February 2002 • NREL/SR-520-30881

Subcontractor Report

Silicon-Film™ Solar Cells by a Flexible Manufacturing System

Final Report
16 April 1998—31 March 2001

J. Rand
AstroPower, Inc.
Newark, Delaware

NREL

National Renewable Energy Laboratory

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TABLE OF CONTENTS

1. EXECUTIVE SUMMARY

AstroPower has developed the technology required for the large-scale manufacture of its Silicon-Film™ solar cell technology. The work sponsored under an NREL-administered PVMaT cost-share program is reported here. The major thrusts of this three-year effort are:

- Development of a new, larger, baseline Silicon-Film™ solar cell, the APx-8;
- Construction and operation of a new high-throughput wafer-making system; and
- Development of a 15 MW single-thread manufacturing process.

The result of this program is a solar cell manufacturing system that is low cost, high volume, and flexible with respect to serving different solar cell and module markets. Specific technical accomplishments from this period are:

1. ***Increase solar cell area by 80%***
   AstroPower has increased the baseline Silicon-Film™ solar cell area from 240 cm^2 to 432 cm^2, once again creating the larger solar cell within the solar electric power industry.

2. ***Increase the generation capacity of a Silicon-Film™ wafer making system by 350%***
   The new sheet manufacturing equipment runs at a rate of 3.1 meters per minute and generates a continuous sheet that is nominally 8 inches wide. A single system has a capacity of 15 MW per year.

3. ***Utilize a new in-line HF etch system in solar cell production***
   A novel, continuous, phosglass etch system was designed, commissioned, and qualified for production use. The prototype system was immediately successful, and a second system was installed and is now in use in production. The replacement of the tank-based systems with the new in-line process has reduced costs, increased throughput, and improved ES&H conditions.

4. ***Design and develop an in-line NaOH etch system***
   A novel continuous silicon wafer surface etching system was designed, installed, and is being tested in production. As with the HF system, the new system has demonstrated reduced costs, increased throughput, and improved ES&H conditions.

5. ***Eliminate cassettes in solar cell processing***
   The new, continuous, in-line process equipment has made the elimination of cassettes possible, paving the way for low-cost, high throughput processing and automation.

6. ***Design a new family of module products***
   The large area APx-8 solar cell can be segmented to manufacture modules from 45W up to 220 W. A roof-mounted module has been designed for the residential on-grid market.

This final report will review the technical activities in these areas and discuss designs for an advanced 15 MW single-thread production line design for manufacturing Silicon-Film™ solar cell.

2. INTRODUCTION

The overall goal of the PVMaT-5A program at AstroPower is to engineer and develop flexible manufacturing methods and equipment to process Silicon-Film™ solar cells and modules. During Phase III of this contract a larger-area (208 mm x 208 mm) Silicon-Film™ solar cell -- the APx-8 -- was developed and introduced. While a few equipment changes in the manufacturing line were required to handle the APx-8 product, the process sequence for this new product was found to be very close to that of its predecessor, the AP-225, a smaller-area solar cell product. Only minor changes to the production line were needed to accommodate the larger-area solar cell because most of our production processes are now belt transport processes. The main process difference is the number of wafers that fit across the furnace belt, and tuning the thermal profiles to accommodate the larger thermal mass of the APx-8 wafer. The required equipment changes have a common theme of either increasing the chamber opening size of access ports, or building larger load/unload fixtures. In addition, new cassettes were required for hydroxide etching wafers, and new vacuum chucks and print screens were needed for contact print and fire processes. The continuous in-line HF etch system can easily accommodate the larger-area wafers. A new AR coating system for larger-area solar cells was assembled and commissioned.

While primary emphasis has been placed on wafer and solar cell manufacturing areas, there are areas where incremental and significant improvements have been realized in Silicon-Film™ module design and manufacturing. In the area of module assembly, the most time-consuming step is the solar cell stringing operation. Automation of this operation using Spire tabber-stringer equipment has yielded significant savings. Some improvements in module manufacturing have been realized by purchasing or developing special tools and fixtures. For example, application of the RTV silicone adhesive to the J-box can be mechanized using an X-Y applicator system, resulting in a faster, more uniform process. Other improvements resulted from the use of lower cost components. For example, a redesigned junction box significantly reduces the number of parts and has resulted in savings of $0.064/W. In the future, mechanization of the layup and framing operations and a continuous lamination process are projected to save $0.055/W.

3. SOLAR CELL MANUFACTURING PROCESS

AstroPower's solar cell manufacturing systems have advanced along a critical path which addresses processes that limit performance and throughput, beginning with processes that have the most impact on throughput. This effort began with the development of the polycrystalline Silicon-Film™ sheet. As the dimensions of the sheet and wafer increased, junction diffusion in tube furnaces became the limiting factor. Development of continuous high temperature processing for impurity gettering and for junction diffusion followed. Wet chemical processing was not limited by wafer area, but by throughput and weight considerations. The replacement of batch processing with in-line, continuous wet chemical process systems has paved the way for the complete elimination of cassettes from the production line. Development in each of these areas is discussed in more detail below.

In 1998 AstroPower began manufacturing AP-225 Silicon-Film™ solar cells (240 cm^2) in the Pencader facility. Since that time the Pencader plant has expanded to 12,000 m^2 (130,000 ft^2), twice its original size, and now produces the new APx-8 Silicon-Film™ solar cell (432 cm^2) as well as single crystal solar cells manufactured from recycled wafers procured from the integrated circuit industry. Figure 1 shows a view of the Pencader solar cell production line. The process sequence in the Pencader plant is presently transitioning from the older, batch type processing to new in-line processes.

Figure 1. View of AstroPower Pencader solar cell production line. The manufacturing facility is located in Newark, Delaware, USA, and has a production capacity of 35 MW.

Silicon-Film™ Cell Process Overview

Table I shows a summary of the AP-225 cell process sequence (circa 1997) compared to a 15 MW/year single-thread production line (STPL) that is being developed for producing APx-8 solar cells. Production systems for the AP-225 solar cell were based on handling 25-wafer cassettes, small batch processes, and limited throughput. The batch process sequence contained

25 discrete operations, and nine places where the wafers were either loaded or unloaded from cassettes or boats. The cassettes performed two functions: in batch-type wet processing cassettes are required for handling wafers in the solution tanks, and in dry processes, such as contact printing, cassettes are used between stations to move batches and to protect the junction. Once the contact firing operation is completed, the solar cells were handled as coinstacks in magazines.

The advanced APx-8 solar cell process sequence in Table I contains 11 discrete operations, and no cassette handling steps. The goal of eliminating cassettes is accomplished in the APx-8 STPL by using conveyorized process equipment in wet chemical and high-temperature steps. Several previously discrete processes are combined, such as contact metallization, where the back and front contacts are printed and fired in one unbroken sequence. Wafers are transferred between stations, such as between print-fire and test-sort, in magazines. In this way the process sequence is simplified and the amount of handling has been reduced.

