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Subcontractor Report

Monolithically Interconnected Silicon-Film™ Module Technology

Annual Technical Report
25 November 1997 — 24 November 1998

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1 Introduction

1.1 Project overview

AstroPower is employing Silicon-Film technology toward the development of an advanced thin-silicon-based, photovoltaic module product. This module combines the design and process features of advanced thin-silicon solar cells, is light trapped, and integrated in a low-cost monolithic interconnected array. This advanced product includes the following features:

- silicon layer grown on a low-cost ceramic substrate.
- a nominally 50 micron thick silicon layer with minority carrier diffusion lengths exceeding 100 microns.
- light trapping due to back- surface reflection and random texturing.
- back surface passivation.

The thin silicon layer achieves high solar cell performance and can lead to a module conversion efficiency as high as 19%. These performance design features, combined with low-cost manufacturing using relatively low-cost capital equipment, continuous processing and a low-cost substrate, will lead to high performance, low-cost photovoltaic panels.

1.2 Technical Approach

Thin film polycrystalline silicon grown on a low cost substrate is one of the most sought after paths to low cost photovoltaic power [1]. Further cost reductions can be realized through the fabrication of large-area, series-interconnected submodules. Figure 1 illustrates the schematic view of the monolithic interconnect device design.

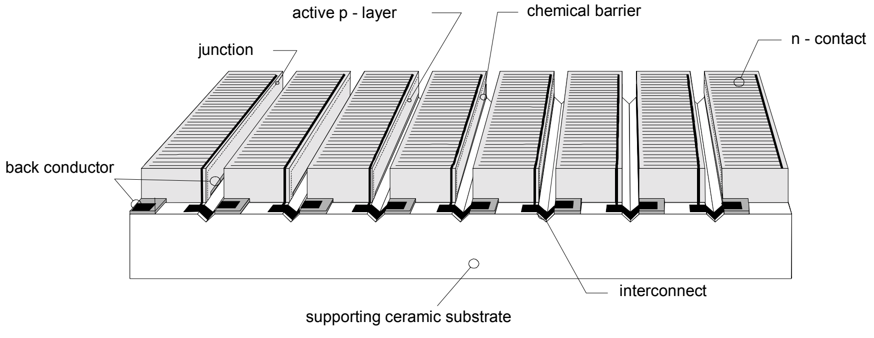

Figure 1. Schematic view of monolithic device design

This design incorporates a method of partitioning the thin-film photovoltaic layer into sub-elements and reconnecting them as a series array. The sub-element device design consists of a thin (35-50 µm) polycrystalline silicon layer which is grown on a low-cost substrate. The thin silicon device structure allows the use of imperfect materials and increased doping levels, and lowers cost by minimizing the use of relatively expensive feedstock material. Diffusion lengths equivalent to twice the device thickness are required to assure high carrier collection through the bulk of the base layer.

The solar cell device structure incorporates light trapping and back surface passivation to improve energy conversion efficiency. Light trapping is achieved by using a diffuse reflector and/or a random texture at the back surface of the thin film, resulting in enhanced optical absorption of weakly absorbed light and improved current generation. Electrical passivation of the back surface is achieved by developing the back layer to minimize surface recombination velocity at the barrier/silicon interface. Back surface passivation results in improved voltage, fill factor, and current by minimizing the reverse saturation current.

1.3 Key Results

The key achievement in the first year of the program has been the development of the ceramic substrate. The ceramic is a self-supporting, electrically insulating, low-cost substrate that is a close thermal expansion match to silicon, and provides the optical properties required for light trapping by random texturing. The ceramic substrates are formed utilizing a tape casting process that allows continuous formation of large-area, thin (25-1250 µm), flat ceramic parts. Implementation of the tape casting process has reduced the number of sequence steps required for substrate preparation and electrical isolation, as the substrate serves as both mechanical support and is an electrical insulator. A previous substrate required a different set of processing steps for the formation of the mechanically supportive substrate and the insulating layer, and therefore was not as cost effective.

A process has been developed to deposit the conductive back layer onto the ceramic substrate. Resistivity of the back contact layer is designed to provide low resistance for good electrical conduction.

The ability to successfully deposit p-type silicon onto our ceramic substrates has been achieved. Different deposition processes including chemical vapor deposition (CVD) have been investigated in parallel, resulting in thin, large-grained p-type active silicon layers after growth.

A deposition technique has been identified to provide a mechanical/chemical barrier between the p-type layer and the back conductive layer. Materials and deposition processes have been evaluated for their compatibility with the growth process, effectiveness at providing good wetting for the film of silicon, and their optical and electrical properties.

