Thin-Film Amorphous Silicon Alloy Research Partnership, Phase I

Annual Technical Progress Report 2 February 1995 - 1 February 1996

S. Guha
United Solar Systems Corp.
Troy, Michigan

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Preface

This Annual Subcontract Report covers the work performed by United Solar Systems Corp. for the period 2 February 1995 to 1 February 1996 under DOE/NREL Subcontract No. ZAF-5-14142-01. The following personnel participated in the research program.

E. Akkashian, A. Banerjee, E. Chen, T. Glatfelter, S. Guha (Principal Investigator),
M. Haag, G. Hammond, K. Hoffman, N. Jackett, M. Lycette, J. Noch, D. Wolf, X. Xu,
J. Yang, and K. Younan.

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Executive Summary

Objectives

The principal objective of this R&D program is to expand, enhance and accelerate knowledge and capabilities for the development of high-performance, two-terminal multijunction amorphous silicon (a-Si) alloy modules. The near-term goal of the program is to achieve 12% stable module efficiency by 1998 using the multijunction approach.

Approach

The major effort of the program is to develop high efficiency component and triple-junction cells with uniform property over large area so as to facilitate fabrication of monolithic modules of one-square-foot area. The component cells use materials of different bandgaps and incorporate Ge for the middle and the bottom cells. In order to reduce manufacturing cost by lowering material cost, improving throughput and minimizing optical and electrical losses associated with module fabrication, a novel laser-drilling approach has been developed and is being optimized. Investigations of long-term reliability of the modules through accelerated testing form an integral part of the program.

Status/Accomplishments

- Investigations have been carried out on Ag/ZnO and Ag/TiO₂/ZnO back reflectors to assess their suitability for use in cell structures. Incorporation of TiO₂ is not found to give any additional advantage. Excellent uniformity has been achieved in the deposition of Ag/ZnO over one-square-foot area.
- Arrays of high efficiency component cells have been made over one-square-foot areas. Single-junction top cells have been made with an average stabilized power density of 48-51 W/m² measured under global AM1.5 illumination. Single-junction middle cells have been optimized to give average stabilized power density of 34 W/m² under global AM1.5 illumination with a cut-on filter with $\lambda > 530$ nm. Both these arrays are made on stainless steel substrate without any back reflector. Single-junction bottom cells have been fabricated on Ag/ZnO back reflectors with an average power density of 33-36 W/m² as measured under global AM1.5 illumination with a cut-on filter with $\lambda > 630$ nm. All these values exceed the milestones stipulated for Phase I.
- Arrays of high efficiency triple-junction cells of 1 cm² active-area have been fabricated over one-square-foot area with average stabilized efficiency of 11.1% as measured under AM1.5 illumination. This exceeds the Phase I milestone.
- Using the novel laser-drilling approach, a stabilized total-area efficiency of 9.8% has been achieved in a triple-cell structure of 12.5 cm² area exceeding the Phase I milestone.
- Reliability studies based on NREL's Interim Qualification Testing have been carried out to confirm the suitability of the module encapsulation materials and processes.

Section 1

Introduction

This report describes the research performed during Phase I of a three-phase, three-year program under NREL Subcontract No. ZAF-5-14142-01. The research program is intended to expand, enhance and accelerate knowledge and capabilities for the development of high-performance, two-terminal multijunction amorphous silicon (a-Si) alloy modules.

It is now well recognized that a multijunction, multibandgap approach has the potential of achieving the highest stable efficiency in a-Si alloy solar cells. In this approach, the bandgap of the materials of the component cells is varied in order to capture a wide spectrum of the solar photons. Significant progress has been made in the development of materials and cell design in the last few years, and a stable module efficiency of 10.2% has been demonstrated over one-square-foot area using a triple-junction approach in which the bottom two component cells use amorphous silicon-germanium (a-SiGe) alloy. In order to meet the Department of Energy goal of achievement of 12% stable module efficiency by 1998, it is necessary to make further improvements in each of the component cells.

New back reflectors also need to be developed to facilitate improved light-trapping performance. Since the aim of the program is to develop a manufacturing technology, the research work must address issues involving scaleup, reliability and cost. It should be pointed out that reliability and cost issues encompass module interconnect and encapsulation methods as well.

The research report describes the activities carried out in Phase I on various tasks that were taken up to address the above issues. In Section 2, we discuss investigations on back reflectors to improve cell performance, and in addition to the Ag/ZnO system, the introduction of a buffer layer of TiO₂ between Ag and ZnO to reduce parasitic loss is studied. In Sections 3 and 4, we present results on performance of cells, both component and triple structures, deposited over one-square-foot area. The uniformity in deposition is investigated by studying the performance of subcells deposited over the entire area. In Section 5, we discuss the novel laser-processing technique that has been developed at United Solar to improve energy-conversion efficiency and reduce manufacturing cost. Detailed description of optimization of the processing steps is discussed, and performance of a laser-processed, triple-junction device of 12.5 cm² area is presented. Experimental results on investigations of reliability of modules are presented in Section 6. Future directions of the research work are outlined in Section 7.

Section 2

Back Reflector Study

Introduction

One of the essential requirements in achieving high efficiency solar cells is that the back reflector must possess high reflectivity with light trapping quality. Although our present textured Ag/ZnO back reflector has these properties and does give rise to significant enhancement in the red response, there still appears to have scope for further improvement in the reduction of parasitic losses (Guha 1993).

In this section, we present results of our study on specularly and uniformity of large-area Ag/ZnO back reflector, and on optical and solar cell characteristics on Ag/TiO₂/ZnO system that we collaborated with Prof. Roy Gordon of Harvard in an attempt to reduce parasitic losses. We shall also present state-of-the-art a-SiGe alloy solar cells on Ag/ZnO with $J_{sc} \sim 25 \text{ mA/cm}^2$.

Specularity and Uniformity Study of Large-area Ag/ZnO Back Reflector

We have produced an Ag/ZnO back reflector using the "Radlas" sputtering machine that meets the Phase I milestone. The milestone states *"that the total integrated reflected reflectance in the 800-900 nm range is greater than 75% with specular component less than 15%."* Figure 1 shows the reflection of this BR. Sections of this BR were measured with our reflection apparatus that uses a large integrating sphere and a monochromator. The samples needed to be smaller to fit into the measurement apparatus, so samples were chosen to represent the whole of the BR (i.e., center and four corners). The specularity of these BR sections was also measured; the results are illustrated in Table 1. The definition of specularity used for this work was the amount of light from a HeNe laser scattered into a detector subtending a small solid angle. The results of Fig. 1 and Table 1 clearly show compliance with the Phase I milestone.

Table 1. Specularity Measurement at Various Locations on a 900 cm² Ag/ZnO Back Reflector.

Location	Specularity
NE corner	10.4%
NW	11.3%
SW	11.5%
SE	10.5%
Center	13.5%

Back Reflector Reflection

Figure 1. Reflection measurements versus wavelength of the incident light at several locations of a 900 cm² Ag/ZnO back reflector.

Optical and a-SiGe Alloy Solar Cell Characteristics of Ag/TiO₂/ZnO Back Reflector

We have coated representative samples of substrates received from Harvard with our standard zinc oxide and produced solar cell structures. Pertinent measurements are shown in Fig. 2. Referring to the figure: the graph marked {A} is the reflection spectra of samples as received from Harvard. {B} shows the reflection spectra of the same samples after ZnO coating at United Solar. {C} shows the spectral response (Q) of a-SiGe alloy solar cells produced on the samples. The Q was measured at short circuit. Also shown on the figure are the integrated currents of the Qs with respect to the whole AM1.5 Global Standard Spectrum and to the portion greater than 630 nm. {A}, {B}, & {C} are blown up separately for clarity.

The a-SiGe alloy solar cells were made in consecutive runs using identical deposition parameters. The solar cells were made in the *n i p* configuration (i.e., *n* layer grown first, light shines through *p* layer). The intrinsic material has a Tauc gap of about 1.45 eV; the *i* layer thickness is about 2,500Å. The ZnO was grown during one deposition run using a large area DC magnetron sputtering machine. Its thickness is nominally 1 µm.