Table I. Comparison of manufacturing sequence for AP-225 (circa 1997) and APx-8 Silicon-Film™ solar cells

AP-225, 5 MW/year	APx-8, 15 MW/year
Fabricate sheet	Fabricate sheet
Size wafer	Size wafer
Getter prep	Getter prep
Getter	Getter
Load into cassette Etch surface	In-line etch surface
Unload from cassette into boat Diffuse wafer Unload from boat	In-line diffuse junction
Isolate junction	Isolate junction
Load into cassette Etch diffusion oxide	In-line etch diffusion oxide
	AR coat, SiN
Unload from cassette Print and dry back Ag busbars Load into cassette	Print and co-fire metal contacts
Unload from cassette Print and fire back Al field Load into cassette	
Unload from cassette Print and fire front Ag contacts	
AR coat, TiOx	
Burnish busbars to remove ARC	
Test and sort	Test, sort, inspect
Inspect	

15MW/Year Solar Cell Production Line Design

Developments such as those described previously were used to design a single thread production line with an annual capacity of 15 MW of APx-8 Silicon-Film™ solar cells. The throughput of the line is governed by the initial sheet formation step. Each of the following processes exceeds the capacity rating of the Silicon-Film™ sheet generation system. No cassettes are used in this manufacturing system.

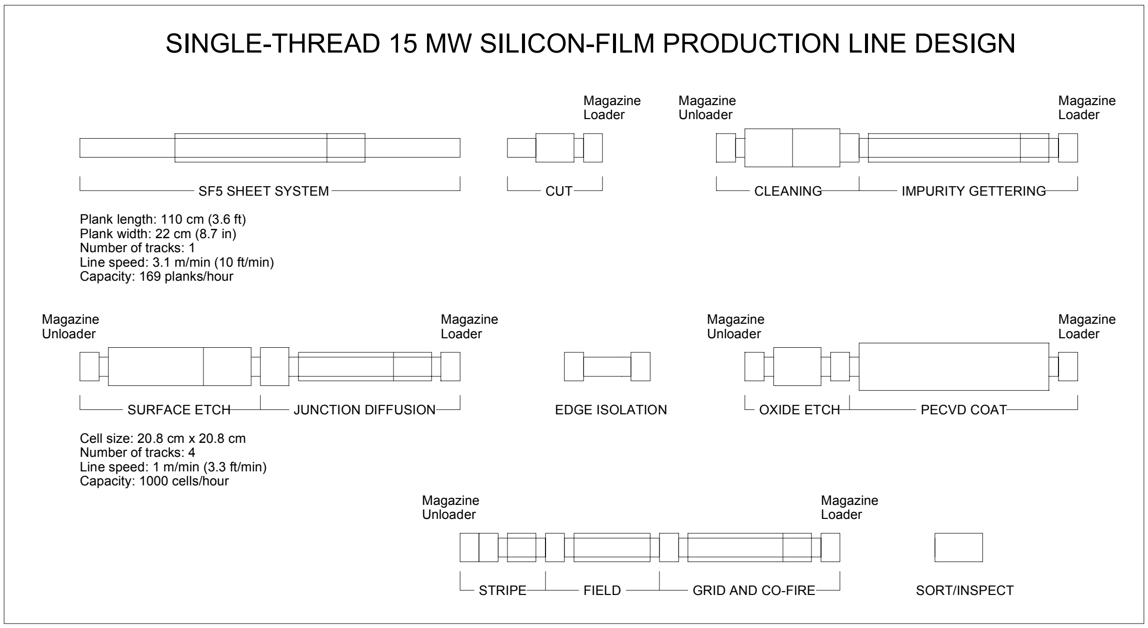

Figure 2. 15 MW single-thread Silicon-Film™ solar cell production line design

Sheet Formation: The Silicon-Film™ single-thread production line is based on a polycrystalline silicon sheet machine that operates at a sheet generation speed of 3.1 m/min and has a capacity of 15 MW per year. This system was commissioned in 2000. The 110-cm long sheets are cut into five APx-8 wafers and loaded into coinstack magazines for transfer to the impurity gettering system.

Pre-Diffusion Gettering: Wafer surface preparation consists of three parts: pre-getter surface cleaning, impurity gettering, and pre-diffusion surface etching. The sized wafers are cleaned and then transferred to a high temperature belt furnace for the impurity gettering. The gettered wafers are loaded into coinstack magazines for transfer to the surface etch system.

Surface Etch/Junction Diffusion: Once the wafers are gettered, they are etched using an in-line caustic etch system and then immediately diffused in a rapid thermal IR belt diffusion furnace. Combining these two processes eliminates any surface contamination between surface etch and junction diffusion steps. At a belt speed of 1 m/min the throughput of the diffusion process is more than 17 MW per year. The diffused wafers are unloaded from the furnace belt to coinstack magazines for transfer to the junction isolation system.

Junction Isolation: The emitter junction is isolated from the back surface by abrading the diffused layer at the wafer edges ("edge isolation"). This is a dirty process and the system is purposely kept separated from any other system. The wafers are loaded into coinstack magazines for transfer to the diffusion oxide etching system.

Diffusion Oxide Etching/PECVD AR Coating: The diffusion oxide is removed by etching the wafers in a dilute hydrofluoric acid solution. This process is performed using a continuous wet chemical process system. The etched wafers are immediately transferred to an in-line PECVD system where they are coated with a silicon nitride layer. This process provides the AR coating and hydrogen passivation. Combining these two processes eliminates surface contamination between the etching and coating steps. The coated wafers are loaded into coinstack magazines for transfer to the contact metallization system.

Contact Metallization: Front and back contact metallizations are based on thick film inks that are printed and "spike" fired using infrared belt furnaces. The contacts are fired through the SiN AR coating. To reduce ink costs, the back metallization incorporates a co-fired aluminum "field" region outside of the solder tabbing areas. There are three printing operations, two low-temperature ink-drying steps, and one high temperature co-fire process. The process is continuous and in-line. The print and fire steps are combined to simplify handling. The metallized solar cells are loaded into coinstack magazines for transfer to the test-and-sort system.

Test, Sort, Inspection: Completed solar cells are electrically tested and sorted into power categories. A vision system on the cell tester-sorter system inspects for any manufacturing defects prior to packaging. This eliminates an additional visual final inspection. The tester-sorter system delivers cells in coinstacks.

4. SILICON-FILM™ WAFER MANUFACTURING

Silicon-Film™ production systems generate low-cost sheets of polycrystalline silicon in a continuous in-line process. The equipment, materials, and processes have been under development at AstroPower for over ten years. Each successive generation of the Silicon-Film™ sheet growth system brought increases in throughput, both through sheet width and sheet growth speed. The fifth generation of the Silicon-Film™ sheet growth system (SF5), shown in Figure 3, was designed, built, and commissioned in 2000. This system has a nominal 20-cm sheet width and operates at 3.1 m/min, which is a throughput increase of 158% as compared to the previous SF4 sheet system. With its higher growth speed and increased width, the SF5 sheet system has a nominal capacity of 15 MW per year.

