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Cast Polycrystalline Silicon Photovoltaic Module Manufacturing Technology Improvements

Annual Subcontract Report 1 January 1996 - 31 December 1996

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PREFACE

This Annual Technical Progress Report covers the work performed by Solarex for the period January 1, 1996 to December 31, 1996 under DOE/NREL Subcontract # ZAI-4-11294-01 entitled "Cast Polycrystalline Silicon Photovoltaic Module Manufacturing Technology Improvements". This is the third Annual Technical Report for this subcontract. The subcontract is scheduled to run from December 8, 1993 to September 7, 1997(.

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EXECUTIVE SUMMARY

The objective of this 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 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 now 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 today on the 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 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 working 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 can be 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 is also assisting Solarex on this task.

ACCOMPLISHMENTS

Accomplishments during the reporting period include:

- Converted 70% of 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.
- Operated the wire saws in a production mode with higher yields and lower costs than achieved on the ID saws.
- Purchased additional wire saws.
- Developed and qualified a new wire guide coating material that doubles the wire guide lifetime and produces significantly less scatter in wafer thickness.
- Al paste back surface field process being run on 25% of all cells in manufacturing.
- Environmental qualification of modules using cells produced by an all print metallization process.
- Qualified a vendor supplied Tedlar/EVA laminate to replace the combination of separate sheets of EVA and Tedlar backsheet.
- Substituted RTV adhesive for the VHB tape after several field problems with the tape.
- Demonstrated the operation of a prototype unit to trim/lead attach/test modules.
- Demonstrated the use of light soldering for solar cells.
- Demonstrated the operation of a wafer pull down system for cassetting wet wafers.
- Presented three PVMaT related papers at the 25th IEEE Photovoltaic Specialist Conference.

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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 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. Task 12 involved making the modifications in equipment and process necessary to cast larger ingots. This effort has lead to an increase in the production capacity of Solarex's casting stations and has reduced the labor content.

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 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%. 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 16 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 was the ability to reduce the variable cost to cut a wafer. This has been successfully demonstrated. Efforts under task 13 involve continued wire saw cost reductions and automation of the wafer clean-up process.

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 under investigation during the third year include:

- Back Surface Field (BSF) Formation
- Selective emitter
- Emitter oxide passivation
- Chemical texturing

The goal of the Task 14 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/m^2, AM1.5, 25° C). This must be 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 Task 4 the 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) at the University of Texas at Arlington served as a subcontractor. ARRI has assisted Solarex in analysis, modeling and development of handling concepts to improve the operation of the module assembly area. In Task 9 the assembly area was modified as modeled, leading to a doubling in assembly capacity. Task 15 efforts involve further modifications to module assembly that will again double the manufacturing capacity of this 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 was achieved during Task 5 without negatively impacting the module reliability.

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 significantly reduce the module selling price. During Task 10, 3M VHB tape was used to attach frameless modules to the mounting structures on several large scale PV systems. Problems at these sites lead us to substitute an RTV adhesive for the tape in subsequent systems.

The junction box also adds appreciable cost to the module, while requiring additional labor for system assembly. In Task 10, a simpler electrical termination scheme costing less than $1.00 per module was tested and qualified for use.

Task 5 also included the design of a nominal 122 watt module using 36- 15.2 cm by 15.2 cm solar cells. Task 15 includes qualification of the design through accelerated environmental and

safety tests (IEC-1215, UL 1703, and IEEE-1262) 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. Tasks 11 and 17 are addressing this issue. Once again, Solarex is supported in this effort by ARRI, whose background and experience are ideally matched to the task of developing handling methods for parts like the large thin wafers to be used in this program. ARRI has perform detailed analysis and modeling of the requirements for thin wafer handling. Prototype wafer handling stations have been built and tested. Design of production units is now underway.

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.

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

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 1. 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 1
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 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 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 3 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 1996.

3.1 TASK 12 - 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. Modifications were necessary to the chamber so it would hold more silicon, and to the heaters and insulation. During the first two years of the program, 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 9 x 11.4 cm by 11.4 cm bricks. Such an ingot requires approximately 20% more silicon than the PVMaT ingot. The initial efforts to cast these "mongo" ingots required changes in the insulation and receiver, but utilized the same pour crucible as the PVMaT ingot.

Recent laboratory efforts have involved the optimization of the casting process for these larger ingots. Several iterations of heater and insulation design have been guided by experimental results from brick lifetime measurements and cell results. 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 the casting capacity could be doubled. 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. Based on these results, Solarex has modified approximately 70% of the production casting stations to the larger configuration. The remaining casting stations will be converted during 1997.

It is important to carefully monitor the performance of this new process to assure that it is running as well as the old process. Figure 3 shows the difference in weight yield between the large ingots and standard ingots as a function of date. While there is significant scatter of the daily values, the 7 day rolling average plotted as the solid curve never deviates more than 2%. The average difference for all of 1996 is 0.01%, with the larger ingots having slightly higher weight yield. Figure 4 is a plot of the difference in average cell efficiency for all cells produced from the large ingots minus the average cell efficiency for all cells produced from standard ingots on a daily basis. The average difference for all of 1996 is 0.04 %, with the larger ingots having a slightly higher average cell efficiency.