The measurements in {A} are essentially the same as measurements provided by Dr. Gordon, as expected. The TiO₂ coating appears to generally increase the absorption of the substrate in air by an average of about 10%. The niobium has the optical effect of decreased blue reflection with increasing niobium concentration. Little difference is seen in the reflection at wavelengths greater than 650 nm. However, after ZnO deposition (drawing {B}), discernable differences in reflection are clearly seen. Interestingly, after ZnO coating *higher* Nb concentration results in *higher* reflection. In other words, the trend in {A} seems to be in contrast to the trend in {B}.

The spectral response measurement is displayed in {C}. The integrated current of the sample without TiO₂ is similar to the undoped TiO₂ (20.5 vs. 20.7 mA/cm²). They are the same also in red light (>630 nm). We use the integrated current in red light to nullify any effects due to variations in ITO and/or *p* layer absorption. Such effects are not apparent in this series of experiments. The integrated AM1.5 current should be equivalent to J_{sc} under standard conditions. The current for the 5% Nb-doped sample is slightly lower. Results for the 2.5% Nb-doped sample were anomalous: the spectral response shape was markedly lower and different, its V_{oc} was much greater than the other samples, and its measured thickness was greater. Therefore, the data from this cell was not included in graph {C} and in the IV analysis given below.

Solar cell I-V characterization is summarized for each sample in Table 2. The solar cells represented in this table are 0.05 cm² dots defined by the ITO deposition. It is difficult to judge whether fill factor differences shown here are significant.

Table 2. Solar Cell I-V Data for this Study.

<u>Sample Description</u>	<u>Jsc</u> (mA/cm ²)	<u>FF</u>	<u>Voc</u> (volts)	<u>Rs</u> (Ω-cm ²)
no TiO ₂	20.5	0.53	0.746	10.5
TiO ₂ undoped	20.7	0.51	0.738	11.9
TiO ₂ with 5% Nb	20.1	0.51	0.731	11.8

Harvard TiO₂

Harvard TiO₂

Harvard TiO₂

	<u>AM1.5</u>	<u>≥630nm</u>
	(mA/cm ²)	
Ag only	: 20.5	8.82
TiO ₂	: 20.7	8.71
TiO ₂ +5Nb	: 20.1	8.30

Figure 2. Comparison measurements integrated spectral response of TiO₂ based structures. The graphs and data are described in the text.

A

TiO2 Study

Ag / TiO

Harvard TiO2

B

TiO2 study

Ag / TiO2 / ZnO

Harvard TiO2

C

TiO2 Study Solar Cells

Harvard TiO2

We believe that some comment can be made at this time regarding the TiO_2 effect on solar cell shunt resistance. Each solar cell sample made in our group has many 0.25 cm^2 cells on them in addition to numerous 0.05 cm^2 cells. Measurements of the 0.25 cm^2 solar cells' room light V_{oc} were made on each of the samples. The samples with TiO_2 did not show statistically measurable improvement in terms of shunting.

Despite some not well understood aspects of these results, it appears that TiO_2 may be used without detriment to solar cell efficiency. Other investigations may include the effect of TiO_2 thickness on solar cell performance and long-term reliability tests to prove whether TiO_2 may serve as a barrier to certain types of solar cell failure.

Narrow Bandgap a-SiGe Alloy Solar Cells on Ag/ZnO with $J_{sc} \sim 25 \text{ mA/cm}^2$

One of the methods to evaluate back reflectors is to deposit a narrow bandgap a-SiGe alloy solar cell and measure its quantum efficiency, paying particular attention to its red response. We have deposited various a-SiGe alloy cells on Ag/ZnO back reflectors and evaluated their performance. The best cell obtained to date measured under AM1.5 global illumination with a $\lambda > 630 \text{ nm}$ cut-on filter has the following characteristics: $J_{sc} = 12.15 \text{ mA/cm}^2$, $V_{oc} = 0.619 \text{ V}$, $\text{FF} = 0.635$, and $P_{max} = 4.78 \text{ mW/cm}^2$. This represents the highest initial power achieved for an a-SiGe alloy cell. The quantum efficiency versus wavelength data are shown in Fig. 3. The photocurrent obtained by convoluting the quantum efficiency curve with respect to AM1.5 global spectrum is 24.8 mA/cm^2 . At $\lambda = 850 \text{ nm}$, the quantum efficiency is 40%, reflecting the high quality of the back reflector.

Figure 3. Quantum efficiency versus wavelength for an a-SiGe alloy bottom cell on Ag/ZnO back reflector.

Section 3

Status of a-Si Alloy and a-SiGe Alloy Component Cells

Introduction

In order to obtain high efficiency multijunction devices for module fabrication, two conditions have to be met. First, it is necessary to optimize the component top, middle, and bottom cells on appropriate substrates. Second, the uniformity of the component cell efficiency over the module area should be good. In this section both issues are addressed. All the results reported here have been obtained on devices made in the 2B machine (a multichamber rf glow discharge system capable of depositing amorphous silicon alloy layers over one-square-foot substrates).

Device Fabrication and Measurement

The starting substrate material is a thin stainless steel (ss) sheet of approximately one-square-foot area. The back reflector (BR) consists of textured Ag/ZnO films deposited over the one-square-foot area by sputtering. The semiconductor devices are made by conventional glow discharge deposition over the entire area. The top transparent conducting oxide (TCO) layer is deposited in two different configurations. In the first, the TCO film covers the entire area. The TCO film is subsequently etched to yield an array of 11 x 12 (total of 132) devices each of active area 0.82 cm² (total area = 0.98 cm²). The array covers an area of approximately 900 cm². I-V measurements are made on each device. The uniformity of device performance is evaluated by making contour plots for the one-square-foot area. In the second type of TCO, the substrate is cut into 2" x 2" pieces and TCO is deposited through an evaporation mask to yield devices of active area 0.25 cm² and 1 cm² area.

The top a-Si alloy cell is normally deposited on ss substrates with no back reflector and measured under AM1.5 condition. The rationale is that the top cell in the triple-junction configuration sees the full spectrum of the incident light but does not receive any reflected light since the underlying a-SiGe alloy cells starve it of any reflected light. It should be noted that the back reflector texture is known to have a deleterious effect (Banerjee et al. 1994-1, Banerjee et al. 1994-2, and Banerjee et al. 1995) on V_{∞} and FF. Therefore, the correlation between the device performance on the stainless steel substrate and the simulated performance of the corresponding component cell in the triple-junction structure has some limitations. Wherever possible, the component cell performance on both ss substrate with no back reflector as well as on Ag/ZnO back reflector is given.

For similar reasons as for the top cell, the middle component a-SiGe alloy cell consisting of intermediate bandgap a-SiGe alloy *i* layer is also deposited on ss substrate with no back reflector. In this case, the error in the simulation is slightly higher since the middle cell in the triple-junction configuration receives a small amount of reflected light. The I-V measurements on the middle cell are done through a bandpass filter of $\lambda > 530$ and/or 550 nm in order to simulate the filtering effect of the incident light of the top cell.

The bottom component cell using narrow bandgap a-SiGe alloy *i* layer is deposited on a textured Ag/ZnO back reflector. The I-V measurements are made through a bandpass filter of $\lambda > 630$ nm in order to simulate the light which the device receives in the triple-junction structure.

Light Soaking

The component cells have been light-soaked to determine the stabilized values. The devices were degraded under one-sun, open-circuit, and 50 °C conditions for over 600 hours. The middle and bottom component cells were illuminated through appropriate high wavelength cut-on filters to simulate the short-circuit current density which the respective devices produce in the triple-junction configuration. The stabilized values of the top and middle cells on ss substrate only and the bottom cell on BR only are reported.