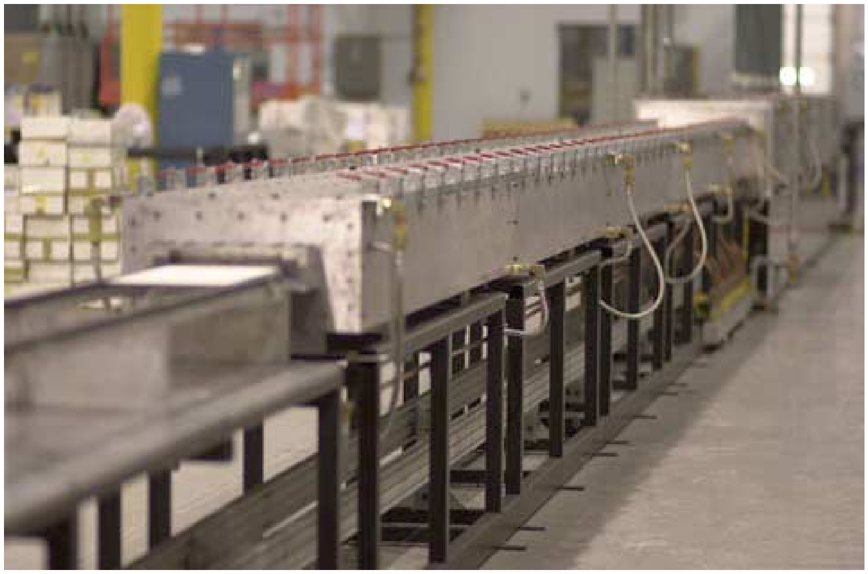

Figure 3. SF5 Silicon-Film™ sheet generation system. This single system has a capacity of 15 MW per year.

The SF5 sheet system was specially designed to supply sheet material to produce the new larger-area APx-8 Silicon-Film™ solar cells. Figure 4 shows the APx-8 solar cell compared to the previous-generation AP-225 solar cell with a six-inch rule for scale. The APx-8 solar cells are 20.8 cm on a side, once again setting a new standard for polycrystalline solar cell area and power. This new solar cell is more than four times larger than the typical polycrystalline silicon solar cell that was manufactured ten years ago. Large-area modules based on the APx-8 solar cells can produce up to 220 Watts and will reduce the balance of system cost by greatly simplifying system installation and maintenance.

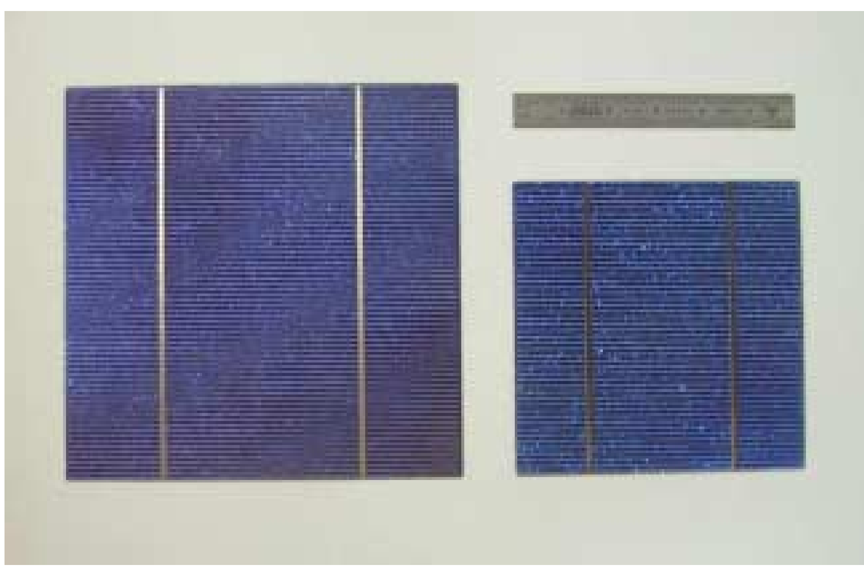

Figure 4. New larger-area APx-8 Silicon-Film™ solar cell compared to earlier AP-225 solar cell. The edge dimension of the APx-8 solar cell is 20.8 cm, an increase in cell area of 80% from the AP-225 solar cell.

The introduction of these larger-area Silicon-Film™ wafers into solar cell manufacturing required more consideration of wafer handling. The mechanical yield during production startup is shown in Figure 5. The improvements are the result of changes in the physical stability of the wafer (due to improvements in sheet growth) as well as improvements in wafer handling through the solar cell production line.

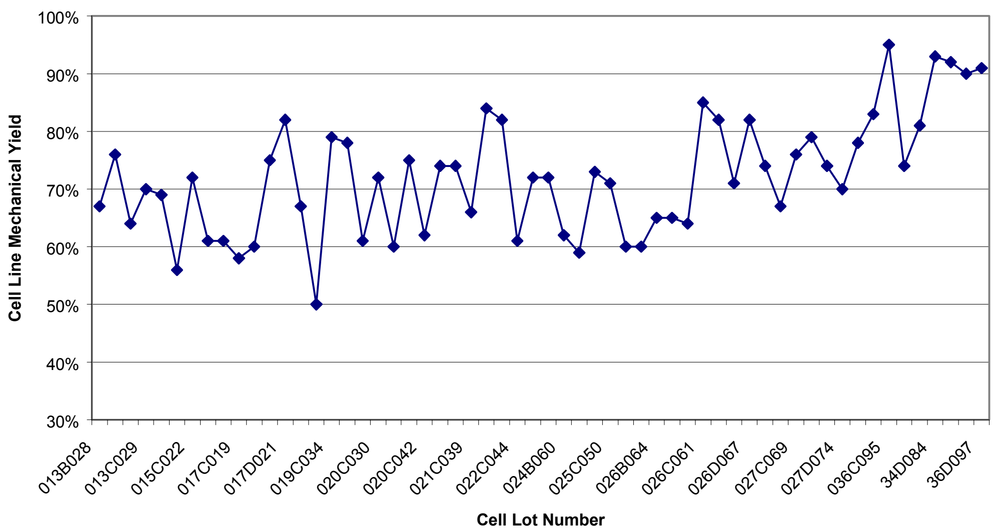

Figure 5. Mechanical yield of large-area APx-8 solar cell production over the initial three-month period. Increased yield was due to reduced breakage in all process steps.

5. CONTINUOUS WET PROCESS SYSTEMS

Several wet chemical process steps, including surface preparation prior to junction diffusion and oxide etching following diffusion, are critical components of the silicon solar cell manufacturing sequence. A tank-based batch chemical process requires wafers to be loaded into cassettes that maintain wafer separation in the solution. The tight wafer spacing within cassettes reduces the liquid flow to the wafer surfaces and results in uneven etching or cleaning at the edges where the wafers contact the cassettes.

Development of cassette-less in-line wet chemical processing systems eliminates many of these limitations. An in-line system is capable of handling wafers of various sizes, and even meter-long Silicon-Film™ sheets. Operator exposure to chemicals is minimized since the process chemicals are completely enclosed -- dry wafers are loaded into the chemical process system, and completely rinsed and dried wafers are unloaded from the system. The composition of the solutions is maintained within operating limits by in-line monitoring and control. Such control reduces material usage and waste stream volume. The throughput of an in-line chemical process system is then no longer limited by tank size or by cassette load-unload operations. Total processing time is further reduced and process quality improved by the more efficient cassette-less rinsing and drying steps that eliminate the obstructions to solution and air flow.

As the first step in developing high-throughput wet chemical processing equipment, AstroPower commissioned a rinser-dryer system in 1998 for the Pencader solar cell manufacturing facility. This system is used to clean Silicon-Film™ wafers immediately prior to the high-temperature impurity gettering process. Compared to cassette-based box drier systems with resistive heaters, throughput is significantly increased and drying quality improved. The handling advantages of continuous in-line processing demonstrated by this initial rinser-dryer application led next to the development of wet process equipment for the post-diffusion thermal oxide etching process, which has now been operating in our manufacturing facility for over a year. Further development of continuous wet chemical process equipment has subsequently been focused on the pre-diffusion caustic-based surface etch process. A prototype in-line etch system has been constructed and is presently being used to assist in the design of a production-scale system.

