June 1999 • NREL/SR-520-26071

Subcontractor Report

Cast Polycrystalline Silicon Photovoltaic Module Manufacturing Technology Improvements

Final Subcontract Report
8 December 1993 — 30 April 1998

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PREFACE

This Final Technical Report covers the work performed by Solarex under DOE/NREL Subcontract # ZAI-4-11294-01 entitled "Cast Polycrystalline Silicon Photovoltaic Module Manufacturing Technology Improvements". This is the Final Technical Report for this subcontract. The technical efforts on this subcontract ran from December 8, 1993 to April 30, 1998.

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

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EXECUTIVE SUMMARY

The objectives of this program were 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 were 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 worked in the following technical areas:

CASTING

The goal of the casting task was 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 previously achieved for 11.4 cm by 11.4 cm bricks.

WIRE SAWS

The goal of the wire saw task was to develop the wire saw technology for cutting 15 cm by 15 cm polycrystalline wafers on 400 µm centers at lower cost per cut than achieved on ID saws.

CELL PROCESS

The goal of the cell task was 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 was to modify Solarex's 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) worked with Solarex on this task.

FRAMELESS MODULE DEVELOPMENT

The goal of the frameless module task was 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 were designed to mount directly onto the support structure without integral frames.

AUTOMATED CELL HANDLING

The goal of the automated cell handling task was 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. ARRI also assisted Solarex on this task.

ACCOMPLISHMENTS

Accomplishments during the program included:

- Converted all of the production casting stations to increase ingot size and operated them at equivalent yields and cell efficiencies. The casting capacity has been doubled at a cost that is 20% of what it would have cost to buy new equipment to achieve the same capacity increase.
- Developed a wire saw process and transferred the process to production with higher yields and lower costs than achieved on the ID saws. Added additional wire saw capacity so that more than 80% of wafering is now done using wire saws.
- Developed an aluminum paste back surface field process to increase cell efficiency by 5% and completed environmental qualification of this all print metallization process. A fully automated printing system was designed, procured and has now been transferred to manufacturing for the production of the BSF solar cells.
- Fabricated 15.2 cm by 15.2 cm polycrystalline silicon solar cells and built modules using these cells.
- Completed modifications to the module assembly area to increase capacity by a factor of three.
- Qualified a single layer Tedlar backsheet that reduced backsheet cost by $0.50/square foot and implemented the change in manufacturing.
- Selected, tested and qualified a low cost (less than $1.00 per module) electrical termination system.
- Qualified the structure and adhesive system for mounting frameless modules and used the system to build several large arrays.
- Completed a study of the fracture properties of cast polycrystalline silicon wafers and provided the information necessary to calculate the maximum stresses allowable during wafer handling.
- Demonstrated the operation of a wafer pull down system for cassetting wet wafers.
- Designed, procured and made operational a cell printing system with automated cell handling.

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1.0 INTRODUCTION

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

- 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 were to reduce the module cost per watt in half, 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.

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.

When the PVMaT Program began, Solarex was casting ingots from which 4 bricks, each 11.4 cm by 11.4 cm in cross section were 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 or 9 bricks 11.4 cm by 11.4 cm. The casting task involved making the modifications in equipment and process necessary to cast larger ingots. The modifications have been completed and Solarex manufacturing is casting only the larger ingots. This effort resulted in an increase in the production capacity of Solarex's casting stations and reduced the casting labor necessary to produce each watt of photovoltaic product.

Wire saws can be used to cut thinner wafers, with less kerf than is possible on the Internal Diameter (ID) saws. The program goal was to reduce the center to center cut distance from 600 microns on the ID saw to 400 microns on the wire saw. This would have resulted 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 would be able to increase its output of PV modules by 50%. 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 than ID saws. One wire saw produces as many wafers as approximately 22 ID saws. To increase capacity with wire saws required a much smaller capital investment than would have been required to achieve the same increase with ID saws. The major issue with wire saws was the ability to reduce the variable cost to cut a wafer. The process developments completed under this program have lead to the wire saws producing wafers for at least $0.10/wafer less than the ID saws. Wire saws now account for more than 80% of the wafer production at Solarex.

In this program, Solarex worked 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 was 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 under investigation during the program included:

- Back Surface Field (BSF)
- Selective emitter
- Emitter oxide passivation
- Chemical and mechanical texturing
- Hydrogen Passivation
- Phosphorous Gettering
- Silicon nitride passivation

The goal of the cell effort was to increase the 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/m^2, AM1.5, 25° C). This will only be of value if it is achieved with an integrated process sequence that lowers the overall module $/Watt manufacturing cost.

At the start of this PVMaT Program, Solarex had a first generation automation system in use at the Frederick facility for tabbing, matrixing and lay-up of the PV modules. During the assembly automation task this system was evaluated to determine how it could be modified to increase production throughput, yield and process control and to minimize production labor and cost. To assist with this effort, the Automation and Robotics Research Institute (ARRI) of the University of Texas at Arlington served as a subcontractor. ARRI assisted Solarex in analysis, modeling and development of handling concepts to improve the operation of the module assembly area. During the program, the assembly area was modified as modeled, leading to at least a tripling in assembly capacity.

Solarex modules use low iron tempered glass as a superstrate and Ethylene Vinyl Acetate (EVA) as the encapsulation system. No change was proposed in this encapsulation system in order to maintain the module reliability. However, a reduction in the cost of the backsheet was achieved during the course of the program.

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 one of the largest single contributors to module cost. In large systems, the support provided by the system structure is adequate, making the module frame redundant. Eliminating this frame significantly reduces the module selling price. During the program an appropriate support structure and adhesive system was developed and used to attach frameless modules to the mounting structures on several large PV arrays.

The junction box also adds appreciable cost to the module, while requiring additional labor for system assembly. A simpler electrical termination scheme costing less than $1.00 per module was tested and qualified for use.

An important issue for many crystalline silicon PV manufacturers is the ability to handle thinner and larger wafers through the production line. Solarex was supported by ARRI in an effort to develop handling methods for large thin wafers. ARRI performed detailed analysis and modeling of the requirements for thin wafer handling. Prototype wafer handling stations were been built and tested. Production units were designed, procured and are now operating in the Solarex production line.

The PVMaT changes to the cast polycrystalline process sequence are shown in Table 1.

Table 1
PVMaT Changes to the Cast Polycrystalline Silicon Process Sequence

Process	Pre-PVMaT	Post-PVMaT
Casting	4 brick ingot	9 brick ingot
Wafering	ID Saws	Wire Saws
Cell Line	Screen Print Front Spray Backs	All Print Cell Al BSF
Cell and Wafer Handling	Mostly Manual	Mostly Automated
Module Construction	3 Part Backsheet J-Box	Tedlar Backsheet Crimp Connector
Module Assembly	First Generation Robots	Upgraded with XY Positioners

Overall results of this program were modifications of Solarex's polycrystalline silicon production facility that:

- Increased production capacity by a factor of three; and
- Reduced the "profitable" selling price of PV modules.

2.0 BASELINE PROCESS AND PRODUCTS

Solarex's Crystalline Silicon Technology is based on use of cast polycrystalline silicon wafers. The process flow used at the beginning of this PVMaT program is shown in Table 2. The primary product was 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 2
Baseline 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 photovoltaics[1]. 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 wafers[2].

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 was done with Internal Diameter (ID) saws. These are the same saws that are used in the semiconductor industry to wafer single crystal CZ ingots. Solarex has many years of experience with these ID 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 can 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 involves soldering 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 were then laid up into a 36 cell matrix by a robot. The tabs were then soldered to the backs of the solar cells using automated equipment. Each tab has 2 back solder joints.

Module Lamination

The module construction consisted of a low iron, tempered glass superstrate, EVA encapsulant and a 3 part Polyethylene-Mylar-Tedlar backsheet. A single sheet layer of Tedlar replaced the three part backsheet during the first year of the program. 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 program.

3.1 POLYCRYSTALLINE SILICON CASTING IMPROVEMENTS

The original goal of the casting task was to develop the ability to cast ingots that yield four 15 cm by 15 cm bricks with at least equivalent material quality as was achieved for the standard 11.4 cm by 11.4 cm bricks. During the first year of the program, Solarex 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.

During the second year efforts turned to casting larger ingots that yield four 15 cm by 15 cm bricks. The first several experiments had well-behaved runs, but the resultant ingots had cracks extending upward from the bottom. An 11.4 cm by 11.4 cm brick was cut from one of these ingots, wafered and processed into cells. The cell efficiency from this brick was significantly lower than normal, with the average cell efficiency for this brick being approximately 90% of a standard production brick.

Analysis of the crystal growth and modeling of the casting process indicated that a larger separation between the bottom heater and the walls of the chamber was required. This change was made and the insulation configuration and process program optimized on standard sized ingots. We verified that this configuration could produce equivalent material by casting and processing 9 standard size ingots (4 -11.4 cm by 11.4 cm bricks). There was no statistical difference in yield or efficiency between these 9 ingots and the overall production line average during that time period.

