NREL/SR-520-25269

Photovoltaic Cz Silicon Module Improvements

Annual Technical Progress Report
9 November 1996–8 November 1997

T.L. Jester
Siemens Solar Industries
Camarillo, California

NREL technical monitor: R. Mitchell

National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, Colorado 80401-3393
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Preface

This report describes work done by Siemens Solar Industries (SSI) from November 9, 1996 to November 8, 1997 during Phase II of a three-phase Photovoltaic Manufacturing Technology (PVMaT 4A) subcontract from DOE/NREL. The work focuses on improvements in the cost per watt of Cz silicon photovoltaic modules through detailed understanding of their cost structure, module design to minimize cost per watt, measures to improve manufacturing yield and productivity, and manufacturing control systems to improve module reliability. The overall project goal is a reduction of Cz silicon module cost per watt of 18% at the end of the three phases of the subcontract.

Acknowledgments

Many people have contributed to the work under this contract. Thanks are due especially to Rick Mitchell, NREL technical monitor, to Ruben Balanga, Dave Bender, Eberth Covarrubia, Heinrich Eichermüller, Chet Farris, Bryan Fickett, Jean Hummel, Dave Jeffrey, Waltraut Klein, Greg Mihalik, Alex Mikonowicz, Jeff Nickerson, Ken Sandland, Maria Tsimanis, Elena Woodard, Eugene Yamamoto, and others in the Engineering, Quality, Manufacturing, and Finance groups at SSI.

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Summary

Work focused on reducing the cost per watt of Cz silicon photovoltaic modules under Phase II of Siemens Solar Industries' DOE/NREL PVMaT 4A subcontract is described in this report. New module designs were deployed in this phase of the contract, improvements in yield of over 10% were realized, and further implementation of Statistical Process Control was achieved during this phase. Module configurations representing a 12% cost reduction per watt were implemented in small scale production under Phase II of this contract. Yield improvements are described in detail, yield sensitivity to wafer thickness is quantified, and the deployment of SPC in critical process steps is reported here.

Table i. Program Summary Results

	Phase I 1st Year	Phase II 2nd Year	Phase III 3rd Year
New module designs to reduce $/W	6% reduction in module $/W ***Complete***	12% reduction in module $/W ***Complete***	18% reduction in module $/W
Improvement of yields and reduction of labor	5% improvement in module mfg. yield 5% increase in module mfg. productivity ***Complete***	10% improvement in module mfg. yield 10% increase in module mfg. productivity ***Complete***	15% improvement in module mfg. yield 15% increase in module mfg. productivity
Improvement of module reliability	Implement SPC on 50% of appropriate mfg. processes ***Complete***	Implement SPC on 100% of appropriate mfg. processes ***75% Complete***	Assessment of SPC protocols, areas for improvement

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Introduction

Program Goals

The Photovoltaic Manufacturing Technology (PVMaT) project is sponsored by the U.S. Department of Energy (DOE) through the National Renewable Energy Laboratory (NREL) in order to assist the photovoltaics industry in improvement of module manufacturing, and reduction of module manufacturing cost. The objective of the DOE/NREL PVMaT subcontract with Siemens Solar Industries (SSI) is to continue the advancement of Siemens Solar Industries' photovoltaic manufacturing technology in order to achieve an 18% reduction in module cost per watt at the end of three phases of work. Each phase lasts a year as shown in Table 1. Phase II of this subcontract began in November 1996. The approaches for reaching the 12% cost reduction goal for this phase have been to analyze existing module cost structure, explore new module designs and materials, investigate the reduction of labor and improvement of yield, and to implement statistical process control (SPC) in module manufacturing.

Table 1. Goals of Siemens Solar Industries' PVMaT 4A Subcontract from DOE/NREL.

	Phase I 1st Year	Phase II 2nd Year	Phase III 3rd Year
New module designs to reduce $/W	6% reduction in module $/W	12% reduction in module $/W	18% reduction in module $/W
Improvement of yields and reduction of labor	5% improvement in module mfg. yield 5% increase in module mfg. productivity	10% improvement in module mfg. yield 10% increase in module mfg. productivity	15% improvement in module mfg. yield 15% increase in module mfg. productivity
Improvement of module reliability	Implement SPC on 50% of appropriate mfg. processes	Implement SPC on 100% of appropriate mfg. processes	Assessment of SPC protocols, areas for improvement

Approaches

The first step toward reducing the cost per watt at the module level was to gain a thorough understanding of the present factors which dominate cost during Phase I of this contract. With this knowledge, the cell and module designs were optimized to minimize the costs of ingot, wafering, cell, and module fabrication, as described in the following sections. The design of larger cells, larger modules, and match of wafer shape to ingot cross-section have shown to be simple but effective means of reducing the cost per watt of silicon photovoltaic modules during Phase II of the program.

In many process steps, yield loss is the greatest single contributor to the module cost per watt. Unlike other types of cost components, such as direct materials, yield loss is not an intrinsic cost of the process, and thus this cost can potentially be driven to zero. Yield loss comes in many forms, such as lost crystal structure, off-spec resistivity, wafer thickness variation, insufficient wafer cleaning, cell breakage and its dependence on wafer thickness and other parameters. Improvement of yield across the various sources of yield loss, and focusing resources on only the most serious yield loss mechanisms was the approach taken in Phase II of this contract.

Four strategies to increase manufacturing productivity at SSI have been deployed further during Phase II: 1) use of automation; 2) development of relationships with vendors to provide preassembled parts or preinspected materials; 3) critical evaluation of staffing requirements of various process steps; and 4) improved efficiency of the internal logistics of material supply. This strategy, combined with yield improvement of over 10% has allowed SSI to meet it's productivity goals.

The approach taken to improve SSI Cz silicon module reliability continues to be one of increased control over manufacturing systems, including design and material procurement, in addition to manufacturing process parameters. Statistical process control of key steps in the fabrication sequence is a cornerstone of this strategy. Many of the steps required for certification under the ISO 9001 quality system directly address the issues of manufacturing control: written documentation of procedures and work instructions; training and certification of operators; measurement of process capability factors; calibration of measurement instrumentation used to control fabrication processes; and internal and external quality audits of manufacturing compliance. SSI received ISO 9001 certification during Phase I of this contract, and passed additional surveillance audits during Phase II of the contract, showing compliance and improvement in this focus of control and manufacturing stability.

Module Cost Analysis and Design

Module Cost Drivers

As shown in the Phase I results, Module Assembly costs, from soldered cells to finished boxed modules represented the largest contribution to total dollar per watt in the four major categories of cost. Figure 1 shows this relationship again as a simple bar chart, normalized to include the yield associated with each area. As can be seen from this chart, it makes sense to work on the module area to lower the dollar per watt contribution.

This has been done in three ways under Phase II of the contract. The first of these involves yield improvement to fully reduce the costs associated with manufacturing processing. Figures 2 and 3 show the yield of soldering, lamination and module processing combined over Phase I and Phase II timeframes. Figure 2 shows the 103 mm (M line) product results, and Figure 3 shows the 125 mm (P line) product results. These figures show a raising and stabilizing of yields to ensure the lowest cost contribution to module dollar per watt.

The second area worked to reduce the contribution to dollar per watt in the module area has been to deploy more watts in a module through a larger cell design. Figure 4 shows the SR100 module which has been produced in small scale production during Phase II of the contract. By the use of thirty six (36) large cells, 100 watts is produced, using virtually the same labor and equipment as thirty six smaller cells. The module assembly labor is also leveraged with this design as the assembly and lamination of these larger cells using the Spire solder machine is comparable to the labor used in both SM55 and SP75 modules produced at Siemens Solar. An SM55 and SP75 module shown in Figures 5 and 6 respectively require approximately the same labor on the stringing level as the SR100 module shown in Figure 4. The layup and lamination labor is size related with the SM55 module requiring 10% less labor than an SP75 module and approximately 25% less labor than an SR100. This labor is a small contributor to the overall dollars per watt. With the module framing and j-box labor comparable on all three designs, the SR100 has the least cost per watt on the module level.