In-line Diffusion Oxide Etching

During the high-temperature junction diffusion process a thin layer of phosphorus-doped silicon dioxide is grown on the surface of the wafers. This oxide must be removed prior to the contact metallization by briefly etching the wafers in a dilute hydrofluoric (HF) acid solution. Historically wafers were loaded into and out of cassettes just so that they could be processed through the oxide etch process tanks.

Safety issues regarding the HF oxide etch solution were a significant concern in the design of the continuous etch system. The HF solution remains as a dilute room temperature solution, rather than vapor. This requirement significantly simplifies containment and reduces safety concerns. All of the piping carrying HF etch solution is contained within the sump except for the gravity drain to the neutralization tank. Any external HF-carrying plumbing has secondary containment for additional protection. The sump and filter lids are interlocked and will shut off the circulating pump during servicing. The HF solution drains from the process chamber and plumbing back into the system's sump reservoir by gravity when the pump is turned off or there is a power outage. A drip tray with a leak detection alarm is located underneath the system and a containment tray was placed under all additional equipment associated with the process. For added protection, the HF immersion and the rinse modules have secondary safety lids and magnetic interlocks, and there is an automatic system shutdown if the exhaust blower fails. Figure 6 shows AP-225 Silicon-Film™ wafers being processed in the immersion etch module.

Figure 6. In-line diffusion oxide etch system. AP-225 Silicon-Film™ wafers in HF immersion etch module

The first cassette-less diffusion oxide etch system for process development was completed in 1999. A second, higher-capacity production system was then commissioned in 2000. The in-line systems are assembled from modules for each step in the oxide etch process sequence: load; rinse; HF immersion; triple deionized (DI) water cascade rinse; brush clean; dry; and unload. Figure 7 shows the unload end the production scale system.

Figure 7. Continuous diffusion oxide etch system, unload end view.

At a conveyor transport speed of approximately 100 cm/min, the system has an annual process capacity for APx-8 solar cells of more than 15 MW. With this system we have met aggressive material and labor cost reduction goals by reducing HF acid usage and disposal costs, by reducing DI water consumption, and by completely eliminating labor costs for cassette loading and unloading that are required by the previous batch-based diffusion oxide etch process. The contained etch bath has greatly improved the environmental, safety, and health aspects of this process in large scale manufacturing.

In-line Surface Etch System

The pre-diffusion etch process is based on a caustic solution that anisotropically etches silicon at a high rate. The critical parameters for the silicon surface etch process are solution temperature, which strongly influences the silicon etch rate, and solution composition, which impacts surface quality. It is also critical that the surface etching action be terminated quickly by flooding the wafer surface with hot water. As a tank-to-tank batch process, the cassettes must be quickly removed from the hot etch solution and immediately plunged into rinse water. The quality of the surface etch process is highly dependent on the performance of the operator, just as it is sensitive to etch solution concentration and temperature.

In the continuous in-line surface etch process wafers are carried through the system by wheeled transport. This transport minimizes any contact of the front surface of the wafer during sodium hydroxide etching. In a cassette-based etching system the wafer edges are masked by the cassette, which reduces the etching and rinsing action and results in process defects on the wafer surface. In addition to eliminating the cassette load and transfer steps, larger wafers, different sized wafers, and even large-area Silicon-Film™ sheets can be processed by the same equipment with virtually no need for fixturing. A prototype surface etch system, shown in Figure 8, is presently being tested. The etch rate parameters of this etch system will be used to specify a production scale pre-diffusion surface etch system.

Figure 8. New continuous in-line sodium hydroxide etch prototype.

Surface Cleanliness Analysis

Wafer surface quality may play a role in several processing steps such as diffusion, metallization and AR coating. Surface contamination may occur either due to residue from the chemical process steps or from wafer handling in the production. An SEM can be used to survey surface contaminants, and EDS can be used for elemental analysis of the surface contaminants. Although EDS analysis is capable of providing valuable information on the surface quality of the wafer, this technique is time consuming, destructive, and limited to small sections of the wafer. A more production-oriented system for quantifying surface cleanliness is needed.

After some investigation, Optically Stimulated Electron Emission (OSEE) was identified as a potential technique that might be efficiently applied to surface cleanliness characterization. With this technique, the wafer surface is illuminated with an ultraviolet light source. Electrons are photoemitted from the surface and are collected by a sensor. Contamination on the surface reduces the number of electrons emitted from the surface, and therefore reduces the OSEE reading. This measurement technique is non-destructive, and no sample preparation is required. It can be used to quantify the level of contamination on a wafer surface although it cannot identify the type of contaminant.

During our evaluation of the OSEE technique we found that it is readily capable of quantifying the difference between clean hydroxide-etched wafers and known contaminated wafers. Also from a “mapping” of the wafer surface for cassette-etched wafers, we found that the center of the wafer appeared to be dirtier than the edges. This result is another indication of nonuniform processing that is inherent in cassette-based wafer etching.

6. SOLAR CELL METALLIZATION

The objective of this task is to reduce the cost of manufacturing large-area Silicon-Film™ solar cells and modules. The primary goals are to improve performance and reduce manufacturing cost through better material usage, improved process yield, and higher volume. Under this task AstroPower developed advanced processes for Silicon-Film™ sheet material and demonstrated them on the baseline solar cell manufacturing process. Efforts in contact metallization were focused on three areas:

- High volume continuous back metallization;
- Low shading front metallization; and
- Simplified co-fire contact processes.

High-volume Screenprinting

An overwhelming majority of silicon solar cells are manufactured with screenprinted metal contacts on front and back surfaces. The print-fire process and materials are adaptable to virtually all of the silicon substrate technologies, the process equipment is mechanically simple and reliable, and production volume is much higher than evaporated or plated metal contact deposition processes. The screenprinting equipment and materials used for solar cell manufacturing were developed for the hybrid circuit industry more than 30 years ago and were readily adopted by the photovoltaic industry in the early 1980's.

Although solar cell manufacturers have easily integrated hybrid circuit screenprinting equipment into their production lines, very little hybrid circuit manufacturing actually takes place today. As a result, many previously independent screenprinting equipment suppliers who supplied the hybrid industry, such as deHaart, AMI and MPM, either have been consolidated into larger organizations or have disappeared altogether. DeHaart and MPM no longer exist. AMI continues to produce screenprinters for hybrid manufacturing, but their largest high-speed rotary screenprinter for solar cell manufacturing is limited to a maximum substrate size of only 5-inches and costs more than $200,000 (for a single screenprinter). These specifications have remained unchanged for years, even while the area of solar cells has rapidly increased. Most screenprinter suppliers no longer provide equipment for hybrid circuit manufacturing; instead they supply printing equipment to the more lucrative surface mount technology (SMT) business.

Any new technical screen printing equipment is now designed only for multi-layer SMT manufacturing. SMT equipment requires very high printing accuracy and reliability. An SMT screenprinter is highly automated, will handle different sizes of PC boards, has a vision alignment system, and will cycle in times that are 15 to 30 seconds long, equivalent to a single-cell/single-print rate of about 240 solar cells per hour. The only way to practically use an SMT printer is to print several solar cells at a time. SMT screenprinters are typically priced at over $150,000 and are usually sold as only one component of a highly integrated, multi-million dollar process line that consists of board handlers, printers, "chip shooters", and reflow furnaces.