Using this configuration full size ingots for four 15 cm by 15 cm bricks were cast. The new configuration and program eliminated the cracking. Sample 11.4 cm by 11.4 cm bricks were cut out of the larger ingots and processed to make standard solar cells for comparison of material quality. Cell efficiencies were equivalent to material cut from standard size ingots during the same time period. A laboratory process was developed that yielded equivalent quality ingots with a 73% increase in the useable silicon obtained from each casting.
.
Most of Solarex's products are still based on the use of 11.4 cm by 11.4 cm solar cells, so an effort was undertaken to develop casting of ingots large enough to produce nine 11.4 cm by 11.4 cm bricks. Such an ingot requires approximately 20% more silicon than the PVMaT ingot. The process to cast these "mongo" ingots required changes to the insulation and receiver, but utilized the same casting stations as modified for the PVMaT ingots. Laboratory efforts involved the optimization of the casting process for these larger ingots. Material with equivalent quality to the standard size ingot has been obtained. Figure 1 shows a 4 brick “mega” ingot and a 9 brick “mongo” ingot. Figure 2 shows a “mongo” ingot sized into 9 bricks.

Based on these experimental results a cost analysis was performed to determine whether expansion of the casting stations was economic. The analysis indicated that modifying the stations for casting of “mongo” ingots would double the casting capacity. The cost of this added capacity would be 20% of the cost required to add a similar amount of capacity by purchasing new casting stations. Solarex decided that this was the most economic way of expanding the casting capacity. All casting stations have now been to the larger configuration and production is only manufacturing "mongo" ingots.

Once the new process was transferred to manufacturing, it was important to monitor the performance to assure that the new process was producing material of equivalent quality at similar yields. Figure 3 shows the difference in weight yield between the larger "mongo" ingots and the standard size "mega" ingots during the time period when they were both being produced. The values plotted as the solid curve are the seven day rolling averages, which never deviate by more than 2.5%. The average difference for the whole time period in which both sized ingots were being cast is 0.21%, with the larger ingots having a slightly higher weight yield. Figure 4 is a plot of the difference in average cell efficiency for all cells produced from the large "mongo" ingots minus the average cell efficiency for all cells produced from the standard size "mega" ingots on a daily basis. The average difference for the entire time in which both products were produced is 0.01% with the larger ingots having a slightly, but not statistically significant, lower average cell efficiency. The larger ingot process was implemented successfully.

Figure 1
Comparison of Large "Mongo" and Standard "Mega" Ingots

Figure 2
Large "Mongo" Ingot Sized into 9 Bricks

3.2 WIRE SAW IMPROVEMENTS

The goal of the wire saw task was to develop the wire saw technology for cutting 15 cm by 15 cm polycrystalline wafers on 400 µm centers at lower cost per cut than achieved on the ID saws.

3.2.1 Wire Saw Operations

The first step in this effort was the selection and procurement of a wire saw. Solarex selected and purchased an HCT wire saw[5]. The HCT wire saw has been operational since July, 1994. During the first year of the program the saw was used to successfully demonstrate the ability to cut 11.4 cm by 11.4 cm, 11.4 cm by 15.2 cm and 15 cm by 15 cm wafers on 500 µm and 400 µm centers. Figures 5 shows a photograph of the whole saw. Figure 6 shows a photograph of the wire guides and wire web.

Figure 3
Difference in Weight Yield Between Large Mongo Ingots and Standard Size Mega Ingots

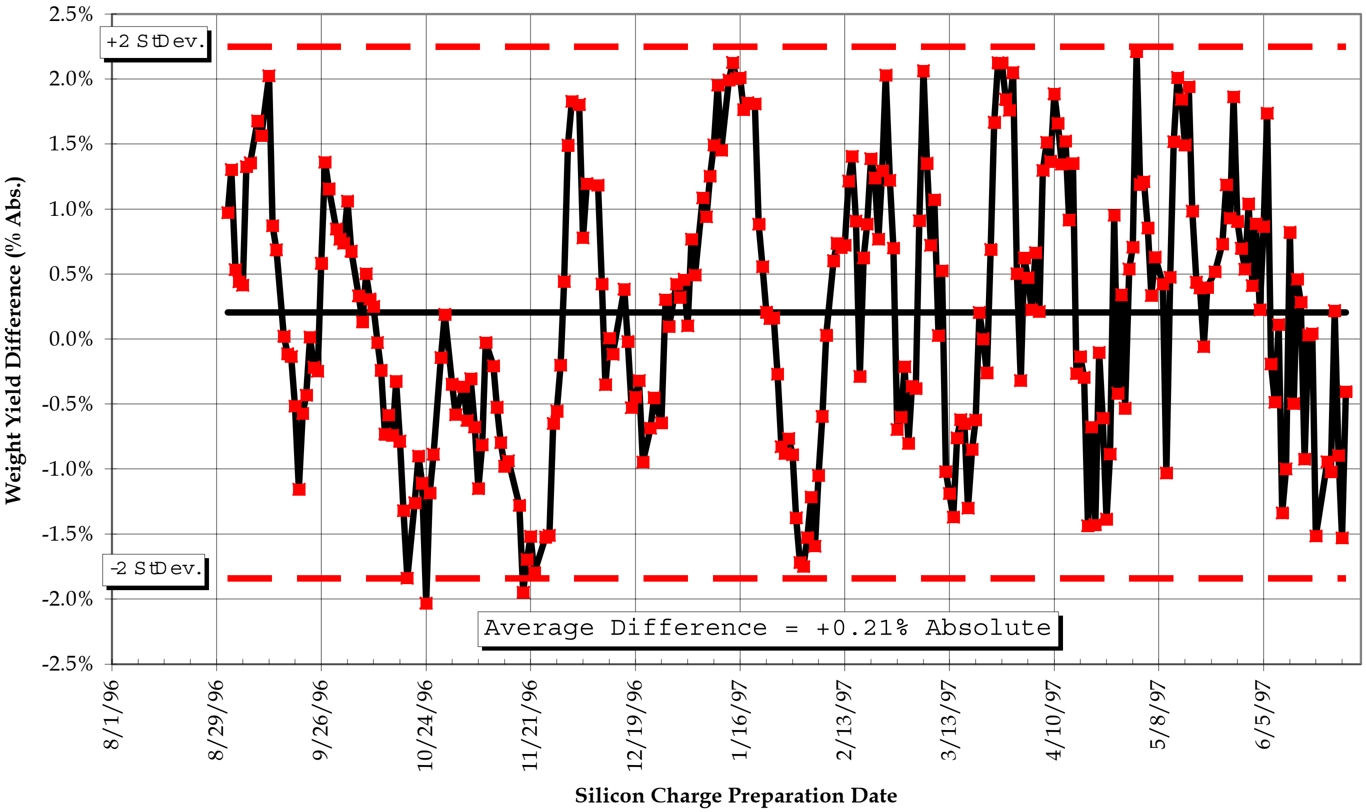
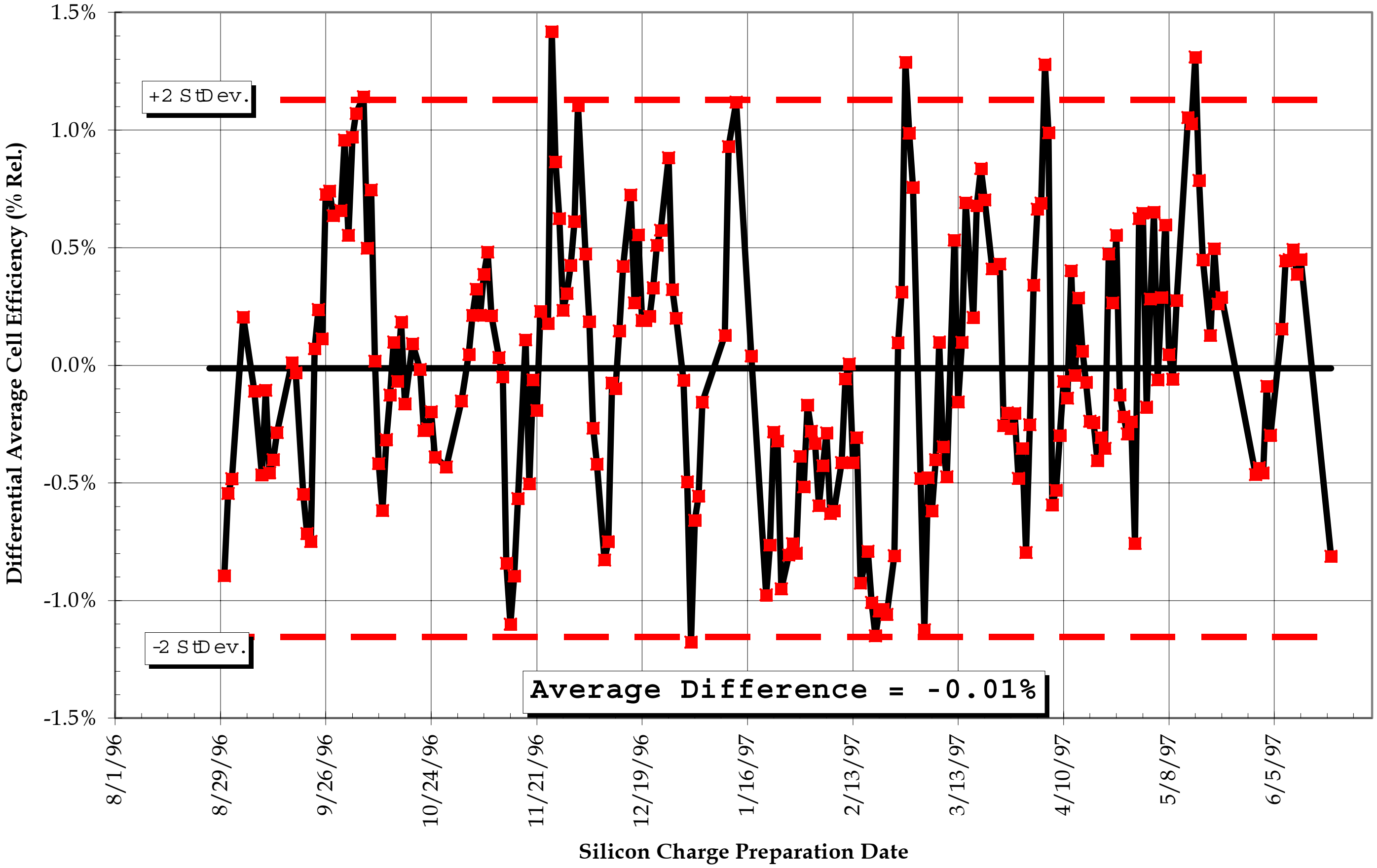