The third area which was focused on during Phase II of the contract was in the reduction of module cost components. Figure 7 shows the cost/watt for direct material in the module fabrication area, with frames and j-boxes contributing over 50% to the materials total. During Phase II of the contract, a new SR50-Z module was designed and produced in small scale which further reduced the junction box and frames costs. The new SR50-Z module is shown in Figure 8, with the j-box and frame shown in Figure 9 and 10 respectively. The new junction box for the SR50-Z allows for ease of installation and a cost savings of over $2 per module. The new frame design eliminates end caps, screws and taping when compared to the traditional SSI module designs.

The combination of yield improvement in the module area, larger cells and more watts in a module, and the new framing and junction box, allowed for a greater than 12% cost per watt advantage, meeting the Phase II goal.

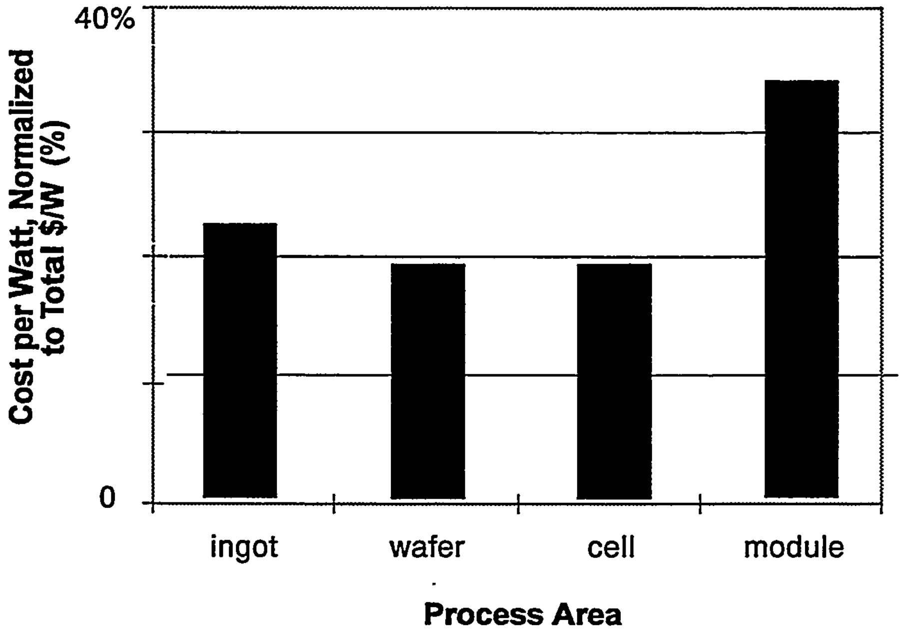

Figure 1. Cost per Watt

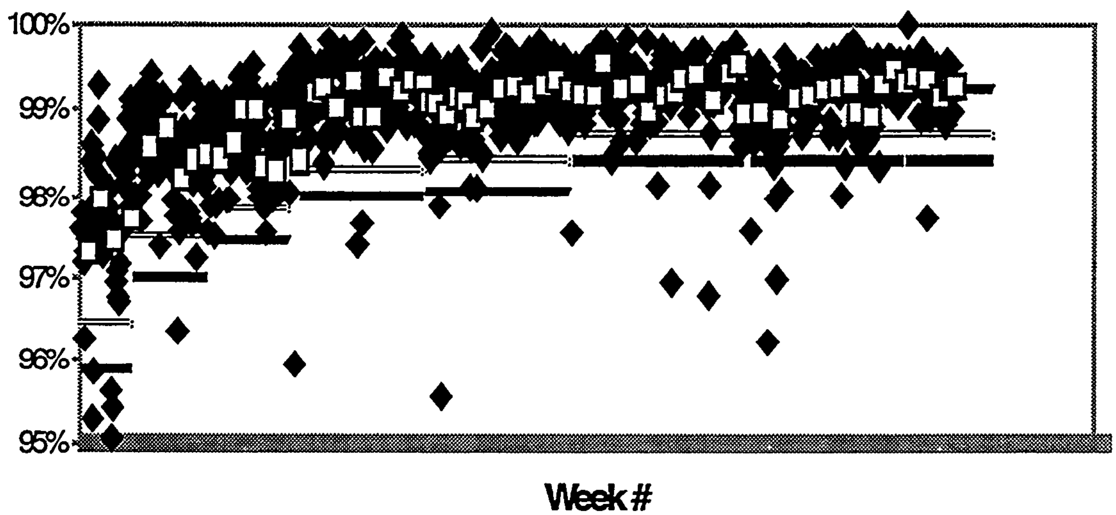

Figure 2. Module Yield for M-line

Figure 3. Module Yield P-line