Status of a-Si Alloy Top Cell on ss

Initial Results

The initial results of the top a-Si alloy cell on ss substrate are summarized in Table 3. It may be noted that all the results presented in Table 3 are typical values except that of the bottom cell on BR which is the best one obtained. Normally, the spread between the best data and the typical value is approximately 5%. For comparison, the results of an equivalent cell on back reflector is also shown. The values of V_{oc} , J_{sc} (from Q measurements), FF, and P_{max} of the device on ss substrate are 1.003 V, 77.2 A/m², 0.747, and 57.8 W/m², respectively. The corresponding values on BR are 1.016 V, 114.5 A/m², 0.710, and 82.5 W/m², respectively. The high values of V_{oc} are attributed to the use of microcrystalline *p* layer.

As mentioned above, the uniformity of the top cell performance on ss substrate has been evaluated by measuring the I-V characteristics of an array of 11 x 12 devices each of active area 0.82 cm². The contour plot of the normalized efficiency is shown in Fig. 4. The contour values range from 0.94 to 1.0 implying an uniformity of approximately 94% over the 900 cm² area.

Table 3. Initial Results of the Top, Middle, and Bottom Component Cells.

Type	Substrate	Area (cm ²)	Measurement Spectrum	V_{oc} (V)	J_{sc} (A/m ²)	FF	P_{max} (W/m ²)
Top	ss	0.25	AM1.5	1.003	77.2	0.747	57.8
	BR	0.25	AM1.5	1.016	114.5	0.710	82.5
Middle	ss	0.25	$\lambda > 530\text{nm}$	0.768	79.5	0.711	43.4
			$\lambda > 550\text{nm}$	0.763	68.0	0.712	36.9
	BR	0.25	$\lambda > 530\text{nm}$	0.801	126.0	0.674	68.0
			$\lambda > 550\text{nm}$	0.798	114.2	0.674	61.4
Bottom	ss	0.25	$\lambda > 630\text{nm}$	0.633	38.0	0.680	16.3
	BR	0.25	$\lambda > 630\text{nm}$	0.681	100.4	0.657	44.9

Figure 4. Contour plot of normalized efficiency of the top cell on ss. The figure represents a solar cell area of 900 cm^2 .

Stabilized Results

The stabilized cell performance of three different runs made on ss substrate, samples A, B, and C, are summarized in Table 4. Note that all the results shown in the table are typical values. Normally, the run-to-run variation is approximately 5%. In each case, one representative 2" x 2" substrate consisting of four 0.82 cm² devices was cut out from the parent 900 cm² substrate which had the 11 x 12 devices array. The samples were light-soaked for 1060 hours. The numbers in Table 4 represent the average value of the devices on each substrate. The stabilized values of V_{oc} , FF, J_{sc} , and P_{max} for the top cell are 0.93 - 0.94 V, 0.69 - 0.70, 72 - 78 A/m², and 48 - 51 W/m², respectively. The corresponding milestone values for Phase I also listed in Table 4 are 0.94 V, 0.67, 73 A/m², and 46 W/m². Thus, the representative samples meet the milestone requirements.

In order to ensure that the entire 900 cm² area satisfies the milestone values, the initial efficiency of all the 11 x 12 devices distributed over the 900 cm² were measured. The initial average efficiency of the devices which were actually light-soaked were then compared with the initial average efficiency of all the devices. The results of samples A, B, and C are summarized in Table 5.

The table shows that the initial efficiency values of the 2" x 2" substrates selected for light soaking for cases A, B, and C are 5.2, 5.6, and 5.3%, respectively. The corresponding values for the entire 900 cm² are 5.2, 5.7, and 5.4%, respectively. The two sets of values are similar implying that the selected small area is typical of the 900 cm² area. Thus, the expected stabilized efficiency of the remainder of the 900 cm² area (and thereby the entire area) is also expected to be similar to the corresponding 2" x 2" result. Further, the efficiency contour plot shown in Fig. 1 shows that the initial performance of the devices over the 900 cm² is very uniform. Hence all areas of the parent substrate are expected to exhibit stabilized values similar to the representative 2" x 2" specimen.

Status of a-SiGe Alloy Middle Cell on ss

Initial Results

The initial results of the a-SiGe alloy middle cell on both ss and Ag/ZnO BR are summarized in Table 3. The device performance under AM1.5 illumination using $\lambda > 530$ nm and $\lambda > 550$ nm cut-on filters are given for both cases. The values of V_{oc} , J_{sc} (from Q measurements), FF, and P_{max} for the ss case with $\lambda > 530$ nm are 0.768 V, 79.5 A/m², 0.711, and 43.4 W/m², respectively. The corresponding numbers for $\lambda > 550$ nm are 0.763 V, 68 A/m², 0.712, and 36.9 W/m², respectively. The values of V_{oc} , J_{sc} , FF, and P_{max} for the BR case with $\lambda > 530$ nm are 0.801 V, 126 A/m², 0.674, and 68 W/m², respectively. The corresponding numbers for $\lambda > 550$ nm are 0.798 V, 114.2 A/m², 0.674, and 61.4 W/m², respectively. The higher values of J_{sc} and P_{max} for the BR case are attributed to enhanced red response of the cell and the lower FF is attributed to the deleterious effect of the BR.

The uniformity of the middle cell has been studied in a slightly different way than the top cell. Different sections of the 900 cm² device on the ss substrate were cut into ten representative 2" x 2" substrates. ITO dots of area 0.25 cm² and 1 cm² were deposited on the devices through an evaporation mask. The I-V characteristics were measured on all ten substrates. The average values of efficiency measured under AM1.5 spectrum on two of the substrates are compared with that of all the ten substrates in Table 5. The uniformity is within 5% over the entire area.

Table 4. Stabilized Values of V_{oc} , FF, J_{sc} , and P_{max} of the Component Cells and the Corresponding Phase I Goals.

2B #	Area (cm ²)	Hours	Measurement Spectrum	V_{oc} (V)	FF	J_{sc} (A/m ²)	P_{max} (W/m ²)
Top cell on ss							
A	0.82	1060	AM1.5	0.94	0.70	72	48
B	0.82	1060	AM1.5	0.93	0.69	78	51
C	0.82	1060	AM1.5	0.93	0.70	74	48
<i>Phase I Goal</i>	1	600	AM1.5	0.94	0.67	73	46
Middle cell on ss							
D1	0.25	1962	$\lambda > 550\text{nm}$	0.71	0.61	66	29
D2	0.25	1962	$\lambda > 550\text{nm}$	0.73	0.57	67	28
D3	1	616	$\lambda > 530\text{nm}$	0.73	0.60	78	34
<i>Phase I Goal</i>	1	600	$\lambda > 530\text{nm}$	0.73	0.55	73	29
Bottom cell on BR							
E	0.82	660	$\lambda > 630\text{nm}$	0.64	0.57	91	33
F	0.82	660	$\lambda > 630\text{nm}$	0.64	0.57	98	35
G	0.82	660	$\lambda > 630\text{nm}$	0.64	0.57	99	36
<i>Phase I Goal</i>	1	600	$\lambda > 630\text{nm}$	0.65	0.55	79	28

Stabilized Results on ss

Two 2" x 2" substrates (samples D1 and D2) with 0.25 cm² devices and one with 1.0 cm² (sample D3) devices, taken from the ten ss samples, were subjected to light soaking. The results, measured under AM1.5 illumination using $\lambda > 530\text{ nm}$ and $\lambda > 550\text{ nm}$, after more than 600 hours of light soaking are summarized in Table 4. The stabilized values of V_{oc} , FF, J_{sc} , and P_{max} measured with a $\lambda > 550\text{ nm}$ filter are 0.71 - 0.73 V, 0.57 - 0.61, 66 - 67 A/m², and 28 - 29 W/m², respectively. The corresponding stabilized values measured with a $\lambda > 530\text{ nm}$ filter are 0.73 V, 0.60, 78 A/m², and 34 W/m², respectively. The *Phase I* milestone values, also listed in Table 4, using a $\lambda > 530\text{ nm}$ filter are 0.73 V, 0.55, 73 A/m², and 29 W/m², respectively. Thus, the three samples meet the milestone requirement. Note that the $\lambda > 550\text{ nm}$ criterion used for measuring samples D1 and D2 is more stringent than the milestone requirement.

