Cast Polycrystalline Silicon Photovoltaic Cell and Module Manufacturing Technology Improvements

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J. Wohlgemuth
Solarex Corporation
Frederick, Maryland

NREL technical monitor: R. Mitchell

National Renewable Energy Laboratory
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Golden, Colorado 80401-3393
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PREFACE

This Annual Technical Progress Report covers the work performed by Solarex Corporation for the period December 8, 1993 to December 31, 1994 under DOE/NREL Subcontract # ZAI-4-11294-01 entitled "Cast Polycrystalline Silicon Photovoltaic Module Manufacturing Technology Improvements". This is the first Annual Technical Report for this subcontract. The subcontract is scheduled to run from December 8, 1993 to December 7, 1996.

The following personnel at Solarex have contributed to the technical efforts covered in this report.

Fiore Artiglieri
Mark Brisson
James Cliber
Mark Conway
Joseph Creager
Thomas Duquaine
Jason Ellis
Daniel Heck
George Kelly
Timothy Koval
Charles Lamport
Jean Posbic
William Poulin
David Ramsey
Madhumita Roy
Jay Shaner
Steven Shea
Timothy Tomlinson
Donald Warfield
Daniel Whitehouse
John Wohlgemuth

In addition, Solarex has been supported by the staff at the Automation and Robotics Research Institute at the University of Texas at Arlington (ARRI). ARRI staff working on the subcontract include:

Brian Huff
Mike Diver
David Vanecek

SUMMARY

The objective of this three-year program is to advance Solarex's cast polycrystalline silicon manufacturing technology, reduce module production cost, increase module performance and expand Solarex's commercial production capacities. Two specific objectives of this program are to reduce the manufacturing cost for polycrystalline silicon PV modules to less than \$1.20/watt and to increase the manufacturing capacity by a factor of three. To achieve these objectives, Solarex is working in the following technical areas:

CASTING

The goal of the casting task is to develop the ability to cast ingots that yield four bricks with a cross-section of 15 cm by 15 cm with at least equivalent material quality as now achieved for 11.4 cm by 11.4 cm bricks. This represents a 73% increase in the useable silicon obtained from each casting.

WIRE SAWS

The goal of the wire saw task is to develop the wire saw technology for cutting 15 cm by 15 cm polycrystalline wafers on 400 μ m centers at lower cost per cut than achieved today on the ID saws. This represents a 50% increase in the useable silicon obtained from each cast and a 50% increase in the yield of wafers per purchased kilogram of Si feedstock.

CELL PROCESS

The goal of the cell task is to increase cell efficiencies to 15%, while decreasing the cost per watt at the module level. The developed process must be compatible with automated manufacturing at large volumes.

MODULE ASSEMBLY

The goal of the module assembly task is to modify Solarex's present module assembly system to increase throughput by 100% and decrease the labor requirement by 50%. The Automation and Robotics Research Institute at the University of Texas at Arlington (ARRI) is to work with Solarex to model the present automated module assembly system and to recommend modifications to increase throughput and reduce labor.

FRAMELESS MODULE DEVELOPMENT

The goal of the frameless module task is to develop and qualify a frameless module design incorporating a lower cost back sheet material (less than \$0.05/square foot) and user friendly, low cost electrical termination (less than \$1.00/module). Since PVMaT is designed for large systems, modules can be designed to mount directly onto the support structure without integral frames.

AUTOMATED CELL HANDLING

The goal of the automated cell handling task is to develop automated handling equipment for 200 μm thick 15 cm by 15 cm polycrystalline silicon wafers and cells with a high yield (less than 0.1% breakage per process handling step) at a throughput rate of at least 12 cells or wafers per minute.

ACCOMPLISHMENTS

Accomplishments during the first year of the program include:

- Designed modifications to casting stations, ceramic molds and sizing saws to allow for casting and sizing of larger ingots.
- Demonstrated casting of ingots with 33% larger volume with equivalent yields and cell efficiencies.
- Demonstrated casting of an ingot with 73% larger volume.
- Selected and purchased a new wire saw from HCT Shaping Systems. The saw was delivered and made operational.
- Demonstrated wafering of 8 bricks (2400 wafers or ~4.4 kilowatts at the cell level) in a 6.5 hour run.
- Demonstrated wafering of 11.4 cm by 11.4 cm wafers on 400 μm centers.
- Demonstrated wafering of 15 cm by 15 cm wafers on 400 μm centers.
- Wire saw manufacturing trials resulted in wafer costs 5% below the PVMaT wire saw goal and 13% less than ID production.
- Demonstrated 14% average cell efficiency in the laboratory using a potentially cost effective aluminum paste back surface field.
- Developed a methodology for evaluating optical coupling techniques.
- Developed a texturing tool that yields a current increase for encapsulated cells equivalent to the best chemical and taper blade texturing.
- Determined that Plasma Enhanced Chemical Vapor Deposition (PECVD) of a silicon nitride anti-reflective coating improves cell performance by improving front surface recombination velocity.
- The Automation and Robotics Research Institute at the University of Texas at Arlington (ARRI) completed a modeling study of the Solarex module assembly process. The study detailed how to increase throughput by 40 %. Several of the recommendations have been implemented and the first phase goal of 40% increase in assembly throughput was achieved.
- Identified and qualified through accelerated environmental tests three (3) new lower cost backsheet materials.
- Identified and began testing low cost electrical connectors.
- Designed and built a test structure for mounting frameless modules, selected an adhesive and began testing its ability to hold modules to the structure.

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1.0 INTRODUCTION

The goal of Solarex's Crystalline PVMaT program is to improve the present Polycrystalline Silicon manufacturing facility to reduce cost, improve efficiency and increase production capacity. Key components of the program are:

- Casting of larger ingots.
- Use of wire saws to cut thinner, larger size wafers with less kerf loss.
- Transfer of higher efficiency cell processes to manufacturing.
- Increased automation in module assembly.
- High reliability mounting techniques for frameless modules.
- Automated handling of large, thin wafers.

The results of these efforts will be to reduce the module cost per watt to less than \$1.20/watt, to increase the production capacity of Solarex's Frederick plant by a factor of 3 and to provide larger, higher efficiency modules that reduce the customer's balance of systems cost. All of this is to be achieved without sacrificing the high reliability already achieved with the crystalline modules in use today.

