Large-Area, Triple-Junction a-Si Alloy Production Scale-Up

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EXECUTIVE SUMMARY

Objectives: The objective of this subcontract over its three-year duration is to advance Solarex's photovoltaic manufacturing technologies, reduce its a-Si:H module production costs, increase module performance and expand the Solarex commercial production capacity. Solarex shall meet these objectives by improving the deposition and quality of the transparent front contact, by optimizing the laser patterning process, scaling-up the semiconductor deposition process, improving the back contact deposition, scaling-up and improving the encapsulation and testing of its a-Si:H modules.

Achievement: In the Phase II portion of this subcontract, Solarex focused on improving deposition of the front contact, investigating alternate feed stocks for the front contact, maximizing throughput and area utilization for all laser scribes, optimizing a-Si:H deposition equipment to achieve uniform deposition over large-areas, optimizing the triple-junction module fabrication process, evaluating the materials to deposit the rear contact, and optimizing the combination of isolation scribe and encapsulant to pass the wet high potential test.

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1.0 INTRODUCTION

In this phase we have made significant improvements in several areas of the large-area module production process. In the area of front contact development we are now routinely producing tin oxide-coated glass with excellent optical and electrical properties using a proprietary feedstock. This material is presently being used to produce all of our large-area substrates for our module development effort. Our laser scribe development efforts have resulted in an increase in area utilization on 0.37 m² (4 ft²) size substrate to over 95% at production-level throughputs. Improvements have been made in our semiconductor deposition process and our module fabrication processes. These improvements have resulted in a 0.37 m² (4 ft²) size multi-junction module with an initial aperture area efficiency of 9.27%, and a 30% decrease in the semiconductor deposition time. Our rear contact development efforts have resulted in two low-cost methods for depositing zinc oxide/aluminum rear contacts. Zinc oxide films deposited by Low Pressure Chemical Vapor Deposition (LPCVD) are now routinely used to deposit zinc oxide/aluminum rear contacts on large-area modules. Our connector and encapsulant development efforts are continuing and we have begun to investigate high-throughput application methods for these processes.

2.0 TASK 15: FRONT CONTACT DEVELOPMENT

2.1 Introduction

During this phase, our effort has focused on continued development of the process and equipment for depositing tin oxide films. We have begun producing significant quantities of coated glass for use in our development of multi-junction 0.37 m² (4 ft²) modules, and we have begun to collect yield and statistical process control data on these runs. In addition, we have also built and tested a zinc oxide deposition system which is to be used for both front and rear contact development.

2.2 Tin Oxide Process Development

In the early portion of this phase, our work included development and testing of some tin IV chloride based tin oxide films. These films were deposited with a single injector head in the APCVD furnace. A high deposition rate process (approximately 200-300 Å/sec) was explored and resulted in good optical and electrical film properties (14 ohm/sq, 80%

transmission, 17% haze). Large-area, 0.37 m² (4 ft²) modules were made on these films with good results. We have since shifted our standard process to the organotin feedstock, however this process will remain an option for future development.

A proprietary organotin feedstock is presently being used on all 0.37 m² (4 ft²) and 0.1 m² (1 ft²) module substrates. This material has resulted in films with good optical and electronic properties which are relatively thin. This proprietary material has several advantages over the tin IV chloride feedstock. First the material utilization of the present feedstock is lower resulting in a lower cost per square meter of coating. Second, the present material is significantly easier to handle. The film properties of a typical film made with this material are given in Table 2.1.

Properties of a Typical Tin Oxide Film	
Sheet Resistance	16.3 ohm/sq
Transmission	80.3 %
Haze	15.8 %
Thickness	5640 Å

Table 2.1 Typical film properties of tin oxide films produced using our proprietary feedstock.