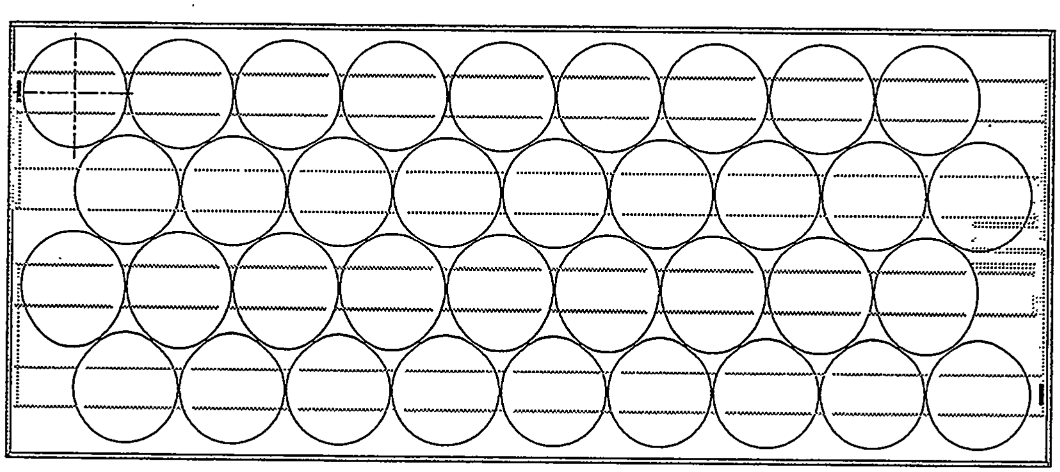

Figure 4. SR100 Module with 150mm cells

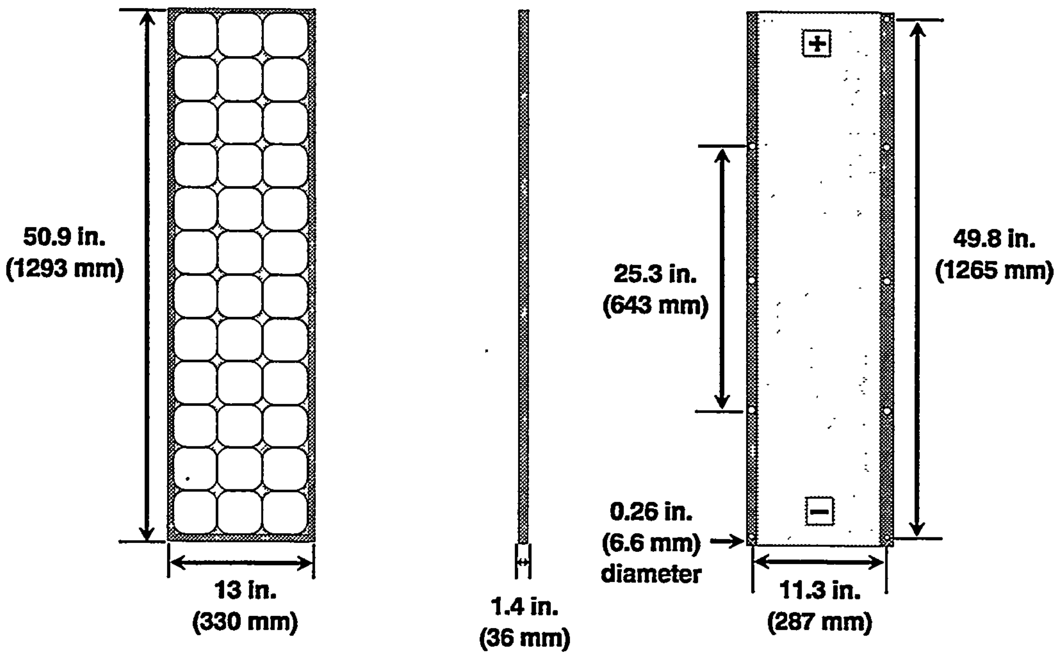

Figure 5. SM55 Module

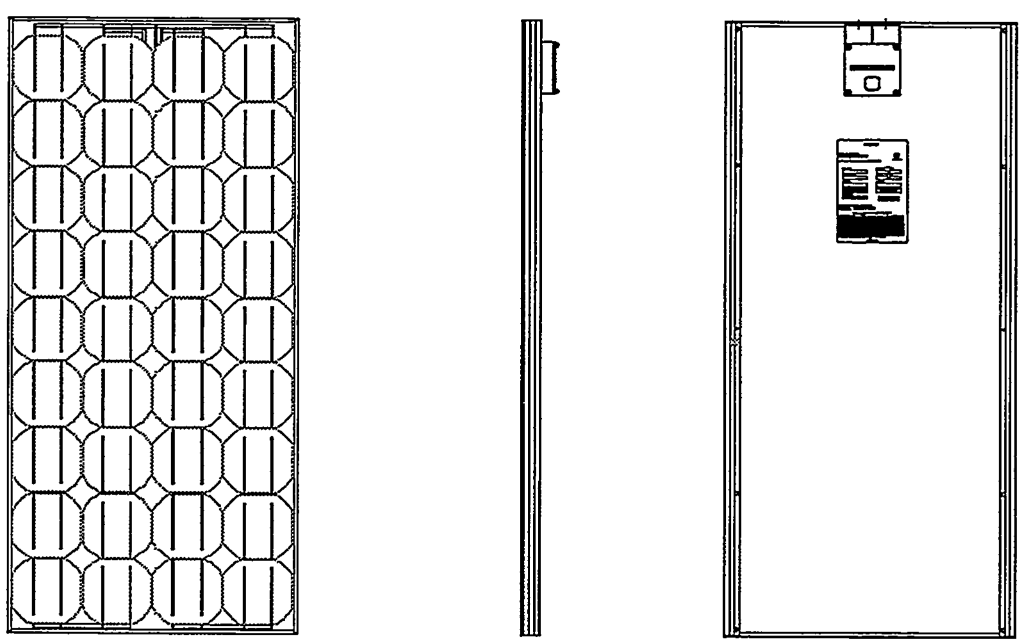

Figure 6. SP75 Module

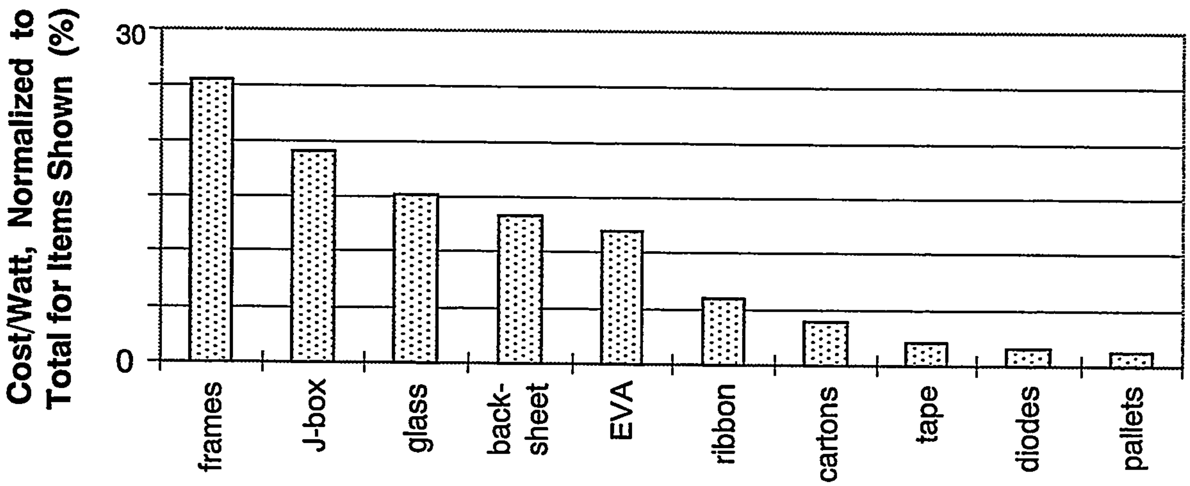

Figure 7. Direct Material Contribution in Module

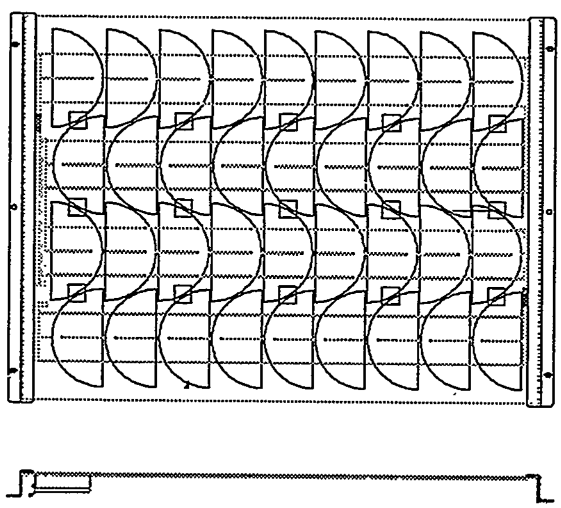

Figure 8. SR50-Z Module

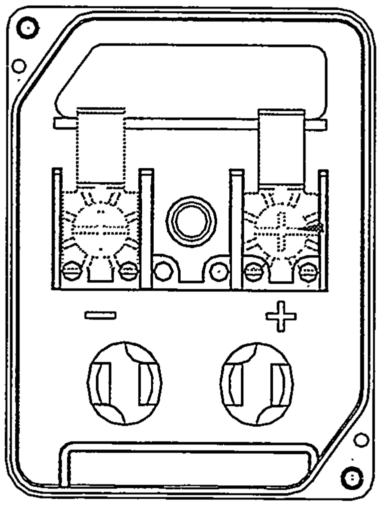

Figure 9. New Junction box

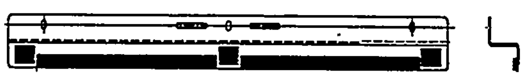

Figure 10. SR50-Z Frame

Yield and Productivity Improvements

Yield Improvements

Yield Improvement in the Cz Manufacturing line has been a focus at SSI starting with PVMaT 2A. In increasing yield, all areas of cost reduction and productivity benefit. A summary of the yield efforts during Phase II of the contract shows that the yields have improved at SSI by over 20% absolute percentage points. The yield gains are shown in Figures 11 and 12 respectively for the M line and P line products over the time frame including PVMaT 2A and 4A.

The M-line yield gain has been 25% over the start of the program and P-Line yield gain has been 40% relative to the 94/95 time frame.