Solar cell manufacturing does not require vision alignment or the level of accuracy that is built into an SMT screenprinter. Also, multi-print systems significantly complicate all the components associated with wafer handling and reduce the print process robustness. It is possible that a "de-contented" SMT screenprinter could satisfy all of the requirements for solar cell contact printing with a significant reduction in capital and operating costs. In general, SMT screenprinter suppliers are not at all interested in the photovoltaic business, or in selling lower-cost screenprinters. The reason is that solar cell manufacturing needs do not provide enough of a business opportunity to justify the time and engineering cost of designing and producing specialized equipment, or even modifying their existing equipment designs, and then supporting the equipment

There is no commercially-available automated screenprinter that can handle large-area wafers at the volumes required for cost-effective Silicon-Film™ solar cell manufacturing. As a result, the present Silicon-Film™ contact metallization process is based on simple, manual large-screen printers that were previously used for hybrid circuit manufacturing. Though obsolete, they serve the purpose. Each printer performs one discrete operation in the contact metallization process sequence. Printed wafers are transferred from printer to printer in 25-wafer cassettes.

There are two key issues that impact high-volume, large-area Silicon-Film™ solar cell manufacturing. First, the throughput of the present un-automated contact metallization process sequence is severely constrained by the ink application step at the screenprinters; the result is that the overall process volume is significantly less than the capacity that is available from the firing furnaces. In some cases two manual printers are used to feed one furnace. Second, handling the wafers before and after every print operation significantly impacts mechanical yield. Based on these observations, and the response of traditional screenprinter suppliers, we concluded that new, novel solutions are needed that will allow us to design contact metallization printing systems that are capable of handling larger-area Silicon-Film™ solar cells at high production volume.

Continuous Metallization Application

There is an increasing need across the industry for highly automated, high-volume printers that can handle large-area wafers and produce fine-line front contact metallizations. Traditionally the same type of equipment used to print the back contacts was also used to print the front of the solar cell. However, the requirements for the two contacts are actually very different. On the back surface, the contact patterns can be very simple, and line resolution and thickness is not an issue. If an aluminum-based back ink is used, then contamination of the front surface by back ink is a critical issue and must be avoided at any cost. On the front surface, the width and height of the lines are critical because they directly impact series resistance (and fill factor), shading (and current generation), and power generation. Contamination of the back surface by the front ink is not a concern.

Compared to evaporated or plated metal contacts, the advantage of screenprinting is that relatively narrow, low resistance metal gridlines can be economically and consistently applied onto flat or nearly flat substrates. However, solar cell screenprinting is inherently a relatively slow, small area process due to the need to move a thixotropic material through a fine mesh screen. The limitations of screenprinting have become more apparent as production volumes and wafer dimensions have increased. The screenprinting process trades off resolution for print speed. An acceptable large-area screenprint process will never exceed 2000 prints per hour due to this fundamental issue. For APx-8 Silicon-Film™ wafers this equivalent to processing sheet material at a rate of only 1 m^2/min. Other industries process sheet materials at much higher rates. The painting and paper conversion industries commonly process sheet materials at rates that are at least an order of magnitude greater. High-throughput coating technologies that are used in these industries with potential for solar cell manufacturing are curtain coating, roller coating, direct dispense and jet printing.

Several new metal application techniques that have significant benefits for large-area Silicon-Film™ solar cell manufacturing were investigated. Although capable of very high speeds, curtain coating is too advanced for solar cell manufacturing. However, various dispenser techniques have potential applications. A direct writing technique for front contact application was demonstrated that is capable of producing narrow, low shading grid fingers. Direct write techniques are presently limited only by the low throughput that a single dispenser head can produce. Multiple-headed systems should be able to bypass this limitation.

The co-fire contact process was shown to be amenable to large-area Silicon-Film™ wafers with no loss in performance. A co-fire process combined with high-throughput metallization application will simplify the process sequence, eliminate one firing furnace, and reduce the total thermal stress that the Silicon-Film™ wafer experiences during solar cell processing.

7. SILICON-FILM™ SOLAR CELLS

Silicon Nitride Anti-Reflection Coating

Silicon nitride (SiN) coatings have been shown to significantly improve the performance of most cast or ribbon polycrystalline silicon solar cells. Previously, Silicon-Film™ material has been shown to benefit from hydrogen passivation. However, the hydrogenation process was not compatible with large-scale, low-cost manufacturing. Recently, advances have been made in high-throughput plasma-enhanced CVD (PECVD) equipment for the deposition of SiN coatings. The advantage of SiN coatings is that hydrogenation passivation of grain boundaries is an intrinsic part of the process. PECVD equipment for SiN coating from two manufacturers was evaluated. The following observations have been made:

- SiN increases diffusion length of Silicon-Film™ solar cells;
- The mechanism is, contrary to most cast and ribbon products, not assisted by aluminum BSF formation; and
- Significant improvement of the emitter is realized by the SiN coating.

These improvements due the SiN coating are summarized in the Silicon-Film™ solar cell performance data shown below in Table II.

Table II. Performance of SiN-coated Silicon-Film™ solar cells. Due to equipment constraints, tests were performed on unoptimized 10 x 10 cm solar cells.

	FF	Voc	Isc	Pmax	FF-gain	Voc-gain	Isc-gain	P-gain
Control	67.8	537	2.48	0.91				
Vendor 1/treatment 1	72.0	549	2.63	1.04	6.2%	2.2%	6.0%	14.3%
Vendor 1/treatment 2	71.9	550	2.64	1.04	6.0%	2.4%	6.5%	14.3%
Vendor 2/treatment 1	72.5	551	2.50	1.00	6.9%	2.6%	0.8%	9.9%
Vendor 2/treatment 2	71.3	547	2.43	0.95	5.2%	1.9%	-2.0%	4.4%

The FF and Voc gains show significant emitter passivation as a result of the SiN coating. A further indication of this emitter effect is that the spectral response of SiN-passivated cells are improved down to wavelengths as low as 500 nm, indicating more than a bulk lifetime effect (see Figure 9). The removal, or passivation of, poor performing material in the emitter can explain some of the effects in both cases. The passivating effect SiN on the material quality can also be seen by analyzing the light beam induced current (LBIC) scan of a Silicon-Film™ solar cell, shown in Figure 10.

Based on this work, AstroPower has committed to incorporating silicon nitride coating into the baseline solar cell process for Silicon-Film™ material. By working with existing equipment vendors two new high throughput designs have been developed and are now commercially available.