Figure 4
Difference in Average Cell Efficiency Between Large “Mongo” Ingots and Standard Size “Mega” Ingots



During the second year production operators were trained on the saw and then operated the saw as a production operation on the off-shifts, while we performed experiments to improve the process and reduce costs during the day shift. In the first year of operation this wire saw was used to process in excess of 1,000,000 wafers at higher yield than achieved on the ID saws.

Cost saving efforts included:

1. Qualified a new oil that costs 32% less than the original oil. This change alone reduces the wafer cost by several cents.
2. Identified and qualified a new vendor of pulleys. The new pulley cost about one-third of what the saw vendor charged for the original pulleys.
3. Identified and qualified grit from several vendors and negotiated a long term contract to save \$0.25 per pound of grit.
4. Reduced the center to center spacing of the wire guide grooves from 500 µm to 475 µm.
5. Developed an improved wire guide coating that doubled the wire guide life while reducing the deviation of wafer thickness, especially toward the end of wire guide life.

Based on the success of this program, Solarex purchased additional wire saws. Over 80% of all Solarex's wafers are now being cut on wire saws. Each wire saw produces as many wafers as 22 to 24 ID saws and does it with higher yields and lower per wafer cost. In addition, the wire saws produce at least 20% more wafers from each ingot, increasing the number of watts produced per kilogram of silicon purchased, an important parameter because of the expense and limited availability of silicon feedstock.

Figure 5
HCT Wire Saw

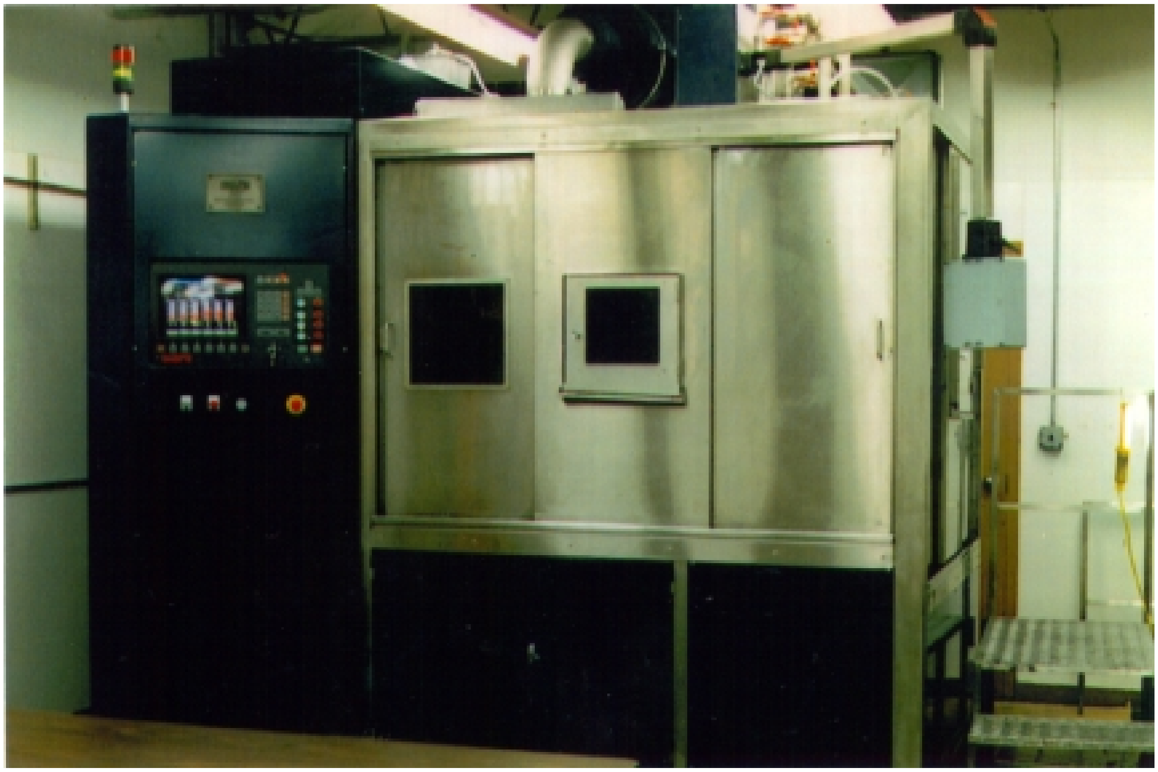
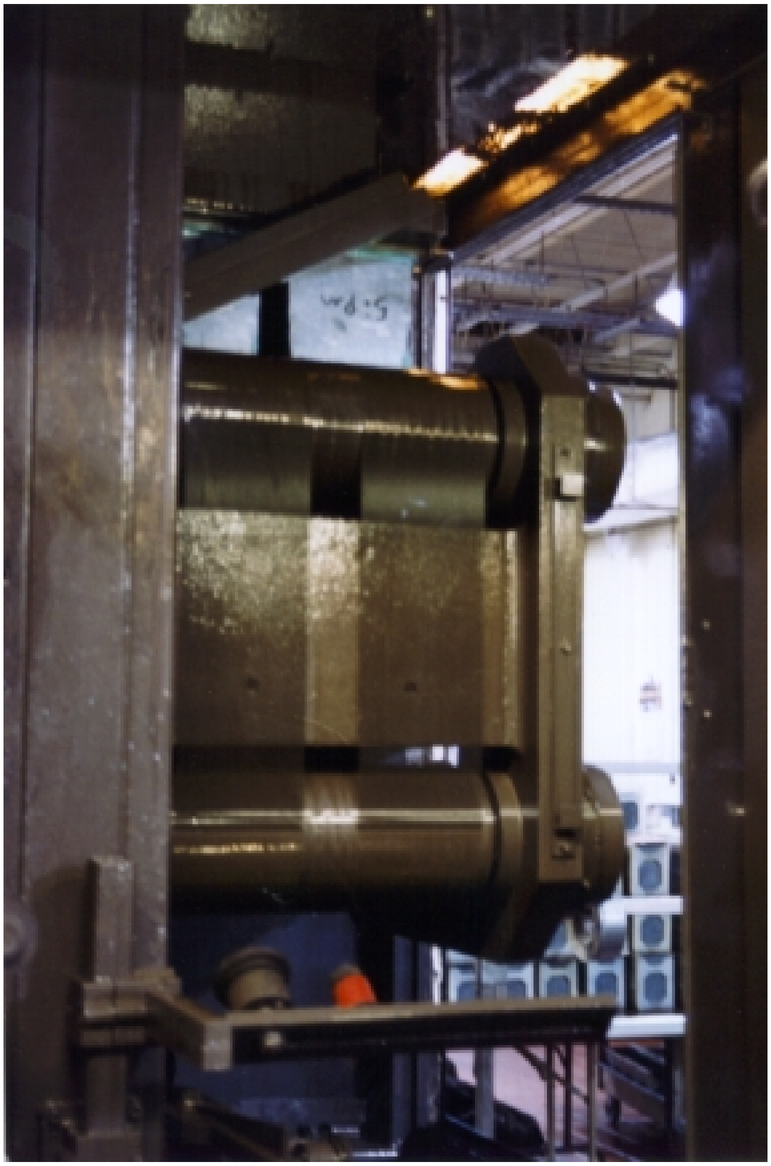


Figure 6
Wire and Wire Guides



3.2.2 Demounting and Cleaning

After wafers have been cut on the wire saw they must be removed from the hold down plate, placed in cassettes and cleaned. This process is done manually. Ultimately an automated process is necessary to reduce cost and increase yield especially as the volume of wire saw wafers increases and the thickness of the wafers decreases.

As a first step to better understand what is involved in removing wet wafers from a stack, the Automation and Robotics Research Institute at the University of Texas at Arlington (ARRI) performed a series of tests to evaluate the difficulty of separating wafers[6].