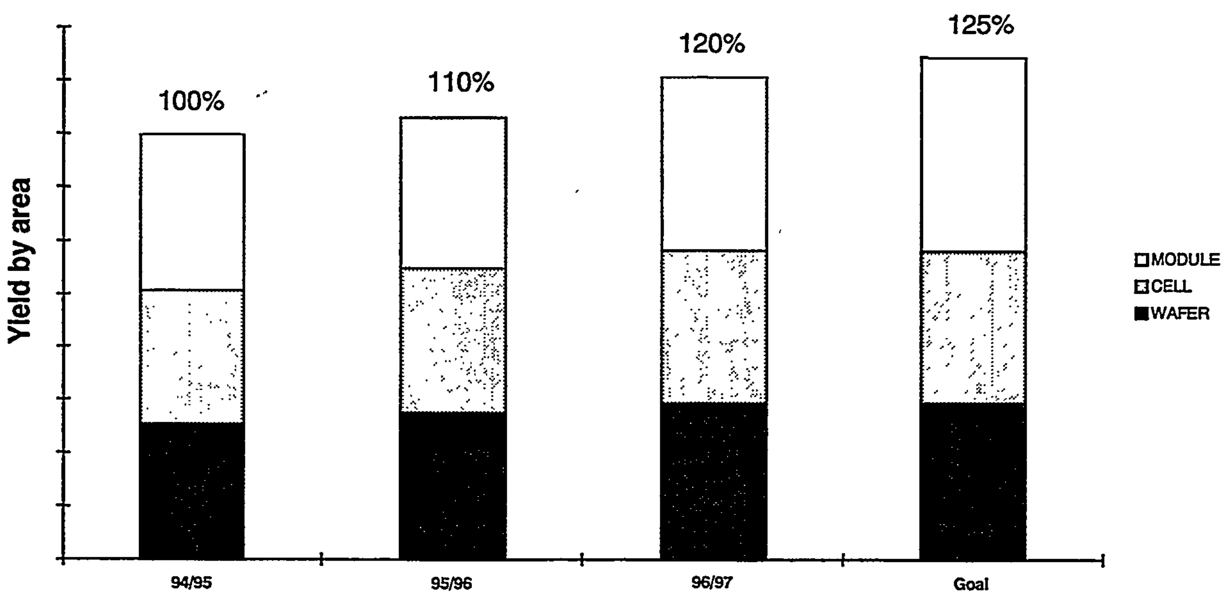

Figure 11. Yield on M-line Product

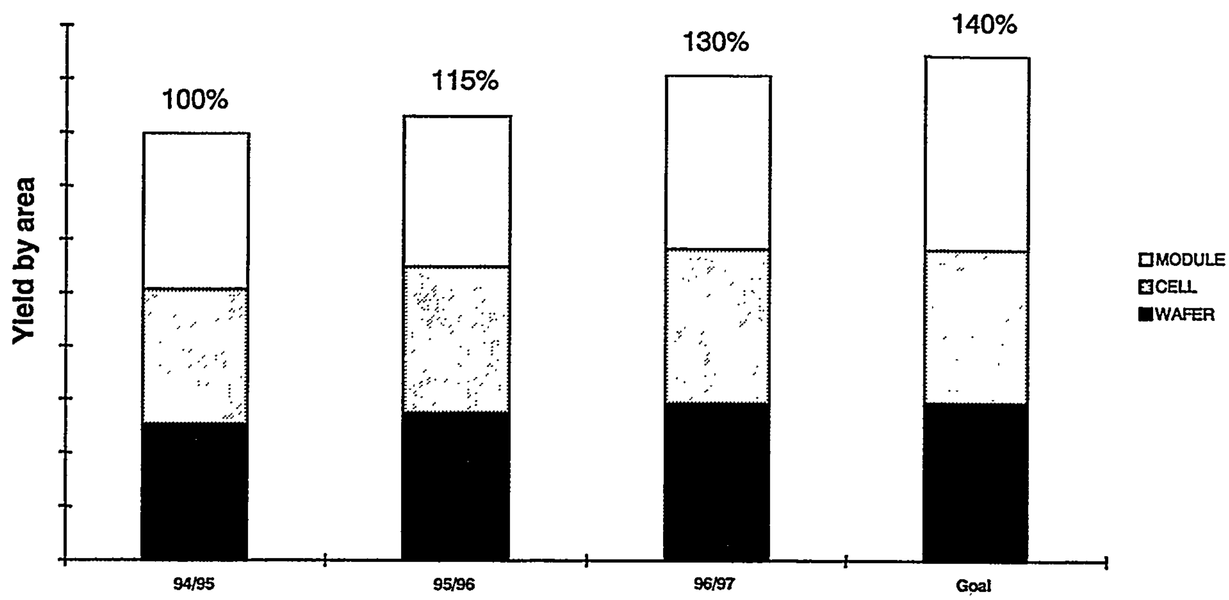

Figure 12. Yield on P-line product

Crystal Yield

Yield in the crystal growth process has been strongly affected by the changes in availability in the polysilicon market. The different types of polysilicon raw material affects growth yields significantly. The differences in raw material feedstock and their affect on growth yields are shown in Figure 13, where the "virgin chunk" feedstock gives the highest crystal pulling yields. Remelt polysilicon is shown as the second highest producer, and potscrap the lowest yielding material. All of these growth yields are with the material as received from the supplier.

An improvement in the growth yields have been realized by etching the various types of polysilicon. Figure 14 shows the same materials as shown in Figure 13, with the etching process performed prior to growth. As can be seen in Figure 14, a lot of the variation in the materials can be reduced, with surfaces being etched. This etching process has been adopted as a standard preparation process for polysilicon at Siemens Solar Industries.

