develop a new string material. While the principal goal was to achieve higher run lengths, there were two other subsidiary goals. One was to eliminate the need for the additional, in-house processing step, and the other was to find a material which would not result in nucleating high-angle boundaries near the ribbon edge.

The main criterion in developing a new material was to find a suitable material with a coefficient of thermal expansion (CTE) match close to that of silicon. Finding a commercially available material with a good CTE match to silicon was a difficult technical problem. For example, Ciszek [3] has grown ribbon in this process using quartz fibers that are known to have a very different CTE value than silicon. The result is that the quartz fibers literally pop out of the ribbon after growth due to the stresses built up from the CTE mismatch.

The development and then deployment in manufacturing of a new string material was, at the onset, viewed as a significant materials science project which would take more than two years before it was ready for manufacturing. Since there was no simple, commercially available compound which had the appropriate CTE value, the discovery first of such a compound, and, secondly, the development of a viable method to manufacture it so that it would be cost-effective were viewed as significant projects.

As it turned out the project was successfully completed in the first year. The approach taken was this. First of all, various compounds with differing stoichiometries were formulated and formed into short lengths of a few feet of string. Then, growth in a standard production String Ribbon machine was attempted. Using the dual criteria of edge quality (i.e., was the edge of the grown ribbon strong and not exhibiting any tendency for the string to break out of it?) and also ease of growth, a number of possibilities were tested.

In this way, several candidates were readily eliminated and a few were found to be very promising. The latter 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.

This initial test proved to be very encouraging, and a vendor who could make this material in quantity and for a reasonable cost was contacted. After extensive interactions with this vendor, a sufficient quantity of this string material was produced such that it could supply all of our production machines for about three months. This was considered the only way to fully test both the efficacy of this new string material and the ability of the vendor to make this string in a consistent and high quality manner. Spools of this string material are shown in Figure 3.

The results of such a full-scale test were, by and large, very positive, We experienced more than a doubling of run length. Furthermore, in general, introducing this new string material into the production line posed no unexpected difficulties.

Two issues did emerge as a result of this test, and were addressed in the next full-scale trial. One was a possible contamination by a particularly pernicious transition metal due to the way the string was processed into the configuration sent to us. The other was variable quality in some batches of the string made at the end of the vendor's run. In the latter case, apparently the stoichimetry of the material was wrong. The incorrect stoichiometry was duly noted and provisions for avoiding this by the vendor were implemented. The vendor was also sensitive to the contamination issue and took the appropriate steps to rectify this as well. Since we represent the only photovoltaic application of this material, we had to work with the vendor to establish the physical and chemical properties of particular importance to our requirement.

A second large quantity of the string was then made and has been in use for three months without any of the earlier problems seen. Not only have we accomplished the average run length objective necessary for commercial scale-up, but the new record run lengths up to four times longer than the prior record have been seen.

Graphite Dissolution—As mentioned above, the other factor contributing to shorter run lengths was dissolution of the graphite crucible. Dissolution of the crucible does eventually lead to run termination, although given further investigation and the development of the string material, crucible dissolution turned out to be much less of an issue than first thought. Initially, we studied various coatings for the crucible and found several vendors who could do this. Visits to the facilities of two vendors in particular were made, and some trials were performed, although their cost-effectiveness was not clear. In parallel, modifications to the crucible's physical design and furnace operating conditions were made to lessen the impact of the dissolution problem. Combined with the unexpectedly rapid success of the new string material, run lengths are now satisfactory, and further work on coatings has been deferred.

Edge Meniscus Control and Thin Edges—One unexpected consequence of the use of the new string material was thin edges. Figure 4 shows cross-sectional micrographs of the edge of as-grown ribbon using our new string material. It can be seen that the edge is thin and then somewhat bulbous at the very end, and also has more of a necked feature as a result of the use of the new string material. This thinner and necked edge was weaker than previous edges and had a negative impact on yields in downstream processing.

Thus, it became important to find a method that would allow us to eliminate this type of edge. After a number of empirical efforts, a method was discovered to control the meniscus at the edge of the ribbon in such a way as to produce a thicker edge. The desired meniscus across the width of the growing ribbon is described as "smiling" or concave facing upward. In our usual growth, the meniscus at the edge of the ribbon is "frowning" or convex facing upward. This frowning edge meniscus contributed to forming a thin edge, particularly when we switched to the newer string material.

The discovery of a method to control the edge meniscus resulted in a non-necked edge as can be seen in Figure 5. The results in terms of downstream yields were extremely dramatic. We experienced downstream yield increases on the order of 15% (absolute) after implementing this method on all of our production furnaces. Evergreen has filed a patent based on this method.

In addition to the dramatic increases in downstream yields, the discovery of a method for edge meniscus control also provided us with another of the originally desired features of any new string material. At the outset, we had hoped to develop a string material that did not wet the molten silicon as it was brought up through the crucible. If a non-wetting material could be found, the reasoning went then that the nucleation of high-angle grain boundaries at the edge would be eliminated. This would then have the result that a source of recombination would be eliminated and higher starting lifetimes could result. The new string material that was developed did, in fact, wet the silicon. However, the method that was discovered which allowed for edge meniscus control did reduce this near-edge grain boundary nucleation significantly while not eliminating it entirely. As a consequence, we are now routinely seeing more extensive regions of coherent twins in the ribbon and also very large grains, in some cases greater than 10cm^2 in area. Figure 6 shows a typical grain boundary structure formed without the edge meniscus control and an example of the very large grains seen using the edge meniscus control method.

The development of the new string material and a method to modify the edge meniscus have been introduced into our production lines and represent two highly significant successes in the first year of this subcontract.

Reduced Consumable Costs—As a result of the introduction of the new string material and the long run lengths which resulted, costs of the hot zone consumable parts was reduced by at least 30%.

In the crystal growth area there are two other projects which have been started this year but are not expected to reach completion until well into the second year of the subcontract. These are automated thickness control and a simplified, smaller furnace design.

Automated Thickness Control—Thickness uniformity across the 5.6 cm width of the ribbon is an important driver of downstream yield. At present, thickness measurement and control are done manually. The crystal growth operator measures ribbon thickness and then makes corresponding adjustments in the crucible temperature distribution as required. Thus, automating thickness control will both increase yield and boost labor productivity.

Three elements were needed to achieve this goal of automatic thickness control: (i) a method to measure thickness as the ribbon grows, (ii) a means of adjusting crucible temperature distribution, and (iii) an appropriate algorithm to provide for a closed feedback loop between the measured thickness and the temperature adjustment. Work has begun in all three of these areas and progress has been very encouraging.

The two most difficult areas technically were the development of a thickness measurement technique that is accurate and low-cost, and the development of thermal balance controls for the growth crucible that could be adjusted electronically.