2.3 Injector Development

The tin oxide injector head development has continued during this phase and we have made significant progress in improving the uniformity of these films. The most important factor affecting film uniformity is the uniformity of the reagent flow from the injector nozzle to the substrate. In an effort to maximize our uniformity, we tested several different flow paths for the reactant gases. For each flow path, a process was developed and the uniformity was evaluated. The most uniform tin oxide films were deposited using the configurations with the longest path of travel for the gases passing through the injector. We concluded in these studies that to form a uniform distribution of gas along the entire width of the injector, the flow from the injector nozzle must be fully developed before the reagents impinge and react on the substrate.

Figure 2.1 illustrates the progress that has been made in film uniformity from 1992 to the present. Both the average non-uniformity and the range of variation in uniformity have significantly improved. Our plans are to continue our development work on the injector to increase run time and improve the repeatability of the process.

2.4 Statistical Process Control

We have begun to make regular "production" runs of large-area tin oxide substrates in order to provide coated glass for the development of the other processes required for module fabrication. The tin oxide yields have been very good, typically greater than 90%. Most of our yield losses are due to uneven deposition due to either injector non-uniformities caused by clogs or other gas flow disturbances. We also lose some glass to breakage and tin oxide debris.

We are in the process of defining the appropriate measurables to track to ensure that we are in control of our process. To date we have measured transmission, haze, sheet resistance, and thickness throughout a run and charted the data. An example of one of these run charts is included as **Figure 2.2** which shows the variation of transmission during the processing of a 35 piece lot.

2.5 Zinc Oxide

Due to its relatively low absorption at certain wavelengths compared to tin oxide, zinc oxide used as a front contact has the potential for increasing the short circuit current of a solar cell. A large-area zinc oxide deposition system has been designed, built, and tested in this period for deposition of both front and rear contacts. A low pressure chemical vapor deposition (LPCVD) technique is used to deposit these zinc oxide films. The LPCVD system is used regularly for rear contact zinc oxide deposition on all of our 0.37 m² (4 ft²) modules. A 1000 Angstrom thick zinc oxide film deposited by LPCVD typically has a sheet resistance of 500 ohms per square and an optical transmission of greater than 85%. To serve as a front contact, the zinc oxide film properties must be adjusted to obtain results similar to those of our present tin oxide: 10 - 20 ohms/sq., greater than 80% transmission and greater than 10% haze. Front contact development work is scheduled for the end of this phase.

LARGE ARE APCVD INJECTOR DEVELOPMENT PROGRESS

Figure 2.1 Progress in Tin Oxide Deposition Uniformity

**RUN CHART FOR TRANSMISSION
LARGE AREA APCVD**

Figure 2.2 Transmission Uniformity of Tin Oxide Films

3.0 TASK 16: LASER SCRIBING PROCESS DEVELOPMENT

3.1 Introduction

During this phase our effort has been concentrated on increasing the active area utilization of laser scribes to 96% while maintaining the laser scribe process throughput rate at 30 plates per hour. We have upgraded our large-area laser system to accommodate dual wavelength optics in order to continue our investigations into the optimum combination of laser wavelength and scribe parameters. In this period we have reduced the total interconnect scribe width from 0.676 mm (0.026 inches) to 0.401 mm (0.0158 inches) resulting in an active area utilization of over 95%. We expect to demonstrate area utilization of over 96% before the end of this period.

3.2 Laser System Upgrades

Previously we reported that changing the wavelength of the scribe laser enabled us to achieve gains in both laser scribe throughput and area utilization. To facilitate these investigations, we have upgraded our large-area laser system to include dual wavelength optical components. These components enable us to switch the laser wavelength from the ultraviolet, to green and into the infrared portions of the spectrum.

We are currently bench-testing a high power laser for the large-area scribe system. This higher power laser should enable us to achieve a significant increase in scribe speed which is particularly important in the isolation scribe process.