In the first experiment the amount of force necessary to pull wafers apart was measured as a function of how wet the wafers are. The results are shown in Table 3. The more water between the wafers, the harder it is to separate the wafers. The pull forces required to separate wet and semi-wet wafers are well within the breakage-causing range, as happened with several of the samples tested.

Table 3
Normal Separation Force

Test #	Dry (grams)	Semi-wet (grams)	Wet (grams)
1	7	2274	>5700
2	3	2018	>5700
3	12	2381	5101
4	16	1907	>5700
5	7	1864	>5700
6	6	1369	5573
Avg.	9	1969	>5700

Rather than pull wafers apart, it is possible to slide them apart. ARRI's second experiment measured the dynamic sliding friction of wafers as a function of how wet the wafers are. The results are shown in Table 4. For this case the required separation force is greatest for semi-wet wafers. Once the wafers are wet they slide relatively easily over each other.

Table 4
Dynamic Friction Force

Test #	Dry (grams)	Semi-wet (grams)	Wet (grams)
1	111	2149	219
2	104	2053	208
3	102	2041	171
4	118	2589	105
5	114	2257	159
6	126	1976	208
Avg.	112	2178	178

These results indicate that it would be best to dry the wafers before destacking. However, drying the wafers at that stage presents a number of problems. The wire saw slurry has to be removed before there is any chance of drying the wafers. The cleaning solvent dries slowly. When we began evaluating the use of a solvent that would dry more quickly, we realized that evaporating slowly is an important feature of the solvent, since it raises the flash point and minimizes the release of organic vapors into the air. Therefore, use of a more rapidly drying cleaning solvent is not recommended. If at all possible, it would be best to have equipment that would take a stack of semi-wet or wet wafers and cassette them. ARRI then proceeded to build a prototype unit to destack wet or semi-wet wafers into cassettes. In this design the stack of wafers lies vertically. A roller presses against the first wafer in the stack, pulling it downward through a slot into a cassette. The cassette is then indexed to accept the next wafer.

A prototype wafer pull down system was built and tested. The concept worked very well for dry, wet and semi-wet wafers. The prototype operated through thousands of cycles without breaking a single wafer and with successful feeding of a single wafer more than 99.95% of the time. Solarex is trying to identify a vendor to manufacture production equipment based on this concept.

All of the goals of the wire saw task have been met. However, while we were able to demonstrate cutting on 400 micron centers, production is not using this spacing because today the remainder of the factory can not handle wafers that are less than 200 microns in thickness. There are still a number of opportunities for further cost reduction in wire saw technology including:

- Thinner wire,
- Recycling of grit,
- Development of automatic cassetting equipment.

3.3 HIGH EFFICIENCY CELL DEVELOPMENT

The goal of the cell development task was 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] The following sections discuss the various efficiency enhancing techniques that were evaluated during the course of the program.

3.3.1 Back Surface Field Formation

Initial laboratory experiments demonstrated that an aluminum paste back surface field (BSF) could be used to cost effectively increase cell efficiency by approximately 5%[7]. During the second year of the program we conducted manufacturing trials, environmentally qualified cells made with the Al paste in a module package, evaluated the impact of cell thickness and developed an all screen printed process[6].

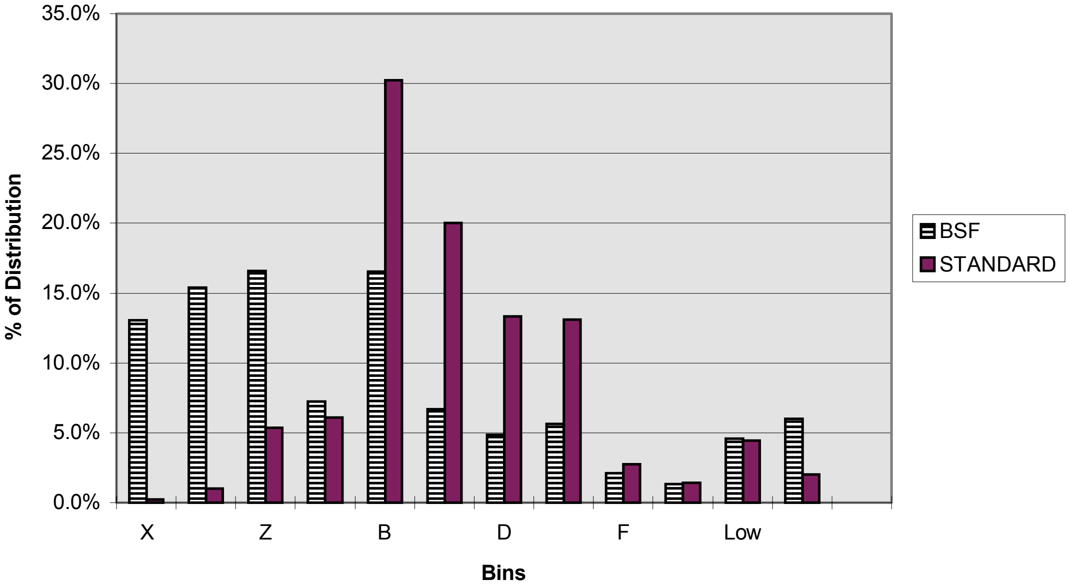
Three BSF manufacturing trials were completed, with more than 40,000 BSF cells produced with all processes except BSF performed in production using production processes, equipment and personnel. The average cell efficiency for all of these BSF cells was more 5% higher than for the non-BSF cells produced during the same time period.

Prototype equipment was then constructed and the BSF process was transferred to manufacturing for use on a significant percentage of all cells produced. Figure 7 shows the bin distribution for both the BSF cells produced on this prototype unit and all of the standard production cells fabricated over a six month period. The X bin has the highest efficiency with G bin the lowest. The BSF process yielded a 5.1 % increase in average short circuit current and a 1% increase in average voltage, but a reduction in fill factor limited the efficiency increase to 4.5%. However, much of the fill factor loss was due to processing the cells with conditions optimized for the standard cells, not for the BSF cells. We expected that optimization of the firing profiles will improve the BSF fill factor and recover at least the 5% efficiency gain demonstrated in the pilot runs.

Solarex then ordered a fully automated screen printing system for implementation of the BSF process in production. This system includes three automatic screen printers, one each for printing of back pads, aluminum paste and front silver grid pattern. This system is now fully operational at Solarex. Figure 8 shows several photographs of the system.

In the first few months of operation the system has operated satisfactorily. Cell handling and printer operations have been excellent. The system has operated with an overall 98% mechanical yield and is now producing cells that are 6.5% more efficiency than those cells manufactured without back surface field. There have been and continue to be systems integration issues particularly in terms of change over in cell size. One initial problem with shunting of cells was attributed to a poorly designed cell flipper. Once this was corrected shunting has not been a problem.

Figure 7
Bin Distribution Comparison of BSF and Non-BSF Cells



The overall PVMaT plan calls for the use of thinner wafers to increase the yield of watts produced per purchased kilogram of silicon. Therefore, this effort included an evaluation of the effect of using thinner wafers on cell performance. An experiment was conducted to study the effect of cell thickness on cell efficiency. A control group of cells was fabricated using Solarex's standard process with no BSF. The results of this experiment are shown in Figure 9. The cells are less efficient as they get thinner. With this technology we would expect to lose approximately one half a percentage point in efficiency when reducing the thickness from 290 µm to 190 µm.

A similar experiment was then conducted using a BSF process. The results are shown in Figure 10. With the BSF process thinner cells are more efficient. With the BSF process we can expect the efficiency to increase by approximately one third of a percentage point when reducing the wafer thickness from 290 µm to 190 µm. The nominal 5% efficiency gain observed for BSF cells with today's cell thickness increases to approximately 10% for the thinner cells under development.

3.3.2 Selective Emitter

One of the approaches to increased cell efficiency is the use of a selective emitter with a deeper junction under the metallization and a shallower junction in the emitter field. In this way the current collection in the emitter can be decoupled from the requirement of the screen printed metallization, which is to have a high surface concentration of phosphorus. This approach had already been evaluated at Solarex using masking and etchback techniques to produce the shallower junction in the emitter field. A cost analysis indicated that this process was not cost effective[4].

Another approach to achieve a selective emitter is to use a screen printable dopant paste for the deeper diffusion under the metallization area. This process sequence may be cost effective, particularly if rapid thermal processing can be used for the light emitter diffusion. Work in conjunction with Ferro Corporation has lead to the development of a screen printable paste for use in a selective emitter. An efficiency gain of 2% has been achieved using this selective emitter process as shown in Table 5. Cell modeling indicates that an efficiency gain of 4% should be achievable with the selective emitter structure.