Figure 1
Comparison of Large (Mongo) and Standard (Mega) Ingots

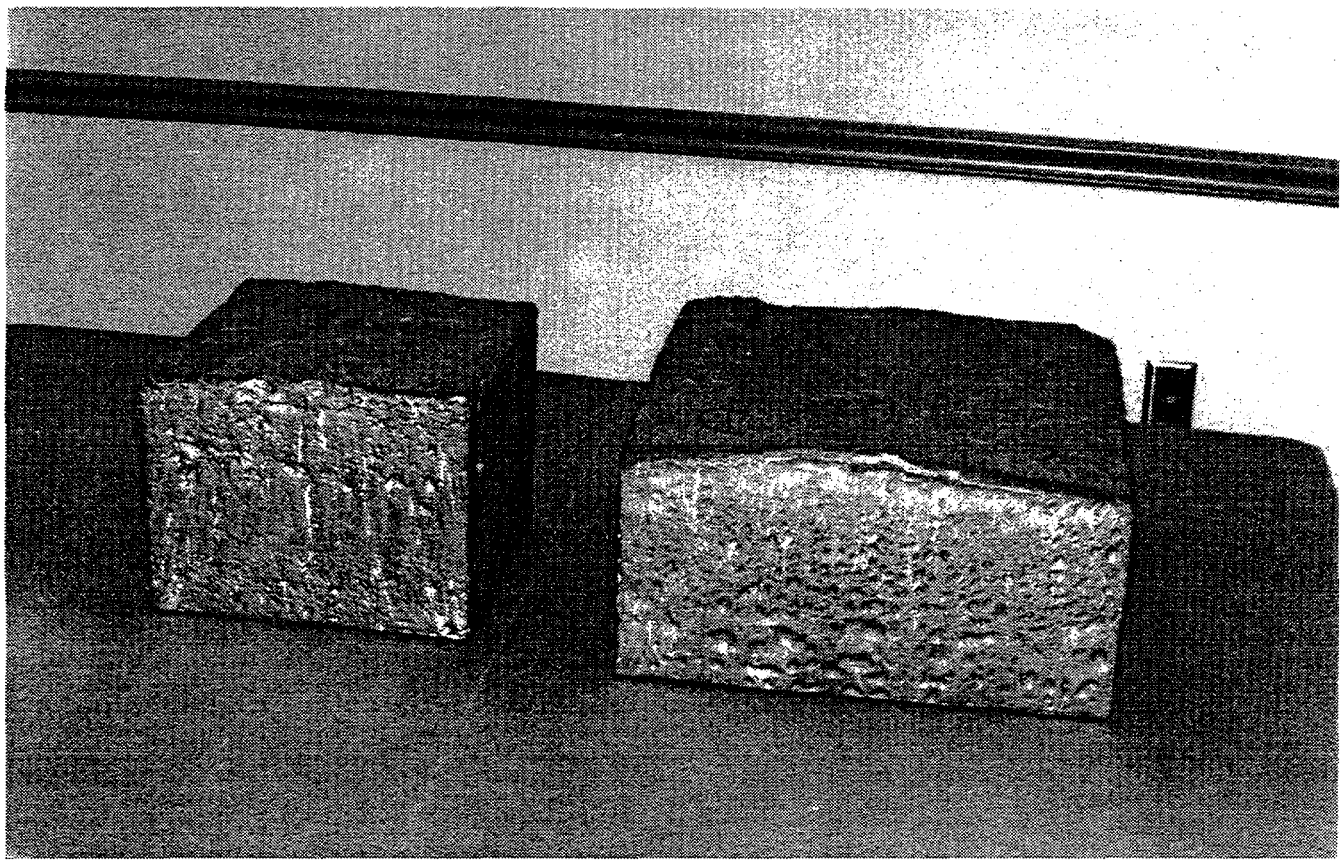


Figure 2
Large (Mongo) Ingot Sized into 9 Bricks

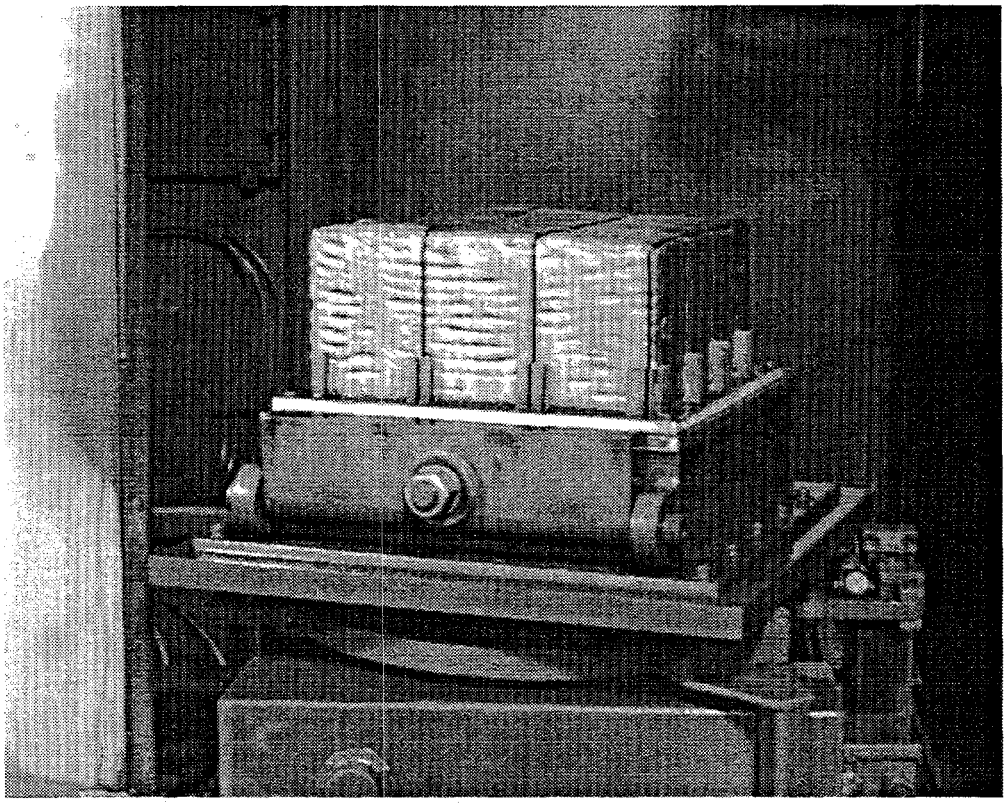


Figure 3

Difference in Weight Yield Between Large Cast Ingots and Standard Cast Ingots

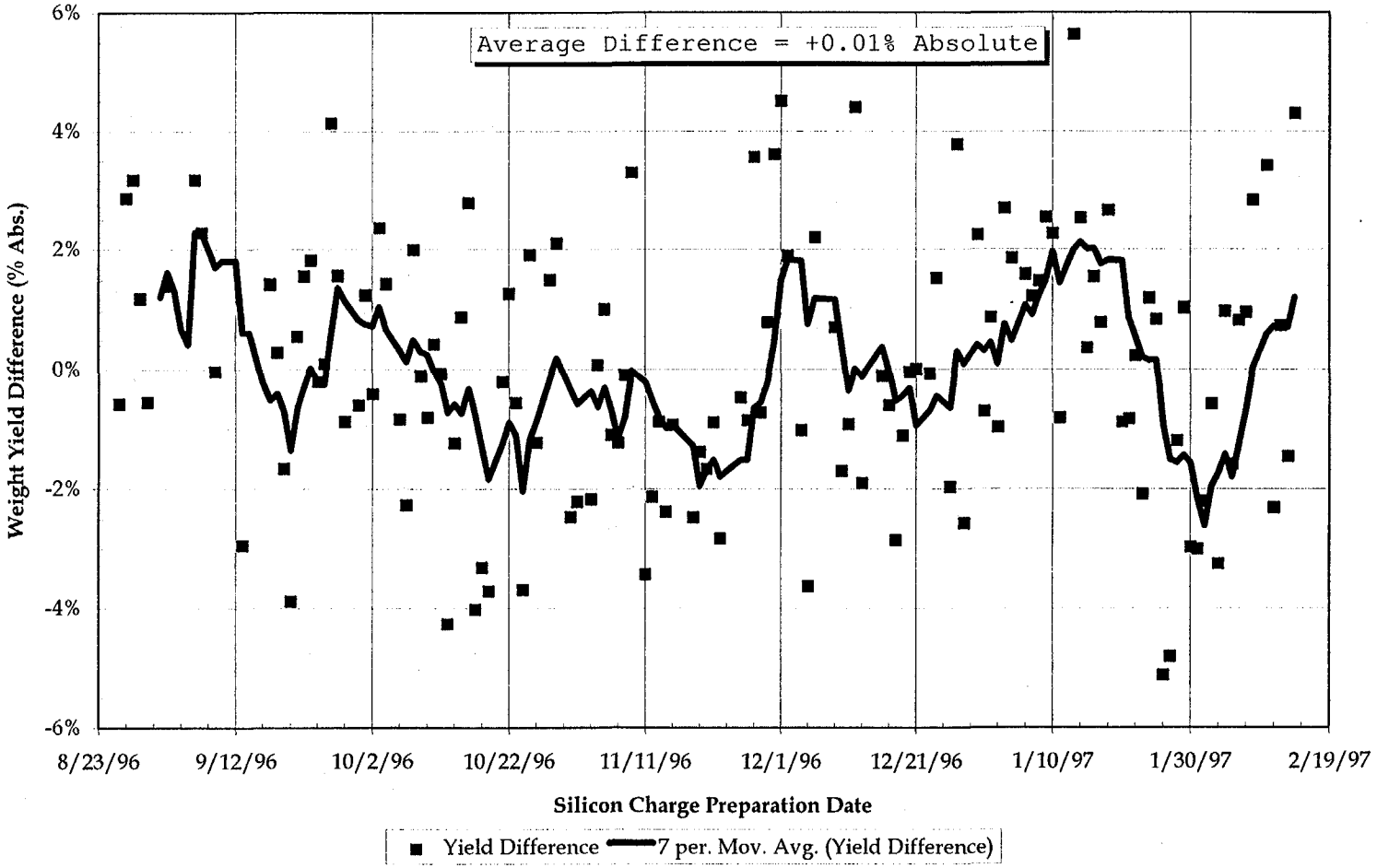
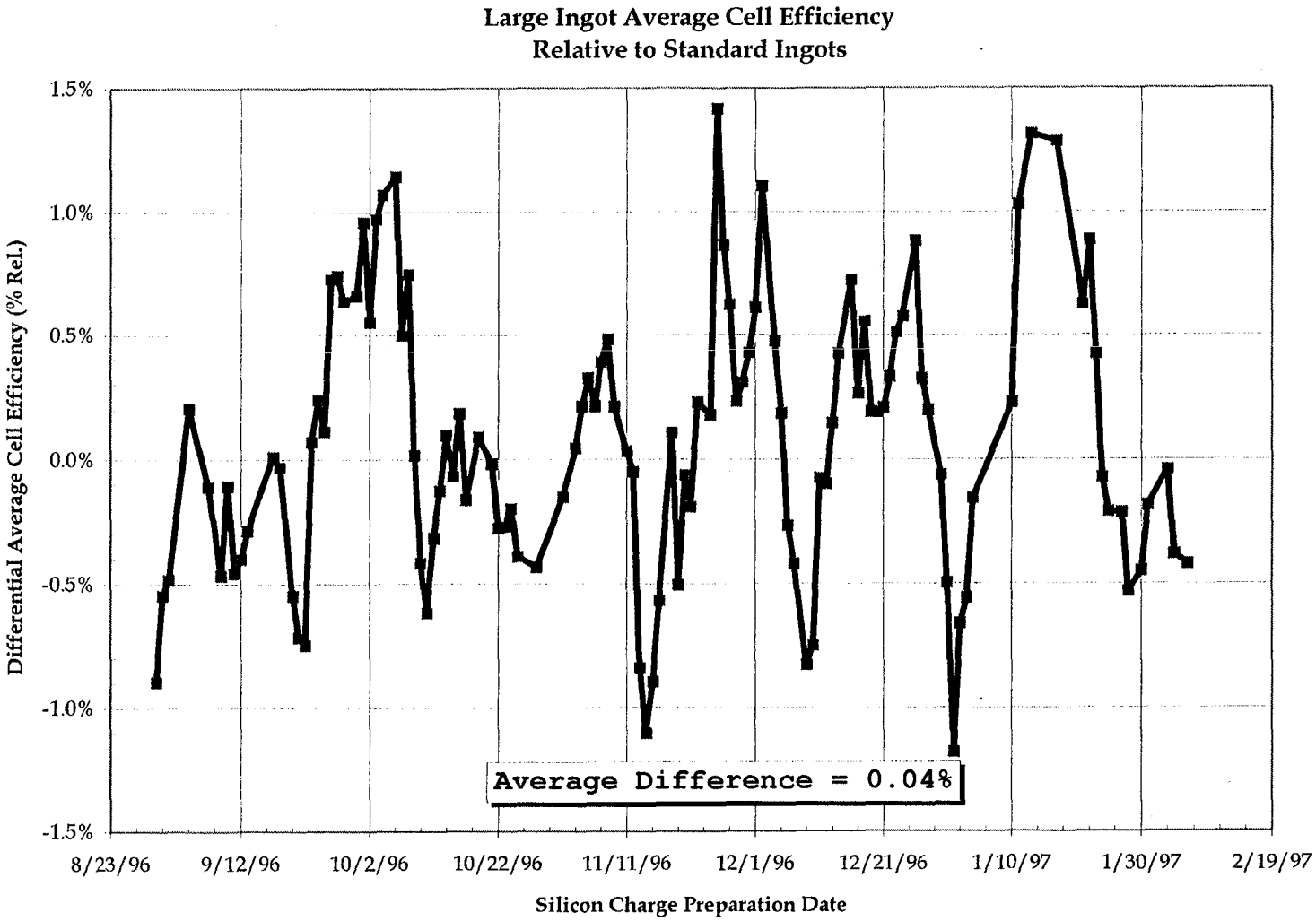


Figure 4


Large Ingot Average Cell Efficiency
Relative to Standard Ingots
Differential Average Cell Efficiency (% Rel.)
1.5%
1.0%
0.5%
0.0%
-0.5%
-1.0%
-1.5%
Average Difference = 0.04%
8/23/96
9/12/96
10/2/96
10/22/96
11/11/96
12/1/96
12/21/96
1/10/97
1/30/97
2/19/97
Silicon Charge Preparation Date

3.2 TASK 13 - WIRE SAW IMPROVEMENTS

The goal of this 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 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.

3.2.1 Wire Saw Operations

Solarex is utilizing an HCT wire saw in this program. Figures 5 shows the whole saw. Figure 6 shows the wire guides and wire web. The saw has successfully demonstrated the ability to cut a variety of wafer sizes including 11.4 cm by 11.4 cm, 11.4 cm by 15.2 cm and 15.2 cm by 15.2 cm on centers from 500 μm down to 400 μm. The saw has been operated in a production mode, producing as many wafers as 16 ID saws at better yields and lower per wafer cost than the ID saws. This saw has been so successful that Solarex has procured additional HCT wire saws.

The major efforts during the third year were to:

- Purchase additional wire saws, install them, make them operational and operate them in production.
- Reduce the center to center spacing of the wire guide grooves from 500 μm to 475 μm.
- Development of 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.
- Establishment of preventive maintenance procedures.

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. Today this process is done manually. 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.

ARRI developed prototype equipment to destack wafers into cassettes that could be utilized on wet or semi-wet wafers. 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 index to accept the next wafer. This concept has the following advantages:

- It requires a single indexing slide rather than say a robotic pick and place.
- It requires relatively simple equipment.
- It is a rapid process with a low cycle time.
- It is highly energy efficient since it uses gravity to place the wafer into the cassette.

A prototype wafer pull down system has been built and tested. This concept worked very well for both dry and wet wafers. The prototype has operated through thousands of cycles without breaking any wafers and with successful feeding of a single wafer more than 99.95% of the time. Efforts are now underway to design and build a production unit based on this prototype design.

The balance of the cleaning process requires processing of cassettes of wafers through a number of baths, rinses and finally a drying step. An automatic wafer cleaning system has been designed and ordered. It will be installed in early 1997.