For thickness measurement two different methods were studied. The first was one that relied on a mechanical method with sensitive air pressure measurements. This was shown to work but its cost and complexity left much to be desired. A second method, based on optical techniques, proved to be the better of the two methods. It was shown to be sufficiently accurate, it was simple and compact, and it was almost one-tenth the cost of the first method. It has been placed on a production machine and its output compared with that measured by an operator in the conventional way. This is shown in Figure 7. Also, Figure 8 shows the first iteration of the apparatus as it was mounted on a production crystal growth machine with ribbon growing.

Of course, the measured thickness is at a finite distance away from the solid/liquid interface. But, even using operator micrometer measurements at this distance, we have found that this is satisfactory from the point of view of thickness control.

Regarding thermal control of the crucible, a means for achieving this was also developed during this first year. The outcome here is a capacity to vary the thermal balance over a broad range but in quite small increments and a mechanical linkage that can then be controlled by a signal from the thickness measurement device. It is anticipated that the full closed loop, after the software algorithm is developed, will be implemented some time early in Year Two of the subcontract.

<u>Lower Cost Furnace Design</u>—In a multi-megawatt factory setting, Evergreen is planning to have a large number of crystal growth machines. Our approach to crystal growth is to simplify and replicate a small, modular, inexpensive, highly automated, high-uptime furnace. While the capital cost of the current design is already reasonably low, the capital cost per machine will become more important with scale-up. The work to accomplish this can be defined into four areas:

1. Redesign and simplification of the hot zone.
2. Redesign and simplification of the water-cooled shell.
3. Redesign and simplification of the continuous melt replenishment feeder.
4. Integration of 1, 2, and 3 into a single, simplified, smaller, and lower cost machine.

During Year One we have done work on 1 and 2 above, and 3 and 4 will be addressed in Year Two.

Regarding hot zone simplification, there are two key aspects to this project. One is a very much smaller and simpler growth crucible whose fabricated cost should be about one-third that of our present crucibles. The other is a simplified multi-zone heating system which will also be lower in cost by about one-half to that of our present heating system. Heating is done by resistance heating in the String Ribbon growth machine. An example of the reduced size of the crucible and, as a consequence, all the other parts of the hot zone, is shown in Figure 9 where the present crucible is also shown in side view. At present, this project is still in its early stages and will be continued for some time. However, some capability in terms of growth has already been demonstrated. Figure 10 shows ribbon being grown with the smaller crucible and a newly designed multi-zone heater. Short lengths of ribbon up to about 3 feet long have been grown this way but improvements to the heater design are clearly still needed and it is expected that a number of iterations will be called for before this work can be termed fully successful.

Regarding redesign of the water cooled shell, the original design of our production furnaces utilizes welded aluminum for the furnace outer shell with welded water cooling on the outside of this furnace shell. While the cost of such a shell was low in comparison to more conventional, stainless steel enclosures, it was felt that further cost reductions could be effected here, in particular by finding a way to avoid having to weld aluminum. Such a method was found and a simplified design that avoids any aluminum welding was conceived and tested. it is estimated that a saving of 10% of the cost of the machine can now be realized using this new shell design. Since we plan to have many such machines in the factory, this is a very significant savings.

There is one final project which was done in crystal growth but its main impact to date has been in the cell area so it will be elaborated on there. This is a method that allows us to eliminate all pre-diffusion etching and is discussed next.

Task 2—Cell Manufacturing

Elimination of the Pre-Diffusion Etch—Virtually all crystalline silicon cell processing schemes involve a wet chemistry etch step prior to diffusion. As is well known, disposal of acids can be more costly than the acids themselves. Thus, the possibility of eliminating the need for at least one major acid step would clearly impact production costs. In the case of String Ribbon, we have generally found it necessary to do such an etch step because the as-grown ribbon surface grown in the conventional way has small dendrites on its surface which are either Silicon Carbide or Silicon Oxycarbide. Figure 11 shows an example of these dendrites. The dendrites are on the surface, tend to follow clear crystallographic directions and so are epitaxial, and likely to be formed from the vapor phase just above the solid-liquid interface. The presence of these dendrites, if not removed, can create regions of unequally diffused junction depth and this can result in lower fill factors. Thus it becomes necessary to do a silicon etch prior to diffusion to either etch off or undercut these dendrites.

Samples of our String Ribbon material were sent to Dr. Larry Kazmerski's group at NREL. In Figure 11 are shown both an Atomic Force Microscopic (AFM) image of some of these dendrites as well as a line scan indicating the height of one of these. The AFM work was done by Helio Moutinho. Chemical characterization of the dendrites was performed for us by Alice Mason, John Webb, and Lynn Gedvilas.

Recently, we have discovered a means of modifying the crystal growth ambient in such a way as to virtually eliminate the formation of these dendrites. The work is still preliminary but there are already clear indications that, with this modification, ribbon can be taken directly from growth into diffusion with no penalties in terms of final cell efficiency. If this turns out to be true in general, then, over and above the potential costs savings, a major step has already been taken towards the goal of eliminating the need to insert and remove cell blanks from plastic carriers. Instead, the cells can always remain horizontal as they are being processed. This possibility clearly will be an improvement in terms of reduced handling and better yields.

Hydrogen Passivation—As is well known, polycrystalline silicon responds well to hydrogen passivation. The effect is due principally to passivation of dislocations either at intragranular locations or at grain and twin boundaries. An original goal in this project was to develop a hydrogen passivation method that would be done without requiring a vacuum process such as plasma nitride. For example, reports in the literature have indicated some passivation using forming gas anneals [4].

We studied this possibility by doing experiments with forming gas anneal both before and after metallization firing. In the before case, we found conditions which gave significant increases in diffusion length as high as 100% prior to the metallization firing. However, the cell structure we have, which includes a TiO_2 AR coating, apparently did not provide sufficient surface blocking layers and the hydrogen, or at least its beneficial effects, were not manifest following the metallization firing.

Doing the forming gas anneal following conventional cell making did show some improvement but it was mostly in fill factor—not what one would expect from hydrogen passivation of dislocations where the benefits are largely in Voc and Jsc. Furthermore, while the contact resistance of the front contact was lowered with forming gas anneal and the fill factor improved thereby, the pull strength of the front metal contacts was weakened to unacceptable levels and so this was not pursued any further.

Based on the above, we have decided to investigate vacuum processing methods for hydrogen passivation. Initial work we have done ourselves as well as earlier work done on String Ribbon at Sandia [5] and at Georgia Tech [6] indicate that String Ribbon responds well to conventional passivation techniques.

High-speed Drying—A method to improve our drying process for cell contacts and to replace the somewhat slow and cumbersome belt furnace we are now using has been developed. The first prototype machine had heaters that were somewhat unsatisfactory and a better design and source for such heaters has been found. The method of transport in the drying equipment has been tested and, while very novel, seems to be very useful. Figure 12 shows a drawing of the next iteration that is now under construction.