Figure 8
Automated Screen printing System

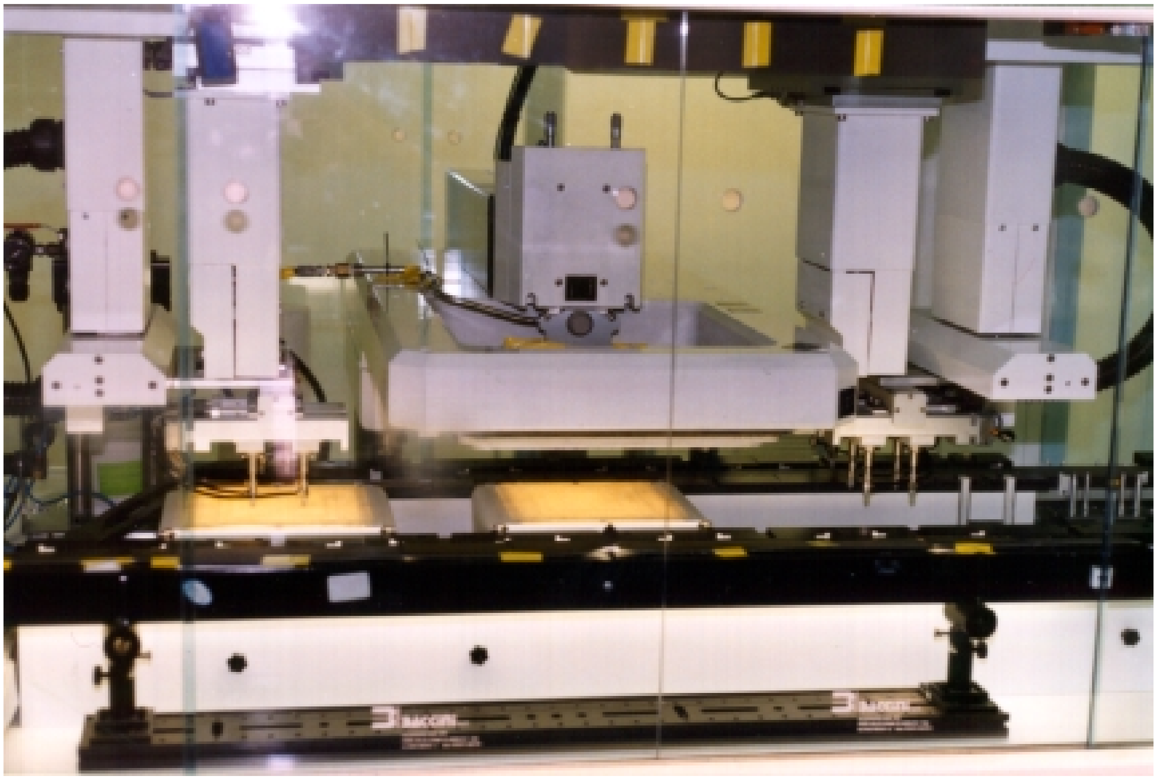


Table 5
Selective Emitter versus Controls

	Efficiency (%)	Jsc (mA/cm^2)	Voc (mV)	FF (%)
Control	12.4	29.0	575	74.4
Selective Emitter	12.7	29.2	580	74.7

3.3.3 Silicon Nitride Processing

One approach to increased cell efficiency is the use of hydrogen passivation on both bulk and surface defects in order to increase the minority carrier diffusion length. Kyocera has reported on the passivation effects of silicon nitride films, that have been deposited by plasma enhanced chemical vapor deposition (PECVD) of SiH_4 and NH_3.[8] Kyocera has been using this process in commercial production, producing 14.5% efficient polycrystalline solar cells.

Figure 9

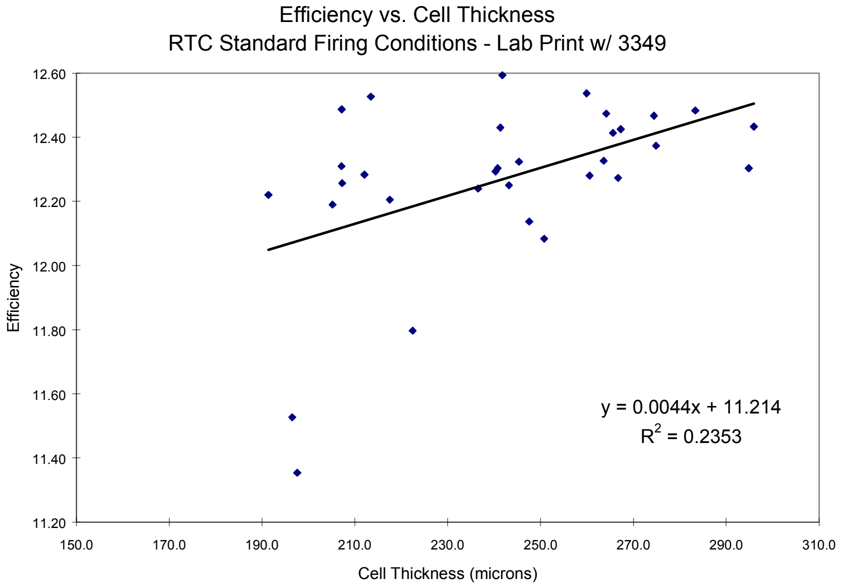
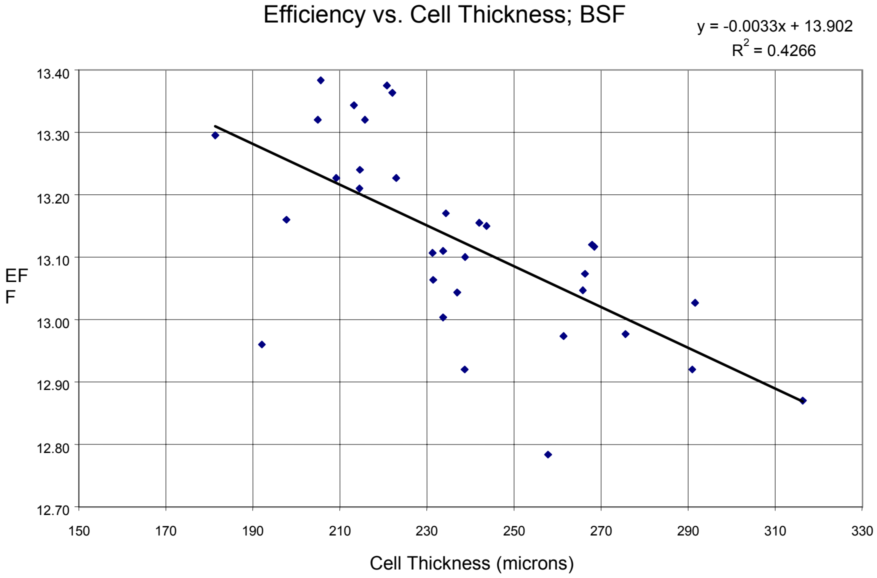


Figure 10



PECVD deposition of silicon nitride appears ideally suited for use on solar cells since it:

1. Serves as the antireflective coating, since its index of refraction is appropriate for use between the EVA encapsulant and the silicon surface.
2. Provides a source of hydrogen for passivation of the underlying bulk silicon.
3. Provides a source of hydrogen to passivate the silicon emitter-AR coating interface.

The Interuniversity Micro Electronics Center (IMEC) in Belgium has reported on incorporation of PECVD silicon nitride, BSF and a selective emitter into high efficiency solar cell processing[9,10]. We initiated experiments in conjunction with IMEC to determine how well their cell process would work on fairly large area (10 cm by 10 cm) Solarex cast polycrystalline silicon wafers. The results are shown in Table 6. All of the cells are made on matched Solarex cast polycrystalline silicon and have screen printed silver contacts and aluminum BSF. PECVD silicon nitride shows promise as a high efficiency cell process. The major issue with implementation is the identification of manufacturing equipment to implement the process in a cost effective manner.

Table 6
IMEC PECVD Silicon Nitride Experiments

Processing	Average Cell Efficiency
Solarex Baseline	12.7%
Solarex BSF	14%
IMEC TiO_2 with BSF	14%
IMEC Silicon Nitride with BSF	16.3%

3.3.4 Optical Coupling

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. A chemical texturing process is utilized by many 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. Historically 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. Recent reports in the literature claim that chemical texturing of polycrystalline silicon can be effective at reducing reflection and therefore increasing cell efficiencies[11].

Solarex subcontracted to the Colorado School of Mines (CSM) to reevaluate chemical texturing of cast polycrystalline silicon. CSM selected the KOH system for the study based on its extensive use for single crystal solar cells. CSM performed a series of optimization experiments and reported that for etching cast polycrystalline silicon:

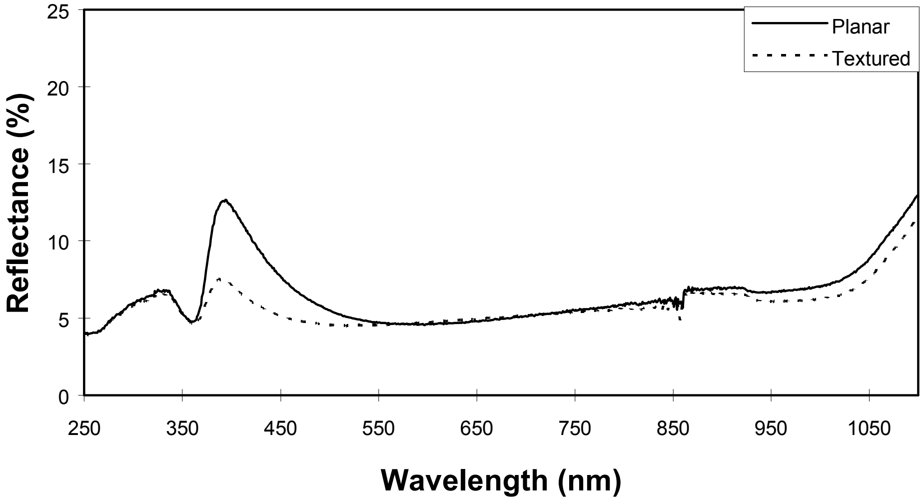
- The optimum temperature is about 10° C below boiling.
- A 20 minute etch is sufficient to remove saw damage and achieve the best texturing.
- Wire sawn wafers are best etched directly without a damage removal etch.
- Surface cleaning affects the etch quality, particularly if residues are left.
- Isopropanol and 1-butanol are the best additives.