Polycrystalline films of silicon have been grown on ceramics utilizing AstroPower's Silicon-Film process. Uniform 50-75 µm thick films with columnar grains extending through the thickness of the film have been grown on the ceramic substrate. Aspect ratios of 5:1 (width:height) have been achieved.

2 Ceramic Substrate Development

2.1 Tape Casting

When designing a substrate for thin-film silicon growth, the primary issues that must be addressed are:

- Mechanical stability at growth temperatures.
- Thermal expansion matched to silicon.
- Minimizing diffusion of impurities to the active silicon layer.

Structured ceramic substrates can be formulated to incorporate these properties and can be manufactured in a cost-effective manner using a tape casting process. The tape casting process pictured in Figure 2 is used to form large-area, thin, flat ceramics on a continuous basis. The advantage to tape casting, over other ceramic forming processes, such as dry pressing or extruding, is that it forms flat pieces with thicknesses in the 25-1250 µm range. During the first year AstroPower has implemented a significant scale-up of our tape casting capabilities. The result of this on-going work is the capability to cast continuous sheets of ceramic 12.5 inches wide.

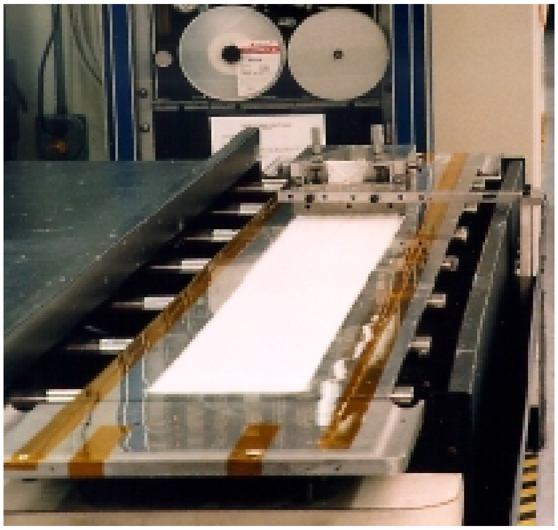

Figure 2. Ceramic tape casting process.

2.2 Ceramic slip formulation

In order to obtain a flat crack free substrate with the tape cast process, a “slip” must be carefully formulated. The “slip” is a solution which contains all of the chemical ingredients required for the ceramic, and the proper chemicals for binding the particles together during the drying process. Based on the stringent requirements of the substrate a mullite family ceramic matrix was chosen. The tape is formed by the use of a “doctor blade”, which evenly coats as the blade is pulled across a smooth surface with the slip.The slip is dried to form a “green-state” tape which is cut to size and then fired (sintered) to form a flat ceramic body. From this “green-state” a density is measured known as the “green density.” It is important to maximize the green density in order to reduce curling and cracking of the ceramic during the sintering process; it is also an early indicator of the final sintered density. The density of the ceramic in the “green” state must be maximized in order to provide a higher sintered mass density for mechanical support of the silicon layer and prevent wet chemicals from leaching into the ceramic during subsequent solar cell fabrication processes. Parameters which have been found to be critical for maximizing the green density are the particle distribution of the ceramic powder, and the selection of a proper binder/solvent system.

Selection of a suitable binder/solvent system is important because it must sufficiently bind the particles together during the drying process but when dried must provide mechanical properties that allow ease of handling before the firing process. The binder must be compatible with the solvent system and needs to be a “film forming type”, which refers to binder systems specifically designed for use in tape casting applications where thin substrate fabrication is required. The binder must also meet the following requirements:

- Easy burn-off
- Good particle adhesion and green strength
- Low cost
- Provide deflocculation and lubrication to the slip

Several binder/solvent systems which utilize either water or organic liquids as the solvent and are commonly employed in industry for the tape casting of ceramics have been investigated. Initial experiments began with the water based solvent/binder systems. The water based solvent system requires that the slip has the proper pH in order to eliminate flocculation and agglomeration of the specific materials being used. The adjustment of pH creates a “zero point of charge” or no net charge on the surface of the particle and depends on the oxide present. This is an important parameter for dispersing powders and ensuring proper fired densities of the final ceramic. In parallel, investigation of organic solvent/binder systems was pursued. Several early tape cast sequences developed severe cracks during the drying process using the solvent based system. It was found that this cracking was due to premature drying, but with modifications to the solvent system an organic solvent/binder system was developed that provides excellent mechanical stability and green density. The water based and organic based solvent/binder sytems are still under investigation.

