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WORLD'S FIRST 15%-EFFICIENT MULTICRYSTALLINE SILICON MODULES

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ABSTRACT

This paper describes the result of a team effort at Sandia to demonstrate the near-term performance potential for multicrystalline silicon modules using commercial mc-Si material and improved cell fabrication processes. Large-area high-performance mc-Si cells were fabricated, prototype modules were built, and world-record module efficiency was confirmed by outdoor testing at over 15% for standard test conditions.

INTRODUCTION

The debate over which photovoltaic technology will ultimately be the most cost effective for terrestrial applications is likely to continue for several years, but there is compelling evidence to suggest that continued evolution of manufacturing processes will result in Czochralski (Cz) and multicrystalline silicon (mc-Si) dominating the future market. Silicon-based technologies enjoy a well established market position, a strong complementary relationship with the microelectronics industry, proven reliability, and continually improving performance [1]. A re-evaluation of manufacturing issues associated with silicon feedstock, crystal growth, wafer slicing and handling, cell processing, and module manufacturing has indicated that Czochralski (Cz) silicon technology will be a contender for the long term [2]. Similarly, cast multicrystalline silicon technology offers low-cost wafers and the potential for high-performance through improved cell fabrication processes [3]. Our goal was to demonstrate the value of improved cell fabrication processes using commercial mc-Si material.

CELL DESCRIPTION

The staff of Sandia's Photovoltaic Device Fabrication Laboratory fabricated the mc-Si cells used to build two prototype modules with record performance. The mc-Si material used was from a single ingot provided by Crystal Systems (1.4 Ωcm , Heat Exchanger Method™ silicon) [4]. Two mc-Si bricks from the ingot were sawn into wafers by Solarex Corporation. The cell fabrication process is described in another paper at this conference [5]. The 42-cm² cells had a chemically etched surface texture, a

single-step emitter diffusion, an aluminum alloy back-surface-field, photolithographically defined collection grids with silver electroplating to final thickness, and an evaporated double-layer anti-reflection coating ($\text{TiO}_2/\text{Al}_2\text{O}_3$). The cell thickness varied from 260 to 300 μm . The cells were produced in six lots of 12 cells each. Sixty-eight cells were completed by the PDFL staff, with a production yield of 94%.

The average efficiency for all 68 cells at standard test conditions was 15.6%, with a high of 16.3% and a low of 15.0%. The average efficiency for the 24 cells incorporated in each of two prototype modules (SNL-2A and SNL-2B) was 15.6% and 16.0%, respectively. Table 1 gives the average and standard deviation of performance parameters for the 24 cells in each module. Also shown in Table 1 is the estimated total uncertainty in each of the performance values. Table 2 gives the temperature coefficients for cell parameters based on an average of 6 cells. All cell performance measurements were made in Sandia's Photovoltaic Device Measurement Laboratory.

Table 1
Average Cell Performance
Standard Reporting Conditions
1000 W/m², AM1.5 Global, 25 °C
Cell Area = 42.0 cm²

Module		I_{sc} (A)	V_{oc} (V)	FF	Eff (%)
SNL-2A	Avg.=	1.384	0.603	0.783	15.6
	S.D.=	.009	0.002	0.006	0.1
SNL-2B	Avg.=	1.409	0.606	0.785	16.0
	S.D.=	.011	0.002	0.005	0.2
	$\pm U_{95}$ =	.024	0.002	0.004	0.3

Table 2
Cell Temperature Coefficients
1000 W/m², AM1.5 Global Spectrum

	dI_{sc}/dT (A/°C)	dV_{oc}/dT (V/°C)	dI_{mp}/dT (A/°C)	dV_{mp}/dT (V/°C)	dP_{mp}/dT (W/°C)
Avg.	.00107	-.00206	.00035	-.00207	-.0026
S.D.	.00011	.00002	.00013	.00003	.00011

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MODULE DESCRIPTION

Fig. 1 shows the two prototype modules during outdoor performance measurements. Each module contained 24 cells connected in series and laminated using a process typical of commercial flat-plate modules. The front surface of the module was Starphire low-iron glass (4-mm thick) and the rear surface was a typical Tedlar-polyester-Tedlar trilayer. Springborn fast-cure (#15295P) EVA was used as the module encapsulant. Cells were interconnected using solder coated copper ribbon, 0.076-mm thick and 2.5-mm wide, and Sn62 solder. The modules were laminated under vacuum as temperature increased to 105 °C, then the top chamber of the laminator was backfilled with air to apply about 400-Torr pressure to the module. Under pressure, the module was heated to 150 °C for 1 minute to cure the EVA. This procedure minimized hydrostatic stresses on the cell strings, while providing a void free laminate. Aluminum frames were fabricated for the modules to provide a well-defined aperture area for electrical efficiency determination.

Fig. 1. Sandia's mc-Si modules during outdoor performance evaluation at the Photovoltaic Systems Evaluation Laboratory.

MODULE PERFORMANCE

Comprehensive performance testing was performed outdoors in Sandia's Photovoltaic Systems Evaluation Laboratory using standard procedures previously used for other record performance modules [6,7]. The test procedures used provided performance at Standard Reporting Conditions (SRC) in a manner consistent with established ASTM procedures [8]. In addition, the procedures made it possible to isolate the influences of irradiance level, air mass, ambient temperature, and wind speed. Table 3 summarizes the performance of the mc-Si modules at SRC measured on three different days. The silicon reference cell used to determine SRC performance had a calibration traceable to the World Radiometric Reference through NREL calibration and to NIST through an alternate calibration procedure [9]. Table 3 also contains the temperature coefficients for these modules. For both modules, the total measurement uncertainty including both bias and random errors is indicated by the U_{95} values in the table.