Figure 5
HCT Wire Saw

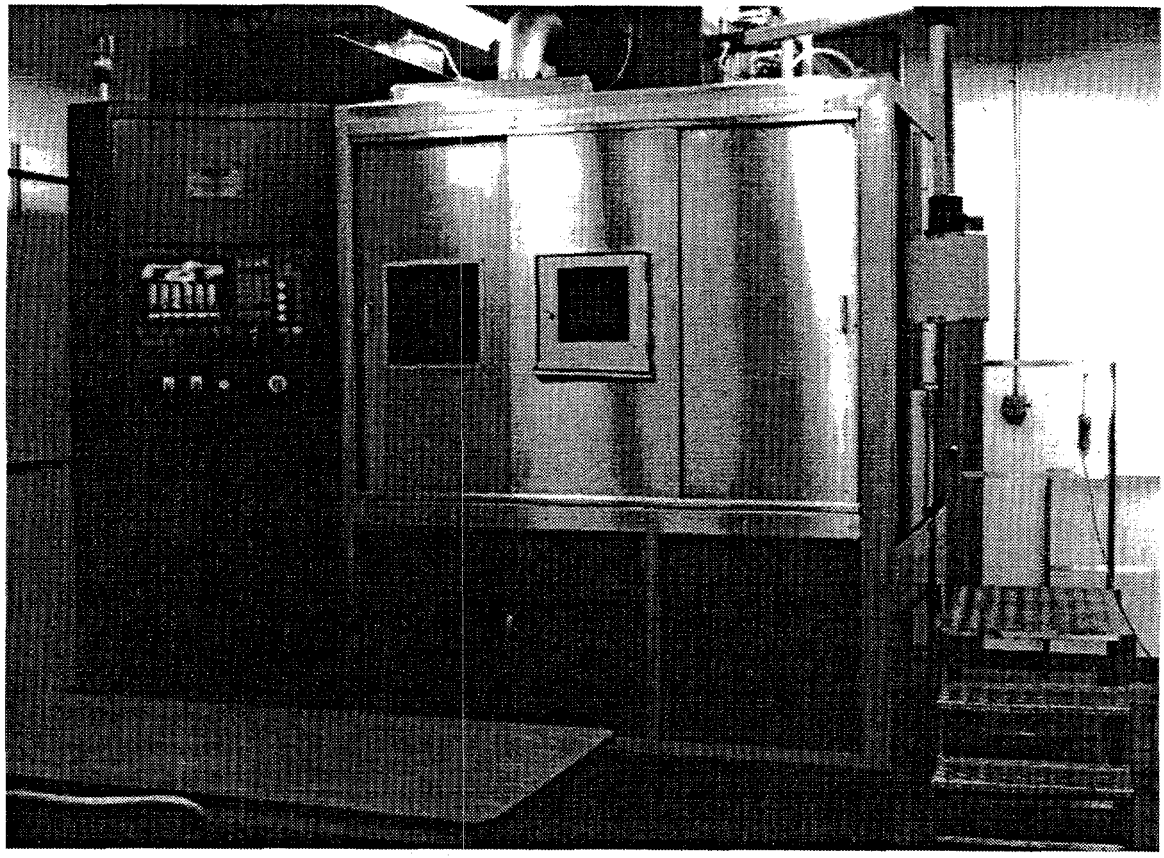
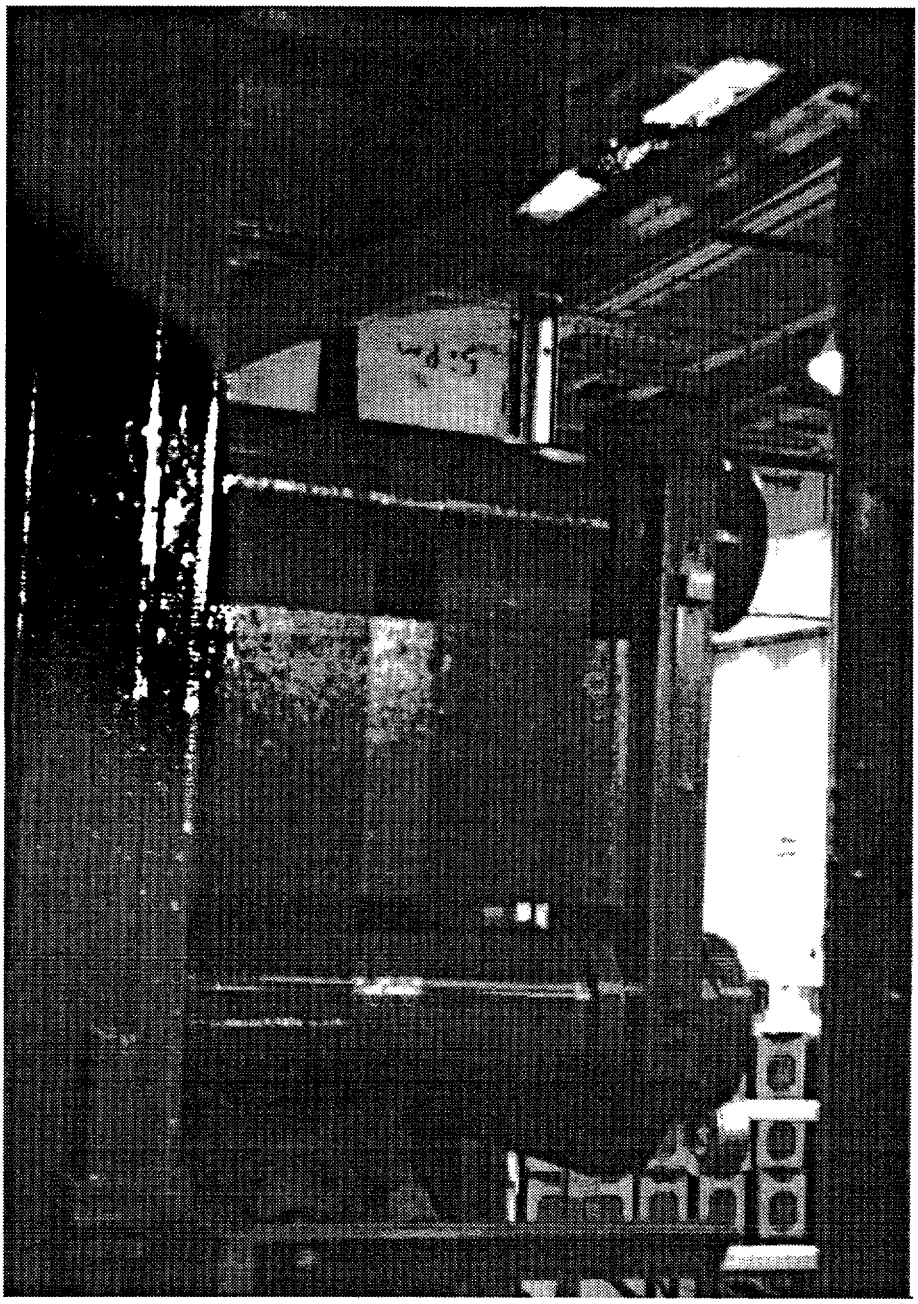


Figure 6
Wire and Wire Guides



3.3 TASK 14 - 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 period cover by this report, the major cell task efforts were in the areas of back surface fields (BSF), selective emitter, oxide passivation and chemical texturing. Each of these areas is discussed below:

3.3.1 Back Surface Field Formation

In the first Annual Report[5] of this program, we reported that an aluminum paste back surface field (BSF) could be used to cost effectively increase cell efficiency by approximately 5%. In the second Annual Report[6] of the program we reported on manufacturing trials, environmental qualification of cells made with the Al paste in a module package, evaluation of the impact of cell thickness and development of an all screen printed process. Efforts during this reporting period included:

- Development and environmental qualification of an all print metallization system.
- Set-up and operation of a prototype production system (auto-printer and belt furnace) for producing a significant quantity of BSF cells on a continuous basis.