The other factor critical in determining green density is the particle size distribution of the powders in the ceramic matrix. After analyzing the particle size distribution of the as received powders it was found that there was a need to refine the current milling process to yield a distribution that provides optimum particle packing in the matrix. Figure 3 shows the particle distribution of a ceramic with poor sintered density, and the preferred particle distribution for optimum density.

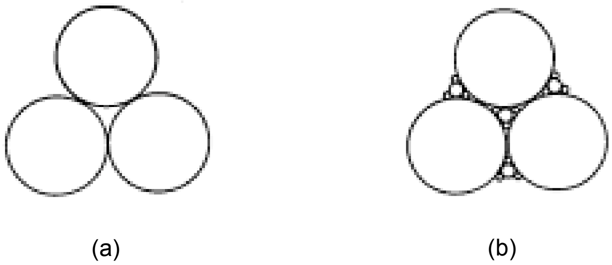

Figure 3. (a) Particle distribution of a ceramic with poor sintered density, and (b) preferred particle distribution for a high mass density sintered ceramic.

In order to achieve the required particle distribution, the milling process for each of the major constituents was investigated at different time durations, resulting in the optimization of green density of the tape cast ceramic.

3 Deposition and Grain Growth

3.1 Deposition

Back contact deposition

A deposition process for the back conductive layer onto the ceramic substrate has been developed. Bulk resistivity measurements of the deposited layer indicate low enough resistivity to provide sufficient back conduction to the monolithic structure, however work is continuing to optimize the back contact for maximum efficiency. Figure 4 shows the back conductor with the fingers for interconnection, deposited onto a 225 cm^2 ceramic substrate.

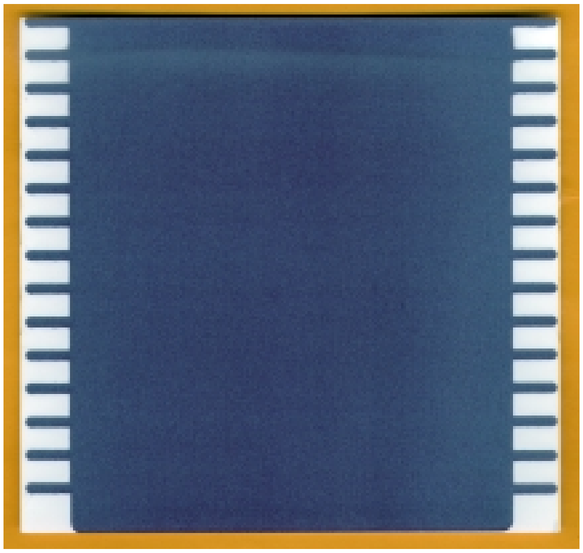

Figure 4. Back conductor deposited onto 225 cm^2 ceramic substrate.

Deposition of chemical/mechanical barrier

Materials and deposition processes have been evaluated for their compatibility with the growth process, effectiveness at providing good wetting for the film of silicon, and optical and electrical properties. A process has been identified that results in intact layers (following growth) between the active p-type silicon and the conductive back layer, with good wetting characteristics. Work is continuing to optimize mechanical stability of the layer at growth temperatures and to identify optimum thickness requirements.

Deposition of p-type silicon layer

The p-type silicon deposition process being used has become fairly straightforward. High purity silicon layers can reproducibly be deposited resulting in layers ~ 50 µm thick following the growth process. In parallel, p-type depositions on the ceramic were performed at The Institute of Energy Conversion (IEC) at the University of Delaware. These depositions were accomplished utilizing a “Hot Wire” CVD system that the Institute is currently investigating. The silicon layers that were deposited are nominally 5 µm thick. SIMS analysis of these thin silicon layers indicates excessive impurity levels, which are believed to be from the CVD chamber. Although devices were not fabricated on these samples due to the high impurity levels, reflectance measurements were done to analyze light trapping and are discussed in further detail in Section 4. IEC has recently reduced the sources of contamination in their CVD process, and work has resumed to develop appropriate bulk resistivity doping of the deposited layers.