3.3 Area Utilization

In this period, we have demonstrated a significant reduction in the area loss due to laser scribe interconnects on large-area modules. At the beginning of this period, the typical scribe interconnect width for 0.37 m² (4 ft²) modules at production rates was 0.676 mm (0.026 inches). This interconnect width resulted in an area utilization of 94%. Since the beginning of the period we have reduced the average scribe interconnect width significantly. **Figure 3.1** is a histogram of the total interconnect scribe spacing measured at various locations over a plate for a representative sample of ten 0.37 m² (4 ft²) size modules. These modules were all scribed at production rates. The average interconnect width is 0.401 mm (0.0158 inches) resulting in an area utilization of over 95%. We expect to attain further reductions in scribe width leading to an average area utilization of over 96% by the end of this period.

Laser Scribe Interconnect Width

Figure 3.1 Histogram of Laser Interconnect widths measured on representative 0.37m² size modules.

4.0 TASK 17: AMORPHOUS SILICON BASED SEMICONDUCTOR DEPOSITION

4.1 Introduction

In this period efforts were concentrated in three main areas: increasing the throughput of the deposition process while maintaining module performance, increasing module performance by optimizing the critical device layers, and investigating the impact of deposition machine configuration and deposition process parameters on the repeatability of the process.

4.2 Deposition Throughput

A major effort in this period was to reduce the cycle time of the semiconductor deposition process over large-areas. The semiconductor deposition process was critically examined to determine changes that could be made to the process that have potential for increasing process throughput without adversely affecting the stabilized performance of the module. After having identified the possible changes, a systematic study was initiated. Candidate changes were introduced into the process in a controlled way and the effect of the change on module initial and stabilized performance was evaluated. Baseline data was continually collected using modules produced with a reference standard process to account for variations over time. Over the course of several months, the deposition time of the semiconductor layers on 0.37 m² (4 ft²) modules was reduced by about 25% with no detectable loss in module performance. As indicated in Figure 4.1, we expect to attain further gains during the balance of this phase.

4.3 Large-Area Module Performance

In parallel with our studies to increase the throughput of the deposition process, we have also made significant progress in module performance. The best 0.37 m² (4 ft²) multi-junction module made in this period had an aperture area conversion efficiency of 9.27% with the following photovoltaic parameters: V_{oc} = 66.98 volts, Fill Factor = .643, and I_{sc} = 742.9 mA. The I-V curve for this module is shown in Figure 4.2.

Several improvements in the module fabrication process have led to this increase in module performance. First, we have used high transmission tin oxide fabricated in-house on the large-area furnace as the front contact. Second, the opto-electronic properties of the first p-layer have been improved significantly. Third, the material properties of the narrow bandgap SiGe alloy back junction has been improved. These three improvements resulted in an incremental increase in the short circuit current of the large-area multi-junction module. In addition, further optimization of the tunnel junction layers resulted in an increase of about 10 mV in the V_{oc} and three percentage points in the fill factor of large-area modules.

Our performance improvement efforts were carried out in conjunction with our effort to reduce the deposition time of the semiconductor layers. Consequently, the changes made to the deposition process to improve performance have not compromised our effort to reduce deposition time.

4.4 Process Repeatability

Our third major effort over this period was to establish and improve the repeatability of the semiconductor deposition process. As part of the effort to reduce the deposition time of the semiconductor layers, standard runs using a reference deposition process were repeated on a regular basis. These repeat runs over time provided us with the opportunity to evaluate both the average of the process and the variation in the process. Initially, the variation in module performance of the standard runs within a week and from week to week appeared to be unusually high based upon prior experience. As a result, the module fabrication process was examined in detail to identify possible causes for the observed variation. Several issues were identified during this investigation. First, ensuring repeatable and adequate substrate grounding during the semiconductor layer deposition was found to have a significant effect on the repeatability of the semiconductor layer depositions. Second, instituting controls over each of the module fabrication steps was also found to have a significant effect on reducing the overall variation in the module fabrication process.

Figure 4.1 Progress in semiconductor deposition time reduction. The dashed line indicates the projected future progress.

Figure 4.2 Initial performance measurement of a 0.37m² (4 ft²) module.