Though only three of the 2" x 2" substrates satisfied the milestone requirements, it is clear that the entire 900 cm² would satisfy it since the average of the initial efficiency of the ten representative 2" x 2" pieces listed in Table 5 is similar to those of the ones actually used for the light soaking experiment.

Table 5. Comparison of the Average Initial Efficiency of the Light-soaked 2" x 2" Substrate Versus the Entire 900 cm² Area.

Type	#	AM1.5 Initial Efficiency (%)	
		2" x 2"	900 cm ²
Top	A	5.2	5.2
	B	5.6	5.7
	C	5.3	5.4
Middle	D1	7.0	7.4
	D2	7.3	7.4
Bottom	E	9.0	9.0
	G	8.5	8.5

Status of a-SiGe Alloy Bottom Cell on Back Reflector

Initial Performance

The initial performance of the bottom a-SiGe alloy narrow bandgap cell on both ss and BR are summarized in Table 3. The device performance under AM1.5 illumination using $\lambda > 630$ nm is given in both cases. The values of V_{oc} , FF, J_{sc} (from Q measurements), and P_{max} for the ss case are 0.633 V, 0.680, 38 A/m², and 16.3 W/m², respectively. The corresponding values for the BR case are 0.681 V, 0.657, 100.4 A/m², and 44.9 W/m², respectively. The higher values of J_{sc} and P_{max} for the BR case are attributed to enhanced red response of the cell and the lower FF is attributed to the deleterious effect of the BR.

The uniformity of the bottom cell performance on BR substrate has been evaluated in a way similar to the top cell. The I-V characteristics of an array of 11 x 12 devices each of active area 0.82 cm² are measured. The contour plot of the normalized efficiency is shown in Fig. 5. The contour values range from 0.94 to 1.0 implying an uniformity of approximately 94% over the 900 cm² area.

Stabilized Results

The stabilized results of three different runs made on BR substrate, samples E, F, and G, are summarized in Table 4. In each case, one representative 2" x 2" substrate consisting of four 0.82 cm² devices was cut out from the parent 900 cm² substrate which had the 11 x 12 devices array. The samples were light-soaked for 660 hours. The numbers in Table 4 represent the average value of the devices on each substrate measured under AM1.5 spectrum using a $\lambda > 630$ nm cut-on filter. The stabilized values of V_{oc} , FF, J_{sc} , and P_{max} are 0.64 V, 0.57, 91 - 99 A/m², and 33 - 36 W/m², respectively. The corresponding milestone values for *Phase I* also listed in Table 4 are 0.65 V, 0.55, 79 A/m², and 28 W/m². Thus, the representative samples meet the milestone requirement.

Figure 5. Contour plot of normalized efficiency of the bottom cell on BR. The figure represents an area of 900 cm².

In order to ensure that the entire 900 cm² area satisfies the milestone values, the initial efficiency of all the 11 x 12 devices distributed over the 900 cm² were measured. The initial average efficiency of the devices which were actually light-soaked were then compared with the initial average efficiency of all the devices. The results are summarized in Table 5.

The table shows that the initial efficiency values of the 2" x 2" substrates selected for light soaking for cases E and G are 9.0 and 8.5%, respectively. The corresponding values for the entire 900 cm² are also 9.0 and 8.5%, respectively. The two sets of values are same implying that the selected small area is typical of the 900 cm² area. Thus, the expected stabilized efficiency of the remainder of the 900 cm² area (and thereby the entire area) is also expected to be similar to the corresponding 2" x 2" result. Further, the efficiency contour plot shown in Fig. 5 shows that the initial performance of the devices over the 900 cm² is very uniform. Hence all areas of the parent substrate are expected to exhibit stabilized values similar to the representative 2" x 2" specimen.

Section 4

Status of Triple-Junction Solar Cells and Modules

Introduction

Triple-junction triple-bandgap approach has been adopted to obtain high efficiency multijunction devices. The bottom and middle cells employ narrow bandgap and intermediate a-SiGe alloy *i* layers, respectively. The top cell uses a-Si alloy *i* layer. The status of the initial efficiency, stabilized efficiency, and uniformity of the component cells have been described in Section 3. In this section, the status of the triple-junction devices is described.

Status of Triple-Junction Solar Cells

The triple-junction devices have been made in the 11 x 12 array as described in Section 3. Representative 2" x 2" substrates have been cut out for evaluation. Table 6 summarizes the status of the initial and stabilized values of V_{oc} , J_{sc} , FF, and efficiency of the triple-junction devices measured under AM1.5 condition. All the devices have been fabricated on Ag/ZnO BR and the active area of the devices is 0.82 cm² (total area 0.98 cm²). The devices are top cell limited and the value of Q of the top cell has been used as the J_{sc} of the device. The stabilized values have been obtained after 1100 hours of one sun illumination under 50 °C and open-circuit condition.

Table 6. Initial and Stabilized Performance of Triple-junction Devices Made on Ag/ZnO BR.

#	Area (cm ²)	Hours	V_{oc} (V)	J_{sc} (A/m ²)	FF	Efficiency (%)
A	0.82	Initial	2.356	73.9	0.757	13.19
B	0.82	1100	2.29	70	0.68	10.9
C	0.82	1100	2.29	70	0.69	11.1
D	0.82	1100	2.29	69	0.69	10.8
<i>Phase I</i> Goal	1	600				10.6

Sample A in Table 6 describes the initial status. The values of V_{oc} , J_{sc} , FF, and efficiency are 2.356 V, 73.9 A/m², 0.757, and 13.19%. The I-V characteristics and Q curves of the device are shown in Fig. 6. The contribution to J_{sc} from the top, middle, and bottom cells are 7.39, 7.81, and 8.52 mA/cm², respectively, and the total current is 23.72 mA/cm². This is the highest efficiency obtained in the 2B machine. The typical value is normally within 5-10% of the champion data. The stabilized values (which are also typical values) of V_{oc} , J_{sc} , FF, and efficiency for samples B, C, and D are 2.29 V, 69-70 A/m², 0.68-0.69, and 10.8-10.9%, respectively. The stabilized numbers are the average of all the devices on the substrate. For comparison, the *Phase I* milestone of 10.6% is also listed in the table. Thus, samples B, C, and D satisfy this objective.

Figure 6. Initial IV characteristics and Q curves of triple-junction triple-bandgap cell.

In order to ensure that the entire 900 cm² area satisfies the milestone values, the initial efficiency of all the 11 x 12 devices distributed over the 900 cm² were measured. The initial average efficiency of the devices which were actually light-soaked were then compared with the initial average efficiency of all the devices. The results of samples B and D are summarized in Table 7.

Table 7. Comparison of the Average Initial Efficiency of the Light-soaked 2" x 2" Substrate Versus the Entire 900 cm² Area for the Triple-junction Case.

#	AM1.5 Initial Efficiency (%)	
	2" x 2"	900 cm ²
B	12.0	12.2
D	11.7	11.7

The table shows that the initial efficiency values of the 2" x 2" substrates selected for light soaking for cases B and D are 12.0 and 11.7 %, respectively. The corresponding values for the entire 900 cm² are 12.2 and 11.7 %, respectively. The two sets of values are similar implying that the selected small area is typical of the 900 cm² area. Thus, the expected stabilized efficiency of the remainder of the 900 cm² area (and thereby the entire area) is also expected to be similar to the corresponding 2" x 2" result. Further, the efficiency contour plot shown in Fig. 7 shows that the initial performance of the devices over the 900 cm² is quite uniform. The normalized contour values of 0.96 to 1.0 show that the uniformity is approximately 96 % over the entire area. Hence all areas of the parent substrate are expected to exhibit stabilized values similar to the representative 2" x 2" specimen.