The initial back surface field work utilized Solarex's standard back spray process on top of the fired aluminum paste. This is not the most cost effective sequence, since both back spray and the BSF process provide enough back conductivity to produce high efficiency cells. Therefore we began work on a process to replace backspray with a screen printed Ag-Al paste grid. Table 2 shows the comparison of using either back spray or back print over the Al paste BSF back. These cells were measured in the standard fashion with the back on a metallic test block. While both processes yield good cells, the back spray cells do have a better fill factor. The configuration with Ag beneath the Al is the preferred approach in terms of ease of manufacturing and has slightly higher cell efficiency, so this approach has been selected for further development.

Table 2
Backspray versus Back Print over BSF

	Efficiency (%)	Jsc (mA/cm^2)	Voc (mV)	FF (%)
Backspray	13.2	31.1	582.6	73.1
Back Print (1)	13.11	31.0	581.8	72.6
Back Print (2)	13.03	31.0	582.0	72.1

Configuration 1 had the Ag beneath the Al
Configuration 2 had the Ag on top of the Al

To better understand the performance of these cells, the cells were remeasured using back probes where solder bonds would normally go rather than a test block. The change in measured

performance is shown in Table 3. This back print pattern does not provide as much conductive path as the back spray process.

Table 3
Change in Performance with Probes versus Test Block

	Change in Efficiency (%)	Change in Jsc (%)	Change in Voc (%)	Change in FF (%)
Back Spray	0.1	-0.1	-0.3	0.5
Back Print (1)	-2.1	0	-0.4	-1.7
Back Print (2)	-2.3	-0.1	-0.5	-1.7

To convince ourselves that the reduced fill factor for the all print system was real, we fabricated cells via the two processes and then matched the best 36 cells. Table 4 shows the cell results, while Table 5 shows the module results. The difference in cell fill factor translates directly into a difference in module fill factor.

Table 4
Cells from Backspray versus Back Print Trial

	Efficiency (%)	Jsc (mA/cm^2)	Voc (mV)	FF (%)
Back Spray	13.65	31.0	584.4	75.3
Back Print	13.51	31.1	584.4	74.4
Difference (%)	-1.0	0.1	0	-1.1

Table 5
Modules from Backspray versus Back Print Trial

	Efficiency (%)	Jsc (mA/cm^2)	Voc (V)	FF (%)
Back Spray	14.22	32.19	21.3	74.5
Back Print	14.01	32.22	21.3	73.5
Difference (%)	-1.5	0.1	0	-1.5

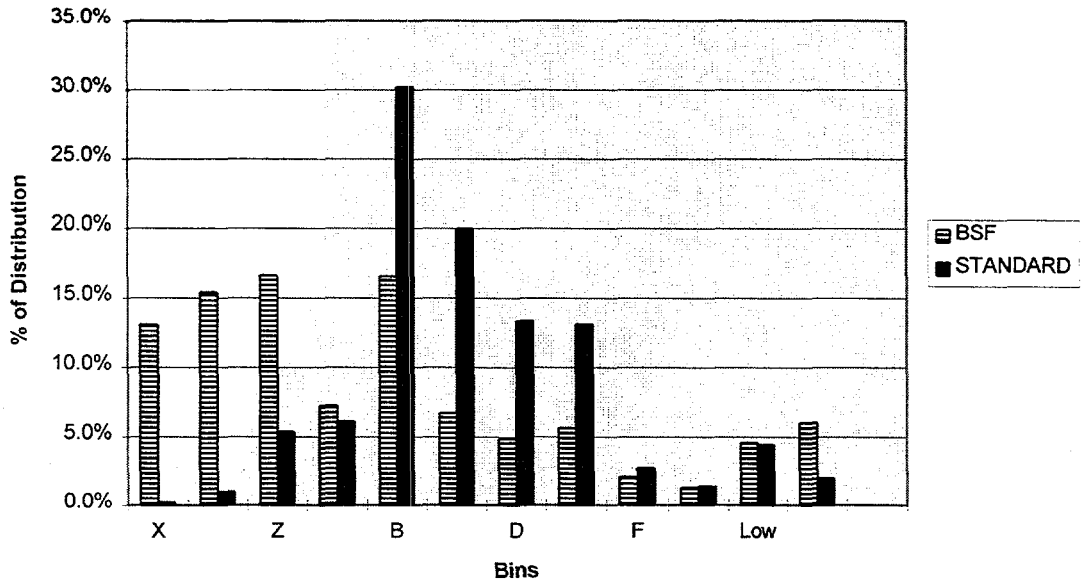
Analysis of the fill factor loss shows that it is the thick sprayed metal parallel to the direction of current flow (and the interconnect ribbons) that is responsible for the better fill factor of the sprayed cells. The print system will now be modified to increase the conductivity in that direction.

Modules made with the all print metallization system were subjected to environmental qualification testing per IEC-1215 and IEEE-1262 with the addition of a second 200 thermal cycles as required for Solarex's 20 year warranty. The BSF modules successfully completed the testing with all power losses well below the maximum allowable by IEC-1215 and IEEE-1262 with no measurable differences between the BSF and standard cell modules subjected to qualification at the same time.

The BSF process has now been transferred to manufacturing for use on a significant percentage of all cells produced. This temporary unit will be operated until the fully automated print system, that is on order, is delivered and made operational. Figure 7 shows the distribution of cell efficiencies for both the BSF and non-BSF cells produced over the last six months of 1996. The X-bin is the highest efficiency, with G being the lowest. The BSF process yielded a 4.5% increase in cell efficiency due to a 5.1% increase in short circuit current and a 1% increase in open circuit voltage. However, the fill factor decreased by 1.6%. Much of the fill factor loss is due to higher series resistance. Our trials indicated that the highest BSF cell efficiency requires a faster belt speed than the standard product. Once the entire line is switched to BSF the front fire furnace can run at a higher belt speed.

The other area of concern from the BSF trials has been the higher than normal incidence of shunting. We believe that this is at least in part due to contamination of the print nest by the Al paste. A nest contamination sensor system is now under development. It will be utilized in the automated printing system to indicate when the nest has to be cleaned.

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



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. This approach has been evaluated at Solarex in the past using masking and etch back techniques to produce the shallower junction in the emitter field. Cost analysis indicated that this process is 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. We have been working with Ferro Corporation to develop such a screen printable paste. Once Ferro had developed a candidate

material, the first step was to verify its performance as a full field diffusion source. The results of this experiment are shown in Table 6. While not quite as good as our standard process, the dopant paste worked reasonably well. We would expect that optimization of the other process steps to the dopant paste would likely improve the performance for those cells.

Table 6
Full Field Diffusion of Dopant Paste

Sample	Efficiency (%)	Jsc (mA/cm^2)	Voc (mV)	FF (%)
Control	13.1	29.5	590	75.2
Dopant Paste	12.8	29.4	588	74.2

The second step in development of the process was to determine the impact of performing the two diffusions on the same sample, particularly in terms of the order in which the two diffusions are performed. The experiment is summarized in Table 7. From this experiment we concluded that the grid followed by emitter scenario could work with dopant paste used for the grid diffusion, then followed by a light emitter doper diffusion. However, the process in which the emitter diffusion is followed by a deeper grid diffusion will not work, since the second diffusion is at a higher temperature than the first and, therefore, lowers the sheet resistivity of the emitter.

