CRYSTALLINE SILICON PHOTOVOLTAIC MODULES WITH ANTI-REFLECTIVE COATED GLASS*

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ABSTRACT

This paper reports on a set of experiments to determine what efficiency gain can be achieved by using AR coated glass and to evaluate the weatherability of the coatings. AR coated glass from three different vendors was evaluated by building and testing full size modules. Only one of the three vendors' glass produced consistent increases in STC efficiency on the order of 2.4 to 3%. All of the three types of coated glass successfully passed the accelerated stress tests from IEC 61215 [1]. Modules made with the glass that consistently produced STC efficiency gains were then deployed outdoors for extended time periods in order to measure the energy production. Preliminary results indicate that the energy production difference between the AR coated glass and the standard low iron glass is in excess of the gain measured at STC.

A pilot run of 231 modules achieved a similar STC efficiency gain. Modules from this trial have now been deployed outdoors to in a large system to determine energy gain from the AR coated glass.

INTRODUCTION

It is well known that use of an anti-reflective coating on the outer glass surface can increase the coupling of light into a PV module and therefore increase its conversion efficiency. While AR coated glass has been available for years, in the past these coatings were unable to survive long term exposure outdoors. Recent advances in glass coating technology have improved the ability of the coatings to survive the outdoor environment. AR coated glass was obtained from three different vendors. Each material was evaluated for encapsulation gain and subjected to accelerated environmental tests. One of the three materials produced consistent efficiency gains. This material was then subjected to more rigorous testing to define the expected performance under standard test conditions (1000 W/m^2, AM1.5 spectrum, 25° C) and to determine the expected energy gain from outdoor use of this material.

EXPERIMENTAL

AR coated glass was obtained from three different vendors. Each of the AR coatings was formed in a different way.

1. Vendor 1 – porous SiO_2 formed by dipping [2];
2. Vendor 2 - deposited multi-layer films; and
3. Vendor 3 – etched coating.

In each case full sized modules, with either 36 (12.5 cm by 12.5 cm) cells or 72 (12.5 by 12.5 cm) cells, were fabricated along with controls using our standard low iron glass. Every effort was made to uniformly mix the cells into the modules.

STC TEST RESULTS

Flash test results taken under Standard Test Conditions (1000 W/m^2, AM1.5G spectrum, 25° C) for the modules made using the Vendor #1 AR coated glass are shown in Table 1. The screen print multicrystalline silicon data is from ten test modules and ten controls from the BP3160 family. The Laser Grooved Buried Contact (LGBC) mono-Si data is taken from six test modules and six controls from the BP7180 family. The screen print mono-Si data is taken from three test modules and is compared to production data on a large number of modules from the BP4175 family. This glass produced a significant increase in power (2.5 to 3%) driven by higher short circuit current (2 to 2.6%) as expected for AR coated glass.

Glass from the other two vendors did not result in measurable gains above our standard glass. In both cases their un-AR coated glass produced less power than our standard glass. So while their AR coated glass resulted in increased output over their non-AR coated glass, it did not provide an advantage over our standard glass.

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Table 1
Laboratory Results for Vendor #1 AR Coated Glass

Cell Type	Glass Type	Voc (V)	Isc (A)	Pmax (W)
Screen Print Multi-Si	Control	43.4	4.96	156.3
3160	AR	43.5	5.10	160.5
3160	Δ	0.2%	2.8%	2.7%
LGBC Mono-Si	Control	43.9	5.52	180.4
7180	AR	44.0	5.62	184.9
7180	Δ	0.2%	1.8%	2.5%
Screen Print Mono-Si	AR	44.2	5.54	180.1
4175	Δ			3.0%

ENVIRONMENTAL TESTING

Modules made using each of the three types of AR coated glass have been subjected to BP Solar's extended version of the IEC 61215 test sequence. The test sequence included exposure to 500 thermal cycles from -40 °C to +85 °C, 1250 hours of damp heat at 85 °C at 85% relative humidity and a combined leg of UV/50 thermal cycles and 10 humidity freeze cycles. All three of the AR coated glass types successfully passed the qualification tests without any visual evidence of degradation of the coatings or power loss from the modules.