- The environment of the etch is very important. The best texture resulted when the distance between the wafer surface and the Teflon holder was restricted.

CSM provided samples with the optimum texturing. Solarex completed the optical processing on these samples, by depositing a single layer TiO_2 AR coating and encapsulating them using EVA and low iron tempered glass, the typical PV module package. When encapsulated the optimum textured sample looked black like textured single crystal silicon. Figure 11 shows the reflectance of the best of these textured samples as well as the reflectance of a typical planar polycrystalline sample. The textured sample has lower reflectance at both ends of the spectrum.

This reflectance data was then utilized to calculate the expected performance of each of these surfaces in terms of the short circuit current from solar cells made using this optical surface[12]. The model utilizes the solar spectrum (AM1.5) and the spectral response expected for Solarex cast polycrystalline silicon. The predicted short circuit current for the best of the chemically textured samples was approximately 0.3% higher than the planar control. With such a small improvement this type of chemical texturing will not be economic.

Figure 11
Reflectance of Chemically Textured and Planar AR Coated and Encapsulated Polycrystalline Silicon



Mechanical texturing is another approach to improving the optical coupling. Using the method developed to evaluate the performance of an optical coupling surface in terms of its performance on solar cells[12], we predicted that chemical and mechanical texturing would increase the short circuit current and maximum power of encapsulated solar cells by approximately 3% over planar cells made on the same material with the same cell process. To verify the model, matched polycrystalline wafers were processed with and without mechanical texturing. The matched cells were measured, encapsulated and remeasured. The results are given in Table 7. Mechanical texturing resulted in a 3.0% gain in encapsulated cell efficiency, as predicted by the model using reflectance measurements.

So the question is not whether mechanical texturing can provide a similar efficiency gain as chemical texturing, but rather whether it can be performed cost effectively. During the course of this program several vendors have been able to fabricate small texturing tools that require many passes to texture a full cell. Attempts to obtain a tool that can texture a whole 11.4 cm by 11.4 cm cell in one pass were unsuccessful. As a compromise, a tool that textures the cell in 5 passes was obtained and used successfully.

An economic analysis of the mechanical texturing process shows that the resultant cost depends strongly on the process yield and tool life. These are the two factors that can not be determined without significant production experience. To gain this experience requires a significant financial investment, which is hard to justify without better data for the cost model.

Table 7
Mechanical Texturing versus Planar Controls

Cell Structure	Unencapsulated Efficiency (%)	Unencapsulated Jsc (mA/cm^2)	Encapsulated Efficiency (%)	Encapsulated Jsc (mA/cm^2)
Planar	12.75	29.7	12.96	30.3
Mech. Tex.	13.19	30.7	13.35	31.1
Difference	3.4%	3.4%	3.0%	2.6%

3.3.5 Phosphorous Gettering

There have been a number of reports on the use of phosphorous gettering to improve the efficiency of solar cells, particularly on polycrystalline material[13,14]. The most compelling results are based on work at Sandia[15] where they measured a large increase in minority carrier lifetime after gettering for Solarex cast polycrystalline material.

In this program we investigated the use of phosphorous gettering in conjunction with the use of a back surface field, as a function of position of the wafers in the ingot and with a variety of surface preparation techniques[16]. The experiments verified that the benefits of phosphorous gettering are additive to the benefits obtained from both BSF and texturing processes. Phosphorous gettering increased the average short circuit current and efficiency up to 2.7% over the non-gettered controls.

3.3.6 Integrated Cell Process

Back surface fields, mechanical texturing and phosphorous getting all increase cell efficiencies. An integrated cell process sequence has been developed to include all three of these efficiency enhancing processes in a cost effective process sequence. The results for encapsulated single cell packages are shown in Table 8. This group of cells nearly met the program efficiency goal of 15%.

A larger number of cells were fabricated using this integrated process. The resultant 36 cell modules produced an average maximum power of 65.8 Watts at STC, which equates to an average cell efficiency of approximately 14%.

Table 8
Integrated Cell Process Sequence
(Encapsulated Cells)

Sample	Efficiency (%)	Jsc (mA/cm^2)	Voc (mV)	FF (%)
Planar Poly	14.0	32.28	599	72.5
Mechanical Texture Poly	14.56	32.90	597	74.1
Mech Tex Poly + Gettering	14.88	33.04	600	75.1

3.3.7 Large Area Cells

The first issue in the design of a larger cell was the selection of the exact size. While the original program called for the cells to be 15 cm by 15 cm, all of the equipment, the cassettes and the glass could accommodate a somewhat larger size. Solarex already had a commercial cell that is 11.4 cm by 15.2 cm in size. Selecting the larger cell to have at least one dimension in common with this commercial cell has a number of advantages in terms of tooling and module BOS. There are also advantages to having a square versus rectangular cell. Therefore, we selected 15.2 cm by 15.2 cm as the dimensions for the new cell.

Using process parameters typical of our standard 11.4 cm by 11.4 cm solar cell our performance model predicted the larger 15.2 cm by 15.2 cm solar cell would be 0.3% lower in efficiency than the standard sized cell due to increased series resistance losses[6]. The model also predicted that some of this efficiency loss could be recovered by utilizing wider and thicker interconnect ribbon and by increasing the number of solder joints on each cell. The option of adding additional bus bars and interconnect ribbons was evaluated, but the calculations indicated that the present two bus system would produce higher efficiency cells. The analysis led to the design of a cell with 53 fingers and 2 bus bars with 6 solder bonds on the front of each interconnect ribbon and 3 solder bonds on the back of each interconnect ribbon. The model predicted that this design would be approximately 0.2% lower in efficiency than an equivalent 11.4 cm by 11.4 cm cell.

Several groups of 15.2 cm by 15.2 cm cells were fabricated. The initial group was fabricated using Solarex's standard process without BSF. The average cell efficiency of this group was 13%, a very respectable value for this technology. The second group of cells was made using the aluminum paste BSF process developed in this program. These cells measured approximately 5% higher in average efficiency than the first group.

Two full size 36 cell modules were fabricated using these cells. The results are given in Table 9. The output of the module without BSF was exactly as predicted from the cell results. The BSF module exhibited the typical BSF increase in short circuit current, but suffered from a 4% lower fill factor. Further investigation indicated that a redesign of the back print pattern was necessary to carry the large current from these cells. With this redesign 15.2 cm by 15.2 cm BSF cells were fabricated with average efficiencies of 13 to 13.5%. These still lost fill factor, from 73.4% when measured on a test block versus 71.7% when tested through tabs soldered on the back of the cell.

While significant progress was made in identifying efficiency enhancing processes, the goal of reaching 15% efficiency in production has not been realized. Achieving an average cell efficiency of 15% would have required the implementation of processes to raise the average cell efficiency by approximately 18% during the program. In reality a 5 to 6% increase in cell efficiency was achieved in production via implementation of the aluminum paste BSF process.

Table 9
PVMaT Modules with 15.2 cm by 15.2 cm Cells

Sample	Pmax (W)	Isc (A)	Voc (V)	FF (%)
#1 standard	108	7.16	21.0	72.0
#2 BSF	109.3	7.59	21.2	68.0

3.4 AUTOMATED MODULE ASSEMBLY

The goal of this task was to modify Solarex's first generation automated matrix and module lay-up system to increase throughput by 100% and decrease the labor requirement by 50%. During the second year of the program this throughput goal was increased to 200% to meet market demand.

Solarex subcontracted to the Automation and Robotics Research Institute (ARRI) at the University of Texas at Arlington to review and model the automated module assembly system in operation at the beginning of this PVMaT Program and to make recommendations for improving the equipment and/or process flow. ARRI prepared a process flow chart detailing all of the module assembly steps and used this information to model and analyze the manufacturing process. A number of minor improvements were recommended and implemented, increasing the production capacity by 40%[5].

ARRI used AT&T's discrete event simulation package called Witness to evaluate expansion scenarios. The Witness software provided an analysis of the capacity and resource requirements for the different scenarios. A new factory concept was developed that allowed for incremental increases to meet the shorter term capacity requirements and that could ultimately result in tripling of the module assembly capacity. The plan was based on replacing the back solder robots with XY positioners to increase the number of solder bonds made at one time from 2 to 4, thereby increasing the throughput by nearly a factor of two. This modification has now been implemented and the XY positioners are operating at the throughput level predicted, meeting all of the goals of this task[6].