High-speed Contact and AR Application Machine—Evergreen has its own unique technology for forming cells. With this technology, the AR coating, front and back metallization are basically all formed in a single final firing step. Prior to this formation, it is necessary to apply the contacts and the AR coating and a high-throughput automated machine is now under active development to accomplish this. In the final deployment, there will be two such machines, one for front contact and AR coating, the other for the rear contact. A good deal of the construction of this first machine, which we have designed in-house, is already complete. In Figure 13 are shown photos of various parts of the machine, including the robot, a rotary table, and the apparatus for moving cell blanks in and out of carriers. Two such machines will have sufficient capacity for Evergreen's first multi-megawatt production line.

Of course, the machine as now constructed assumes the use of plastic carriers and our present AR coating. If we are able to eliminate totally the use of carriers and modify the type of AR coating, both of these changes can be readily accommodated with this machine.

Automated Diffusant Glass Etching—A method for accomplishing this has been developed on an R&D scale. The appropriate polymers which will allow this to work have been identified and conceptual designs of both a prototype apparatus and a production-sized apparatus have been produced. The successful completion of this project along with the successful completion of the effort described earlier in eliminating the pre-diffusion etch will then allow for the elimination of plastic carriers. This then means that the cell blanks are always horizontal and this should then lead to easily automated, high-volume production with minimal handling.

Task 3—Module Lay-up

In an earlier PVMaT subcontract, Evergreen had developed a new backskin material to replace Tedlar, a frameless module design based on this new backskin material, a new encapsulant material to replace EVA, and a non-vacuum, continuous lamination method based on the use of this non-EVA encapsulant. [7,8]

In Task 3 of the present PVMaT subcontract, we have tried to build on the foundation laid down in the earlier subcontract. We have done this by exploring means for automating module lay-up, based on these earlier developments.

The first thing we have done is investigate methods of applying the ¼" wide crosstie material directly onto the backskin so that interconnected strings of cells could be soldered directly onto this crosstie material, thereby reducing the labor in the layup operation. We have found that this can be accomplished quite readily using our continuous lamination process. In this operation, the crosstie material bonds neatly to the backskin material forming what we term a patterned backskin. An example is shown in the top of Figure 14. In Figure 14 at the bottom is shown a small 10-cell module made using the patterned backskin material, the continuous lamination process wherein the new encapsulant is bonded to the front glass, and made using our frameless module design.

Task 4—Factory Layout and Automation

To help Evergreen in Task 4, we have enlisted the help of the Manufacturing Institute at Boston University, which is part of the worldwide Fraunhofer Institute for Manufacturing technology. All the work described below has been as a result of the collaboration with them. Evergreen is planning to expand into a multi-megawatt factory in late 1999. Section 3 below describes some of the work by the Fraunhofer staff on factory layout, and manufacturing process.

Manufacturing Process Analysis of the Pilot Line—A process-step by process-step analysis of the existing pilot manufacturing line was performed. During this intense analysis, performance data from the individual manufacturing processes was collected. The subsequent time studies and process analyses provided information required for identifying operations with low efficiency. Emphasis was placed on the operator, machine, and operator-machine interface efficiencies.

Manual operations were observed as sources of high variability in some steady flow processes involving repetitive operator intensive steps. Conversely, in processes with inherent variability the operators were able to adjust to changing situations to maintain a steady flow. Machine characteristics were analyzed based on speed, volume, part interaction, variability, and output quality. Operator-machine interfaces were observed for ergonomics and ‘user friendly’ characteristics.

Product and Process Improvements—Based on the manufacturing process analysis, improvement potentials in both the product and the process field were identified.

One of the first steps taken in the product design was to reduce the number of soldered joints to minimize labor intensive process steps.

Process combination was suggested to both maximize output and minimize product/transportation. Multiple operations were grouped into a single manufacturing cell to increase product throughput by synchronizing the operations.

An appropriate factory simulation package was selected and will be used to evaluate alternative line layouts and determine required capacity at each process step, such that the overall line target capacity is met. Based on these results, the physical plant and line layout will be refined and detailed.

Factory Layout Alternatives for the Scaled-up Production—In the process of finding the optimum solution for the factory layout of the scaled-up production, multiple solutions were developed with consideration of potential facility boundaries.

The general approach consisted of three steps. The first step was to identify the optimal layout for the subsystem of the manufacturing process. The layouts created within this step were locked. The second step was to identify the optimum layout for the subsystems to form the complete manufacturing process. The different alternatives suggested different solutions of where to place the individual subsystems. The last step was the integration or adjustment of the completed layout to the supply and environmental requirements imposed by the process, legal requirements and facility layouts.

Overall, layout activities were based on the product throughput, process requirements and facility boundaries. The organizational issued also played a big role in the design phase to enable efficient teamwork by utilizing both the maximum skill level and available productive time from all operators.