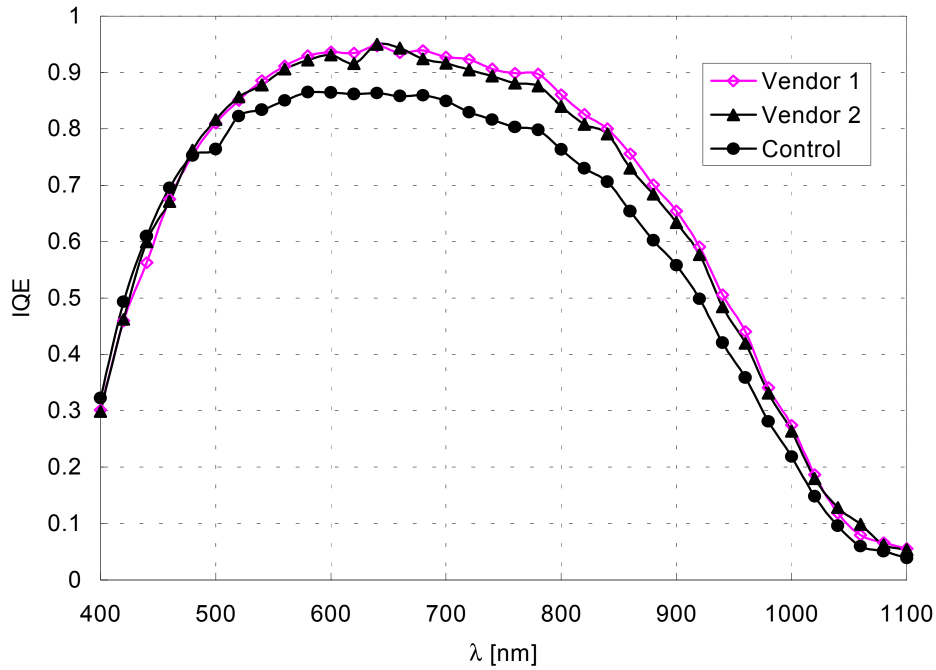

Figure 9. Internal quantum efficiency of SiN-coated Silicon-Film™ solar cells compared to a TiO_2-coated (control) solar cell.

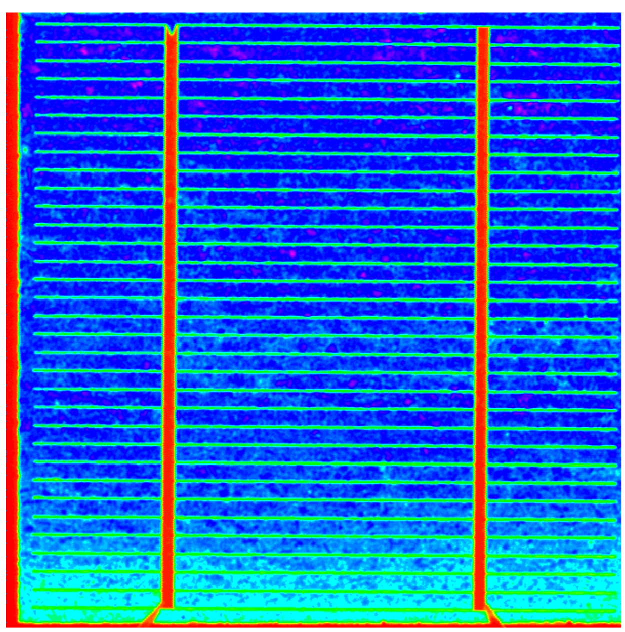

Figure 10. LBIC image of a Silicon-Film™ Solar Cell processed with silicon nitride AR coating.

8. SILICON-FILM™ MODULES AND SYSTEMS

The objective of work performed under this Task is to reduce the cost of manufacturing large-area Silicon-Film™ modules. Included under this task is work to reduce the cost of module materials and module fabrication processes and to develop larger-area Silicon-Film™ modules. Efforts by AstroPower were focused primarily in three areas:

- Larger-area roof-mount modules based on the APx-8 Silicon-Film™ solar cell;
- Components that reduce module material costs and system installation costs; and
- Manufacturing systems that increase the production throughput.

The Pencader facility for manufacturing solar cells and for module assembly, which was dedicated in March 1998, was significantly enlarged by an additional 20,000 sq ft and re-commissioned in Spring 2000 with additional tabber-stringer (from Spire) and laminator equipment. By the fall of 2000 the dimensions of the Silicon-Film™ solar cells increased to 208 x 208 mm. A solar cell tester-sorter for this larger-area APx-8 solar cell and a large-area laminate tester for modules built with these solar cells were designed, assembled and commissioned for production.

APx-8 Silicon-Film™ Module Family

Figure 11 shows the design family of Silicon-Film™ modules based on the larger-area solar cells that are now being produced. The design of the APx-8 cells permits them to be cut into smaller area cells. Modules with nominal power rating of 150 and 220 Watts (DC) are constructed using full-size cells. A 75-W module is assembled from halves, and a 50-W module from cells divided into thirds.

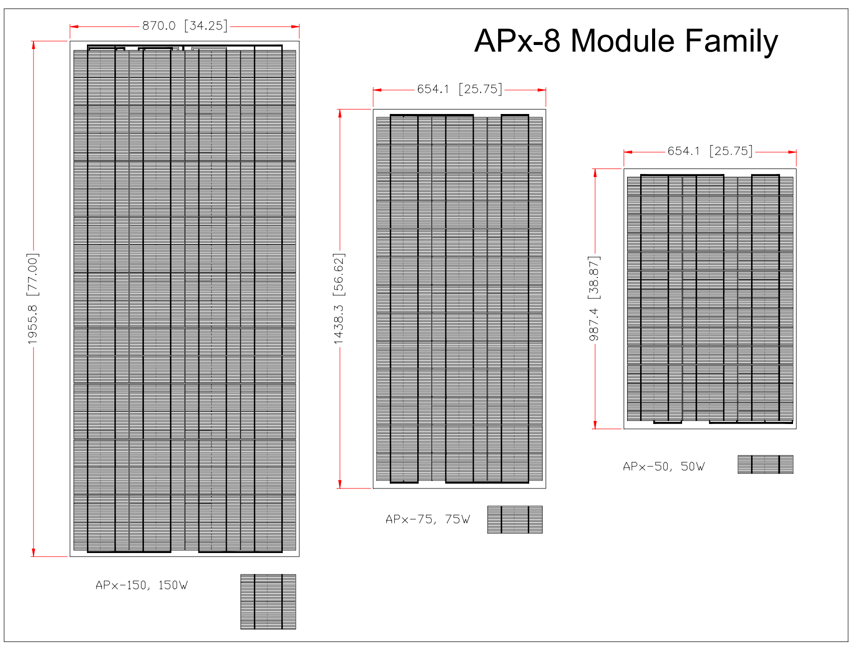

Figure 11. Comparison of APx-8 Module Family

A photograph of the 36-cell APx-150 module is shown in Figure 12. The overall dimensions of the module are 196 x 88 cm (77.2 x 34.6 inch). Modules are being assembled and testing for UL compliance is in progress.

Figure 12. APx-150 module assembled with APx-8 Silicon-Film™ solar cells.

Large-area Direct Roof-mount Modules

Aesthetics, integrity of the existing roofing, installation cost, and ease of installation become critical issues for successful introduction of residential grid-connected solar electric systems. The objective of this work is to develop an easily installed grid-interactive power system that incorporates direct roof-mount modules that are constructed using large-area Silicon-Film™ solar cells. Our goal is to develop a total system package that meets all National Electrical Code (NEC) requirements, eliminates the need for the installer to select and procure components, and significantly reduces the labor and cost of a rooftop installation. We have developed a flexible module framing system that is scaleable and allows for directly attached or offset roof mounting. We have designed and tested a complete power system package and can provide an assembled kit of approved components to system installers.

AstroPower currently offers two system products, the SunUPS® and SunLine™ kits, to serve the growing residential solar electric market. These systems utilize conventional framed modules mounted to a substructure on the customer roof. The Large Area Roof-Mount Silicon-Film™ Module was developed to supplement the existing offerings with larger, specialized module designs.