Solarex is a recognized leader in polycrystalline silicon PV technology, one of the largest commercial PV technologies in the world today. Solarex was one of the pioneers in this technology and has been a commercial leader in polycrystalline silicon PV for more than ten years.

The rationale behind the Solarex program is to use as much as possible of the present equipment and processes, making improvements that lead to larger sizes, better utilization of materials, higher efficiencies and reduced labor requirements. In this way the maximum increase in capacity and reduction in cost can be achieved with justifiable capital investments in equipment modifications. Specific areas to be addressed in the program are discussed briefly below.

Today Solarex casting stations are used to produce ingots from which 4 bricks, each 11.4 cm by 11.4 cm in cross section are cut. The stations themselves are physically capable of holding an ingot that would be large enough to cut 4 bricks 15 cm by 15 cm in cross-section. The first task involves making the modifications necessary to cast these larger ingots. This effort will increase the production capacity of Solarex's casting stations by 73% and reduce the labor content by an equivalent percentage.

Wire saws can be used to cut thinner wafers with less kerf, than is possible on the Internal Diameter (ID) saws now in use at Solarex. The program goal is to reduce the center to center cut distance from 600 microns on the ID saw to 400 microns on the wire saw. This will result in a 50% increase in solar cell and module output from the same silicon feedstock purchased and cast. That is, with the same amount of feedstock material and the same casting capacity Solarex will be able to increase its output of PV modules by 50% (on top of the 73% increase achieved by casting larger ingots). In addition, wire saws can also be utilized to cut larger wafers, something ID saws can not do.

Finally, wire saws have a much higher production capacity. One wire saw may produce as many wafers as 20 ID saws. To increase capacity with wire saws requires a much smaller capital investment than would be required to achieve the same increase with ID saws. The major issue with

wire saws is the ability to reduce the variable cost to cut a wafer. The technical effort in this program involves the use of the latest available wire saw, purchased by Solarex. Efforts to reduce the cost of grit, oil, wire, spare parts and labor make up the major part of Task 2.

In this program, Solarex is working on the transfer of high efficiency cell technologies from the laboratory to production. Issues involved in the successful transfer include process cost, ability to scale to large volume, adaptability to automation and the degree to which each step integrates into the overall cell process sequence. Therefore, it is necessary as a part of this program to evaluate each component of the sequence that has proven effective at increasing cell efficiency to determine the most cost effective cell process sequence. Specific areas being evaluated include:

- Optical Coupling
  - double layer AR coating
  - mechanical texturing
  - porous silicon etching
- Passivation/Gettering
  - hydrogen passivation
  - phosphorous gettering
- Back Surface Field (BSF) Formation
  - Al paste BSF
  - back surface diffusion
- Interaction of metallization with emitter
  - screen printed Ag paste
  - plated buried contact system

The goal of the Task 3 cell effort is to increase average cell efficiency (as obtained from a production line, not just from the laboratory) to 15% as measured at STC (Standard Test Conditions - 1000 W/m², AM1.5, 25° C). This must be achieved with a process sequence that lowers the module \$/Watt manufacturing cost.

Solarex has a first generation automation system in use at the Frederick facility for tabbing, matrixing and lay-up of the PV modules. This system has been highly successful at reducing manual labor in the assembly process. During Task 4 the present system will be evaluated to determine how this system can be modified to handle the larger wafers for this program, to improve throughput, yield and process control and to minimize production labor and cost. To assist with this effort, the Automation and Robotics Research Institute (ARRI) at the University of Texas at Arlington is serving as a subcontractor. ARRI is assisting Solarex in analysis, modeling and development of handling concepts to improve the operation of the module assembly area.

Solarex modules use low iron tempered glass as a superstrate and Ethylene Vinyl Acetate (EVA) as the encapsulation system. No change is proposed in this encapsulation system to maintain the module reliability. However, a reduction in the cost of the backsheet is possible, although it is extremely important that this change does not negatively impact the module reliability and is compatible with frameless mounting techniques developed in Task 5.

Today most PV modules are sold with a frame to provide means for mounting the module and a junction box for electrical connection. This frame is the largest single contributor to module cost. In large systems, the support provided by the system structure is adequate making the module frame redundant. Eliminating this frame can reduce the module selling price by more than \$0.50/Watt. During Task 5, mounting requirements have been evaluated and analyzed. Testing of candidate frameless module mounting schemes has begun.

Similarly, the junction box adds appreciable cost to the module, while requiring additional labor for system assembly. In Task 5, simpler electrical termination schemes are being evaluated and tested. These approaches must be consistent with automated manufacturing as well as with systems design requirements, like the incorporation of by-pass and blocking diodes.

Task 5 also includes the design of a 122 watt module using 36- 15 cm by 15 cm solar cells. This task will include qualification of the design through accelerated environmental tests (Block V, CEC-503, IEC-1215, U.L., and IEEE-1262 now under development) and design of the automated equipment necessary to finish the module.

An important issue for many crystalline silicon PV manufacturers is the ability to handle thinner and larger wafers through the production line. Task 6 will address this issue. Once again, Solarex will be supported in this effort by ARRI, whose background and experience is ideally matched to the task of developing handling methods for parts such as the large thin wafers to be used in this program. ARRI will perform detailed analysis and modeling of the requirements and then build prototype stations to evaluate various approaches to handling such wafers. Once the concepts have been verified at ARRI, Solarex will design and have built a production unit to verify its capability.

The results of this program will be the modification of today's polycrystalline production facility to:

- Increase production capacity by a factor of three
- Reduce the "profitable" selling price from over \$4.00 per peak watt to less than \$2.00 per peak watt.

Solarex plans to continue an aggressive market development program that would support the increased capacity obtained as a result of this program.

2.0 PRESENT PROCESS AND PRODUCTS

Solarex's Crystalline Silicon Technology is based on use of cast polycrystalline silicon wafers. The process flow is shown in Table 1. The primary product is a module with 36 solar cells each 11.4 cm x 11.4 cm, that produces 60 or 64 Watts under Standard Test Conditions (STC).

Table 1
Cast Polycrystalline Si Process Sequence

Casting

ID Wafering

Cell Process
(Thick Film Print)

Module Assembly

Lamination

Finishing

The various segments of Solarex's module manufacturing process as practiced at the beginning of this PVMaT program are described below.