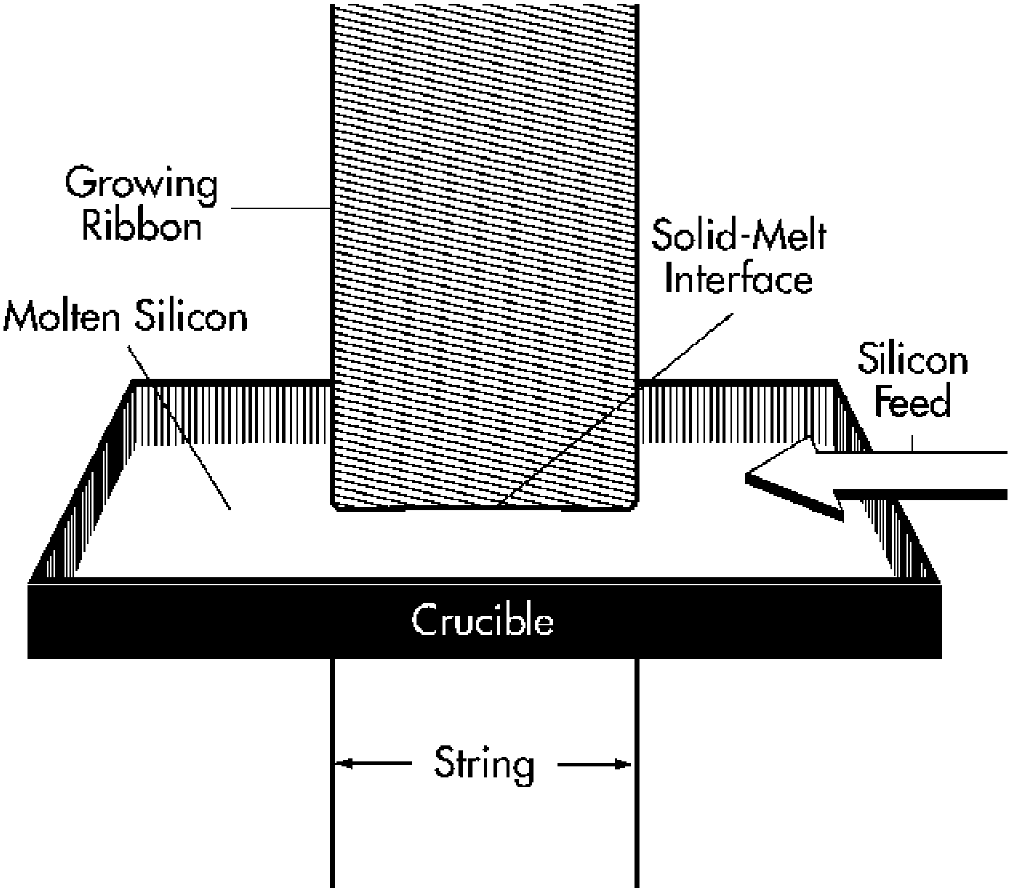


Figure 1 **String Growth Process**

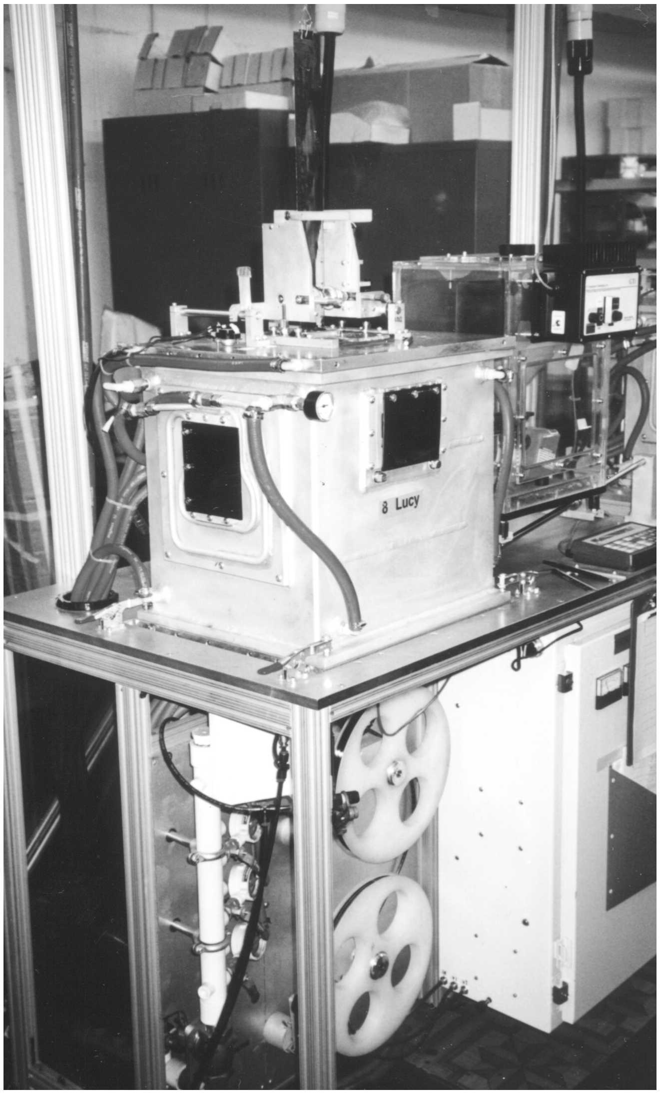


Figure 2   Production Crystal Growth Machine

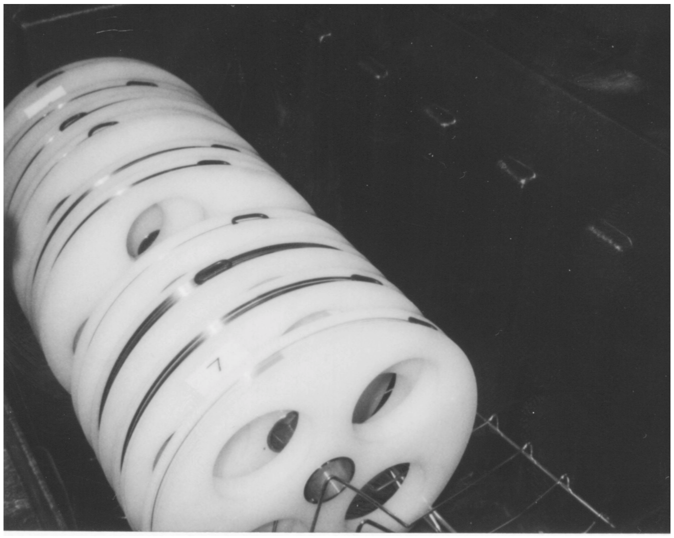


Figure 3 Spools of the New String Material

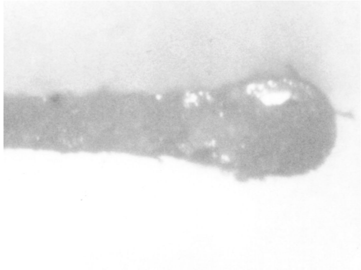


Figure 4 Micrograph of As-grown Ribbon Edge