Status of Triple-Junction Modules

We are in the process of making modules of aperture area approximately 900 cm² using the finger-approach. It may be recalled that in the past under a previous NREL contract a stabilized module efficiency of 10.2 % has been obtained using the grooved-approach. The 10.2 % efficiency was confirmed by NREL. We will be soon be reporting the new results.

Figure 7. Contour plot of normalized efficiency of the triple-junction cell. The figure represents an area of 900 cm².

Section 5

Laser-Processed Cell Status

Introduction

In order to reduce the cost of module manufacturing, we need to increase the degree of automation, decrease the cost of module finishing materials and increase module efficiency. First, a cost reduction in module manufacturing may be accomplished by simply extending the roll-to-roll process as far into the module fabrication line as possible. We may also reduce the cost of module manufacturing by using less expensive materials or reducing the amount of materials utilized. Finally, an increase in efficiency, achieved by a reduction in module parasitic losses, will serve as a cost reducer.

To accomplish these goals, we are developing a laser-interconnected monolithic module process. This laser process will have advantages over present fabrication designs in terms of both cost and efficiency. The cost of modules using this laser process will be dramatically reduced because of the high degree of automation obtainable by extending the roll-to-roll process further into the manufacturing line. Also, since the feature heights for this type of module are very small, it will be possible to consider less expensive, more reliable alternative encapsulations that are not possible in the present module designs. The modules produced by this laser process will also have considerably less module losses (shadow, electrical resistance) than present modules, thus making them more efficient. The total module losses can be reduced to near 1% using this approach.

Laser-processed Cell

Device Design

To achieve this laser-interconnected design, we have developed a computer-automated, high-precision laser device processing system. This system utilizes a Nd:YAG laser which can be operated at 1.06 μm or 0.53 μm . We are operating this laser in a Q-switched single shot configuration. Both the table and laser pulses are controlled by a computer. The system specifications are listed in Table 8.

In Fig. 8 we show the laser device fabrication process. This module will be a parallel laser-interconnected device, unlike other laser-interconnected modules that use series cell interconnections. We begin the process by depositing an insulating layer onto the stainless steel substrate. This layer could be made of many materials, but we envision using a silicon oxide alloy deposited at high rates in a CVD process. We next deposit the back reflector onto the insulator. We now have a back reflector that is electrically isolated from the stainless steel substrate, forming a metal-insulator-metal (MIM) structure. We next drill a matrix of holes, arranged across the surface, through the back reflector and insulator. The back reflector must be cut back further than the insulator such that the diameter of the back reflector hole is larger and approximately concentric with the smaller insulator hole. Therefore, we still have an electrically isolated MIM structure. This is achieved with a single laser pulse. We next deposit the a-Si alloy triple-junction device. This is followed by drilling a second concentric hole through the a-Si alloy device, thereby exposing the stainless steel substrate. The diameter of this hole will be less than the diameter of the back reflector hole to maintain electrical isolation. The next step is to deposit a transparent conducting oxide over the entire surface. The TCO would then make electrical contact to the stainless steel substrate. Finally, we will then be able to encapsulate the surface with a thin film clear coat, again a CVD deposited silicon oxide alloy.

Laser Module Process

Insulator Deposition (Microwave Plasma CVD)

Insulating Layer
SS Substrate

Back Reflector Deposition (Sputtering)

Back Reflector
Insulating Layer
SS Substrate

Laser Drilling

Back Reflector
Insulating Layer
SS Substrate

a-Si Deposition (RF/Microwave Plasma CVD)

a-Si Triple Junction Device
Back Reflector
Insulating Layer
SS Substrate

Laser Drilling

a-Si Triple Junction Device
Back Reflector
Insulating Layer
SS Substrate

ITO Deposition (Sputtering)

Indium Tin Oxide
a-Si Triple Junction Device
Back Reflector
Insulating Layer
SS Substrate

Figure 8. Fabrication process for the laser-interconnected module.

Table 8. Specifications for the Computer-automated, Precision Laser Device Processing System.

System Specifications	
Laser	
Laser:	Nd:YAG, Q-switched, freq. doubled
Wavelength:	1.064 μ m or 0.532 μ m
CW power:	3 Watts
Single pulse energy:	3mJ
Q-switching frequency:	single shot - 20kHz
Table	
Travel (2-axis):	15 inches
Max. table speed:	4"/sec
Positional accuracy:	5 μ m
Positional resolution:	0.3 μ m
Imaging system	
Display:	CCD camera and monitor
Magnification:	240x
Laser focus spot size:	<20 μ m

The electrical conduction paths are provide by the TCO and back reflector. The current is collected from the device along the surface by the TCO to the hole and down to the stainless steel now acting as the positive electrode. At the bottom of the device, current is collected from the device and traverses along the back reflector to either edge of the module to the negative electrode. In Fig. 9 we show a multi-plan view of the finished device. It can be seen from the figure that the negative electrode connection takes place on the edge of the module where the back reflector is exposed, either by masking or etching of subsequent depositions.

Given the diameter of the holes at less than 100 μ m and hole spacing of 2 mm, we would achieve a shadowing loss of approximate 0.2%. These values combined with the electrical losses due to transport of current across the TCO and back reflector sheets give us a total electrical and shadow loss of approximately 1%.

Metal-Insulator-Metal Structure

The basic foundation for the laser parallel-interconnected module is the metal-insulator-metal structure. This structure incorporates the stainless steel substrate as the base metal. This is followed by an insulating layer and a subsequent device back reflector. For the insulating layer, we are presently using AlO_x . This layer must be a good dielectric, which it is, but just as importantly, it must be deposited defect or void free. This is important to avoid shunt paths between the back reflector metal (negative electrode) and the stainless steel substrate (positive electrode) that would drain power away from the module. This insulating layer is presently being used at a thickness of between 1 μ m and 2 μ m. This has been generally adequate to insulate the two metal electrodes with a resistance of 200k Ω -cm² or greater. For comparison, the load resistance of a triple-junction device is approximately 300 Ω -cm², nearly 1000 times less than the shunt resistance of the MIM structure. After the insulator, we deposit our standard device back reflector consisting of Ag/ZnO.

We have studied the effect of various insulating films, combinations of films and film thicknesses. To test various film systems, we deposited the standard Ag/ZnO back reflector on top of the film system and measured the shunt resistance from the BR to the s.s. substrate.

z-axis view

z-axis view

x-axis view

y-axis view

10
a-Si
BR
Insulator
S.S.

IO
a-Si
BR
Insulator
S.S.

24

Table 9. Average Shunt Resistance for Various Insulating Film Structures.

Structure	Log R_{sh} ($\Omega\text{-cm}^2$)
$\text{Al}_2\text{O}_3(1.5\mu\text{m})$	7.0
$\text{Si}_3\text{N}_4(1.5\mu\text{m})$	5.6
$\text{Al}_2\text{O}_3(3000\text{\AA})/\text{Si}_3\text{N}_4(1.5\mu\text{m})$	7.0
$\text{Al}_2\text{O}_3(1500\text{\AA})/\text{Si}_3\text{N}_4(1.4\text{-}1.6\mu\text{m})$	6.3
$\text{Al}_2\text{O}_3(1500\text{\AA})/\text{Si}_3\text{N}_4(1.6\text{-}2.0\mu\text{m})$	6.2

In Table 9 we show the average shunt resistance as a function of insulator structure. It is apparent from the table that the Al_2O_3 layer is the most effective insulator. To be effective, the Si_3N_4 film needs to be in combination with the Al_2O_3 film to have sufficient resistance. We also see that the Si_3N_4 thickness, in the range of 1.4 to 2.0 μm , is not very important. The effect of doubling the thickness of the Al_2O_3 , however, results in an increase in the shunt resistance of the combination MIM structure by about a factor of five.