With ARRI support, Solarex worked on improving the process and equipment in a number of assembly areas.

3.4.1 Trim/Lead Attach

ARRI designed, built and delivered a prototype work station for inspection, lead attach and testing without requiring operators to lift large modules. The prototype system consisted of a rotating table for trimming, a conveyor for lead attach, a flip station for large modules and a section for flash test and visual inspection. While the prototype unit had a number of problems, it served as a model for improvements to the manufacturing equipment, particularly in the trimming area.

3.4.2 Framing

ARRI recommended a number of changes to the framing robot system that would decrease the cycle time. They constructed a prototype of a framing feeder/dispenser system in which the frame pieces were fed off onto a fixture that pushes them under the butyl dispenser and then handed them off to the robot. This concept is designed to reduce the framing cycle time from 150 seconds to 80 seconds per module. Separation of the butyl dispensing process from the robot was a critical factor in a redesign of the Solarex framing system.

3.4.3 Tabbing

Volume requirements, process yields and size limitations led to a requirement for the design and procure of new tabbing equipment. Solarex worked with Ascor to develop the machine concept to automatically hot bar solder ribbons onto cells up to 15.2 cm by 15.2 cm in size. The Ascor machine was designed to unload from stacks, align the cell pattern, erase the AR coating, flux, deliver and solder the tabbing ribbon, and either stack the cells or feed a stringing machine.

Ascor built and delivered two machines to Solarex during the course of this effort. These machines have met their design specifications and are in use in production. Figure 12 is a photograph of one of the Ascor tabbing machines.

3.4.4 Matrix System

Volume and size limitations lead to a requirement for the design and procurement of a new matrix lay-up system. The system was designed to utilize a process similar to the present unit with upgrades to address known deficiencies. The new system was designed to handle larger cells (up to 15.2 cm by 15.2 cm) and matrices with more than 36 cells. The ARRI end-effector design discussed in Section 3.6 served as a guide to the large transfer mechanism in this unit. The unit was built and is being successfully utilized in production.

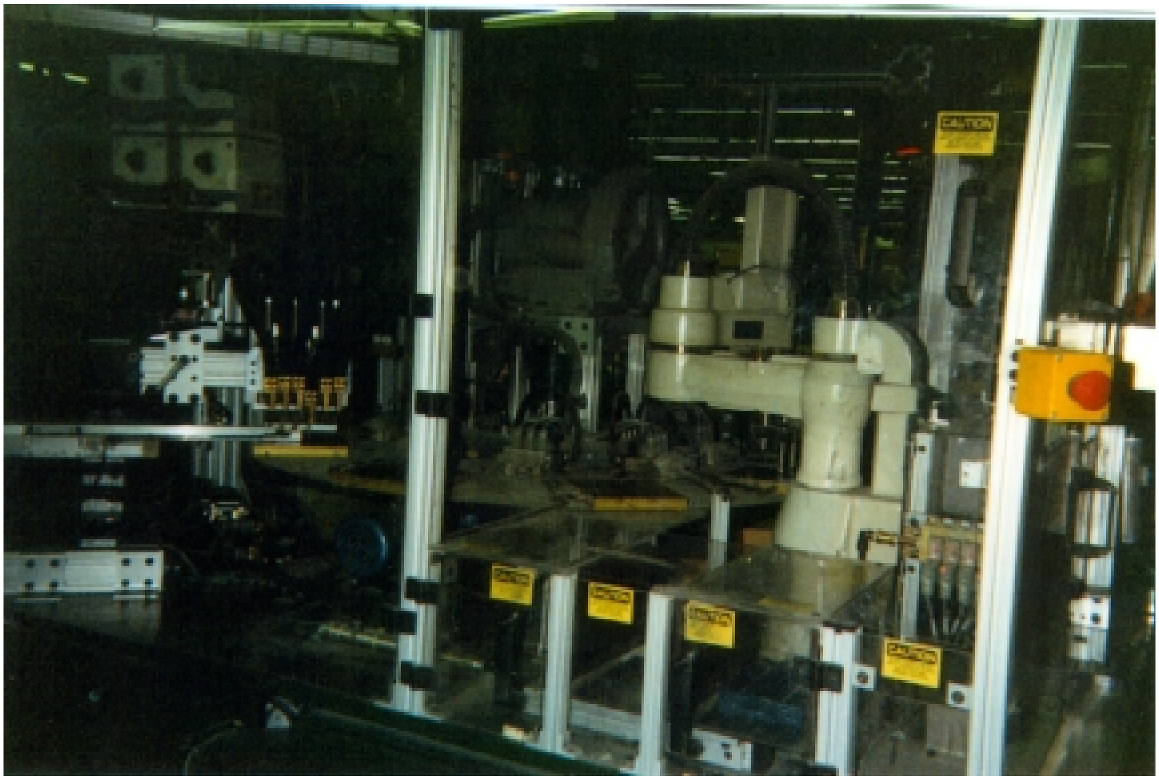
3.4.5 Stringer

Solarex has always assembled modules using a matrix system where tabbed cells are laid up in a matrix pattern before they are soldered together. The alternate approach is to use a stringer system, where a cluster tool makes a string of cells that is later laid up in the appropriate pattern. The advantages of a stringer system are:

- Reduced floor space requirements.
- Improved ability to handle different size cells.
- Improved flexibility to build different matrix lay-ups (for example 3 by 12 or 4 by 9).
- Ability to handle larger modules.

With ARRI's assistanc, a preliminary specification was written for a Stringer System. Several potential candidate vendors were reviewed. Solarex selected Ascor as the vendor because of our familiarity with their equipment and because their stringer will be designed to accept cells from the Ascor tabbing machines that Solarex has already purchased. Therefore the tabbers can feed either the older matrixing system or the new stringer system. The Ascor stringing system is due at Solarex in late 1998.

Figure 12
Ascor Tabbing Machine



3.5 FRAMELESS MODULE DEVELOPMENT

In this task Solarex was 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).

3.5.1 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 three part backsheet being used at Solarex at the start of this PVMaT Program.

During the first year of the program, three candidate materials were selected for evaluation[5]:

- Pigmented chlorinated polyethylene (CPE)
- Affinity™ polyolefin
- Thin Tedlar – (polyvinyl fluoride)

Each of these materials successfully completed environmental qualification testing to IEC 1215 and IEEE 1262 and successfully passed in-house simulated UL fire tests. Each material was then exposed directly to an equivalent of 2 years UV in Phoenix, AZ. All of the materials except for the CPE exhibited no degradation after the UV exposure. The CPE samples turned a dark black color with evidence of leaching of green pigment from the samples exposed to UV. Based on these results, CPE was dropped as a candidate back sheet material. White pigmented polyolefin was utilized as a backsheet in the standard EVA lamination process. After lamination all of the samples had numerous pin holes through the back sheet. It appears that the polyolefin gets too soft at the lamination temperature and is easily punctured by any irregularities that occur behind the cells.

We were then left with only single sheet thin Tedlar as a candidate material. Tedlar does meet all of the technical requirements of a back sheet and Solarex has been using a single layer Tedlar backsheet now for several years. Tedlar will not meet the $0.05/square foot cost goal of this PVMaT program. However, it does represent at least a 70% reduction in back sheet cost over the three part material that Solarex was using at the beginning of this PVMaT program.

3.5.2 Electrical Termination

For electric termination, we needed a system that has low material cost, but also does not require appreciable labor for field assembly. Junction boxes and weather tight quick connects, that would meet the environmental requirements, were not available in the price range of interest. Pig tail wires with a butt crimp connector and shrink tubing were selected for electrical termination of the modules[6]. These connectors have successfully passed all of the environmental testing requirements of IEC-1215 and IEEE-1262 without measurable change in internal contact resistance or leakage current during wet hi-pot testing at 2750 volts. This electrical termination system meets the technical requirements and the cost goals of the program.

3.5.3 Mounting System

Since PVMaT is designed for large systems, the modules were designed to mount directly onto the support structure without integral frames. The first step was the design of a compatible support structure and the identification of 3M Very High Bond Tape for mounting the modules to the structure. This system was used on several large arrays, but major problems were encountered relative to the use of the tape. The problems appear to be related to incorrect application and to the mounting of modules in such a way that there is a continual pressure/torque between the tape and the beams. The failure mode is separation of the module from the beam. While correct assembly may alleviate this problem, it is likely that actual systems will not be assembled by well trained personnel. Therefore, the main adhesive was switched from tape to RTV silicone. The modules are panelized several days before installation, so the RTV can cure. This method has now been used successfully on several systems and it does meet the overall goal of this task.

Overall there is still an issue as to whether frameless module systems are reliable and cost effective. During system construction there has been greater breakage for the frameless arrays than for standard framed modules. Several frameless systems have experienced increased module breakage and problems with backsheet delamination. A module edge seal may solve these problems, but also may increase the cost to almost the same level as use of a standard frame. More analysis and data is required before a firm decision can be made concerning frameless modules.

3.6 AUTOMATED THIN CELL HANDLING

In this task Solarex was to develop automated handling equipment for 200 µm thick 15 cm x 15 cm polycrystalline silicon wafers and cells that has high yield (less than 0.1% breakage per process handling step) and can handle at least 12 cells per minute. ARRI is also supporting Solarex in this task.