Casting

Solarex has developed and patented a directional solidification casting process specifically designed for photovoltaics¹. In this process, silicon feedstock is melted in a ceramic crucible and solidified into a large grained semicrystalline silicon ingot. In house manufacture of low cost, high purity ceramics is a key to the low cost fabrication of Solarex semicrystalline wafers².

The casting process is performed in Solarex designed casting stations. The casting operation is computer controlled. There are no moving parts (except for the loading and unloading) so the growth process proceeds with virtually no operator intervention.

Wafering

Wafering is done with Internal Diameter (ID) saws. These are the same saws that are used in the semiconductor industry to wafer single crystal CZ ingots. At present ID saws are the lowest variable cost wafering option. Solarex has many years of experience with these saws, resulting in low labor and process costs. This is a mature technology with little opportunity for significant increases in productivity or reduction in kerf loss.

Cell Process

The cell process sequence is based on the use of Thick Film Paste (TFP) metallization, where a commercially available screen printed silver paste is applied as the current carrying grid on the front of the solar cell. This process has been designed to be as cost effective as possible. The high temperature process steps including diffusion, firing of the front print paste and Chemical Vapor Deposition (CVD) of a TiO_2 antireflective (AR) coating are all performed in belt furnaces.

Polycrystalline cells processed through this line have an average cell efficiency of 12.5 to 13% at STC. There are many modifications to this process sequence that will increase cell efficiencies. However, many of these modifications would actually increase the total dollar per watt module cost rather than decrease it. Detailed cost analyses indicate what changes in cell processing can lead to both higher cell efficiencies and lower dollar per watt module cost.^{3,4} Implementation of these changes require laboratory verification of the candidate process sequences as well as improvement in the accuracy of the input cost data.

Module Assembly

The first part of the module assembly sequence is to solder two solder plated copper tabs onto the front of the solar cells. Each tab is soldered in 4 places for reliability and redundancy. Solarex uses automated machines to perform the tabbing. Tabbed cells are then laid up into a 36 cell matrix by a robot. The tabs are then soldered to the backs of the solar cells by another robot. Each tab has 2 back solder joints.

Module Lamination

The module construction consists of a low iron, tempered glass superstrate, EVA encapsulant and a 3 part Polyethylene-Mylar-Tedlar backsheet. The lamination process, including the cure, is performed in a vacuum lamination system. Then the modules are trimmed and the leads are attached. Finally, every module is flash tested to determine its STC power output.

Finishing

Most modules are sold with a frame to protect the edges and provide a means of mounting. Solarex uses an extruded aluminum frame that is attached both with a butyl rubber adhesive between frame and glass as well as with 2 screws in each corner of the frame. The framing process is performed by an automatic, robotic framing system.

Most modules are also sold with a junction box to protect the output wiring and provide the terminals for electrically connecting the module to the balance of the system. The area where the lead wires are attached to the module is potted to protect the laminate from moisture incursion. The junction box is then attached to the module with adhesive to seal it to the back of the laminate.

3.0 PVMAT PROGRAM EFFORTS

The following sections detail the progress made during the first year of the program.

3.1 TASK 1 - POLYCRYSTALLINE SILICON CASTING IMPROVEMENTS

The goal of the casting task is to develop the ability to cast ingots that yield four - 15 cm by 15 cm bricks with at least equivalent material quality as now achieved when casting four - 11.4 cm by 11.4 cm bricks. During the first year of the program, Solarex has designed and fabricated new larger ceramic pieces, designed and implemented modifications to a casting station and designed and implemented modifications to the sizing saws in order to be able to cast and size larger ingots.

Two possible modifications to enlarge the casting stations were evaluated in detail. The first proposal retained all of the present chamber with the addition of a height extension. The second proposal involved replacing the pour chamber with a new larger chamber. The height extension option required less capital investment and time to implement, as well as requiring less input power to melt the silicon charge. Therefore, chamber modification was selected for the program. The necessary modifications were designed, the parts fabricated and installed and the modified system used to cast ingots.

Solarex manufactures its own ceramic vessels. Casting of larger ingots requires producing larger pour vessels and larger receivers. The size and shape of the receivers into which the silicon pours are dictated by the shape of the ingot desired. For the PVMaT program the ingot cross-section increases from approximately 24 cm by 24 cm to 32 cm by 32 cm, so the receiver must increase in size accordingly. Patterns for the molds were designed, built and used to produce the molds. Sample receivers have been produced and used to cast ingots.

The largest ceramic piece is the crucible in which the silicon feedstock is melted. A potential problem was the ability to fire larger pieces of ceramic, while maintaining yield and physical properties. Just extending the height of the crucible to hold the additional silicon feedstock would likely result in a ceramic piece that is difficult to produce and hard to load with feedstock. The cross-section of the crucible was modified from cylindrical to elliptical to fit around the heating elements. This change increases the volume of the crucible by approximately 20%. An elliptical crucible mold pattern was designed, built and used to make elliptical molds. The molds were used to cast elliptical crucibles. These crucibles were fired and successfully used to pour an extra 20% silicon, producing ingots with larger cross-section.

To achieve the remainder of the increase in volume, an extender was designed. The extender is mounted on top of the elliptical crucible after the crucible has been loaded with silicon. The extender mold pattern has been designed, built and used to produce a mold. Extension pieces have been produced and used to cast ingots.

Casting experiments began with an intermediate size ingot, 33% larger than the standard 4 - 11.4 cm by 11.4 cm ingot. The initial runs produced ingots that had lower yields due to cracking of the silicon at the bottom of the ingot. Modifications to the insulation package and some minor changes to the casting program lead to improved yields. Recent runs resulted in higher yields than production standard and in average cell efficiencies equivalent to co-processed production size ingots. The first full size ingot (for 4 - 15 cm by 15 cm bricks) has now been successfully cast.

3.2 TASK 2 - WIRE SAW IMPROVEMENTS

The goal of this task is to develop the wire saw technology for cutting 15 cm by 15 cm polycrystalline wafers on 400 μ m centers at lower cost per cut than achieved today on the ID saws. This represents a 50% increase in the useable silicon obtained from each cast and a 50% increase in the yield of wafers per purchased kilogram of Si feedstock.