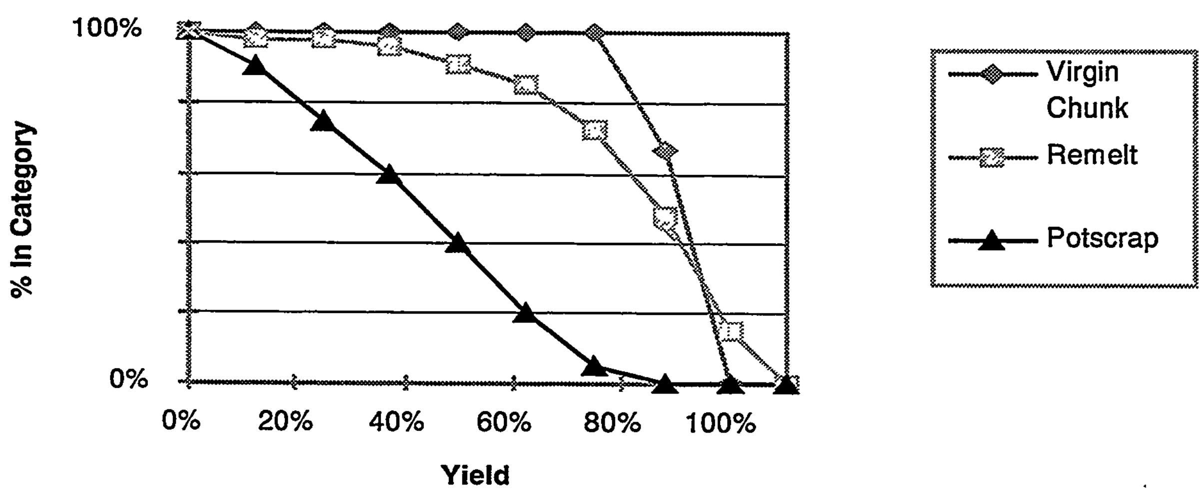

Figure 13. Growth Yield by polysilicon type as received from supplier

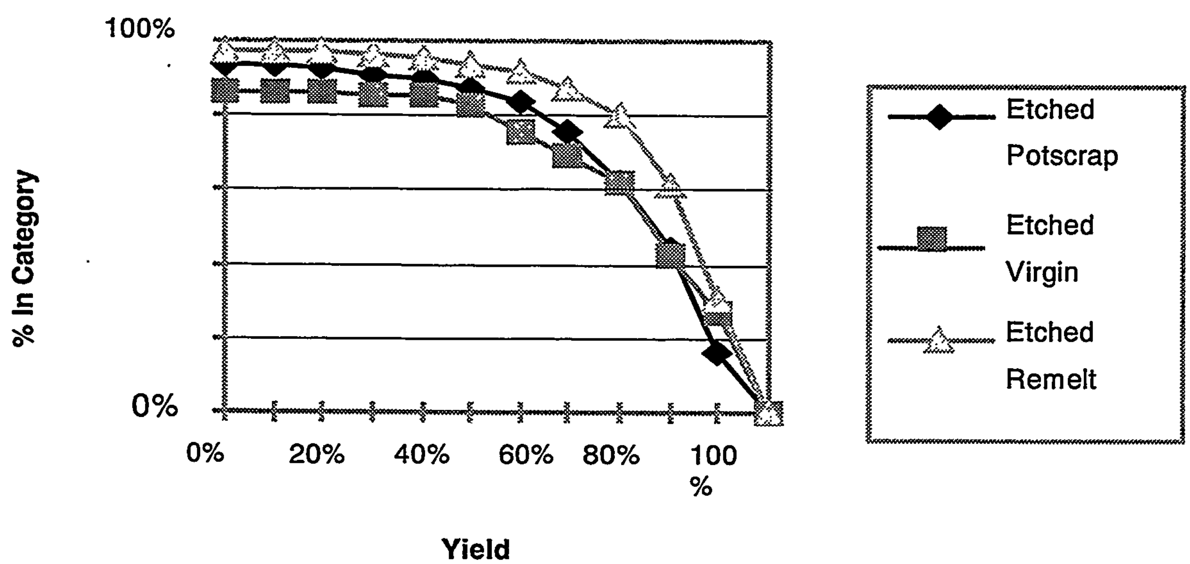

Figure 14. Growth yield by polysilicon type after etching

Yield in crystal growth is also affected by the process procedures and hot zone or graphite design deployed in the growing equipment. Work on two different hot zone sizes has been done to look at yield and productivity. The hot zone designs deployed are 16" diameter and 18" diameter assemblies, this number denoting the heater opening diameter. In CG6000 machines, large camera controlled systems, both hot zones were used for over six months. Figure 15 Shows the yield and productivity of the CG6000's with the two hot zones. As can be seen by the comparison, the yield and productivity for the 16 inch assemblies is higher. This design has been deployed in all CG6000 growers at SSI.

Wafer Yield

The wafering area yield and productivity is driven by the number of yielded wafers produced per inch of ingot fed into the process. In phase two of this program yield gains have been accomplished and reported during the PVMaT 2 program, the wire thickness has been reduced from 175 microns to 160 microns, resulting in a 3% gain in productivity in the wafering process. Figure 14 shows the thinner 160 micron wire test data on a population of 200,000 wafers. Based on this data and the supporting yield information, which stayed constant, the thinner wire is being deployed across all wire saws at Siemens Solar. As stated above, this is a 3% productivity gain across all wafer types.

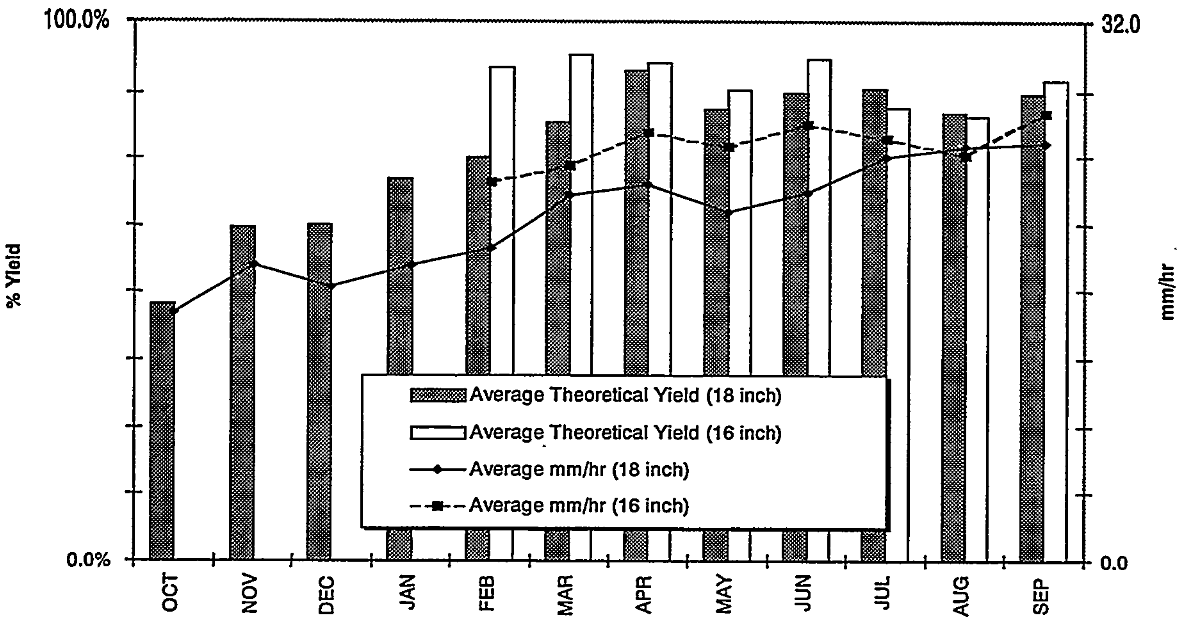

Figure 15. Grower Yield Over time

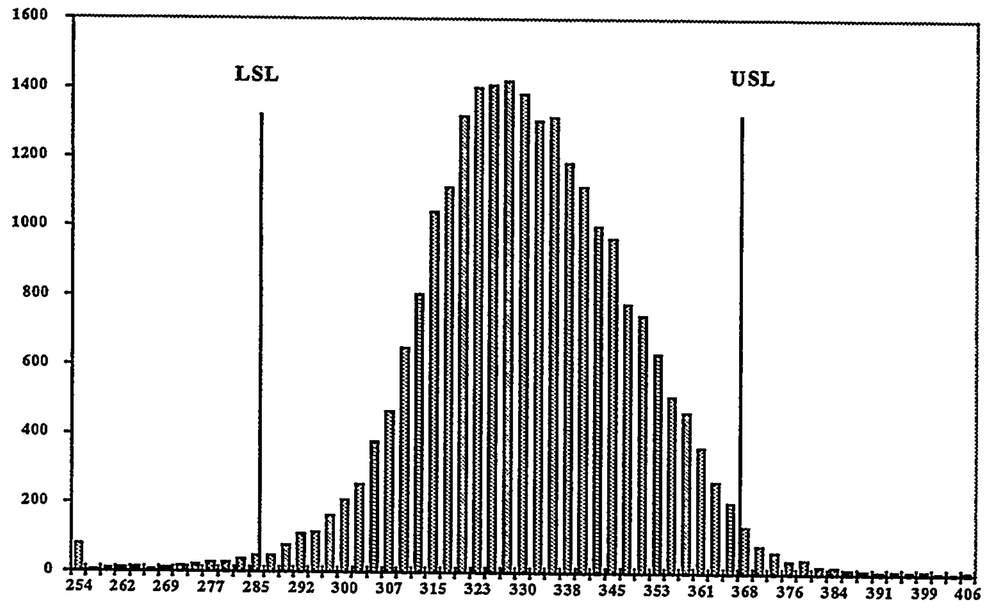

Figure 16. Thin Wire Thickness Test Data

Cell Yields

Cell fabrication yields are highly dependant upon both the mechanical and electrical yields of the process. The electrical yield in Siemens Solar's process is linked directly to the sheet resistance of the diffusion process. Figure 15 Shows the reduction in variation implemented in the diffusion process by better profiling and control of the tube to tube thermal calibration. More work is planned in this area in phase three of the contract, as this reduction in variation is a direct link to improved electrical yields.