3.6.1 Wafer Fracture Testing

ARRI began this effort by studying the strength and fracture behavior of Solarex cast polycrystalline wafers. A four point bend test and a cantilever test were devised and used to measure the mechanical strength of the wafers. The scatter in measured strengths was modeled using Weibull statistics, and a distribution of the probability of failure as a function of strength was determined. The ultimate strength in bending for the standard thickness polycrystalline wafers was found to be 119.3 MPa. In addition, the Young's modulus was found to be 168.8 GPa and the Weibull modulus was calculated to be 9.56[6].

3.6.2 Simulation of Wafer Handling

A finite element model was then developed to determine the distribution of stress and deflection in a wafer based on the applied load. This model along with the Weibull modulus can be used to determine the probability of breakage of the wafer under the specified load. The model was used to simulate a typical wafer handling situation, to estimate the maximum load that can be applied during handling and the corresponding probability of failure.

3.6.3 Handling Equipment

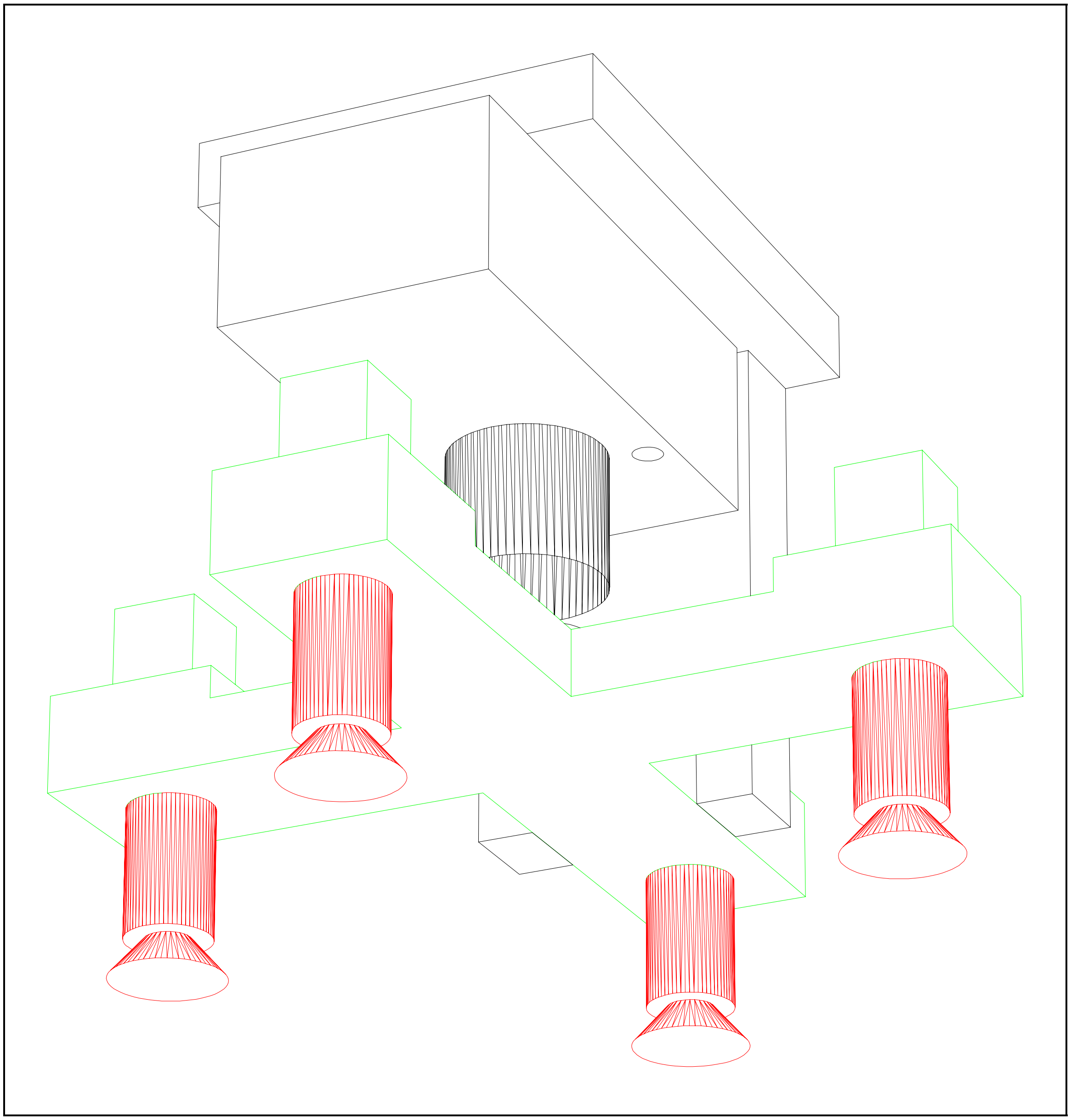
ARRI undertook a study of commercial and academic information sources related to the handling of silicon wafers. The purpose of this literature search was to gain an understanding of the wafer handling methods that are commercially available, or that are documented in the open research literature, in order to assist in design of a wafer end-effector.

Most information about wafer handling has appeared in the context of semiconductor manufacturing. Semiconductor manufacturing is extremely sensitive to contamination (Class 1 environment capability is normal), making vacuum grippers a preferred solution over other kinds of holding devices. The gripper jaws are allowed to come in full contact with the "back" face of the wafer, which is simply a featureless substrate. Non-vacuum methods involve arms that "push" the wafers in and out of their slot in the cassette, and are typically used in transfer and inspection operations. Such arms come in contact with both sides of the wafer in a small ring-shaped section in the periphery of the wafer.

The typical gripper design in semiconductor wafer sorting and transfer machines consists of flat prongs with embedded vacuum ports flush with the surface or slightly below it. This provides a greater surface-to-surface contact between the gripper and the wafer than using vacuum cups alone, which likely helps to restrict movement of the wafer during transport and minimizes breakage due to bending of the wafer. Vacuum sensors are used to detect that the wafer is latched onto the jaws.

Based on the results of this study, ARRI has developed a wafer pick-up end-effector. The objective of this device is to provide a safe, fast and reliable mechanism to acquire and release wafers to and from various horizontal surfaces. This mechanism may be attached to a standard robot arm or to a Cartesian manipulator. The design is shown in Figure 13 below. This design provides a compact design, four point compliance, minimum force on the cell during each pick up and limit switches for eliminating cell breakage. A prototype of this design was assembled test. Solarex then used the prototype to design and build a production system for the assembly area that picks up all of the cells in a matrix and places the matrix in position on top of an EVA/glass package.

Figure 13
Prototype End Effector



4.0 SUMMARY

The Cast Polycrystalline Silicon Photovoltaic Module Manufacturing Technology Improvement Program has lead to the development of and/or improvements in processes, products and equipment. The following developments from this program have been implemented in manufacturing:

- Casting of larger ingots;
- Use of wire saws in operations;
- Addition of a back surface field to the cell process;
- Implementation of a fully automated screen printing system;
- Introduction of a larger cell (11.4 cm by 15.2 cm) into commercial production;
- Upgrade of the module assembly equipment;
- Use of a lower cost back sheet;
- Qualification of a lower cost electrical termination system; and
- Use of frameless modules in a number of PV systems.

During the course of this PVMaT program:

- The production volume at Solarex has tripled;
- The cost to manufacture a framed power module has been reduced by 20%; and
- The cost to manufacture the lowest cost module has been reduced by 40%.

These cost reductions occurred while the cost of silicon feedstock increased and while the factory was running at full capacity to meet increased demand. Without this PVMaT program it is likely that the consumer's cost for PV modules would have increased instead of decreasing and that less production capacity would now be in place.

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13. ABSTRACT *(Maximum 200 words)*

This report summarizes work performed by Solarex, A Business Unit of Amoco/Enron Solar, under this subcontract. Among the accomplishments during the program are the following:

- Converting all of the production casting stations to increase ingot size, operating them at equivalent yields and cell efficiencies, and thus doubling the casting capacity at a 20% lower cost than the cost of new equipment.
- Developing a wire-saw process and transferring the process to production; as a result, more than 80% of wafering is now done using wire saws, at higher yields and lower costs than achieved on the internal diameter saws.
- Developing an aluminum paste back-surface field (BSF) process to increase cell efficiency by 5%; researchers also designed, procured, and transferred to manufacturing a fully automated printing system to produce the BSF cells.
- Fabricating 15.2-cm by 15.2-cm polycrystalline silicon solar cells and building modules using these cells.
- Modifying the module assembly area to increase capacity by a factor of three.
- Implementing a single-layer Tedlar backsheet that reduced backsheet cost by \$0.50/ft^2.
- Selecting, testing, and qualifying a low-cost (< \$1.00 per module) electrical termination system.
- Qualifying the structure and adhesive system for mounting frameless modules and using the system to build several large arrays.

14. SUBJECT TERMS
photovoltaics ; polycrystalline silicon ; casting ; wire saws ; cell process ; module assembly ; frameless module development ; automated cell handling

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