OUTDOOR FIELD TESTING

The AR coating on the glass could change the module's energy rating by changing the spectral response or the angle of incidence response of the module. The most direct way to determine the effect on energy is to measure modules both with and without AR coated glass in the same outdoor system over an extended period of time so that they experience the same weather conditions. Then the effect of the AR coating can be determined directly.

BP Solar have been studying outdoor module performance data from ISET in Kassel, Germany for the last 5 years and from the roof of the BP Solar Homebush factory in Sydney, Australia for 2 years. [3][4] At ISET the modules are maintained at peak power by a maximum power point tracker and the dc module data are measured every 15 seconds. In Homebush the modules are maintained at peak power by a maximum power point tracker. An I-V curve is swept every minute for the dc performance to be measured. At both sites the data are usually averaged every 30 minutes, every hour or every day depending on the type of analysis required. Some of the important parameters measured and calculated to compare different modules are given in Table 2.

Table 2
Some Important Normalized Parameters

Symb	Name	Units	Range	Definition
G_I	Plane of Array Irradiance	kW/m^2	0~1.4	
T_{AM}	Ambient Temperature	C	-40~100	
T_M	Module Temperature	C	-40~100	
YR	Insolation	kWh/m^2	0~1.4/h	$=\Sigma_t(G_I)$
V_{DM}	Normalized DC voltage		0~1.4	$=V_{DC}/V_{MAX}$
I_{DN}	Normalized DC current		0~1.4	$=I_{DC}/I_{MAX}/G_I$
YA	DC Yield	Wh/Wp	0~1.4/h	$=\Sigma_t(P_{DC})/P_{MAX}$
YF	AC Yield	Wh/Wp	0~1.4/h	$=\Sigma_t(P_{AC})/P_{MAX}$
PF	Performance Factor (DC)		0~1.4	=YA/YR
PR	Performance Ratio (AC)		0~1.4	=YF/YR

Figure 1 shows a plot of power gain versus time for both multicrystalline and Saturn mono modules installed at ISET in Germany. In all cases the modules with AR coated glass produce at least 4% more power than the control modules made with the same efficiency cells but with standard glass. Another way to look at the data is to plot the Performance Factor (the normalized DC yield) versus the irradiance (See Figure 2 plotted from the Australian data). While the curves show a variety of effects including reduced PF at high irradiance due to higher module temperatures, the PF for the AR coated glass module tracks from 4% to 6% higher than the control module across the various irradiance levels.

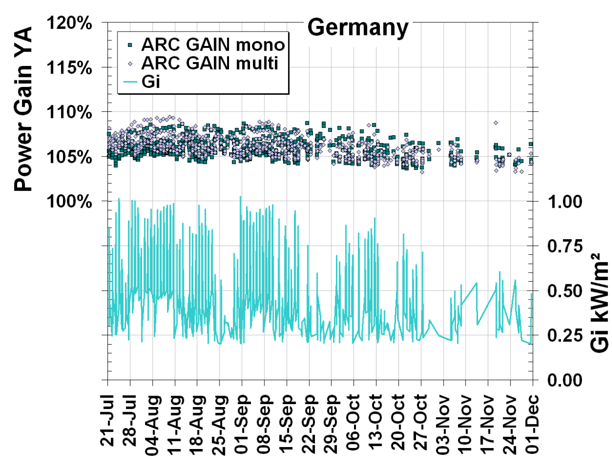

Figure 1: Power gain versus time for AR coated glass in Germany for irradiances > 200 W/m^2