Figure 5 Micrograph of As-grown Ribbon Edge
with Edge Meniscus Control

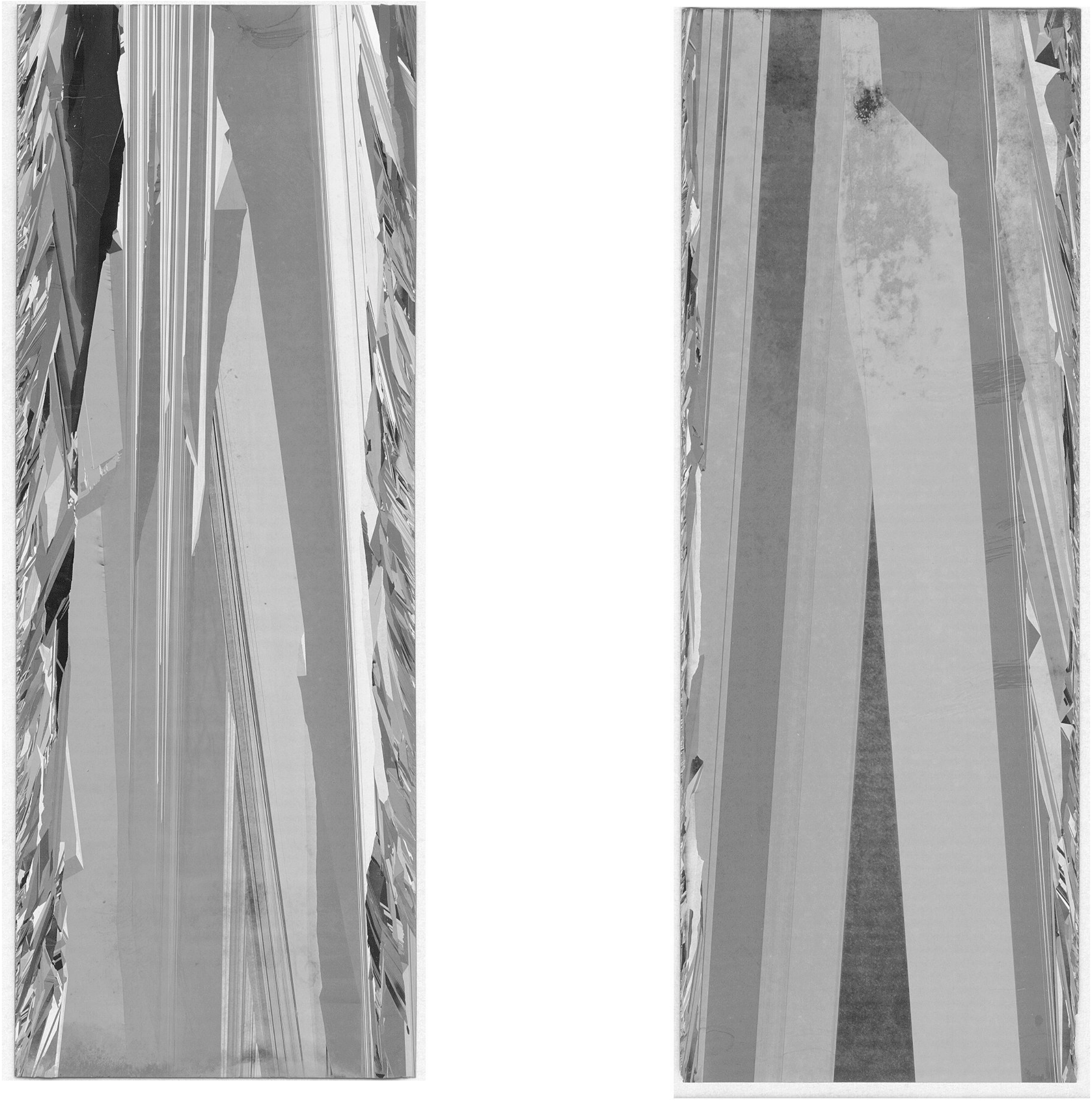
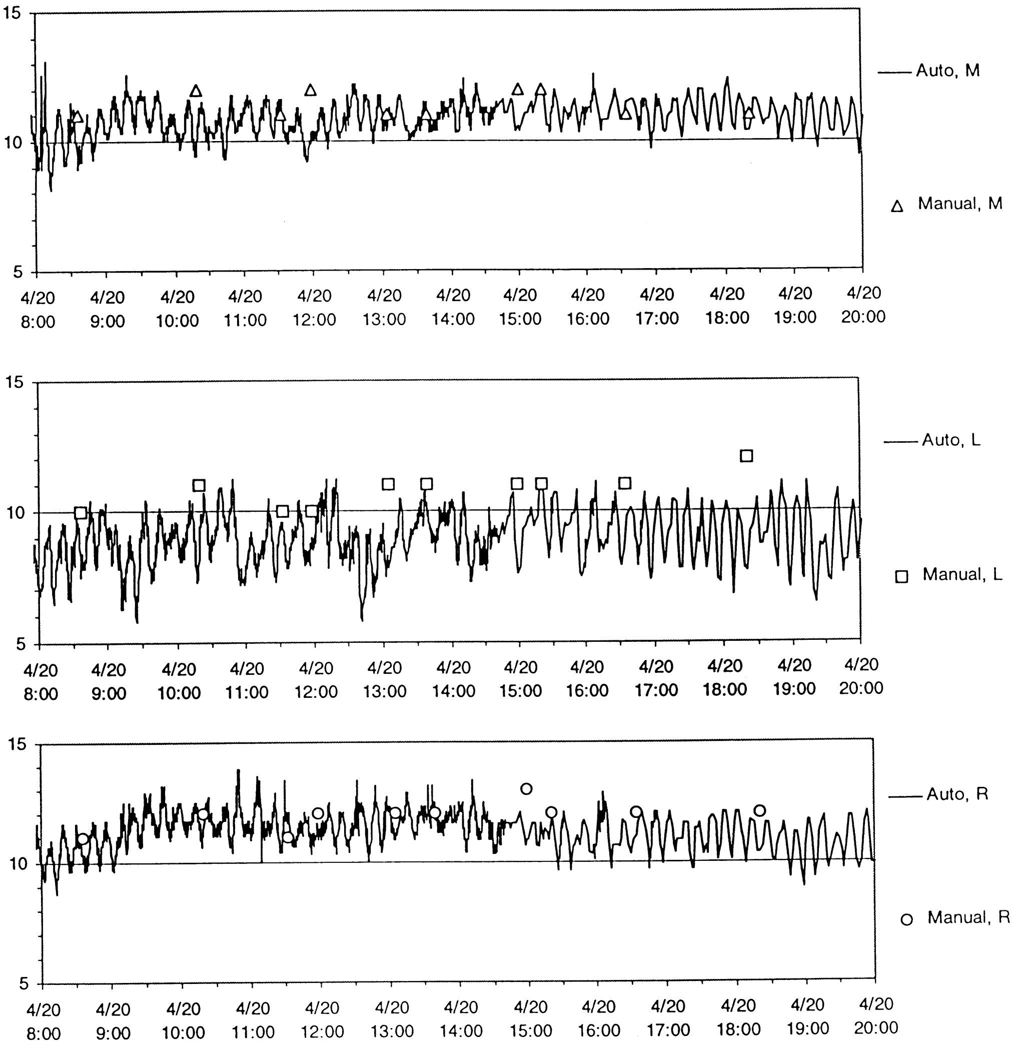


Figure 6 **Typical Grain Structure and example of very Large Grains**



Plot of automatic thicknes measurement in mils versus time, as compared with manual measurements, for left, middle and right sections of the growing ribbon.