Table 7
Selective Emitter Sequence Experiment

First Process	Second Process	Second Profile Ω/square	Resultant Sheet Resistance Ω/square
50 Ω/square Dopant Paste	Standard dopant	120 Ω/square	60 Ω/square
50 Ω/square Dopant Paste	No dopant Fired only	120 Ω/square	52 Ω/square
120 Ω/square Standard Dopant	Dopant Paste	30 Ω/square	28 Ω/square
120 Ω/square Standard Dopant	No dopant Fired only	30 Ω/square	30 Ω/square

Screens were then designed to print dopant paste in the same locations that the screen printed Ag front metallization will be printed. Table 8 compares a control group with the best selective emitter group. The selective emitter process gave a 2% improvement in cell efficiency, with small improvements in current, voltage and fill factor.

Table 8
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

Since the AL paste BSF process is being implemented for all production, an experiment was run to evaluate the effect of combining selective emitter and BSF. The results are shown in Table 9.

The selective emitter yielded a similar improvement over the controls. The combination did not result in as much improvement as we expected due to a lower fill factor. At this time we believe that the fill factor can be improved by optimizing the front firing profile to the BSF/selective emitter structure.

Table 9
Selective Emitter and BSF Trail

Emitter	BSF	Efficiency (%)	Jsc (mA/cm^2)	Voc (mV)	FF (%)
Control	No	12.50	28.8	583	74.4
Selective	No	12.69	29.1	585	74.7
Selective	Yes	13.05	30.4	592	72.6

3.3.3 IMEC Processing

A set of experiments have been inititated in collaboration with the Interuniversity Micro Electronics Center (IMEC) in Belgium. IMEC has reported on incorporation of surface passivation, BSF and a selective emitter into high efficiency solar cell processing[7]. The goals of the first experiment were to determine how well their cell process would work on fairly large area (10 cm by 10 cm) Solarex cast polycrystalline silicon wafers and to evaluate the effects of the selective emitter and the oxide passivation steps. The results are shown in Table 10. All of the cells have screen printed Ag contacts, BSF and TiO_2 AR coatings. IMEC achieved a 5% increase in cell efficiency with the selective emitter and another 2% increase in efficiency with oxide passivation of the emitter. These results indicate that the selective emitter process can achieve significantly better performance than we have been able to demonstrate so far.

Table 10
IMEC Selective Emitter and Oxide Passivation Experiment

Emitter	Oxide Passivation	Efficiency (%)	Jsc (mA/cm^2)	Voc (mV)	FF (%)
Control	No	13.26	29.83	590	75.3
Selective	Yes	14.27	31.82	592	75.7
Selective	No	13.97	31.79	588	74.7

3.3.4 Chemical Texturing

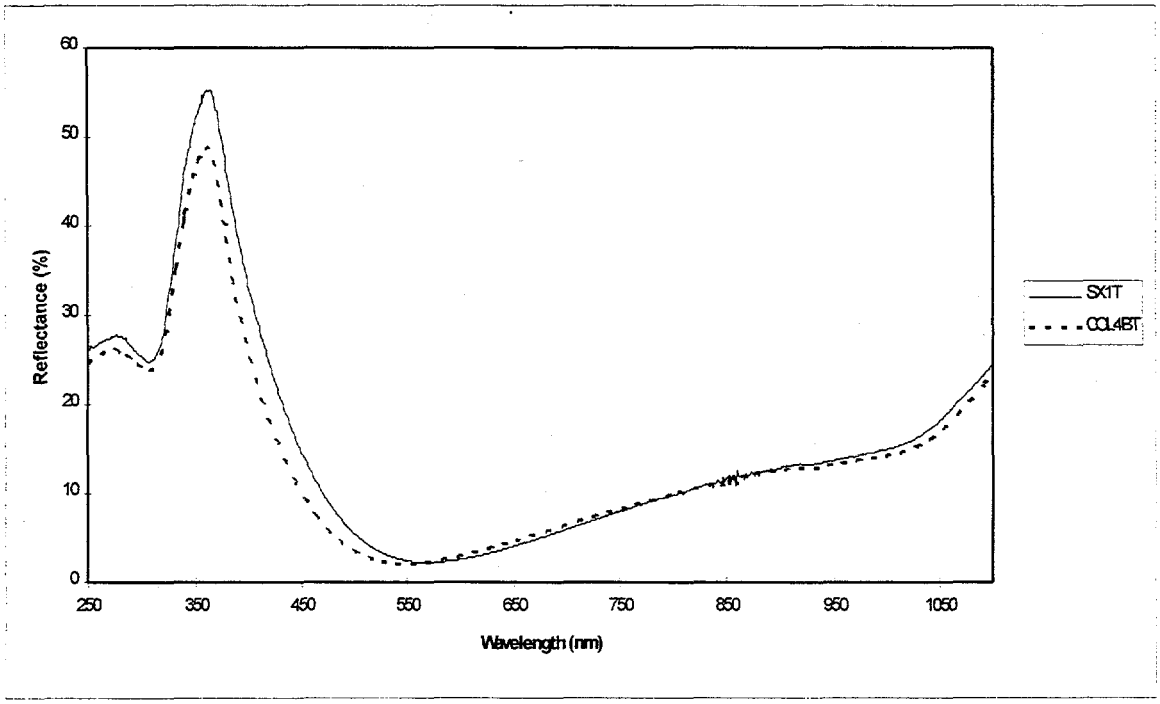
Recent reports in the literature claim that chemical texturing of polycrystalline silicon can be effective at reducing reflection and therefore increasing cell efficiencies[8]. Colorado School of Mines is assisting Solarex in taking a new look at chemical texturing of polycrystalline silicon. For the CSM study the KOH system was selected for study. Based on observations via microscope of texture formation, the following conclusions were made:

- 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.

A series of etched samples has been prepared and shipped to Solarex for reflectance measurements. The reflectance as a function of wavelength was measured on the bare samples and on the samples after coating with a TiO_2 AR. In Figure 8 the best textured sample is compared with a standard NaOH sample (both measured with a TiO_2 AR coating). The texturing process has reduced the reflectance. These samples will now be encapsulated behind glass and EVA and remeasured a final time. The encapsulated reflectance will be used along with the typical internal spectral response of our polycrystalline cells to predict how much current increase each of the texturing procedures will yield.

Figure 8
Reflectance of Chemically Textured and Planar AR Coated Samples



SX1T is a standard NaOH etched sample.
COL4BT was the best chemically textured sample from Colorado School of Mines

3.4 TASK 15 - 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%. 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.

During the first year of the contract ARRI modeled and analyzed the manufacturing process. As a short term goal they identified changes necessary to increase module assembly production capacity by 40% to meet Solarex's short term business plan. These changes were successfully implemented during that year[5].