The first step in this task was to identify what wire saws are available commercially. Solarex identified four vendors of wire saws and visited each vendor to see their wire saws. Three of the vendors were able to wafer a Solarex brick and provide the resultant wafers for evaluation. A detailed comparison of the characteristics of the four available saws appears in Table 2.

Table 2
Comparison of Wire Saws

Company	Type of Business	Wire saw Experience	Solarex Material	Capacity 11.4x11.4	Capacity 15x15	Cost
Meyer-Berger	Semiconductor Equipment	> 10	good	4	2	mod
HCT	Wire saws	> 60	excellent	8	4	mod
M. Setek	Crystal growing & wafering	10 to 20	good	2 or 3	1	mod
Nippei Toyama	Machine tool manufacturer	~ 36	NA	2 or 3	2 or 3	high

HCT Shaping Systems has the most experience building wire saws. A test run on the HCT saw provided the best uniformity of surface texture and wafer thickness. Probably the most important factor in the evaluation was the ability of the HCT machine to cut up to 8-11.4 cm by 11.4 cm bricks or up to 4-15 cm by 15 cm bricks at the same time. Preliminary cost analysis indicated that the throughput rate, that is the number of wafers cut in a given amount of time, was the single most important factor in determining the cost payback of the investment in the wire saw. Solarex selected and ordered an HCT wire saw.

The HCT wire saw has been operational since July, 1994. The saw has performed well once start-up problems were solved with the help of HCT staff. By the end of 1994, the saw has been used to cut nearly 400 bricks (> 125,000 wafers) with an average yield of 93% (97% if you don't count aborts). Other important technical accomplishments are:

1. Demonstrated the ability to cut 8 - 11.4 cm by 11.4 cm bricks at one time, resulting in the cutting of 2400 wafers in one 6.5 hour run.
2. Experimented with slurry formulations and developed one that has repeatedly been utilized to cut 20 bricks with a single batch of slurry.

3. With this slurry formulation, demonstrated that the brick feed (or cut) rate could be increased by 30%.
4. Defined a wire saw process and operated it in a trial production mode. This process produces wafers with an estimated cost that is 5% below the program goal for the wire saw and 13% below the ID saw production cost.
5. Demonstrated the ability to cut 11.4 cm by 11.4 cm wafers on 400 μ m centers with very high cutting yields.
6. Developed the technology to cut larger ingots, initially scaling up to 11.4 cm by 15.2 cm to produce cells for Solarex MSX-83 and MSX-77 modules and then cutting wafers as large as 15 cm by 15 cm for the PVMaT module.
7. Demonstrated the ability to cut 15 cm by 15 cm wafers on 400 μ m centers with high cutting yields.
8. Thousands of wire saw wafers have been processed through the Solarex cell line. The wire saw cells had a 3.6% higher mechanical yield and a 4.4% higher total yield than the co-processed ID sawn wafers. In addition, there was no statistical difference between the wire saw and the ID saw cell efficiencies.

3.3 TASK 3 - HIGH EFFICIENCY CELL DEVELOPMENT

The goal of this task is to increase cell efficiencies to 15%, while decreasing the cost per watt at the module level. While a number of approaches to achieving high efficiency have been reported, many of these utilize processes and material that are not likely to be cost effective when applied to cast polycrystalline silicon in a manufacturing environment. The key to achieving the goal of this task is to select modifications to the present process that increase efficiency while lowering the cost per watt. That is, the increased cost of the process is less than the value of the increased power produced by the improvement.⁴ During the first year the major cell task efforts were in the areas of optical coupling, back surface fields (BSF), and hydrogen passivation. Each of these areas is discussed below:

3.3.1 Optical Coupling

It is important to maximize the amount of sunlight that is optically coupled into the solar cell. A single quarter-wave layer AR coating like the titanium dioxide AR used on Solarex cells is very effective at reducing reflection at the one particular wavelength where the quarter wave condition holds. However, over the whole solar spectrum such a single layer will reflect about 7 % of the total energy when covered via a glass-EVA system. There are 3 major approaches to improving the optical coupling that can lower this reflection and increase the cell efficiency. These three areas are discussed below:

3.3.1.1 Double Layer AR Coatings

The Aerospace industry has utilized double layer AR coatings for years to increase optical absorption. A well designed double layer AR coating can increase the current from an unencapsulated solar cell by 4 to 5 % by providing a much broader minimum in the reflectance. In selecting materials for a double layer AR coating, care must be taken to assure that the system will actually increase the operating efficiency when used in an encapsulated package. Therefore, the index of refraction of the top layer must be at least 1.6 to 1.7 or the current after encapsulation will be less than that for a well designed single layer AR system. For example when magnesium fluoride is used as the top layer over titanium dioxide, the unencapsulated cells are more efficient than cells with a single layer titanium dioxide AR coating. However, upon encapsulation, the double layer system (magnesium fluoride - titanium dioxide) actually produces less power (lower efficiency) than the single layer titanium dioxide cell. Solarex successfully utilized an evaporated 2 layer anti-reflective coating system consisting of titanium dioxide and aluminum oxide in its Aerospace Division. This system can also be deposited using a Chemical Vapor Deposition⁵ process. As part of the PVMaT program the effectiveness of this double layer AR has been evaluated.

The results for a typical double layer AR coating experiment measured under Standard Test Conditions (1000 W/m², AM1.5 spectrum and 25° C) are given in Table 3. For unencapsulated cells the second layer of the AR system leads to a 3.5 to 4.0 % increase in short circuit current resulting in an equivalent increase in cell efficiency. However, when these cells are encapsulated with EVA and glass, the single layer AR cells increase in efficiency, while the cells with double layer AR decrease, resulting in virtually no current or efficiency gain from the second layer of the AR system. To determine if this result was process dependent or determined by the physics of the system, we used the PC-1D Program⁶ to model the expected performance of this single and double layer AR system for the AM1.5 solar spectrum with the device structure and materials parameters typical of the Solarex polycrystalline cells. The results are given in Table 4. The model predicts a small increase in short circuit current for the encapsulated cells, but with a gain that is probably less than can be measured experimentally.