Based on the successes of the IEC work with the CVD deposition of silicon on substrates at low temperatures (~ 400-500° C), AstroPower is developing its own in-house CVD system. Due to the ability of the ceramic substrate to remain stable at high temperatures the CVD system was designed to do depositions at 1200° C. At this temperature material utilization and grain aspect ratios (width: height), that have not been obtained with the hot wire process at conventional CVD processing temperatures, have been achieved. The current in-house system is capable of depositing onto two 1” x 1” samples per run and these initial deposition results have provided the process data that enabled the design of a CVD system for the deposition of silicon over larger areas. The CVD system being designed and built will accommodate 225 cm^2 samples and have the ability to do depositions at high temperatures.

3.2 Grain Growth

Polycrystalline films of silicon have been grown on ceramics utilizing AstroPower’s Silicon-Film process. The present growth system is capable of 30 cm wide sheets of ceramic, and the linear rate of work transport is 33 cm/min. Initial growth of the silicon layers on the ceramics resulted in varying degrees of substrate warping. In an effort to understand this post-growth warp, ceramic substrates of varying formulations were subjected to the growth temperatures without a silicon layer. With proper modifications to the ceramic formulation a ceramic was developed that remains flat through the growth process.

Figure 5 shows the morphology of a thin silicon layer on ceramic after the growth process. Cross sectional analysis reveals uniform 50-75 µm thick films of silicon with columnar grains extending through the thickness of the film with aspect ratios ranging from 5:1 to 20:1 (width: height). Figure 6 shows a cross section of a growth having aspect ratios of 5:1.

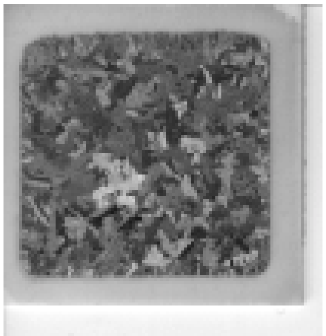

Figure 5. Front view of thin silicon morphology on a 1”x1” ceramic substrate.

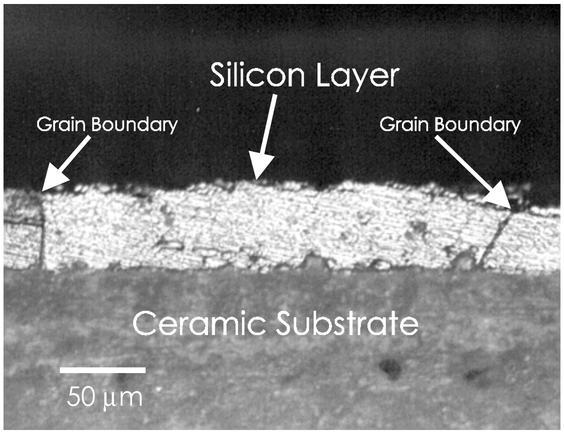

Figure 6. Cross-sectional view of silicon layer grown on ceramic.

Initial device results (1 cm^2 device) on these structures have exhibited promising open-circuit voltages (average 560 mV), however, the short-circuit currents are lower than expected (average 19 mA/cm^2) after AR. The present Si feedstock is currently being investigated as a contributor to the low Jsc values.

4 Light Trapping

The optical path length of light in a thin-film crystalline silicon solar cell must exceed the thickness of the device to generate high light-generated currents. Extended path lengths can be achieved by making the interface surfaces of the silicon layer and ceramic reflective through pigmenting [2] and random texturing.

Since the front surface of the device requires an antireflective coating that provides little or no reflection to normally incident light, internal reflection requires some degree of texturing to redirect the trapped light.

Texturing of a thin film of silicon can be done on either surface; the surface exposed to light, or the imbedded surface at the film-support interface. Our approach has been to utilize the natural texture of the silicon-ceramic interface to texture the back surface of the thin film device. Optical measurements of silicon on ceramic structures can be analyzed to extract significant optical design parameters [3].

Figure 7 displays reflectance data for a 5-µm film of silicon deposited on a ceramic substrate. Included in Figure 7 as a control is the reflectance data for a conventional, 500-µm thick, polished silicon wafer. The near-bandgap region (900 to 1300-nm) indicates that some degree of light trapping is occurring in the thin film. The front surface reflection (R_{front}) of both samples is approximately 30%, which is expected for silicon in this range. The escape reflection (light that enters the device and escapes after some number of internal reflections) varies considerably for the two structures. The control wafer reaches a total reflectance value of approximately 47% for non-absorbed light. This implies a back surface reflectivity of 27% [3], which agrees well with the R_{front} of 30%. The escape reflectance of the silicon on ceramic continues to increase with increasing wavelength. The optical properties of the ceramic, as well as redirection of the light through texturing are leading to this change.