Thinner Large Area Wafers and Cells

In increasing yield and productivity and decreasing cost, the overall strategy is to increase the number of watts produced per kilogram of silicon, as in the work on increased growing yield with etching, increasing the number of wafers per inch of crystal as in the thinner wire deployment, and significantly decreasing cost with larger wafers as in the SR100 production. The combination of these three items needs to be done to maximize the benefit of cost reduction potential.

To this end, a series of experiments have been run to test the sensitivity of mechanical yield to wafer size and thickness. The crystal sizes used for the experiment represent the 103 mm, 125 mm, and 150 mm ingots which are standard sizes at Siemens Solar Industries. The wafer thickness used for the experiment ranged from 125 microns to 400 microns.

Figure 18 shows the yield of various wafers sizes at various thicknesses through the wafer slicing process. The x axis of the chart is slicing thickness in microns, the y axis is yield of wafers out divided by wafers in reported in percent, and the lines represent different cell sizes. As can be seen from the graph, the yield of all wafer sizes drops as the thickness is reduced below 200 microns.

This is also evident in the cell yield graph, shown in Figure 19, where cell yield is declining at values lower than 300 microns.

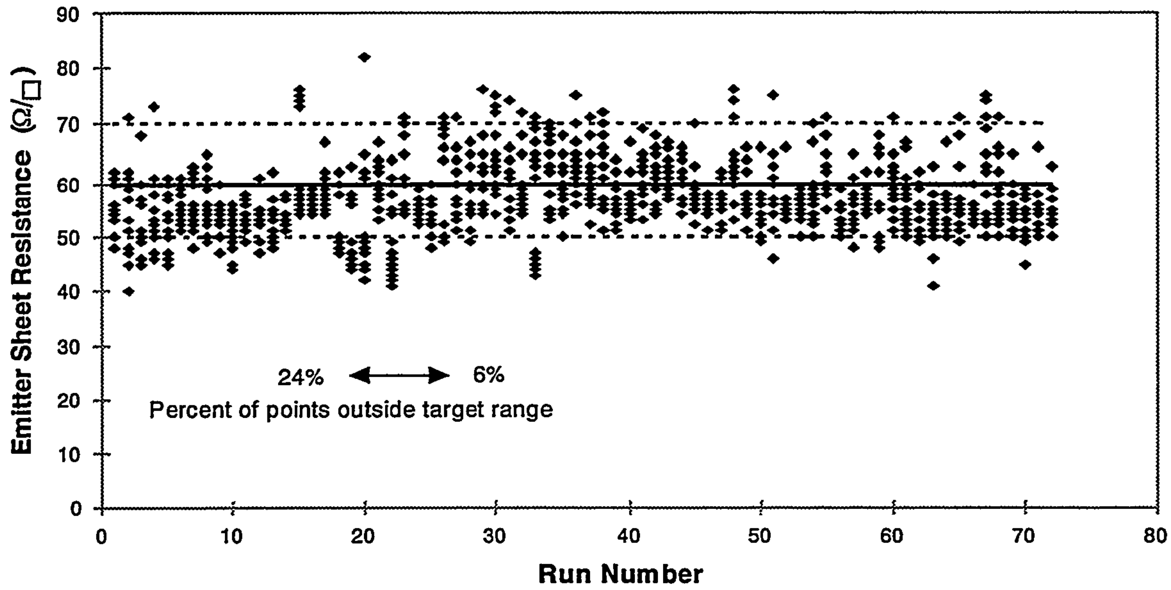

Figure 17. Sheet Rho Improvement in Diffusion Process

Figure 20, shows the combined effect of the wafering and cell yields, versus the potential productivity gain. As is evident in the chart, the productivity potential by making the wafers thinner is very high, as much as 180% relative to 400 micron slices. As is also evident in the graph, many areas of the production line will need to be modified to produce high yield, large area, thin cells.

This work is planned to commence during phase three of the project with design studies of automated cell and wafer handling, combined with slicing experiments to better utilize the ingot growth capacity.