In addition to the Al_2O_3 , Si_3N_4 and combination films, we have tested SiO_2 films at a thickness of 4 μm . These films had a resistance of $250\text{M}\Omega\text{-cm}^2$, while the best $\text{Al}_2\text{O}_3/\text{Si}_3\text{N}_4$ films give a resistance of $125\text{M}\Omega\text{-cm}^2$. Presently we are using an AlO_x film to perform this electrical isolation. This is accomplished by reactively sputtering the film to a total thickness of approximately 1.5 μm . We envision using a SiO_2 alloy film deposited by microwave CVD processing in the near future. This film should increase the film resistance, provide higher deposition rates and better yields.

Laser Processing

After the MIM is deposited, we drill holes through the back reflector and insulating layers. This is done with a Nd:YAG laser operating in the Q-switched single shot mode. We are utilizing the laser at its fundamental wavelength at 1.064 μm . The Ag/ZnO layers are vaporized by the laser in the initial part of the pulse. The fact that the silver is textured and has ZnO on the top allows it to absorb the laser radiation at the laser wavelength. The insulating layer does not readily absorb the radiation but primarily transmits it to the stainless steel substrate. The surface of the substrate material is vaporized, thereby ablating the insulating layer above it. This process occurs later in the same laser pulse. As a result of the Ag/ZnO layer being vaporized first, it is vaporized to a larger diameter (where the energy from the beam is less intense) than the insulator ablated diameter.

In Figs. 10a and 10b we show SEM photographs of a laser-drilled hole in the MIM structure. In Fig. 10a the outermost diameter hole is where the back reflector has been cut back. The diameter of this hole is approximately 100 μm . Inside of this diameter there is a crater-like hole with a rim. This is the exposed stainless steel with the rim being molten material pushed out from the center of the hole. The relatively smooth region between the remaining back reflector and the center hole is the insulating layer being exposed. Figure 10b shows the same hole at a large oblique angle to demonstrate the absence of large thrown debris on the surface. The largest feature heights on this surface are about 1 μm or less.

After we have laser etched holes in the MIM film structure, we deposit the a-Si alloy device (refer to Fig. 8). Once the device has been deposited, we drill a second hole that is concentric within the first hole. The diameter of this hole is typically 30-40 μm in diameter. Again, this is an ablation process since the a-Si alloy does not absorb the laser radiation readily. Here the stainless steel is vaporized, removing the

Figure 10. SEM photographs of a) a laser ablated hole in a MIM structure and b) the same hole at a large oblique angle.

b)

a)

a-Si alloy layer above it. Finally, the TCO layer is deposited completing the device by making contact through to the stainless steel for the positive electrode. The negative electrode is the back reflector and is contacted near the edge of the device (see Fig. 9).

Fig. 11 shows a SEM photograph of a device after it is completed (after TCO deposition). Again, the outermost diameter is the back reflector, as it is apparent through the a-Si alloy device and TCO because of the conformity of both layers. The next diameter, with the rim, is the first exposure of the stainless steel substrate. The innermost diameter, with rim, is the second exposure of the stainless steel (as seen through the TCO) from the a-Si alloy cut. In this hole there is TCO on top of the exposed stainless steel.

The accuracy of the second cut is paramount to the finished device. The acceptable position is such that the second hole lies completely inside the outermost diameter, i.e., the back reflector cut. The result of any part of the hole cut over the back reflector area might result in a shunt path from the TCO to the back reflector. We presently use a precision x-y motion table with sufficient accuracy to reproduce the second cut. We believe this type of accuracy is readily obtainable over large areas with present positioning technology.

Effect of Thrown Material on Device Performance

Much work has been done on optimizing the laser power, laser beam size and focus diameter as well as individual film thicknesses to optimize the drilling of the laser hole. This hole must be cut with a minimum of material thrown onto the back reflector surface. This thrown material can take two basic forms. The first is in the form of resolidified globules or debris. These can be quite large and may later contribute to shunt paths through the device from the back reflector to the top TCO contact and therefore must be minimized. The second problem caused by thrown material is on the molecular or atomic level where a film is deposited or recast onto the back reflector surface near the hole. This may cause additional device series resistance since this film may not be conducting. This thin film of recast material may manifest itself in a reduction of the device fill factor as a result of the increased series resistance. This film may also be a source of parasitic optical absorption, reducing the effect of the back reflector to optically enhance the device current.

To study this effect, we prepared several devices on (MIM) structures (in this case s.s./ Si_3N_4 /Back Reflector) with various thicknesses of insulator. For each sample we cut laser holes on half the substrate while the other half was left with no laser processing. We then deposited an a-Si alloy single cell over the entire area. This was followed by the deposition of 0.25 cm^2 ITO dots to define discrete devices to be tested on both areas with and without laser processing. (In this structure we did not cut holes through the a-Si alloy device before depositing ITO as we do in the complete laser-connected devices.) Any film deposited by thrown material during the laser process that adhere to the back reflector (BR) would produce a barrier layer between the BR and the n^+ layer of the device. This test structure allows us to look at the effect of the laser cut and material recast layers on device performance. This is done by measuring the I-V characteristics and comparing the results of devices built on the laser-processed half of the sample with those on the unprocessed half.

To help minimize recast onto the surface of the sample in our laser processing system, we utilize inert gas jets focused on the point of the laser strike. This technique is very effective in removing recast without causing other unwanted effects. We have found, however, that this is still not sufficient to completely prevent the recast from forming on the surface.

Figure 11. A laser hole in a finished device.

In Fig. 12 we show a plot of the device parameters versus insulator thickness. From the figure it is apparent that for thin Si_3N_4 (5000Å), we see almost no effect of the recast layer on device performance. This is a result of less laser power being required to completely break through the BR and insulating layers, causing less material to be thrown. With a thicker film we need higher power, throwing more material, and we see significant degradation due to this recast film. This layer degrades the fill factor through an increase in the series resistance of the device. The current is also affected, presumably due to a decrease in back reflection. The magnitude of these two effects on the device are similar.

Unfortunately, the thinner insulating layers may not be sufficient to provide consistently good device shunt resistance across the insulator. Only at insulator thicknesses of 1.5 μm do we have consistently acceptable resistance. We have been able to develop successfully a proprietary technique to completely eliminate the recast caused by laser drilling the first back reflector holes even with thicker insulator layer. Again, we built test cells consisting of a Ag/ZnO back reflector on $\text{Si}_3\text{N}_4/\text{s.s.}$ The insulator thickness on these samples was about 2.5 μm . The back reflector/insulator was then laser drilled on one half of the sample, and an a-Si alloy single cell and ITO was then deposited without a second hole drilling. This structure has allowed us to examine the effect of recast produced by the first cut. Table 10 shows the percentage difference in the I-V characteristics between the devices on the laser-processed half of the sample to devices on the unprocessed half. From the table it can be seen that the new technique had a significant effect on the I-V characteristics. There was an improvement in the series resistance and the current of the samples.

Other Parasitic Resistances

Even though the recast removal has been very effective in the reduction of the device series resistance, there still exists significant excess series resistance. This was determined by comparing the series resistance of the laser processed devices with the series resistance of small area devices fabricated with standard grid fingers. The series resistance of the improved device listed in Table 10 is still about $14\Omega\text{-cm}^2$ compared to about $21\Omega\text{-cm}^2$ before recast removal, while the small area gridded cell typically gives $6\Omega\text{-cm}^2$.

Table 10. Losses Due to Parasitic Recast Layer with and without New Removal Technique.