Figure 7 Automatic Thickness Measurement

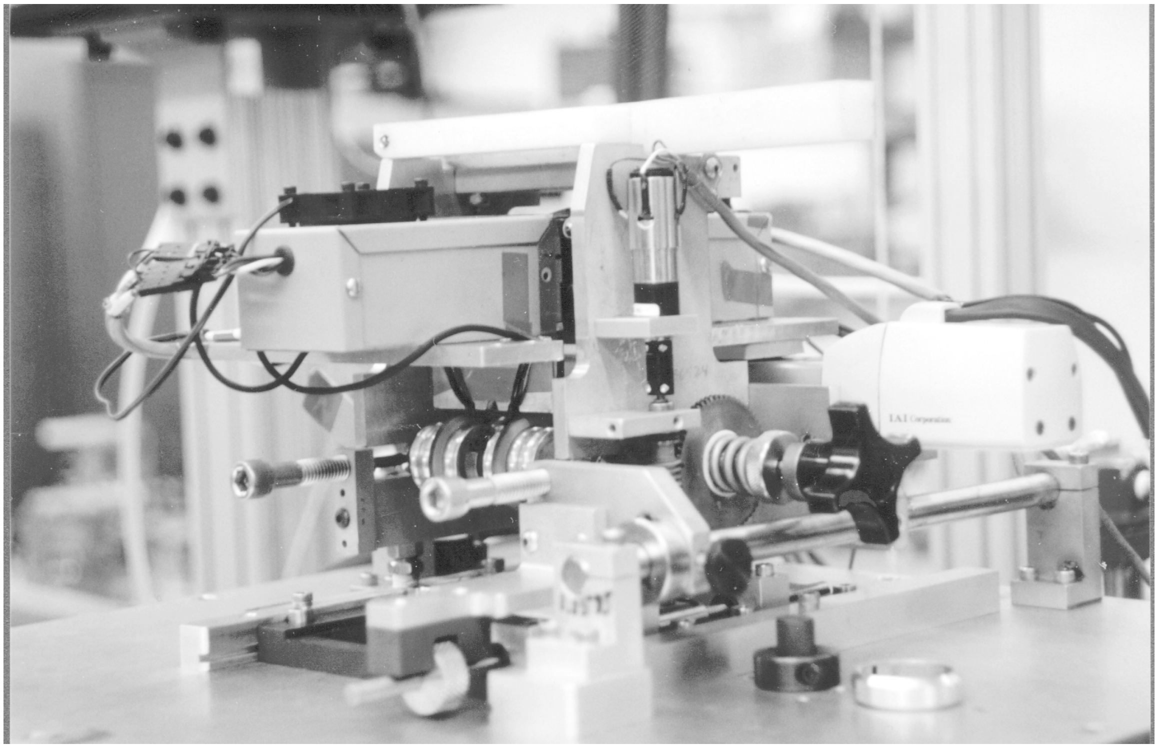


Figure 8 Prototype installation of automatic thickness measurement on a production machine