Table 3
Al₂O₃ -TiO₂ AR Coating Experiment

Samples	Unencapsulated		Encapsulated	
	Isc (A)	Eff. (%)	Isc (A)	Eff. (%)
Single Layer AR	3.71	12.71	3.84	12.8
Double Layer AR	3.85	13.15	3.84	12.8

Table 4
PC-1D Modeling of Al₂O₃ -TiO₂ AR Coating

Samples	Unencapsulated		Encapsulated	
	Isc (A)	Eff. (%)	Isc (A)	Eff. (%)
Single Layer AR	3.812	13.15	3.853	13.3
Double Layer AR	3.864	13.3	3.866	13.3

This may not be the case for all double layer AR systems. The optimum double layer AR system, to couple between EVA-glass with an index of refraction of approximately 1.4 and silicon with an

index of refraction of 3.87 in the wavelength range of interest, is a system where the top layer has an index of refraction of 1.9 to 2.0 and the bottom layer has an index of refraction between 2.7 and 2.8. The results of PC-1D modeling for this system are given in Table 5. So with the higher index bottom material a double layer AR coating system can provide a current gain over our present single layer system. However, we don't have any low cost candidate materials with an index as high as 2.7 to 2.8, so we can't effectively improve cell efficiencies with a double layer AR system.

Table 5
PC-1D Modeling of Optimum Double Layer AR System

Samples	Unencapsulated		Encapsulated	
	Isc (A)	Eff. (%)	Isc (A)	Eff. (%)
Double Layer (1.96-2.75)	3.891	13.4	3.989	13.7

3.3.1.2 Chemical Texturing

The highest silicon cell efficiencies have been achieved using textured surfaces to increase the amount of incident sunlight that is coupled into the solar cell. Chemical texturing is used by most manufacturers of single crystal silicon solar cells. In this process an alkaline etch is used to etch the 100 silicon surface leaving the exposed 111 planes that etch at a slower rate, resulting in a surface covered with small pyramids. Tables 6 and 7 shows a typical comparison of planar versus textured single crystal CZ cells made with the thick film paste process. Even when using chemically textured cells, a majority of the absorption advantage goes away when the cells are encapsulated.

Table 6
Chemical Texture Etching of Single Crystal Silicon
(Unencapsulated)

Samples	Isc (A)	Efficiency (%)
Planar	4.00	14.0
Chemical Texture	4.35	15.0

Table 7
Chemical Texture Etching of Single Crystal Silicon
(Encapsulated)

Samples	Isc (A)	Efficiency (%)
Planar	4.12	14.4
Chemical Texture	4.23	14.6

The alkaline etch technology has not worked well on polycrystalline silicon because this material contains crystal grains of different orientations. A large fraction of the grains are typically oriented close enough to the 111 plane that they etch slowly and do not produce pyramids. To verify that

there is no current or efficiency gain from chemical texturing, a group of polycrystalline wafers was processed through the alkaline etch process that we use to texture single crystal CZ wafers. When encapsulated the difference in current and efficiency between the texture etched samples and the planar samples was less than the measurement error.

Recent work has shown that electrochemical etching of polycrystalline silicon can produce a highly textured surface with low reflectivity⁷. We were able to texture the polycrystalline silicon using an electrochemical etch, reducing the bare silicon reflection to approximately 28%. However, the process produces a reactant oxide on the surface. If this oxide is left on the surface and a TiO₂ anti-reflective coating is applied, the resultant system produces approximately 6% less short circuit current than the same single layer AR coating applied directly onto a planar surface. If the oxide is stripped before the TiO₂ is applied, the reflection and the resultant short circuit current are similar to that observed for a cell with a single layer AR. However, the open circuit voltage is lower because of the junction damage caused by the etch. This process has not been successful at producing improved cell efficiencies.

3.3.1.2 Mechanical Texturing

Both lasers⁸ and/or dicing saws with beveled blades⁹ have been used to mechanically texture silicon, resulting in increased absorption and improved cell efficiency. Solarex has demonstrated the use of a beveled blade to increase the efficiency of CZ buried contact solar cells to 17.9%¹⁰. In this experiment mechanical texturing resulted in a larger increase of short circuit current, than was achieved using the more traditional chemical texturing.

Our goal in the PVMaT Program is to develop a cost effective method of mechanical texturing. The usual approach to evaluating optical coupling techniques is to fabricate solar cells and then to measure their performance under Standard Test Conditions (1000w/m², AM1.5 spectrum, 25° C) using the short circuit current as the figure of merit. There are two major problems with this approach.

1. Cell measurements are usually taken using a solar simulator, for example with a xenon light source. The light intensity should be set using a reference cell with a matched spectral response. However, since the test cell has an experimental optical coupling surface, it is impossible to have a matched reference cell. Often the new process turns out to be optimized for the simulator spectrum rather than for the solar spectrum.
2. The optimum cell processing parameters are likely to be a function of the geometry of the emitter surface. Therefore, the structure of the optical coupling surface and the process to turn it into a cell must be optimized concurrently. Typically a new optical coupling process does not produce the expected current gain because the cell process has not been optimized for this surface, even if the cell is actually better optically.

To get around these problems, an improved method for evaluating the performance of an optical coupling surface has been developed¹¹. Rather than build solar cells, this method only requires fabrication of samples of the optical surface under study. The reflectance of the surface is measured as a function of wavelength. If the reflectance is then multiplied by the solar spectrum, it yields the energy or the number of photons entering the material at every wavelength. Integrating this value over the entire wavelength, yields a value for total energy entering the material. This

value has been used as a figure of merit for optical coupling, but since it does not take the spectral response of the cell into account, it is not a good predictor of solar cell performance.

In the improved method, a cell technology (for example a screen printed contact cell on cast polycrystalline silicon or a high efficiency buried contact cell on float zone silicon) is chosen to test with the optical coupling surface under study. For the cell technology selected, the internal quantum efficiency as a function of wavelength is determined from measurements of completed planar solar cells. Multiplying the internal quantum efficiency at each wavelength by the energy entering the cell at that wavelength calculated from the reflectance curve, yields a predicted (external) quantum efficiency curve for the selected cell with the new optical coupling surface.

The external quantum efficiency at each wavelength can be multiplied by the energy in the solar spectrum at that wavelength. This product is then integrated over the entire wavelength range of interest. A percentage of the active area can be removed to take the shadowing of grid lines into effect. The result is an estimate of the short circuit current of the selected cell technology with the experimental optical coupling surface. Various surface treatments can now be compared to determine which is best suited for the particular cell technology of interest.