5.0 TASK 18: REAR CONTACT DEPOSITION PROCESS

5.1 Introduction

A highly reflecting zinc oxide/aluminum rear contact structure is presently used to produce high performance large-area modules. Over this period several low-cost methods for depositing the zinc oxide layer have been developed. Good quality zinc oxide films suitable for use in the rear contact structure have been deposited over large-area substrates by two methods: reactive sputtering from a low cost zinc metal target and Low Pressure Chemical Vapor Deposition (LPCVD).

5.2 Low Cost Rear Contacts

In previous periods we explored sputtering from a zinc oxide/aluminum oxide target and reactive sputtering from a zinc/aluminum target as methods of depositing zinc oxide films over large-areas. Both of these methods yielded zinc oxide films that can be used to deposit highly reflecting zinc oxide/aluminum rear contacts. In this period we have explored two additional methods for depositing zinc oxide: reactive sputtering from a pure zinc target and Low Pressure Chemical Vapor Deposition (LPCVD). Both these methods are potentially lower in cost than the previous methods because the cost of the starting materials is significantly lower.

The first method to be scaled up to large-areas in this period was direct current (DC) reactive sputtering from a pure zinc target. In this method there is no controlled doping of the zinc oxide films, rather conducting films are obtained by adjusting the deposition conditions so as to incorporate oxygen vacancies in the film. For this reason, critical deposition parameters must be identified and carefully controlled. Our investigations suggest that substrate temperature, target voltage, and oxygen flow are the important deposition parameters. Typical zinc oxide film properties achieved by this method on 700 Angstrom thick films are: sheet resistance = 500 ohms per square and optical transmission = 87%. These films have been used in rear contacts of both 0.1 m² and 0.37 m² size substrates with good results.

Also in this period, we have built and tested a large-area LPCVD system to deposit zinc oxide films. This reactor is capable of depositing uniform zinc oxide films over areas greater than 0.37 m² (4 ft²). The uniformity of zinc oxide film sheet resistance typically achieved over a 0.37 m² (4 ft²) size substrate using LPCVD is shown in **Figure 5.1**. The

average sheet resistance measured on this film was 437 ohms per square with a standard deviation of 32 ohms per square. The optical transmission of this film was greater than 85%.

Zinc oxide films deposited by LPCVD are now used routinely to deposit zinc oxide/aluminum rear contacts on large-area substrates. Table 5.1 is a comparison of photovoltaic parameters measured on a sample of 0.1 m² (1 ft²) size modules with zinc oxide/aluminum rear contacts where the zinc oxide has been deposited by reactive sputtering from a pure zinc target and LPCVD.

Parameter	Reactive Sputtering	LPCVD
Volts per Segment (volts)	1.51 +/- 0.04	1.50 +/- 0.01
Fill Factor (%)	0.62 +/- 0.03	0.61 +/- 0.01
Short Circuit Current Density (mA/cm ²)	9.57 +/- 0.11	9.56 +/- 0.15

Table 5.1 Comparison of average photovoltaic parameters measured on samples of 0.1 m² (1 ft²) size modules with zinc oxide/aluminum rear contacts. The zinc oxide films were deposited either by reactive sputtering from a zinc target or by LPCVD. The errors limits for each measurement are the two standard error limits. The differences in standard errors are not significant.

Sheet Resistance of Zinc Oxide Film

Figure 5.1 Uniformity of zinc oxide film deposited by LPCVD over a 0.37m² substrate.

6.0 TASK 19: BUSS/WIRE/ENCAPSULATE/FRAME

6.1 Introduction

During this period we have begun to investigate alternative delivery systems for the buss material, continued to investigate low-cost buss formulations, continued to develop and refine approaches to low-cost connector attachment, and investigated alternative materials and methods of encapsulation. Initial results using a positive displacement pump to deliver buss material have been promising. We plan to continue these investigations and perform a direct comparison between this new delivery system and our standard delivery system. We have carried out an extensive study of the factors effecting connector attachment. We find that the most promising bonding system is a combination of potting material around the perimeter of the connector base and an adhesive on the underside of the connector. The highest success rate is achieved when these two different materials are used. Finally, we have continued to investigate proprietary encapsulation materials and begun to investigate high speed application methods for these materials.