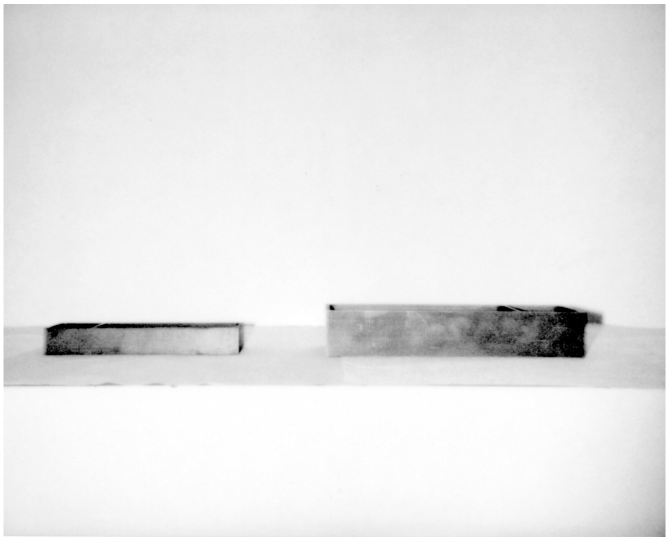


Figure 9 Reduced crucible size for low cost hot zone

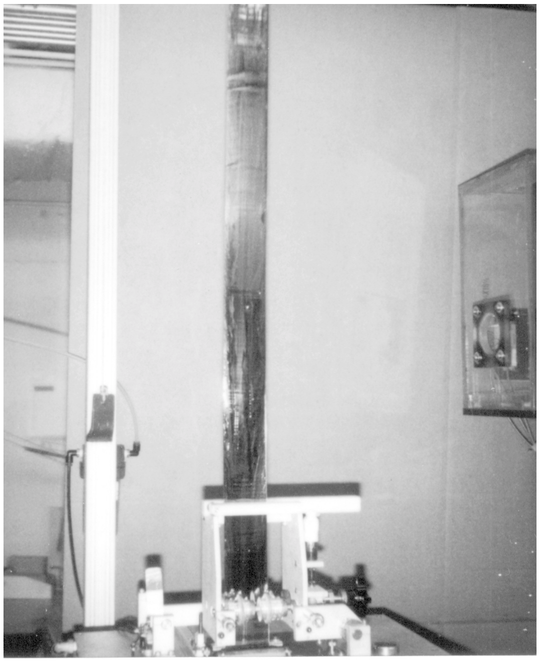


Figure 10 Ribbon growth using the low cost hot zone

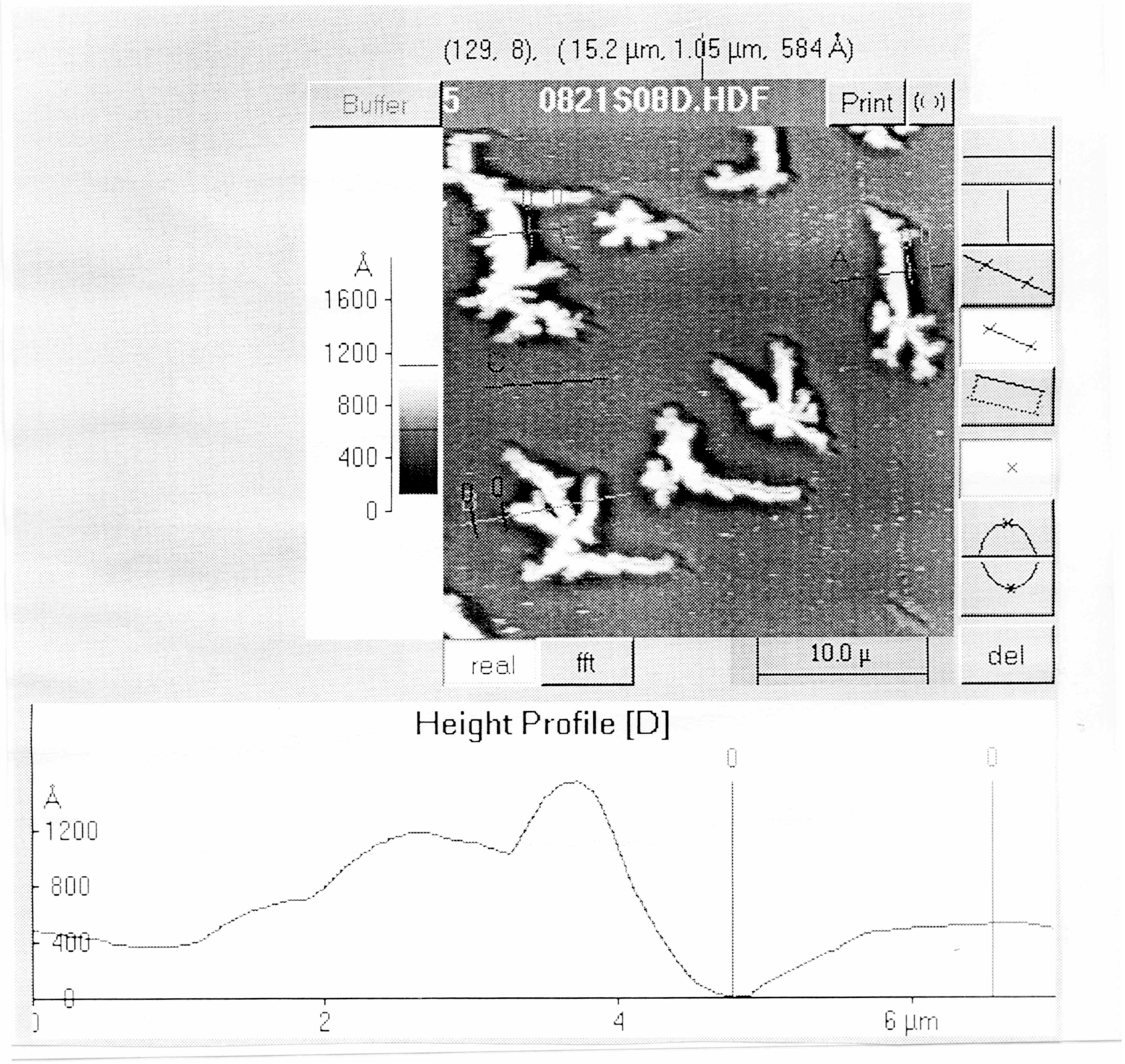


Figure 11 **Dendrites on as-grown surface**

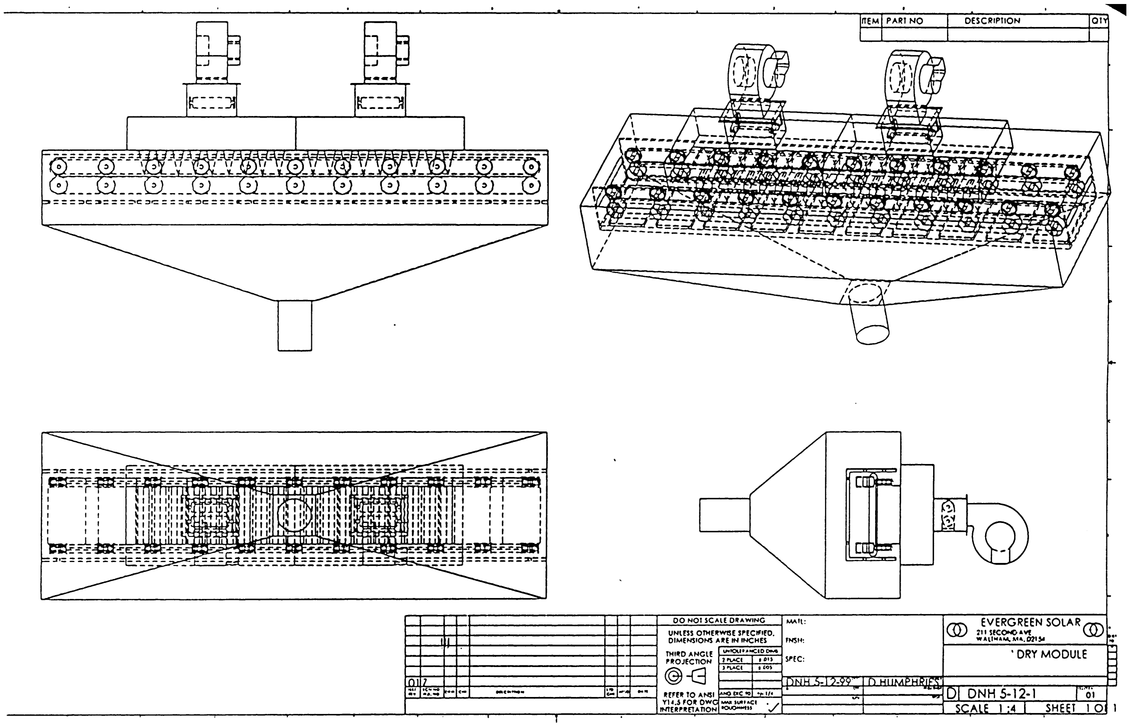


Figure 12 High Speed drying machine

Figure 13 High speed contact and AR application machine

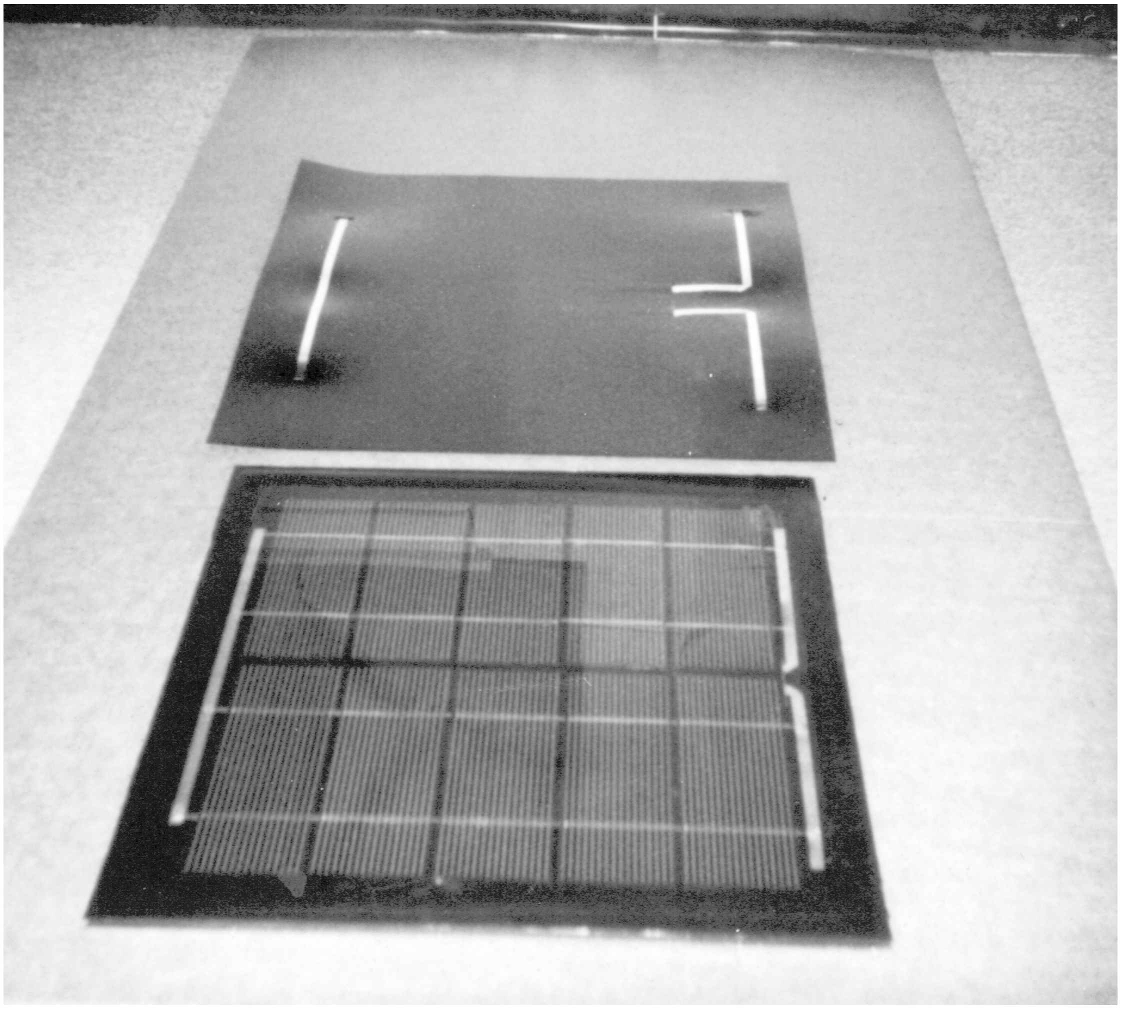


Figure 14 Examples of patterned backskin material and Frameless Module

REFERENCES

[1] R. Janoch, R. Wallace, and J. I. Hanoka, 26th IEEE PVSC, Oct. 1997, Anaheim, p. 95-97.

[2] R. L Wallace, R. E. Janoch, and J. I. Hanoka, 2nd World Conference on PV, Vienna, July 1998, p. 1818-1821.

[3] T. F. Ciszek, J. L. Hurd, and M. Schiezelt, *J. Electrochem. Soc.*, Dec. 1982, 2838-2893.

[4] B. L. Sopori, X. Deng, J. P. Benner, A. Rohatgi, P. Sana, S. K. Estreicher, Y. K. Park, and M. A. Roberson, “Hydrogen in silicon: current understanding of diffusion and passivation mechanisms,” Proceedings 1st WCPEC, Waikoloa, Hawaii, 1994, p. 1615.

[5] D. S. Ruby, W. L. Wilbanks, C. B. Fledderman, and J. I. Hanoka, 13th Eur. PV Conf., Nice, 1995, p. 1412-1414.

[6] V. Yelundur, A. Ebong, S. Kamra, A. Rohatgi, J. Hanoka, A. Gabor, “Approach Towards High Efficiency, Manufacturable Thin String Ribbon Silicon Solar Cells,” Proceedings of the 8th Workshop on Crystalline Silicon Solar Cell Materials and Processes, Copper Mountain, CO, Aug. 17-19, 1998.

[7] J. I. Hanoka, P. E. Kane, J. Martz, and J. Fava, 26th IEE PVSC, Anaheim, 1997, p. 1081-1084.

[8] J. I. Hanoka, 2nd World Conf. on PV, Vienna, July 1998, p. 1974-1977.

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB NO. 0704-0188*

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE October 1999	3. REPORT TYPE AND DATES COVERED PVMaT Phase 5A2 Subcontract; First Annual Report, 21 May 1998 – 20 May 1999

4. TITLE AND SUBTITLE Continuous, Automated Manufacturing of String Ribbon Si PV Modules; PVMaT Phase 5A2 Subcontract; First Annual Report, 21 May 1998 – 20 May 1999	5. FUNDING NUMBERS C: ZAX-8-17646-07 TA: PV906101
6. AUTHOR(S) J.I. Hanoka	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Evergreen Solar, Inc. 211 2nd Ave. Waltham, MA 02451	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401-3393	10. SPONSORING/MONITORING AGENCY REPORT NUMBER SR-520-26891
11. SUPPLEMENTARY NOTES NREL Technical Monitor: M. Symko-Davies	