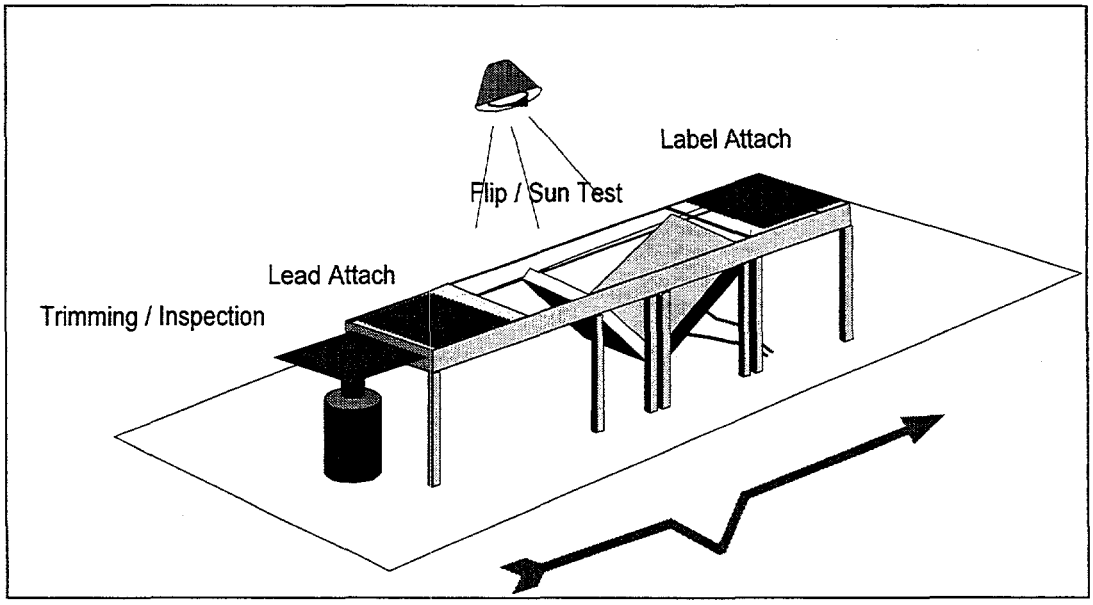
The second phase of the program Solarex and ARRI developed a new factory concept that would allow for incremental increases to meet the shorter term capacity requirements and would ultimately result in achieving Solarex's announced goal of tripling the module assembly capacity. The plan was based on 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 through-put by nearly a factor of two. This modification was implemented during the second year of the program[6].

During this period ARRI continued to support Solarex to improve and streamline the module assembly operation. Areas of emphasis are:

Trim/Lead Attach

ARRI designed 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 as shown in Figure 9. The prototype was delivered to Solarex for testing. During testing several problems were identified including tearing of the backsheet on the rollers and a tendency for operators to hit their hand on the support structure during the trimming operation. These issues were addressed in the design of a production unit.

Figure 9
Trim/Lead Attach/Test Work Station

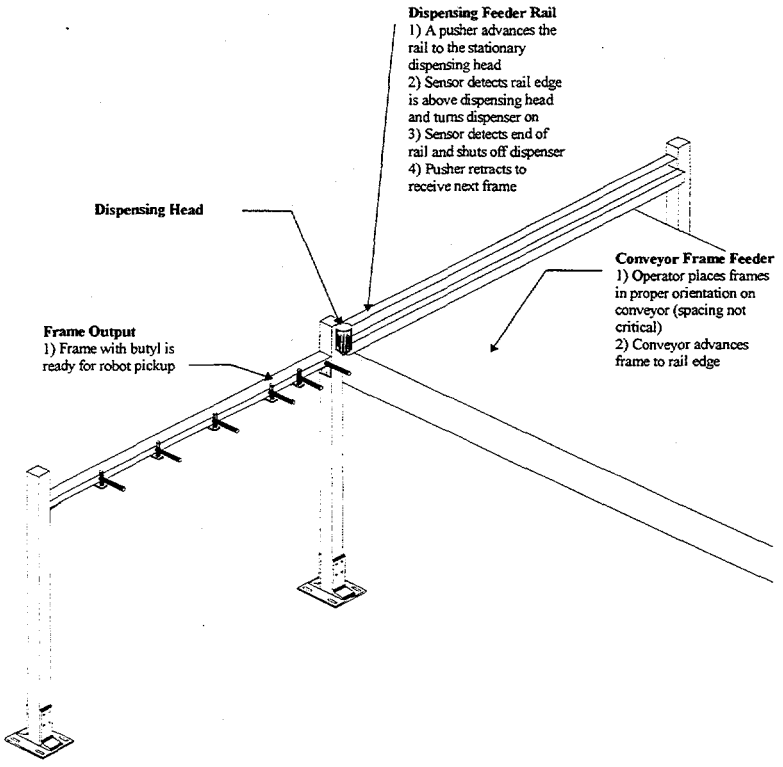


Framing

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 shown in Figure 10. In this system the frame pieces are fed off onto a fixture that pushes them under the butyl dispenser and then hands them off to the robot. This concept is designed to reduce the framing cycle time from 150 seconds to 80 seconds per module.

The prototype validated the concept. Modifications to the production unit will be based on this design.

Figure 10
Framing Feeder/Dispenser



Soldering

One of the key process steps involved in determining module reliability is the process of soldering the interconnect ribbons to the solar cells. The selection of a soldering process is also an important factor in the design of the module assembly system. ARRI performed a detailed literature search to gain a better understanding of soldering techniques. The results of this study were published in the last Semiannual report for this program[9]. The result of this study was the selection of the hot bar reflow and laser soldering systems as the prime candidates for soldering of polycrystalline silicon solar cells. When ARRI approached Panasonic, one of the vendors of laser systems, they were told that because of safety issues they can not sell their LASER system

in the US. Panasonic does have a Soft Beam Fiber Optic Light System designed to solder interconnects, so this system was evaluated in the study.

Similar hot bar reflow equipment to that used at Solarex was delivered to ARRI. A soldering test station was set up utilizing an adept robot to control the positioning of the solder joints. Once the flux is applied to the cells, the holding fixture is placed on the triple beam balance with cell and ribbon in place. The balance is set to the desired force setting. This allows a simple constant force control to be maintained over the course of the soldering cycle. Once all of the equipment is in place, the cycle is begun. The robot indexes to the appropriate position, initiates the start cycle on the controller. The controller performs the programmed soldering cycle and issues a release command to the robot. The robot then proceeds to the next joint.

The pull strength measurements are made using a triple beam balance and a vacuum chuck to hold the cell. The ribbon is grasped by a gripper on the balance plate of the scale. The 90° force is gradually increased in a continuous fashion until the joint yields. Parameters of temperature, dwell time and force were optimized to yield the highest pull strength. Optimum parameters resulted in an average pull strenght of 225 grams on the front side metallization and 130 grams on the back side. Temperature had the major impact on the soldering pull strength. Temperature settings of 400°C appeared to provide optimal soldering characteristics. Dwell also had a significant impact on pull strengths. Maximum joint strengths were achieved with dwells at 0.5 seconds with longer dwell times showing degradation of joint strength at a greater rate than those of shorter dwell times. Force had no effect until the joint force was below 200g. Force values between 200 grams and 1500 grams were used with no apparent damage to cells.