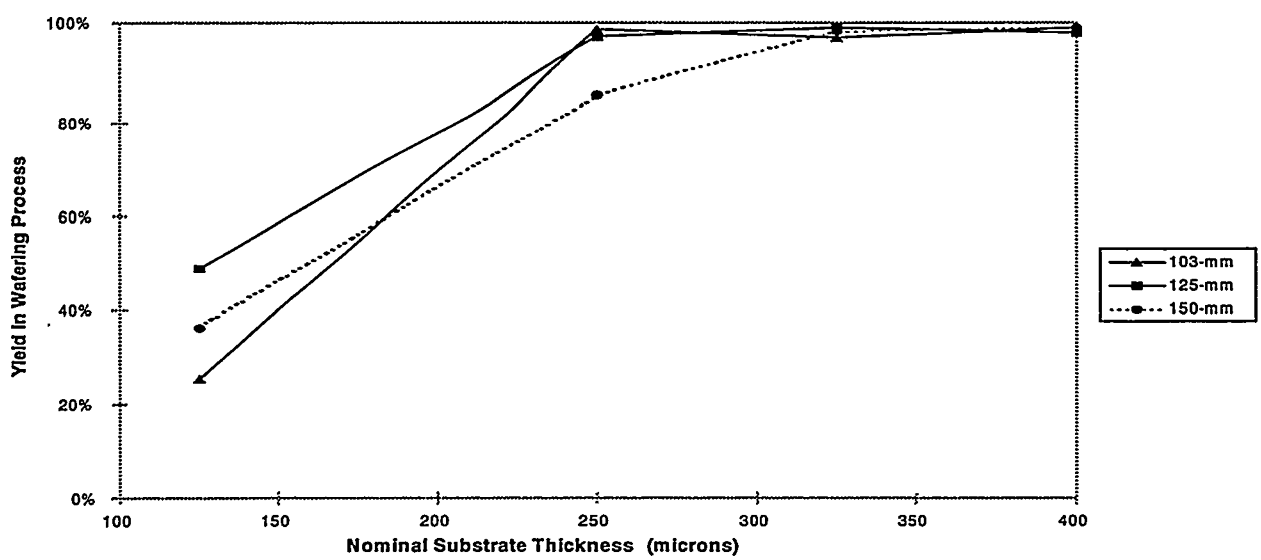

Figure 18. Yield in Wafering vs. Thickness and Size

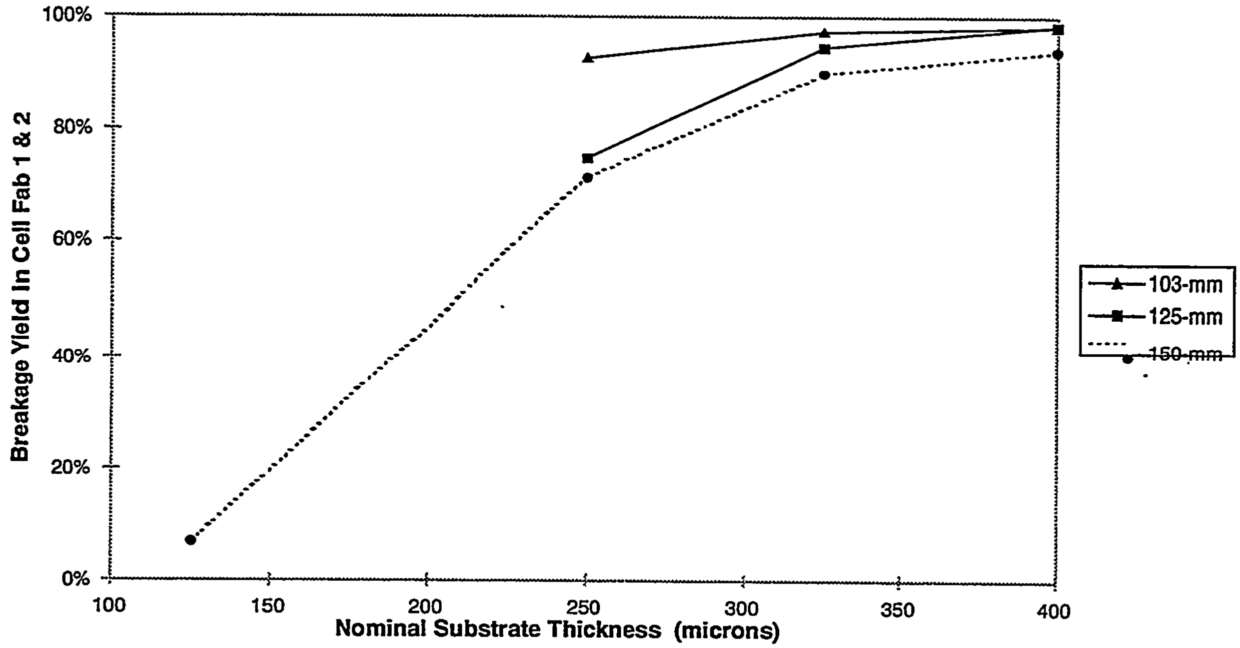

Figure 19. Yield in Cell Fab vs. Thickness and Size

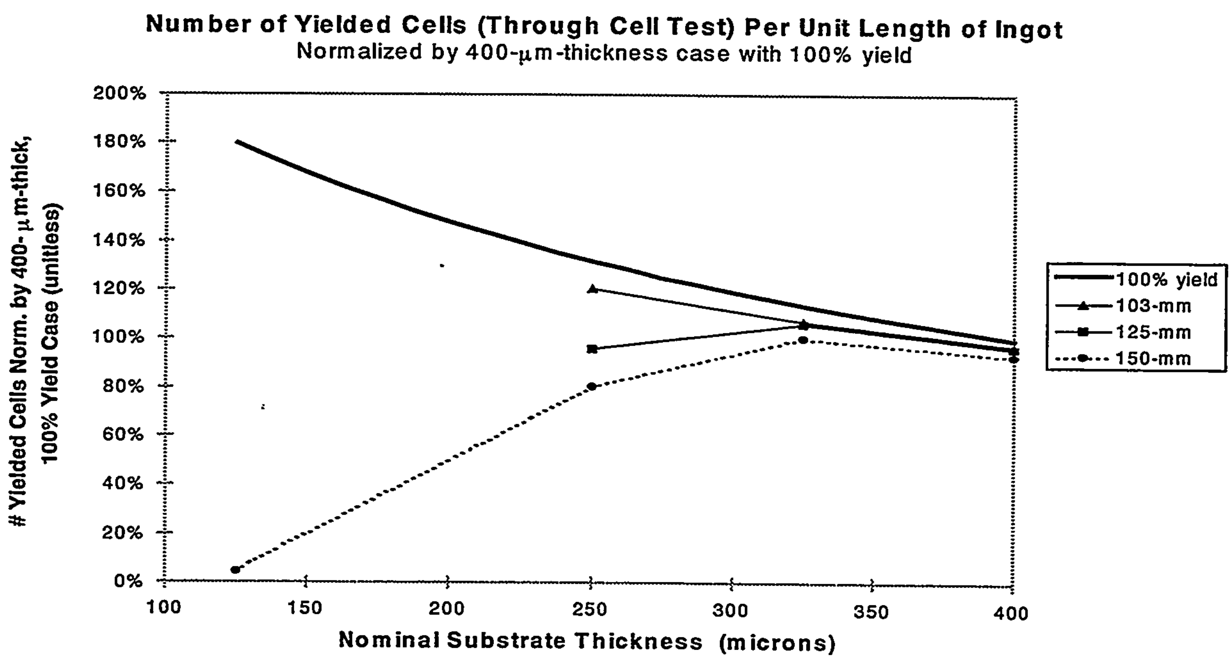

Figure 20. Yield vs. Increase Cell Productivity

Manufacturing Systems to Improve Module Reliability

ISO 9001 Certification

The SSI Camarillo plant received ISO 9001 certification in March 1996. This is a major milestone in the pursuit of quality manufacturing systems, and represents a very substantial effort by the company to establish and document procedures, operator work instructions, and maintenance and calibration schedules. The benefit is a profoundly improved system to ensure manufacturing compliance and control of its processes. It is, however, only a beginning. The follow on support has been successful as SSI has passed additional ISO surveillance audits during Phase II.

Statistical Process Control Implementation

In order to maintain reproducible and reliable photovoltaic manufacturing, key process control points have been established. Wafer thickness variation, emitter sheet resistance, cell fill factor, and lamination defects are now monitored run by run, shift by shift and day by day. Part of the statement of work of this contract has been to identify which measurements are suitable for tracking by statistical process control (SPC), and to implement SPC charting on those points by the end of Phase II. SPC charts are in place and used in each of these key process steps.

An area where Siemens Solar is fully deploying the use of SPC charting is in the evaluation of routine monitoring of the reliability of its product. Every month Siemens Solar randomly selects samples of its production product and runs these products through the standard environmental sequence of Thermal and Humidity Freeze (T50 10 HF) cycles, 200 thermal (T200) cycles and 1000 (Damp Heat 1000) hours of damp heat exposure at 85 degrees C, 85% relative humidity. This deployment of SPC in the gathering and analysis of the data, is the baseline which has allowed Siemens Solar to have a 25 year warranted product. As can be seen from the charts which cover the period of 1992-1997, the control is excellent.

Figure 21 shows the performance of Siemens product to the T50 10HF test cycle with all points in the control band.

Figure 22 shows the data from the T200 testing, where a few points are out of the control range. These points were later traced to a simple process fix which could be implemented rapidly to further enhance process control on the production line.

Figure 23 shows the data from the DH1000 testing, showing three recent points out of the control range and a variation in the data starting in the latest time period. This data has shown to be related to the change in humidity resistance of a module component which is now being worked with the supplier of that component. This work has commenced based on this long term statistical information and has been useful in troubleshooting with the supplier, where there has been a change in the supplier's process.

Deployment of this type of SPC analysis continues at Siemens Solar Industries and is invaluable, not only for warranty assessments, but as a very valuable tool to indicate overall process stability and conformance to specifications on Siemens Solar's production line. This maturity in process control is unique to SSI and is a result of both the ISO 9000 effort and PVMaT program combined to focus on the elimination of process variation, and the confirmation of that reduction by the use of statistical tools.

Analysis of the effectiveness of the SPC program will continue and be summarized during Phase III of the contract.