12a. DISTRIBUTION/AVAILABILITY STATEMENT National Technical Information Service U.S. Department of Commerce 5285 Port Royal Road Springfield, VA 22161	12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This report describes the first year of a 3-year PVMaT Phase 5A2 program. Evergreen Solar will soon be expanding into a multi-megawatt facility and the PVMaT work will be used to further the objective of a high-throughput automated production line in every aspect of PV module making from producing silicon ribbon to making a finished module. The project has four task areas for this first year: crystal growth; cell manufacturing; modules; and factory layout and automation. The vast majority of the work this first year has been in the crystal growth and cell manufacturing areas. Evergreen Solar has its own unique technology in each of these areas. In crystal growth, a key goal of this PVMaT project has been developing and deploying an improved string material. The high-temperature string materials are used to stabilize the edges of the growing silicon ribbon in our String Ribbon silicon sheet growth. The result has been one of the major successes of this first year. Significant cost reductions and yield improvements have emerged from this improved string material. In addition, some of the groundwork for automation of the String Ribbon crystal growth process has been laid and shows much promise. A method for controlling the edge meniscus height was developed, and a patent has been filed based on this discovery. In the cell manufacturing area, the focus has been on reducing the number of processing steps and on design and construction of high-speed processing equipment. The possibility of eliminating all pre-diffusion etching and going directly from growth to diffusion has been demonstrated on an R&D scale. Unique designs for high-speed drying equipment and for a high-speed contact and AR-coating application machine have been developed. In the latter case, the basic concepts underlying various aspects of the machine design have been successfully tested for viability. The integration of the different components of this machine into a smoothly working whole is now well under way. In addition, nonvacuum methods of hydrogen passivation have been investigated, but no production-viable process has emerged from this work. In the module area, initial work has shown that the unique properties of the backskin developed under Evergreen's earlier PVMaT Phase 4A1 contract can be expected to make the lay-up process simpler and involve less labor. For factory layout and automation, we have enlisted the Fraunhofer Manufacturing Institute at Boston University to aid us with the layout and process flow of our new factory. In general, the project is on schedule, with no significant technical barriers to reach our ultimate objectives.

14. SUBJECT TERMS photovoltaics ; Photovoltaic Manufacturing Technology ; PVMaT ; crystal growth ; cell manufacturing ; hydrogen passivation ; silicon ; String Ribbon	15. NUMBER OF PAGES 30
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT UL