Residential solar electric systems have design requirements that differ from traditional PV systems. Aesthetics, installation cost and installation convenience are very important considerations. In order to address these special issues, the design of a large area Silicon-Film™ rooftop module system began by surveying selected PV system installers. The installers were asked to describe and order the features that they felt should constitute an "ideal" residential system. Through several iterations of concept proposal and feedback, a design was developed.

The most common request was for larger modules with more area. In general terms, large modules are desirable because they improve installation efficiency by filling the roof more quickly. Large modules also reduce the number of electrical and mechanical connections in a system, which also speeds up the installation process. Figure 13 shows an example of a large-area 9x6 laminate constructed using APx-8 (208 mm) solar cells compared to a more convention 9x4 module assembled using 150-mm solar cells.

Figure 13. Comparison of a high-power rooftop module based on APx-8 cells to a conventional module based on 150-mm single-crystal solar cells.

In addition to larger area modules, a specialized module framing system was rated as another desirable feature by the installers. This is due to the fact that very few modules on the market are designed to meet the unique mounting needs of residential installations.

Based on our research, the "ideal" residential solar electric system has the following features:

Size and shape:

- Module should be larger than existing designs, but no larger than 48" x 84".
- Module should be rectangular shape; a 2:1 ratio is ideal.
- Module should weigh no more than 100 pounds.
- Two installers should be able to handle the module without any special lifting equipment.

Frame and mounting:

- Bare edges of tempered glass laminates should be protected. The frame or a strip provides this protection.
- The mounting system should allow the module to be mounted in either portrait or landscape orientation.
- Penetrations into the roof should be made inline with rafters to minimize the potential for roof leaks and to improve uplift resistance. Rafters cannot be assumed to be regularly spaced (e.g. 24- or 36-inch centers).
- For appearance, the height of the modules should be no more than 2" – 2½" from the roof surface.
- The finished array should appear monolithic with minimal holes and gaps between modules.
- In general, aesthetic considerations often outweigh performance issues in residential installations.

Electrical:

- Module strings should be configurable from 36 to 48 Volts to interface with commonly available inverters.
- Modules should be equipped with quick connectors and adequate cable length to speed field wiring.
- Sides of module frame should form a "conduit" for the system wiring to hide and protect the wires.
- The system must conform to UL-1703 and IEEE-1262 standards

Module Junction Box

The goal of this task was to design and to qualify a new junction box for module assembly that incorporates features that were identified by module customers as either essential or highly desirable. An example of a necessary feature is an electrical feedthrough that is sized for a 1/2-inch conduit because many system designs still require enclosed wiring, even for the module-to-module string wiring. An example of a desirable feature is a junction-box cover that seals without an O-ring, which would reduce installation errors ("left the ring out") and improved long-term reliability. Another objective of this project was to reduce the cost of the assembly components by a factor of two.

As a result of this work, a new module junction box was designed and produced that meets all of these performance and cost goals, and is flexible enough to address additional future module design needs, such as higher current bypass diodes for modules with larger-area solar cells. The parts count for the new junction-box assembly is reduced from the previous fifteen to presently eight components. The total cost for the junction-box components has been reduced by more than 25%, and additional savings are possible. Significant savings have also been realized in assembly time. The new junction box successfully passed all UL tests, and modules with the new junction box are being manufactured.

Although the new J-box can accommodate printed circuit (PC) cards with a terminal block for the field wiring, it was designed so that an UL-listed double-row terminal block could also be used to replace the PC card. This change would significantly reduce component cost since the PC card is the most expensive component of the J-box assembly.

Soldered connections between the terminal block and the laminate tabs would be replaced by welded connections to tabs that are screwed into the block. Because the tabs are welded, rather than soldered, there is no need to thread the tabs through a strain relief, as is required with a PC card. This greatly simplifies and speeds up the assembly process. The junction box was designed so that the terminal block assembly could optionally be attached to the junction box by heat "staking". This would eliminate the Tinnerman nuts presently used, and a staking operation is easily automated with simple tools. Figure 14 shows the new junction box with the low-cost terminal block and weld tabs installed.

Figure 14. New junction box assembly with low-cost terminal block and weld tabs.

Pre-wired Modules with Leads and Field Connectors

Solar electric modules are typically supplied with electrical junction boxes that contain a 600V UL-listed terminal block for the electrical connection. An electrician typically field wires the array using conduit between the junction boxes on the modules. An alternate approach that is particularly beneficial on roof-mount arrays and high voltage strings are modules that are pre-wired with interconnection leads and UL-recognized electrical connectors. No field wiring within the array is then needed. This approach significantly reduces the time and cost involved during system installation. It is generally thought that pre-wired modules are significantly more expensive that standard, unwired modules. However we found that the difference is cost is much smaller than predicted based on savings in other components. As a result of the minimal cost impact, there is a significant increase in the quantity of pre-wired modules now being manufactured.

Having modules factory wired with interconnect cables and MC® PV-KBT3 field connectors created an opportunity to simplify the junction-box assembly and further reduce component costs. Since the junction-box connections for roof mount modules are made in the factory, the cables can be attached directly to the card (see Figure 15). The elimination of the terminal block from the junction-box assembly provides significant cost savings and offsets the added cost of the cable and connectors.

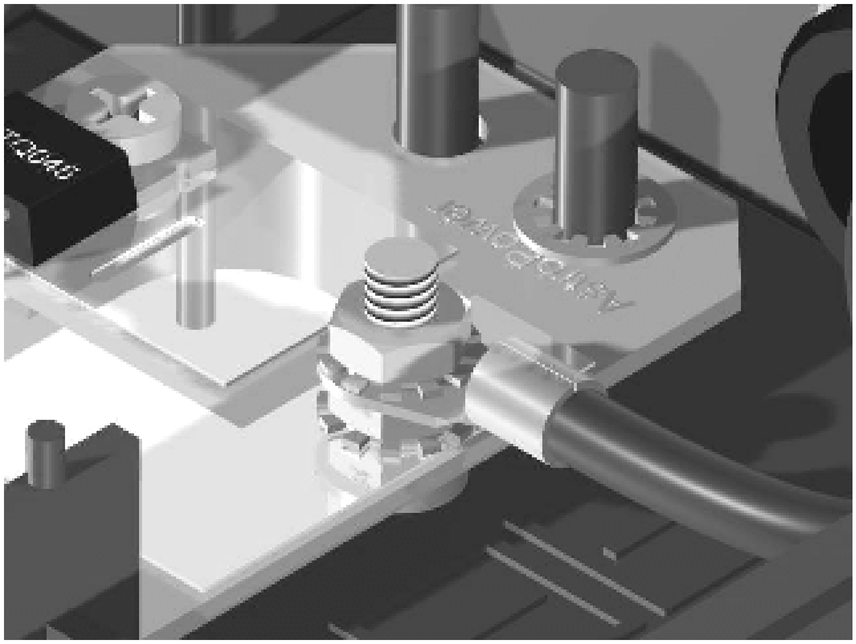

Figure 15. Simplified PC card connection, stainless steel stud replaces the standard terminal block.

Automated J-box Sealant Application

The module junction box is attached to the back side of the laminate with silicone adhesive. The adhesive is manually applied to the box lip seal using a pneumatically-operated hand tool applicator. The assembly operator is also assisted by an alignment jig for consistent positioning of the box on the laminate. Because the task as presently performed is fully manual, there are several areas for improvement -- throughput, completeness of the seal, and consistent bead appearance.