	Conventional	New
Pmax	-7.1%	-0.7%
ff	-3.5%	-0.1%
Voc	-0.5%	-0.3%
Jsc	-3.2%	-0.4%

We believe there are three possible sources of extra series resistance in these laser-connected devices. These are ITO sheet resistance, recast after the second laser cut and hole contact resistance (ITO to stainless steel contact). We have repeatedly tested the effect of recast resistance due to the first laser cut and have found no contribution to the device series resistance since we have adopted the procedure to remove this material. We have modeled each of the three possible sources of resistance as a function of hole spacing and each effect has a different dependency. The total effect on series resistance can be estimated by

$$R_{\text{excess}} = \frac{R_r R_d}{R_r + R_d} s^2 + R_c s^2 + \frac{s^2 \rho_{\square}}{2\pi} \ln\left(\frac{s}{h}\right)$$

Figure 12. A plot of the laser device I-V parameters versus thickness of insulator.

where R_r , R_c , R_d , and $\rho_{\square}$ are the recast, contact, device and sheet resistances respectively and s and h are the hole spacing and hole diameter. The first term is the recast resistance term, the second is contact resistance and last is sheet resistance. The final term is only dependent on ITO sheet resistance, hole spacing and hole diameter, all of which are independently measurable quantities. In the first term the device series resistance was determined independently by assuming it to be the same as in the small-area gridded sample. This leaves us with only two unknown parameters, the contact resistance, R_c , and the recast resistance, R_r due to the second (a-Si alloy) cut.

Figure 13 shows the effect of hole spacing on the sheet, contact and recast resistance as well as on actual devices. We have measured $\rho_{\square}$ to be $125\Omega/\square$, h is about $40\text{ }\mu\text{m}$ and R_d is $6\Omega\text{-cm}^2$. In this figure we have split up the components of resistance into the three terms in the excess resistance equation. The curve labeled *Total* would then be the sum of the component resistances, namely, R_{excess} . We varied R_r and R_c to obtain a best fit (labeled *Total*) to the measured data. The curves labeled *Contact*, *ITO* and *Recast* are the component resistances obtained from a best fit to the data. It appears that the contact resistance dominates over the recast resistance. This is an important result; since the first cut causes no excess series resistance and the recast resistance of the second cut is small, we have eliminated all series resistance due to thrown material.

It is also important to note that the excess resistance expected from the laser device structure, even if the contact and recast resistance were to be eliminated completely, is several ohm-cm^2 even for relatively close hole spacing. This extra resistance is only significant for a single-junction device. For a triple-junction device this excess series resistance would have almost no effect on the fill factor of the device.

One possible source of this resistance is a poor ITO to s.s. interface. Another possible source derives from the consequence that most of these devices have heavy ITO passivation and may be passivating the ITO more in the region surrounding the dots. This region may have more shunts due to debris from the BR laser drill. This would "appear" as a contact resistance in the above experiment because all the current would have to pass through this "higher resistance" ITO to get to the hole.

To test the source of this "contact" resistance, we measured the series resistance of devices after varying passivation exposure. We were not able to measure any device with no passivation because the shunt resistance was too poor. In each case we observed the series resistance to climb dramatically with increased passivation. One device increased from $15\Omega\text{-cm}^2$ after 10 seconds to $21\Omega\text{-cm}^2$ after 30 seconds. A second device went from $14\Omega\text{-cm}^2$ to $25\Omega\text{-cm}^2$ after an additional 20 seconds of passivation. For a normal device we do not see a significant rise in series resistance for the same "amount" of passivation.

We have found that when the first BR hole is drilled, it is necessary to strike the surface with multiple pulses (2 or 3) to completely cut through the entire stack (BR and insulator). We have found that on the second and third pulses, the material tends to accumulate on the perimeter of the hole leaving large balls of material or an uneven surface. We believe this leads to shunting and subsequent excess series resistance after passivation (due to excess passivation in the region near the hole). We have found that if the diameter of the second cut is significantly greater than the first cut ($100\text{ }\mu\text{m}$ compared to $40\text{ }\mu\text{m}$), debris does not accumulate around the perimeter. We therefore cut the back reflector/insulator with two separate pulses. The first cut is with a 3 mm laser beam to produce a $40\text{ }\mu\text{m}$ cut and the second pulse with the 1 mm laser beam to produce a $100\text{ }\mu\text{m}$ cut. This combination produces the flattest and the most featureless surface we have been able to obtain.

Figure 13. Excess device series resistance and its component resistances as a function of laser hole spacing.

To test the effect this laser-processed back reflector would have on the series resistance of a device, we built a-Si alloy single-cell devices on these back reflectors. This indeed did result in less shunting around the hole and dramatically decreased the passivation in this region. As a result, the series resistance of the device did not increase after passivation. This result was confirmed on several laser-processed samples by measuring series resistance before and after passivation. We made 12 cm² single-cell devices with series resistances of 9 Ω -cm². This resistance is slightly higher than the series resistance on small area a-Si alloy single cells, but this additional series resistance when incorporated into a triple-junction device will have little effect on the device efficiency.

Device Interconnects and Environmental Testing

In Figs. 8 and 9 we showed the laser module process and layout. As a result of the insulator separating the substrate from the back reflector, we now must make electrical connection to the back reflector (negative) as well as the stainless steel substrate (positive). In this module design, the positive electrode ITO carries the current to the stainless steel substrate (via laser drilled holes through the device and insulator) where the final output connection can be made by welding or some other mechanism. The negative electrode back reflector carries current to the two edges of the module where the final output connection can be made.

We have succeeded in making a low resistance interconnect to the laser device back reflector. This is done by means of connecting the back reflector metal (Ag) to a copper bus using a silver filled epoxy. We have measured the total resistance from one copper bus bar to the copper bus bar on the opposite side of the device. This resistance, which includes two BR/bus bar interconnects and BR sheet resistance, was about 100 m Ω . The BR sheet resistance accounts for about 80 m Ω of this resistance. This results in a contact resistance of 5 m Ω /cm of interconnect. For a triple-junction module this will result in a series resistance increase of only 0.3%.

In Fig. 14 we show the results of testing of the environmental stability of these 12 cm² laser-processed devices under environmental stresses. The plot shows the normalized efficiency up to 200 standard thermal cycles (-40°C to 90°C) on two different laser-processed single cell devices. It can be seen from the plot that although there is some degradation, it is not severe. The resultant increase in series resistance if applied to a triple junction device, rather than the single-junction devices under test, would produce considerably less degradation. We will continue to test possible sources of the degradation shown in Fig. 14. These might include contact resistance increases between the back reflector/conducting epoxy, conducting epoxy/copper foil or ITO/stainless steel interface.

Laser-processed Triple-junction Solar Cell Status

We have fabricated a laser-interconnected triple-junction device measuring 11.5% initial efficiency and 9.8% stabilized efficiency. The device structure was a-Si/a-Si:Ge/a-Si:Ge. The laser fabrication process was similar to the one described in the previous section. Again we built the triple-junction device on an MIM structure (s.s./insulator/back reflector) with holes drilled into it. We next processed the triple device by drilling a second set of holes through the device and concentric with the MIM holes. The device was then finished by depositing ITO as the top contact defining an area of 12.6 cm². Fig. 15 shows the I-V characteristics for the initial performance while Fig. 16 shows the stabilized result. The degradation of 15% is higher than expected for a triple-junction device. This was due to the current matching conditions of this triple and not any problem associated with the laser interconnecting. We believe we can improve this efficiency further by reducing the parasitic shunt and series resistance losses in the structure.

Figure 14. Normalized output power of two laser-interconnected devices plotted as a function of the number of thermal cycle exposures.

```

(no filename)
ID, No. 2423322
06-12-1995, 13:35:20
Sun = 100 mW/cm2
Temp = 24 degC, 24
Voc = 2.45 V
Isc = .95 mA
Pmax = 146 mW
Vmp = 1.85 V
Imp = .79 mA
FF = .625
Rs = 4.42 Ohms
Rsh = 185.3 Ohms
Ef,c = 11.5 %

```

Figure 15. Initial I-V characteristics of an 11.5% laser-interconnected triple-junction device.

Figure 16. Stabilized I-V characteristics of a 9.8% stable laser-interconnected triple-junction device.

Section 6

Reliability Testing

Introduction

We have been testing our modules following IEEE PAR 1262 (Draft 8) which is more stringent than the NREL Interim Qualification Test (NREL/TR-213-3624). The detailed test sequence is shown in Table 11. Three different configurations were used for the test: (1) L-strip laminate on Ag/ZnO back reflector which is essentially a monolithic encapsulated module of area 24 by 36 cm², (2) 1 ft. by 4 ft. 10-strip interconnected encapsulated module on Al/ZnO back reflector and (3) 1 ft. by 4 ft. 10-strip interconnected encapsulated module on Ag/ZnO back reflector. The results of the tests are shown in Tables 12-14. Some important observations are given below.