Assuming the simple model of non-absorbed light, the effective reflectance of the silicon-ceramic interface is over 60%. This effect combined with the slow increase of escape reflectance with wavelength for such a thin film implies a high degree of internal reflections and randomization of the light is occurring.

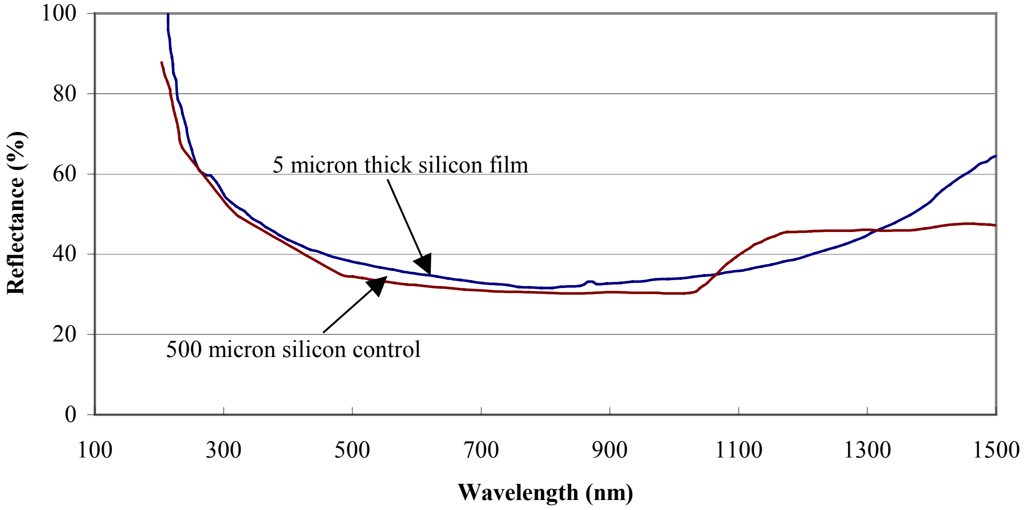

Figure 7. Reflectance of a 5 µm thick film of silicon deposited on a ceramic substrate and a 500 µm thick conventional polished silicon wafer.

5 Summary

AstroPower has continued its development of an advanced thin-silicon-based photovoltaic module product. This module combines the performance advantages of thin, light trapped silicon layers with the capability of integration into a low-cost monolithically interconnected array. This report summarizes the work carried out over the first year of a three year cost-shared contract which has yielded the following results:

- Development of a low-cost insulating ceramic substrate that provides mechanical support at silicon growth temperatures, is thermal expansion matched to silicon, provides the optical properties required for light trapping through random texturing, and can be formed in large areas on a continuous basis.

- Different deposition techniques have been investigated and deposition processes for the back conductive layer, the p-type silicon layer, and the mechanical/chemical barrier layer have been developed.

- Polycrystalline films of silicon have been grown on ceramics utilizing AstroPower's Silicon-Film process. These films are 50-75 μm thick with columnar grains extending through the thickness of the film. Aspect ratios from 5:1 to 20:1 have been observed in these films.

6 References

[1] 2nd World Conference on Photovoltaic Solar Energy Conversion, Proceedings (in press), Vienna, Austria, July 6-10, 1998.

[2] J.E. Cotter, Ph.D. Thesis, University of Delaware (December, 1996).

[3] J.A. Rand and P.A. Basore, "Light-Trapping Silicon Solar Cells Experimental Results and Analysis", 22nd IEEE PVSC, (1991), pp. 192-197.

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13. ABSTRACT *(Maximum 200 words)*

AstroPower continued its development of an advanced thin-silicon-based photovoltaic module product. This module combines the performance advantages of thin, light-trapped silicon layers with the capability of integration into a low-cost, monolithically interconnected array. This report summarizes the work carried out over the first year of a three-year, cost-shared contract, which has yielded the following results:

- Development of a low-cost, insulating, ceramic substrate that provides mechanical support at silicon growth temperatures, is matched to the thermal expansion of silicon, provides the optical properties required for light trapping through random texturing, and can be formed in large areas on a continuous basis.
- Different deposition techniques have been investigated, and AstroPower has developed deposition processes for the back conductive layer, the p-type silicon layer, and the mechanical/chemical barrier layer.
- Polycrystalline films of silicon have been grown on ceramics using AstroPower's Silicon-Film™ process. These films are from 50 to 75 µm thick, with columnar grains extending through the thickness of the film. Aspect ratios from 5:1 to 20:1 have been observed in these films.

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