As a first step toward automating this operation, an improved process utilizes a robot to apply adhesive to a J-box while the operator is positioning the J-box that had been previously treated. To test this, a dispensing system for applying the silicone bead to the box lip was commissioned and tested for production use.

The compact unit, with a footprint of about 0.25 sq-m, can follow any line or arc, with simultaneous control of all three axes, including height, to follow any irregular contour. Parts up to 30x30 cm can be handled. The dispenser nozzle can travel up to 10 cm/sec, but the actual speed is dependent on the flow characteristics of the material being applied. Test modules were assembled using the system and were evaluated for dispenser accuracy, bead completeness and appearance. Using this system, the productivity of this process step can be more than doubled by allowing the operator to focus on positioning the junction box on the laminate rather than applying adhesive to the seal. Further benefits accrue from the uniformity of the glue line that is possible by the robotic dispenser (see Figure 16).

Figure 16. Junction box adhesive glueline example.

Large-area Module Testing

As the dimensions of the Silicon-Film™ solar cell have increased, extended area light sources for testing have become more expensive and sensitive to the production environment. A 1600W xenon arc lamp system was used for testing AP-225 solar cells. Even with optical feedback, this source was ultimately found to be too unstable and unreliable for practical use, and severely limited in useful area. As a result we have developed distributed area light sources based on low-cost halogen lamps for commercial-scale PV measurement applications such as solar cell testing and laminate testing. These extended-area light sources feature unlimited scalability, excellent stability and uniformity, low cost, and long life. We have found that these lamps are acceptable for production testing.

Our solar cell and laminate simulator light sources are based on a distributed array of filtered halogen lamps. While halogen lamps have been used in solar cell laboratory equipment for decades, we have extended and qualified their use for commercial scale PV measurement applications. For solar cell testing, the distributed light source is based on seven lamps arranged in a close-packed hexagonal pattern. For laminate testing, the light source is a grid of lamps. The uniformity of the laminate test system is better than +/-5% across the illumination area. The light source is designed for continuous (not flash) operation, and therefore the data acquisition system can be designed for steady-state rather than transient measurements, which greatly increases measurement accuracy, reliability and speed. To keep the module from heating and to conserve power, the lamps are actually operated at a low voltage until the module in placed into the test position. The low voltage setting is high enough to activate the halogen cycle but low enough that no observable heating in the module occurs. Because of the distributed nature of our simulator light sources, we are able to easily scale our testers to any required area and we do not rely on optics to correct uniformity. Redundant DC power supplies for the continuous light source are readily available and very low cost when compared to customized arc lamp and flash lamp power supplies. The halogen lamps are mounted on a pull-out drawer that allows easy servicing. Operating the lamps in simmer-run mode extends their useable lifetime by factors of 10 to 100.

During Phase III of this contract a very large-area laminate tester was developed that will accommodate large-area modules based on the APx-8 cells and is scalable in area to any module that can be possibly laminated in AstroPower's laminators. The test plane on this large-area laminate test system is 72 inches wide and 96 inches long. Figure 17 show the completed system from the operator's position. Because of the size of the modules, handling has become more difficult. Modules are handled using an integral roller conveyor in- and out-feed conveyor system and vacuum pick-and-place. The laminate is moved from the conveyor to the test plane by a vacuum pick-and-place arm. The module is transported with face down, with the leads up. This makes it easy for the operator to attach the Kelvin probes.

Figure 17. Large-area module test system with laminate handling.

9. SUMMARY

AstroPower has developed the technology required for the large-scale manufacture of its Silicon-Film™ solar cell technology. The major thrusts of this three-year effort are:

- Development of a new, larger, baseline Silicon-Film™ solar cell, the APx-8;
- Construction and operation of a new high-throughput wafer-making system; and
- Development of a 15 MW single-thread manufacturing process.

The result of this program is a solar cell and module manufacturing system that is low cost, high volume, and flexible with respect to serving different solar cell and module markets.

Specific technical accomplishments from this period are:

1. ***Increase solar cell area by 80%***
   AstroPower has increased the baseline Silicon-Film™ solar cell area from 240 cm^2 to 432 cm^2, once again creating the larger solar cell within the solar electric power industry.

2. ***Increase the generation capacity of a Silicon-Film wafer making system by 350%***
   The new sheet manufacturing equipment runs at a rate of 3.1 meters per minute and generates a continuous sheet that is nominally 8 inches wide. A single system has a capacity of 15 MW per year.

3. ***Utilize a new in-line HF etch system in solar cell production***
   A novel, continuous, phosglass etch system was designed, commissioned, and qualified for production use. The prototype system was immediately successful, and a second system was installed and is now in use in production. The replacement of the tank-based systems with the new in-line process has reduced costs, increased throughput, and improved ES&H conditions.

4. ***Design and develop an in-line NaOH etch system***
   A novel continuous silicon wafer surface etching system was designed, installed, and is being tested in production. As with the HF system, the new system has demonstrated reduced costs, increased throughput, and improved ES&H conditions.

5. ***Eliminate cassettes in solar cell processing***
   The new, continuous, in-line process equipment has made the elimination of cassettes possible, paving the way for low-cost, high throughput processing and automation.

6. ***Design a new family of module products***
   The large area APx-8 solar cell can be segmented to manufacture modules from 45 W up to 220 W. A family of modules based on the larger-area APx-8 Silicon-Film™ solar cell was designed and is now being prepared for commercial introduction. A roof-mounted module has been designed for the residential on-grid market. Modules with factory-installed interconnect cables and UL-recognized field connectors that will significantly reduce installation costs were developed and are now available.

Significant improvements in module manufacturing systems that can increase the productivity of processes were identified. A robotized system for junction-box sealant applicator that can double productivity while improving reliability is now implemented for production. Replacement of the labor-intensive tape application process for the frame edge gasket is feasible using low-cost hot-melt materials such as butyl rubber, but will require automated equipment and continuous and scrupulous attention to details of the process. A very large-area laminate tester was developed that will accommodate large-area modules based on the APx-8 cells and is scalable in area to any module that can be possibly laminated. We have developed distributed area light sources based on halogen lamps for commercial scale PV measurement applications such as solar cell testing and laminate testing. They feature unlimited scalability, excellent stability and uniformity, low cost, and long life.

During this contract period AstroPower has continued its pattern of reducing solar cell and module production costs and increasing manufacturing volumes. A new product was introduced that once again created the largest solar cell in the industry. New processes and equipment have been put on-line in the areas of wafer-making, HF etching, and NaOH etching. This work has moved us closer to a high-throughput, low cost 15 MW single-thread manufacturing process.

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13. ABSTRACT *(Maximum 200 words)* This report describes the overall goal to engineer and develop flexible manufacturing methods and equipment to process Silicon-Film™ solar cells and modules. Three major thrusts of this three-year effort were to: develop a new larger-area (208 mm x 208 mm) Silicon-Film™ solar cell, the APx-8; construct and operate a new high-throughput wafer-making system; and develop a 15-MW single-thread manufacturing process. Specific technical accomplishments from this period are: Increase solar cell area by 80%, increase the generation capacity of a Silicon-Film wafer-making system by 350%, use a new in-line HF etch system in solar cell production, design and develop an in-line NaOH etch system, eliminate cassettes in solar cell processing, and design a new family of module products.

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