Figure 1 demonstrates how the method is used to calculate the expected short circuit current for an encapsulated cast polycrystalline cell with mechanical texturing and a single layer TiO_2 AR coating. In the left hand column the reflectance as a function of wavelength has been entered as data. This data is plotted in the bottom curve of the figure. The top curve in the figure is the internal quantum efficiency as measured for a typical screen printed cast polycrystalline cell. Multiplying the reflectance at each wavelength by the internal quantum efficiency at that wavelength yields the external quantum efficiency, which is plotted as the middle curve in the figure. The expected short circuit current can then be calculated for any input spectrum of interest. In Figure 1 an AM1.5 spectrum was utilized to predict a short circuit current of 3.888 Amps and a cell efficiency of 13.53 %.

This method has been applied to a number of different surface textures yielding calculated predictions of short circuit current for screen printed cells on cast polycrystalline silicon. The results are summarized in Table 8. This data shows that texturing the surface of a solar cell can increase its short circuit current up to 7 or 8% when measured on a bare, unencapsulated cell. When textured cells are encapsulated, the current is reduced due to the reflection off of the glass. However, when planar cells are encapsulated, the short circuit current increases due to the better match of the AR coating's index of refraction with the glass/EVA index of refraction. So the 7 or 8% additional current from texturing reduces to approximately 3% upon encapsulation. It is this lower value, the encapsulated number, that must be used when evaluating the cost effectiveness of an optical coupling technique, because these cells are almost always used in an encapsulated module package.

Figure 1
Mechanically Textured Polycrystalline Silicon - Encapsulated

Reflectance Analysis Model

Solarex Corporation

International Electrotechnical Commission AM1.5 Spectrum
Integrates from 350 to 1200 nanometers
Assumes reflectance values represent oxide-on-silicon (no metal present)
TDK-4/14/94
Version 1.0

CellSize (cm): 129.96
Coverage (%): 8.0%
IQE Selection: 3
Reflectance Selection: 5

Reflectance ID: 41E WHEEL TEXTURE Encapsula
IQE ID: YYCell

Collected Current: 29.9 mA/cm²
Jsc: 32.5 mA/cm²
Device Isc: 3.888 Amps
Simulated Efficiency: 13.53 (%)
(Assumes 595 Voc, 76% FF)

Wavelength	Reflectance
350	0.063
400	0.086
450	0.056
500	0.049
550	0.048
600	0.046
650	0.045
700	0.046
750	0.047
800	0.047
850	0.054
900	0.050
950	0.052
1000	0.065
1050	0.085
1100	0.124

Table 8

Predicted Short Circuit Current for 130 cm² Cell Calculated by Model

Surface Preparation	Unencapsulated Cell Isc (A)	Encapsulated Cell Isc(A)
Planar	3.737	3.777
Chemically Textured	4.024	3.883
Textured with Tapered Blades	3.964	3.880
Textured with Mechanical Tool	3.974	3.880

All of the texturing methods produce approximately the same short circuit current when encapsulated. This means that the use of a lower cost texturing tool should be as effective as chemical texturing and as effective as the use of tapered blades, in reducing the surface reflectance for cells used in a module. Experiments are now underway to optimize the cell process for wafers textured with the mechanical tool to verify the results of the modeling.

3.3.2 Back Surface Field Formation

Aluminum pastes have been used successfully to improve the efficiency of solar cells for years. Table 9 compares the results for non-BSF cells with those made using Al paste from two different vendors. Back surface fields usually increase cell efficiency by 5 to 6% on Solarex cast polycrystalline silicon. For use of a back surface field to be economic, the cost of the additional

process must be less than the value of the additional power produced. The process represented in Table 9 was not cost effective.

Table 9
Vendor Al Paste Results

Paste	Efficiency (%)	Voc (mV)	Jsc (mA/cm ²)	FF (%)
None	13.13	580.9	29.4	76.8
Vendor 1	13.92	592.2	31.2	74.8
Vendor 2	13.99	589.6	31.6	75.1

The first attempt to reduce the cost was to use less paste by gridding the p+ region. An experiment was conducted comparing a variety of coverage areas. The results are shown in Table 10. The degree of improvement in current and voltage depends upon the area of paste coverage on the back of the cell. The more paste coverage, the better the cell efficiency, so reducing the area of paste coverage does not appear to be a good way to reduce cost.

Table 10
Partial Coverage of BSF

BSF Pattern	Efficiency (%)	Voc (mV)	Jsc (mA/cm ²)	FF (%)
No BSF	12.85	581.7	29.4	75.0
25% BSF	12.94	582.7	29.6	74.9
50% BSF	13.03	583.6	29.9	74.6
100% BSF	13.12	585.9	30.1	74.8

Another method of reducing the cost is to eliminate the need to clean the back surface after the BSF fire. The initial efforts in this area resulted in good electrical results, but beading of the paste during firing leading to excess breakage during front printing. We then worked with our paste vendors to eliminate this beading. This work has now been successful. Table 11 shows cell data for cells with and without BSF. One of the BSF groups has the standard Solarex backspray on top of the BSF. The other group has a screen printed Ag-Al paste grid on top of the BSF. While the results for the printed back were slightly lower, optimization of the back grid pattern is likely to result in performance equivalent to the BSF-backspray group.

Table 11
No Clean BSF

Back Metal	BSF	Efficiency (%)	Isc (A)	Voc (mV)	FF (%)
Backspray	No	12.81	3.897	574.8	74.3
Backspray	Yes	13.62	4.102	586.8	73.5
Ag-Al Print	Yes	13.55	4.111	586.6	73.0

Work with paste vendors has now resulted in a reduced cost for the paste. The process appears to be cost effective. The new material and process must now be environmentally qualified before being implemented in manufacturing.

3.3.3 Hydrogen Passivation

Recently Rohatgi¹² reported on increased cell efficiency via forming gas anneal. We have evaluated the use of forming gas annealing at a number of different places in the cell process. In the first set of experiments, cells were annealed in forming gas (4% H₂ in N₂) at 400° C immediately after they were front printed and fired. After the forming gas anneal the cells were completed using the standard Solarex AR coating and back spray processes. The results are given in Table 12. There was no measurable improvement in short circuit current and the fill factor got progressively worse as the length of the anneal increased, indicating that the metallization system is not stable at 400° C.