6.2 Buss Material Delivery System and Buss Formulations

We have carried out preliminary studies using a positive displacement pump to meter the delivery of buss material to a substrate. Preliminary studies have established that the repeatability in the quantity of buss material dispensed using this system is superior that of our present dispensing system. Unfortunately while the degree of control of the dispensing process is improved, the actual quantity of material dispensed can be varied over a limited range. Discussions with the manufacturer of the pump are continuing in an effort to more fully develop the capabilities of this dispensing system.

Also in this period we have identified several alternative buss material formulations which are lower in cost than our standard formulation. A study to evaluate five distinct formulations with variations in the solids content, viscosity, and the ratio of the component mix was initiated. The five formulations were dispensed on test specimens and evaluated for their dispensing characteristics, initial pull strengths, and pull strengths after Thermal Cycling. Our preliminary results with these formulations are encouraging. All five formulations offered good control during the dispensing and curing processes and the initial pull strengths of these materials were comparable to those obtained with our standard formulations. Three of the five formulations have completed Thermal Cycling stress testing. Of these, one formulation resulted in significant numbers of pull strength failures however the pull strengths of the other two formulations are better than those obtained with our standard formulation. Plans are to complete the evaluation of the two remaining formulations and to confirm these results with subsequent studies.

6.3 Connector Attachment

There are two main requirements of the connector attachment system. First, the adhesive used to attach the connector must supply adequate bond strength so that the connector remains attached to the module during normal handling and module installation. The bond strength must also be stable with continued exposure to environmental stress. Second, the connector must be sealed to protect and isolate the module electrical connections.

To address these issues, a series of investigations were performed to establish the effect of adhesive material, the deposition pattern of the adhesive material, the type of contact, and the potting material on the adhesion and environmental integrity of the connectors. Connectors were mounted on test specimens using various configurations of adhesive and potting materials and these specimens were subjected to a series of tests. Initial visual inspections, pull strength measurements and wet and dry high-potential tests were performed on all specimens. After each of 50 thermal cycles, 150 thermal cycles and 10 humidity-freeze cycles, visual inspections pull strength measurements and high-potential testing were repeated. This investigation yielded several major findings. First, a high rate of failure occurred when the same adhesive material was used to bond the connector and seal the connector. The material properties that provide high pull strengths tend to compromise the environmental integrity of the system. These failures were apparent from both visual inspection, as evidenced by delamination, and from high-potential testing. Where different materials were used to bond the connector and to seal connector both pull strength and environmental integrity were achieved. Second, any one of several adhesive materials can provide the required pull strength for the connector. Third, for a particular adhesive the pull strengths achieved were effected by the pattern of adhesive application, as well as the surface treatments of the connector housing. Based upon these findings, several adhesive/potting systems have been selected for further development. Samples of these systems will be used to fabricate modules for outdoor testing and methods to utilize these systems in a production-sale process will be explored.

6.4 Encapsulation Development

In this period we have continued our development work with several encapsulation materials. The low cost encapsulation systems currently under investigation include acrylic urethanes and UV curable materials, as well as these materials in combination with films such as tefzel and tedlar. We have performed dry and wet high-potential testing on modules encapsulated with these systems initially and after several environmental stress tests. Figure 6.1 summarizes the results of one round of testing done on modules with a combination encapsulant system.

**Wet Hi-Pot Test Results
2250 volts**

Figure 6.1 Wet Hi-Pot test results for a combination encapsulant after environmental stress testing.

In addition to our work on encapsulant materials we are currently exploring high-speed application methods for these materials. These application methods offer a high degree of process control and have the potential for attaining encapsulation line speeds of up to ten times the methods currently employed to encapsulate photovoltaic modules.

7.0 TASK 20: MATERIALS HANDLING

7.1 Introduction

In this period we have begun to explore concepts to accomplish equipment integration in some detail. Station-to-station transport of material and a universal indexing system concepts are under consideration. In addition, finished goods inventory storage, prior to module finishing has been considered.