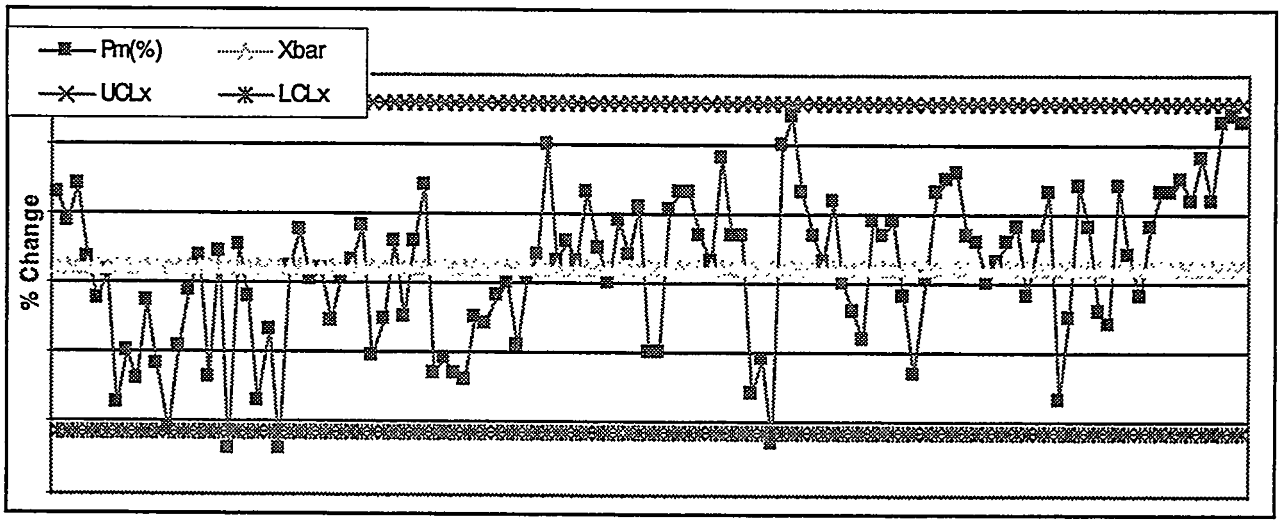

Figure 21. T50 10HF SPC chart for test data

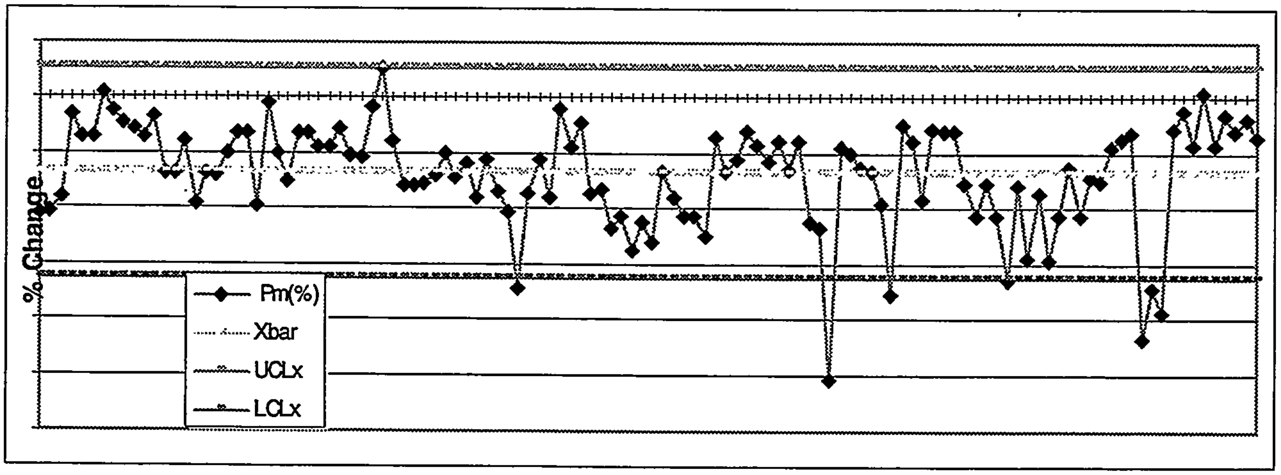

Figure 22. T200 Exposure Data SPC Chart for test data

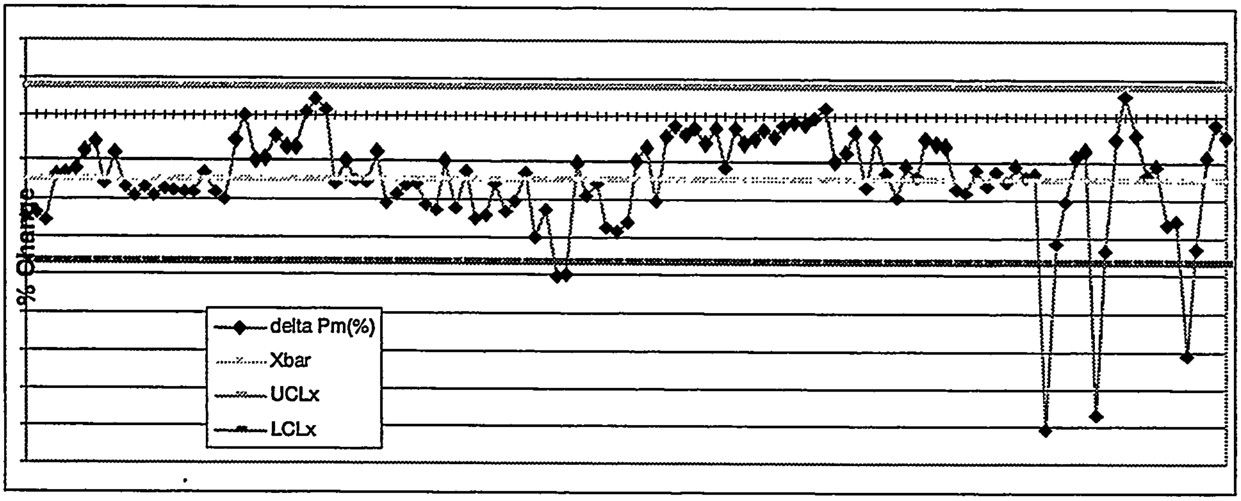

Figure 23. Damp Heat 1000 SPC chart for test data

Conclusions

Cost drivers for Cz Si solar cell modules have been analyzed and confirmed. Cost reduction by process area (ingot, wafer, cell, or module), have been proven and deployed in manufacturing. Cell size and shape, material usage, module size, and cell and module yields have an especially strong influence on cost. A quantification of cell size, thickness and yield has been finished. Specific module designs to address cost issues have been implemented, as have numerous other measures to reduce the cost per watt. Broader changes to the module configuration based on the 150-mm-diameter round cell are implemented and being produced on the manufacturing line at Siemens Solar Industries.

Productivity and yield improvement in every major process area has been achieved. Better pulling yield in crystal growth with an emphasis on material cleanliness has been realized, as well as productivity and yield gains in the large machines deployed in Siemens Solar's Vancouver growth plant. Wafering yield and productivity has been improved by thinner wire implemented for cutting. Cell processing yield has been improved by the reduction in variation in the diffusion process.

SPC deployment is complete in the key process areas throughout the manufacturing line. More work is planned for the less significant process control points through Phase III. Full use of SPC in evaluating environmental data is on going.

As a result of yield gains in wafering, cell, and module fabrication, productivity gains throughout the plant, and design and procurement improvements, items directly related to the PVMaT statement of work sum to greater than 12% savings in cost per watt at the module level through the end of Phase II, meeting the 12% goal for cost reduction. Module production of larger modules, larger cells, and better match of the wafer shape to the ingot cross section, has led to the development of a new, low cost-per-watt module line based on 150-mm-diameter round cells. Based on the approach of large modules with 150-mm-diameter round cells, a 17% reduction in module cost per watt is projected, with production beginning in Phase III.

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T.L. Jester

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Siemens Solar Industries
4650 Adohr Lane
Camarillo, CA 93012

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13. ABSTRACT *(Maximum 200 words)*
This report describes work done by Siemens Solar Industries (SSI) during Phase II of a 3-phase Photovoltaic Manufacturing Technology (PVMaT) 4A subcontract from DOE/NREL. The work focuses on improvements in the cost per watt of Cz silicon photovoltaic modules through detailed understanding of their cost structure, module design to minimize cost per watt, measures to improve manufacturing yield and productivity, and manufacturing control systems to improve module reliability. During this phase of the contract, SSI researchers deployed new module designs, realized improvements in yield of over 10%, and achieved further implementation of statistical process control. Module configurations representing a 12% cost reduction per watt were implemented in small-scale production. Yield improvements are described in detail, yield sensitivity to wafer thickness is quantified, and the deployment of statistical process control in critical process steps is reported here.

14. SUBJECT TERMS

photovoltaics ; Photovoltaic Manufacturing Technology ; PVMaT ; Cz silicon ; modules ; statistical process control ;

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