The Rohatgi paper¹² suggests that an aluminum alloy is required for the forming gas anneal to be effective. Therefore, the anneal experiment was repeated using cells with an Al paste BSF. The results are given in Table 13. Once again there is no evidence of improved short circuit current and the fill factor still degraded with time at temperature, but not as dramatically as the previous group.

To eliminate the effect of temperature degradation of the metallization, another group was annealed in forming gas before front fire. The results of this experiment are given in Table 14. Now there is no degradation of fill factor and possibly a small increase in current. A new set of experiments is planned using higher anneal temperatures.

Table 12
Forming Gas Anneal at 400° C after Front Fire - Cells without BSF

Anneal	Efficiency (%)	Isc (A)	Voc (mV)	FF (%)
none	12.83	3.804	585	74.9
1 hour	12.29	3.785	585	72.1
2 hours	11.32	3.779	584	66.6

Table 13
Forming Gas Anneal at 400° C after Front Fire - Cells with BSF

Anneal	Efficiency (%)	Isc (A)	Voc (mV)	FF (%)
none	13.21	4.021	583	73.2
1 hour	13.16	3.987	583	73.6
2 hours	12.96	3.979	582	72.8

Table 14
Forming Gas Anneal at 400° C before Front Fire - Cells with BSF

Anneal	Efficiency (%)	Isc (A)	Voc (mV)	FF (%)
none	13.25	4.034	584	73.1
1 hour	13.16	4.076	586	71.6
2 hours	13.21	4.060	584	72.4

3.4 TASK 4 - AUTOMATED MODULE ASSEMBLY

The goal of this task is to modify Solarex's present automated matrix and module lay-up system to increase throughput by 100% and decrease the labor requirement by 50%. Solarex is presently using first generation automated module assembly equipment. This equipment has been very successful at eliminating labor, while producing reliable products. This system does not have the throughput that Solarex requires as the PV market grows. To assist Solarex in analyzing how this equipment can be improved to increase capacity and reduce labor, the Automation and Robotics Research Institute (ARRI) at the University of Texas at Arlington is serving as a subcontractor.

The first step in this task was the development of a process flow chart detailing all of the module assembly steps. This process flow chart includes information on the process cycle times, labor requirements, product mix and its effect on cycle time and labor, equipment maintenance, process yields and equipment up time. All of this information has been provided to ARRI for modeling and analyzing the manufacturing process.

ARRI completed a preliminary analysis of the module manufacturing process. As a short term goal they were requested to identify the changes necessary to increase production capacity by 40% to meet Solarex's short term business plan. The following sections summarize the results of this analysis.

FactoryFlow analysis

FactoryFlow provides an automated method of generating total material handling cost, distance intensity charts, and work center utilization reports to determine the efficiency of a system's operations. This analysis identifies the costs associated with the handling of material throughout the manufacturing process. For the Solarex module assembly process the total calculated cost for handling represents less than 1 cent per watt and so does not offer a significant potential for cost savings.

MPX modeling

The MPX Rapid Modeling software uses queuing theory to evaluate a network model of the proposed designs. This analysis identifies bottlenecks in the production process which limit the potential for increasing output capacity. The original bottlenecks identified were cycle times for the Matrix lay-up robot, the Frammer robot and the Tabbers.

Resource Capacity analysis

This work was undertaken to support machine loading analysis and bottleneck identification under different product change over strategies and annual production volumes. A secondary benefit of this analysis, is that it provides independent verification for the results obtained from the queuing theory model discussed above. Assuming a steady flow of upstream materials, the overall capacity of the auto-matrix and lay-up system appeared to be constrained by the Matrix lay-up robot, the Frammer station, and to a lesser degree the tabbers. These findings correlate very closely with the findings of the queuing theory analysis discussed above.

Man / Machine Charts were also developed for the lamination area to investigate the impact of resource interaction. These charts indicated that the capacity of the lamination area is constrained by the ability of the operator to service the laminators and the lay-up station. This man-power limitation could potentially result in the blocking of the lay-up station, further limiting the output of this constraining resource.

Based on ARRI modeling results, three specific areas were selected for further study. These areas are the matrixing lay-up robot, the lamination operator and the framing system. Each of these three areas has been evaluated for possible improvements.

- **Matrixing Lay-Up** - The robot flow path has been broken down into the individual steps that the robot performs and their cycle times. Two changes (use of an integrated end effector and non-robot removal of the paper between EVA sheets) were proposed. Implementation of the end effector recommendation resulted in a significant reduction in cycle time of the process. The matrix robot now waits for the solder robots to provide it product, so it is no longer the process limiting step and provided a 40 % increase in production volume.
- **Lamination Operator** - Videotapes of the operation were made covering 4 hours over 2 different days. A detailed breakdown of the tasks performed and their cycle times was determined. This information was used in a discrete event simulation package to determine the resource utilization and the impact that any changes would have to the output of the area. While the original analysis indicated that the lamination operator would be a bottleneck, it turns out that with the above mentioned change in the matrix lay-up robot, the laminators themselves are the limiting factor in production volume. While small improvements in product flow could improve the operators productivity, the volume of product was limited by how many modules can be laminated. The only solution to this is to increase the lamination capacity, which was done to provide the 40% capacity expansion need.
- **Framer/Finishing** - Videotapes of the framing system determined that the actual process cycle times were shorter than those stated in the process flow chart. Based on the correct cycle time, the "What-if" analysis indicates that framing system is not a bottleneck and can meet the short term goal by expanding capacity by 40%.

The initial analysis phase was used to make those changes necessary to increase the assembly area capacity by 40%. The next phase was originally designed to meet the PVMaT contract goal of increasing capacity by a factor of 100% from the original 1993 baseline capacity. ARRI developed two Factory of the Future concepts. They used AT&T's discrete event simulation package called Witness to evaluate each scenario. This simulation model provides additional capabilities over the MPX model used earlier in the project. The Witness software is capable of modeling resource interactions in more detail and providing a more accurate representation of the factory using statistical analysis. The Witness software was used to analyze the two Factory of the Future concepts.

Major components of Concept 1 include:

1. Combining cell test and tabbing;
2. Lay-up strings of the required length directly from the tabbing machines;
3. Providing raw materials in magazines from vendors in a ready to use state.