7.2 Transport and Equipment Integration

Concept designs for automatic station-to-station transport of material and universal indexing are being developed. Station-to-station transport designs include the movement of substrates from one processing station to another processing station where the movement is external to an integrated machine. Designs which address movement within a machine will be included in the overall machine design and are not considered here.

The purpose of station-to-station transport is to accomplish total integration of the production process. That is, to integrate those process steps which are performed external to vacuum processes. Several vendors of material transport equipment have been contacted to determine the extent to which commercially available equipment can be used or can be modified to provide station-to-station transport capability. A number of transport schemes have been identified which may provide the needed capability with minimal modifications. These include transport systems based on air-float principles, conveyor rollers, and ball transfers systems. An important consideration is the extent to which these systems may be integrated with indexing systems that will be used in several of the process locations.

Several of the module fabrication processes require precise and repeatable locating mechanisms to carry out the fabrication step. To provide the needed locating mechanisms, precision indexing systems will be used. Since there are several processes which require precise location, we propose to develop a universal indexing system that can be employed at any of these locations. A universal indexing system offers the advantages of inter-changeability of parts and one-time integration of the indexing system to the station-to-station transport system. We are presently exploring the concept of a universal indexing system and plan to fabricate a mock-up of a system for evaluation.

7.3 Finished Goods Inventory Storage

Recently we have purchased and are now using several commercially available storage racks which may be suitable for storage of unfinished modules. These racks are moveable, providing the capability for transporting unframed modules to and from inventory for subsequent finishing as needed. These racks are available in several sizes, and will accommodate modules of several sizes with no modification to the storage rack. In addition the racks are color-coded and labeled to facilitate inventory control systems.

8.0 TASK 21: ENVIRONMENTAL TEST, YIELD, AND PERFORMANCE ANALYSIS

8.1 Introduction

In this period work was continued on an automated cure station to burn out electrical shorts in large-area multi-junction modules. Testing has begun on this system and comparison studies have demonstrated its effectiveness in curing 0.37 m^2 (4 ft^2) size modules. Also in this period we have initiated a large-area module fabrication tracking system to facilitate our yield analysis of modules. Through this system, we have installed controls on all process steps to reduce the variation in the overall module fabrication process and to identify the major sources of yield loss.

8.2 Automated Cure Station

In this period we have continued process development work on the automated cure station. **Figure 8.1** is a run chart showing the change in module power output of 0.37 m^2 (4 ft^2) size modules that were cured on the automated system and then hand cured. The final hand cure was done to determine the extent to which the automated station was successful in burning out electrical shorts. For this group of modules the average change in power as a result of the final hand cure is 0.002 watts indicating that the automated cure station does cure the module. Comparison studies of this type will be continued in order to monitor the process over time. We expect to utilize this automated cure process routinely in the near future in our large-area module development effort.

Minor systems components and computer interface connections will be installed on this system shortly. This upgrade will provide a permanent record of the cure process which will aid in failure analysis and yield analysis of 0.37 m^2 (4 ft^2) modules.

Automated Cure Station

Figure 8.1 Change in Maximum Power output of modules cured on the automated system and subsequently hand cured.

8.3 Yield Analysis

In this period we have steadily increased the rate of fabrication of large-area modules. We have initiated a lot card system to track each module through the major process steps and have begun to establish better control over the processes. Through this tracking system we have begun to collect data on the major sources of yield loss and to initiate corrective action to reduce the yield loss. The major sources of yield loss include: mechanical damage due to handling and machine breakdown, laser scribe misalignment, deposition equipment failures, incomplete laser scribes, and debris from deposition systems causing increased shunting.

Corrective actions taken to reduce the yield loss have included: the use of more user-friendly module transport and storage devices, more regular and more thorough equipment maintenance, and establishing equipment maintenance and cleaning procedures and increased training on equipment maintenance and cleaning procedures. Yield losses have been reduced from about 15% to under 7%. Further gains are expected.

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