Similar cells were sent to Panasonic for testing in the Soft Beam system, a non-contact localized micro soldering fiber optic light system. The heating source is a Xenon lamp, producing white and near-infrared light that is transmitted through a convergence mirror, shutter, light guide, and optical fiber to a convergence lens, then onto the object to be heated. A few key features of the system are; 1) the beam can be focused to do single point soldering or a continuous line, 2) the system can be interfaced by the user to an existing controller and 3) the white and near-infrared light source used avoids LASER's safety and maintenance issues. This technology is used mainly in the microelectronics industry for soldering printed circuit board assemblies.

One of the key process parameter settings of interest is the Beam Diameter. This was set at 4 mm in all of the experiments. The diameter of the heating area can be made smaller or larger by using a different size lens. A preheat plate (150° C) was used to reduce the actual cycle time per solder joint. If no preheat is used the reflow, the time per joint would have to increase to get the proper heat cycle. According to Panasonic's observations, the leads appeared to solder better when a glass plate was placed over the cell to hold the leads in place. The only problem with using the glass plate is that it has to be cleaned after each cell is soldered. The flux makes the plate cloudy affecting transmission of energy to the object being soldered. Panasonic feels that the fixture problem can be resolved by using other means to hold the leads in place.

Table 11 shows the pull strengths measured for the Soft Beam soldered joints. The Hot Bar results are included as a comparison. In the initial experiment the Soft Beam system resulted in better pull strengths than the standard hot bar process. It is also surprising that the average back side joint strength is slightly stronger without the use of the glass plate.

Table 11
Soldering Pull Tests

Side	Soft Beam No Glass (g)	Soft Beam Glass Plate (g)	Hot Bar (g)
Back	359	322	131
Front	258	270	230

3.5 TASK 16 - 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 3 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 a 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.

Large area samples of white pigmented polyolefin were provided by Richmond Technology. This material 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. Most of these pin holes occurred directly over solder bonds, although others appeared over back tabs, but not where they were soldered. It appears that the polyolefin gets too soft at the lamination temperature and is easily punctured by any irregularities that occur behind the cells. Unless we can find an inexpensive way to strength the polyolefin, it will not work as our back sheet.

We are now 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.

Both Springborn and Richmond Technologies have provided us with samples of Tedlar/EVA laminate. By obtaining the Tedlar/EVA already bonded together, it reduces handling costs. Modules with the Tedlar/EVA laminate have now successfully completed environmental qualification testing to IEC 1215 and IEEE 1262 and are qualified for use at Solarex.

Experiments to evaluate the use of thinner EVA and thinner Tedlar were conducted. Modules made using thinner EVA failed environmental qualification because they exhibited delaminations during thermal cycling. Modules made with thinner Tedlar were more susceptible to pin holing during processing.

3.5.2 Electrical Termination

In the last Annual Report, we reported on the selection of a butt crimp connector and SPC Technology type PHS black polyolefin shrink tubing for electrical termination of the module[6]. These connectors have successfully passed all of the requirements of IEC 1215 and IEEE 1262. Samples continue to perform well in extended outdoor testing.

3.5.3 Mounting System

During the first year of the program, we selected 3M's Very High Bond (VHB) Tape to attach the back of the module directly to metal cross members[5]. A prototype system was built at the Solarex facility in Frederick, Maryland. Performance of the tape in this system was carefully monitored. The success of this system led Solarex to use this mounting system to build several large PV arrays. However, recently we have experienced significant problems related to the use of the 3M VHB tape.

There appear to be two problems related to the use of this tape adhesive. The first occurs when the tape is not properly applied to the module. The second occurs when the modules are mounted such that there is a constant force tending to twist the modules off of the beams. In both cases, some of the modules have peeled loose from the mounting beams.

We have now switched from the tape to an RTV adhesive. The RTV itself is actually cheaper than the tape. Our original selection of the tape was based on a desire to speed up installation, since the RTV requires curing time before it can be installed. What we have found in the actual installation of systems, is that the modules can be panelized several days before installation so that the panels are ready when the installation crew arrives. This appears to reduce the total time required to install the array.

A test array using RTV has been out as long as the test array with tape and it is doing fine. We have now installed several more test systems at Frederick using the same mounting concept, but with RTV as the adhesive. We are continuing to monitor the performance of these systems.

3.6 TASK 17 - Automated Thin Cell Handling

In this task Solarex is developing 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 under subcontract to assist Solarex in the development of handling methods and equipment for large thin wafers and cells.

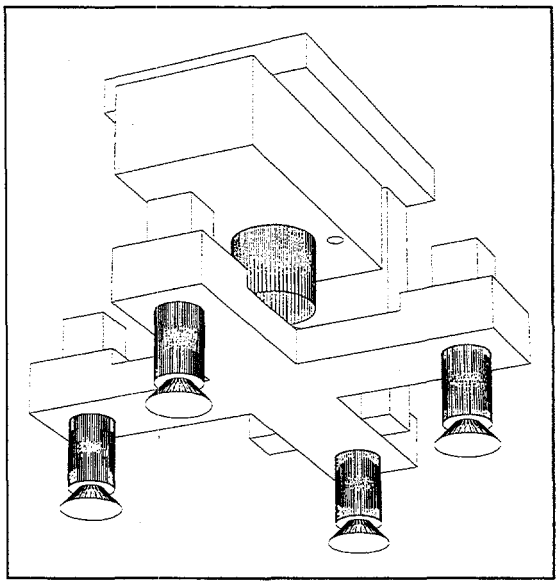
ARRI undertook a study of commercial and academic information sources related to the handling of silicon wafers. The purpose of this literature search was to gain an understanding of the wafer handling methods that are commercially available, or that are documented in the open research literature, in order to assist in design of a wafer end-effector. Details of this study were presented in the last Semiannual Report[9].

Most information about wafer handling have 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 11 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 has been assembled and is now under test.

Figure 11
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 a significant fraction of all cell produced;
- Introduction of a larger cell (11.4 cm by 15.2 cm) into commercial production;
- Doubling of production capacity;
- 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.

At this time in the program, we believe that all of the objectives of this PVMaT program will be met. Our analysis indicates that through the year 2000, Solarex will save $5.00 for every dollar it invested in PVMaT and our customers will save approximately $7.00 for every dollar that NREL invested in this PVMaT Program.

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13. ABSTRACT *(Maximum 200 words)*

This report describes Solarex's accomplishments during this phase of the Photovoltaic Manufacturing Technology (PVMaT) program. During this reporting period, Solarex researchers converted 79% of production casting stations to increase ingot size and operated them at equivalent yields and cell efficiencies; doubled the casting capacity at 20% the cost of buying new equipment to achieve the same capacity increase; operated the wire saws in a production mode with higher yields and lower costs than achieved on the ID saws; purchased additional wire saws; developed and qualified a new wire-guide coating material that doubles the wire-guide lifetime and produces significantly less scatter in wafer thickness; ran an Al paste back-surface-field process on 25% of all cells in manufacturing; completed environmental qualification of modules using cells produced by an all-print metallization process; qualified a vendor-supplied Tedlar/ethylene vinyl acetate (EVA) laminate to replace the combination of separate sheets of EVA and Tedlar backsheet; substituted RTV adhesive for the 3M Very High Bond tape after several field problems with the tape; demonstrated the operation of a prototype unit to trim/lead attach/test modules; demonstrated the use of light soldering for solar cells; demonstrated the operation of a wafer pull-down system for cassetting wet wafers; and presented three PVMaT-related papers at the 25th IEEE Photovoltaic Specialists Conference.

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