Concept 1 minimizes change and capital expense. Witness predicts an increase in production capacity of 58% over the present "As-Is" system or 120% increase over the PVMaT baseline. Labor utilization analysis indicates that Concept 1 requires no more labor than the baseline case, thereby reducing the labor content per module (or per watt) to 45% of the baseline. So the analysis predicts that Concept 1 will meet the PVMaT goals.

Major components of Concept 2 include:

1. Build strings of cells:
2. Lay-up strings onto glass with EVA:
3. Use a robot to trim excess EVA off modules:
4. Development and utilization of a cart system for feeding modules into test and framing:
5. Providing raw materials in magazines from vendors in a ready to use state.

Concept 2 requires more development and capital expense than Concept 1. Witness predicts an increase in production capacity of 75% over the present "As-Is" system or 146% increase over the PVMaT baseline. Labor utilization analysis indicates that Concept 2 requires one less operator than the baseline case, thereby reducing the labor content per module (or per watt) to 37% of the baseline. So the analysis predicts that Concept 2 exceeds the PVMaT goals.

Efforts are now underway to define the requirements for implementation of the two concepts.

3.5 TASK 5 - FRAMELESS MODULE DEVELOPMENT

In this task Solarex will develop and qualify a frameless module design incorporating a lower cost back sheet material (less than \$0.05/square foot) and user friendly, low cost electrical termination (less than \$1.00/module).

The key to reducing the finishing cost is to develop frameless system designs. In most larger systems the structural support provided by the frame is duplicated by the support structure. Therefore, frames can be eliminated, significantly reducing the module cost. A number of concepts have been proposed for mounting of modules without frames. Actual deployed systems include the clips used on the Solarex PV USA emerging technology array and a number of Arco Solar systems where the modules are glued directly to the support structure. The selected frameless mounting schemes must provide low cost and be able to withstand the expected mechanical loads, such as wind and snow.

3.5.1 Mounting Structure

The module proposed for this program uses 36 - 15 cm by 15 cm solar cells on a 56.00" by 25.63" piece of glass. A modular mounting array has been designed for the project. The mounting structure uses 2 C-channels behind each module, 2 K-series steel support girders and 2 pipe

support legs for each sub-array. The mounting structure concept is shown in Figures 2. The designed structure was then analyzed and determined to be capable of withstanding 125 mph wind loading with a minimum design safety factor of 1.3. The costs for this system are shown in Table 15. The structure for a 3.8 kilowatt array is projected to cost \$ 765 or \$0.202/watt.

Table 15
Structural Support Costs

Item	Quantity	Cost per System	Cost per Watt
Galvanized B-line	8	\$ 402	\$0.106
Steel Girders	2	\$ 268	\$0.071
Pipe Legs	2	\$ 95	\$0.025
Total		\$ 765	\$0.202

3.5.2 Adhesive System

To bond the PV modules to the support structure we have selected 3M's Very High Bond (VHB) Tapes. Scotch VHB tapes are used throughout industry instead of screws, rivets, welds and liquid adhesives to permanently assemble a variety of products. Use of VHB tapes offers an opportunity to improve performance while lowering the material and assembly labor cost for PV systems.

A sample array structure has been constructed at the Solarex Frederick site and modules attached using the 3M VHB Tape. This system has already successfully withstood winds in excess of 60 miles an hour from the north (back of the array) the worst case condition for the tape adhesion. Another system has been built using this at SMUD's Hedge Road substation. The taped Solarex modules at this site have already withstood an extreme windstorm without any damage.

3.5.3 Backsheet

A key component in frameless module design is the backsheet, since the electrical termination and the support system itself must adhere to the backsheet. This offered an additional opportunity to reduce cost from the 3 part backsheet being used at Solarex.

Three candidate materials were selected for evaluation in this program. The three materials are:

- Chlorinated polyethylene (CPE)
- Affinity polyolefin
- Thin Tedlar - polyvinyl fluoride

Figure 2
Mounting Structure
Rear View

TYPICAL SUB-ARRAY
VIEWED FROM REAR

CONTRACT NO.		 630 SOLAREX COURT FREDERICK, MD 21701 301 698 4200	
APPROVALS	DATE	PVMAT TRUSS CONCEPT	
DRAWN S. WINIGLER	4/29/94		
CHECKED			
APPROVED			
SIZE	DWG. STATUS	SOLAREX STOCK NO.	REV.
A		SK-042994-01	A

Small modules were fabricated using the experimental backsheet materials. These small modules were then subjected to a set of environmental qualification tests similar to IEC 1215 - "Crystalline Silicon Terrestrial Photovoltaic (PV) Modules -Design Qualification and Type Approval", but with the addition of a wet high-pot test. The three materials successfully passed all of the environmental tests except CPE samples made without pigmentation, which does not appear to have adequate adhesion to the EVA. However, pigmented CPE films have much better adhesion to the EVA and pass all of the qualification tests. Finally, modules made with all three materials have successfully passed in-house simulated UL fire test.

The major open issue with the candidate backsheet materials is their ability to withstand UV exposure. To evaluate their performance, sample backsheet materials are being exposed to an equivalent UV exposure of 2 years in Phoenix, Arizona. Two years of direct exposure should represent more UV than the backsheet will normally experience in 20 years of operation on the back of a PV module.

3.5.4 Electrical Termination

Most commercial modules have junction boxes for electrical termination. While these provide for a great deal of flexibility in use, they are expensive to purchase, probably will not meet the PVMaT cost goals and require significant labor of skilled electrical personnel for field installation. Our initial approach was to use a quick connect-disconnect system that would eliminate most of the field assembly labor. However, we were unable to find such a system that would meet our environmental requirements and cost less than \$1.00 per set of male and female connectors. Therefore, we changed our approach and decided to use a quick connect system that doesn't offer quick disconnect. This may actually have some advantages in the field because it will make it more difficult for unauthorized personnel to disconnect modules and such systems are less likely to accidentally become all or partially disconnected.

We have selected a Raychem SolderSleeve termination system. The lead wires from the module are soldered together and environmentally sealed in one simple heat step. These shrinkable tubing - butt connectors are designed for splicing wires in an outdoor environment. In our preliminary tests these connectors have passed wet hi-pot testing after 1000 hour exposure to 85° C at 85% Relative Humidity. Field testing of these connectors has begun.

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