Initial Tests

All modules pass the initial tests specified in Table 11. Please note that the Spire simulator was recalibrated since the lamp was changed after the first measurement, and the modules were measured both before (b.1) and after. Note that the new values are about 4-5% lower (Table 12).

Sequence B Tests

The results are shown in Table 13. Note that no UV test was done.

Thermal Cycles

All the modules pass the thermal cycles.

Humidity/freeze Cycles

The modules showed increase in the leakage current after the test. The magnitude of the leakage current and also the power output were acceptable and met the acceptance criteria.

Surface Cut Susceptibility

The modules passed the cut tests.

Sequence C Tests

The results from these tests are shown in Table 14. Note that although all the modules give acceptable power output, the leakage current is higher for the strip-interconnected modules. Further investigations are in progress with slightly thicker layer of encapsulant.

Table 11. PV Module Qualification Test Program.

Note: the number designated at the right of each box corresponds to the required test or inspection procedure given in Section 5.0

Table 12. Module Performance After Dry and Wet Highpot Tests.

Type	Ser.#	Initial Tests:		(micro-amps)		(watts)	P/P(b.l.)	Voc(1 klux)	redo Pmax (init)	P/P(b.l.)
		Pmax (b.l.)	Voc(1 klux)	dry Hipot	wet Hipot	Pmax (init)				
L-strip	(Ag)	212	7.09*	1.47		0.5	7.16*	1.0099	1.47	
L-strip	(Ag)	214	7.1*	1.47		0	7.11*	1.0014	1.48	
L-strip	(Ag)	217	7.12*	1.47		0	7.13*	1.0014	1.45	
L-strip	(Ag)	218	7.12*	1.47		0	7.06*	0.9916	1.47	
L-strip	(Ag)	219	7.06*	1.46		0.5	7.08*	1.0028	1.47	
1'x4'	(Al)	C1	35.93*	14.1	0.5	O.L.	36.36*	1.012		34.5 0.9602
1'x4'	(Al)	C2	34.55*	14	0.5	4	34.78*	1.0067		
1'x4'	(Al)	C3	36.5*	14.1	0	3	36.64*	1.0038		
1'x4'	(Al)	C4	36.17*	14.1	0.5	4	36.13*	0.9989		
1'x4'	(Al)	C5	37.11*	14.1	0.5	3	36.98*	0.9965		
1'x4'	(Ag)	U1	32.04*	10.4	0	3	32.14*	1.0031		
1'x4'	(Ag)	U2	31.21*	10.4	0	2	31.69*	1.0154		
1'x4'	(Ag)	U3	40.87*	13.3	0	3	40.94*	1.0017		
1'x4'	(Ag)	U4	40.5*	12.8	0	3	40.79*	1.0072		
1'x4'	(Ag)	U5	32.18*	10.3	0	2	32.74*	1.0174		

* = before spire lamp change; redo = remeasurement of I-V

Note: U1, U2 and U5 had 8 strips and hence the lower power.

Table 13. Module Performance after Sequence B Tests.

		Sequence B:														
	Type	Ser.#	50 T/C Pmax (w)	50 T/C P/P(b.l.)	50 T/C Voc(1 klux)	50 T/C dry Hipot	50 T/C wet Hipot	redo 50 T/C Pmax (w)	redo 50 T/C P/P(b.l.)	redo 50 T/C Voc(1 klux)	redo 250T/C Pmax (w)	redo 250 T/C P/P(b.l.)	10 H/F dry Hipot	10 H/F wet Hipot	10 H/F Pmax (w)	10 H/F P/P(b.l.)
L-strip	(Ag)	212	7.14*	1.0071	1.46	0	1	7.24*	1.021157	1.47	6.83	0.963329	0	6	6.99	0.9859
L-strip	(Ag)	214	7.12*	1.0028	1.46	0	0	7.13*	1.004225	1.48	6.84	0.96338	0	2	6.84	0.9634
1'x4'	(Al)	C2	33.42*	0.9673		0.5	3	32.78	0.94877				3	5	33.83	0.9792
1'x4'	(Al)	C3	34.42*	0.943		0.5	2	34.33	0.940548				5	6	34.93	0.957
1'x4'	(Ag)	U2	29.36*	0.9407		0	2	29.14	0.933675				4	5	29.26	0.9375
1'x4'	(Ag)	U3	38.7*	0.9469		0	2	38	0.929777				2	2	37.59	0.9197

* = before spire lamp change; redo = remeasurement of I-V

Note: The columns under dry and wet Hipot indicate leakage current in microamperes.

Table 14. Module Performance after Sequence C Tests

Sequence C:

	Type	Ser.#	239hD.H. dry Hipot	239hD.H. wet Hipot	239hD.H. Pmax (w)	239hD.H. P/P(b.l.)	239hD.H. Voc(1 klux)	384hD.H. dry Hipot	384hD.H. wet Hipot	384hD.H. Pmax (w)	384hD.H. P/P(b.l.)	144hD.H. dry Hipot	144hD.H. wet Hipot	144hD.H. Pmax (w)	144hD.H. P/P(b.l.)	1006hDH dry Hipot	1006hDH wet Hipot	1006hDH Pmax (w)	1006hDH P/P(b.l.)
L-strip	(Ag)	217	0	4	7.1*	0.997191	1.49	0	1	6.89	0.967697					0.5	6	6.94	0.974719
L-strip	(Ag)	218						0	1	6.86	0.963483					1	4	6.9	0.969101
1'x4'	(Al)	C4										0	4	34.11	0.943047	12	85	34.26	0.947194
1'x4'	(Al)	C5										0	4	34.55	0.931016	20	50	34.82	0.938292
1'x4'	(Ag)	U4										0	3	37.49	0.925679	9	26	37.6	0.928395
1'x4'	(Ag)	U5										0	2	29.75	0.924487	18	20	29.82	0.926663

* = before spire lamp change; 144 and 384 hr damp heat ended at only 65% RH; 1006 hr damp heat tripped 17.5 hrs before hi-potting

Note: The columns under dry and wet Hipot indicate leakage current in microamperes.

Section 7

Future Directions

We have completed the Phase I of the research program and met the major milestones. This has been accomplished by improving the component cell performance, optimizing the laser-drilling processes and carrying out the relevant reliability studies. The focus of the Phase II of the program will be the continuation of the work on large-area deposition. Major efforts will be directed toward the development of deposition of the insulating layer for the laser-drilling approach over one-square-foot area. This will be accomplished using a microwave plasma CVD process, and a deposition system capable of handling one-square-foot substrate has already been built. The same equipment will also be used for the deposition of the encapsulating inorganic layer. Further investigations will be carried out on reliability studies, and the aim is to develop the process technology for a low-cost a-Si alloy multijunction module which meets and exceeds the reliability requirement of the users.

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13. ABSTRACT (Maximum 200 words) This report describes the research performed during Phase I of a three-phase, 3-year program that is intended to expand, enhance, and accelerate knowledge and capabilities for developing high-performance, two-terminal, multijunction amorphous silicon (a-Si) alloy modules. A multijunction, multibandgap approach has the potential of achieving the highest stable efficiency in a-Si alloy solar cells. In this approach, the bandgap of the materials of the component cells is varied to capture a wide spectrum of the solar photons. Significant progress has been made in the development of materials and cell design in the last few years; however, to meet the Department of Energy goal of 12% stable module efficiency by 1998, it is necessary to make further improvements in each of the component cells. New back reflectors also need to be developed to facilitate improved light-trapping performance. The aim of this program is to develop a manufacturing technology; the research work must address issues involving scale-up, reliability, and cost, and issues that encompass module interconnect and encapsulation methods, as well.					
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