Performance at typical operating conditions is of more importance to system designers than performance at SRC because the cell temperature associated with SRC is unrealistically low. Our outdoor performance measurement process also provided performance at other user-specified conditions. For example, those specified by PVUSA; 1000 W/m², Air Mass 1.5, ambient temperature of 20 °C, and wind speed of 1 m/s. Table 4 gives the module performance at PVUSA test conditions along with U_{95} uncertainty estimates.

Table 3
Performance at Standard Reporting Conditions
1000 W/m², AM1.5 Global, Cell Temp. = 25 °C
Module: SNL-2A Aperture Area = 1028 cm²

Date	I_{sc} (A)	V_{oc} (V)	I_{mp} (A)	V_{mp} (V)	FF	Eff (%)
10/3/94	1.355	14.58	1.275	12.13	0.783	15.05
10/6/94	1.358	14.56	1.282	12.12	0.786	15.11
10/11/94	1.354	14.55	1.276	12.11	0.785	15.04
Avg.	1.356	14.56	1.278	12.12	0.785	15.07

Module: SNL-2B Aperture Area = 1017 cm²

Date	I_{sc} (A)	V_{oc} (V)	I_{mp} (A)	V_{mp} (V)	FF	Eff (%)
10/3/94	1.357	14.61	1.281	12.17	0.786	15.33
10/6/94	1.356	14.59	1.285	12.18	0.791	15.39
10/11/94	1.352	14.58	1.279	12.15	0.789	15.29
Avg.	1.355	14.59	1.282	12.17	0.789	15.34
$\pm U_{95}$	0.024	0.10	0.023	0.10	0.005	0.30

Temperature Coefficients

dI_{sc}/dT (A/°C)	dV_{oc}/dT (V/°C)	dI_{mp}/dT (A/°C)	dV_{mp}/dT (V/°C)	dP_{mp}/dT (W/°C)
.0011	-0.050	0.00035	-0.050	-0.062

Table 4
Performance at PVUSA Test Conditions
1000 W/m², AM1.5 Global, T_{amb}=20 °C, Wind=1m/s
Module: SNL-2A

I _{sc} (A)	V _{oc} (V)	I _{mp} (A)	V _{mp} (V)	FF	Eff (%)	T _{cell} (°C)
1.380	13.35	1.285	10.89	0.759	13.61	49

Module: SNL-2B

I _{sc} (A)	V _{oc} (V)	I _{mp} (A)	V _{mp} (V)	FF	Eff (%)	T _{cell} (°C)
1.376	13.48	1.287	11.04	0.766	13.96	47
±0.024	±0.094	±0.023	±0.088	±0.005	±0.28	±3

The comprehensive nature of our outdoor module testing made it possible to identify other significant attributes of these mc-Si modules. First, the modules showed no evidence of the initial I_{sc}-degradation mechanism we have observed in several commercial flat-plate silicon modules. Consistent with observations made 16 years ago [10,11], we have observed that commercial silicon modules can lose up to 5% of their initial short-circuit current during the first few hours of solar exposure, and remain stable thereafter. This phenomenon is not well understood but is often attributed to interactions between the boron and oxygen atoms in the silicon wafer. Nonetheless, the cell processing procedure used for the Sandia mc-Si modules appears to eliminate this I_{sc}-degradation mechanism.

Fig. 2. Influence of solar spectrum (air mass only) on the normalized I_{sc} and I_{mp} from a Sandia mc-Si module.

It is widely recognized that the current from a photovoltaic module is influenced by the solar spectrum, and that the spectrum is influenced to decreasing degrees by the air mass (AM), precipitable water vapor content of the atmosphere, and atmospheric turbidity. Standard Reporting Conditions defined by ASTM specify only one condition; AM=1.5, 1.42-cm of water, and 0.27 turbidity. However, to better understand the annual performance

characteristics of photovoltaic systems, it is also useful to know how varying atmospheric conditions will influence performance. Figure 2 illustrates the influence of air mass on the short-circuit and maximum-power current from one of the Sandia mc-Si modules. In this figure, the currents were translated to a common cell temperature and normalized to 1000-W/m² irradiance using an Eppley PSP pyranometer. The 6% increase in current from AM=1 to AM=3 is typical of many silicon flat-plate modules; beyond AM=4 the normalized current begins to drop. Higher bandgap cells such as amorphous silicon and GaAs behave differently; their current is highest at AM=1 and drops monotonically, by about 10% at AM=3.

CONCLUSIONS

The mc-Si modules produced and evaluated at Sandia established a new performance standard for commercial multicrystalline silicon. They demonstrated that the quality of industrial mc-Si wafers is not presently the limiting factor in module performance. In addition, progress is being made in industry in maintaining or improving the material quality while lowering the cost per wafer. The challenge is to realize the material's potential with lower-cost commercial cell processes. Gettering effects from the emitter and back surface processing can be achieved with little change to current commercial processes. The cell metallization process appears to be the critical performance inhibitor since it is the primary difference between our cells and typical commercial cells. Buried-contact and/or all-plated metallization processes could bridge at least part of the gap between our cells and commercial mc-Si cells. Our emitter diffusion and aluminum alloy back-surface-field processes may also effectively eliminate the photon-induced changes observed when commercial cells are first exposed to sunlight.

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