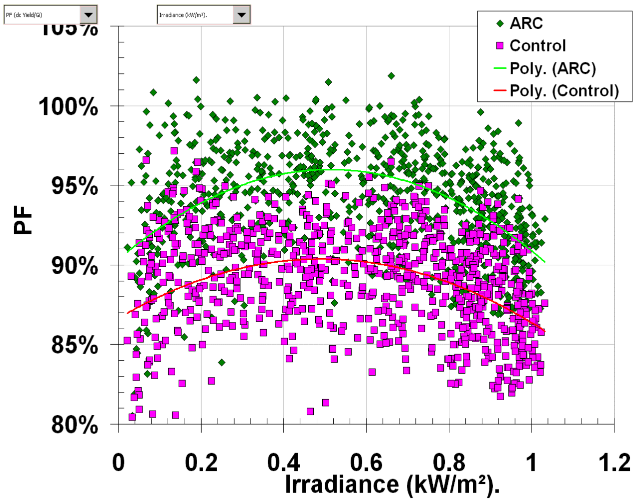

Figure 2: Performance Factor versus Irradiance for AR Glass and Control Modules with Multi Screen Print Cells in Australia

Since the AR coating improves the optical coupling of light into the module, it is the current that should be higher for the modules made with AR coated glass. Figure 3 is a plot of the normalized current, I_{DN} as a function of time for 2 modules with AR coated glass and a control module under outdoor test in Homebush, Australia for more than a year. In all cases the AR coated modules produce 4 to 6% more current than the control module. These results indicate that the coatings were stable over the time frame of the test.

Analysis of the data from Australia and Germany indicates that in all cases the energy gain due to the AR coated glass is greater than the increase in STC power as measured in a simulator. The increase in energy is typically 4 to 6% (depending upon the time frame and location) versus the measured STC power gain of 2.5 to 3.0% that was shown in Table 1. However, because of the small sample size it is impossible from this data to predict with any accuracy how much additional energy will be produced when these modules are used under varying weather conditions around the world.

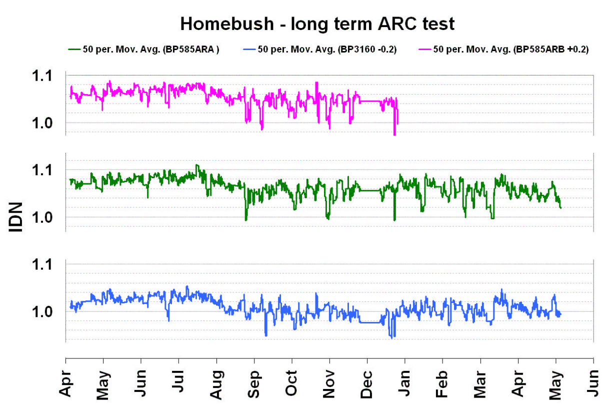

Figure 3: Normalized DC Current for 2 Modules with AR Coated Glass (top and middle) and 1 Control (bottom) in Australia

PILOT RUN

In order to further evaluate the performance of AR coated glass, a pilot run was conducted building modules with 72 mono-crystalline Saturn cells. The pilot run was designed to:

- Provide improved statistics to determine the STC flash test power increase;
- Determine what precautions are necessary in handling AR coated glass through the production line; and
- To provide modules for a much larger outdoor test designed to determine the energy gain from the AR coating.

The pilot run included 231 AR coated glass modules and 231 control modules made with standard low iron glass. The modules were processed alternately (one AR and then one standard) in order to eliminate variability in the results.

A summary of the performance of the two groups is given in Table 3. In this case the power improvement for the AR coated glass was 2.4%, just slightly less than the 2.5% measured in the laboratory on Saturn cells.

Table 3
Pilot Run Results

Glass Type	Voc (V)	Isc (A)	Pmax (W)
Standard	44.1	5.42	179.5
AR	44.2	5.54	183.8
Δ	0.2%	2.2%	2.4%

Figure 4 shows the distribution of module powers obtained during the pilot run. There is little overlap between the two distributions with the AR coating shifting all modules to higher bins by approximately the same amount.

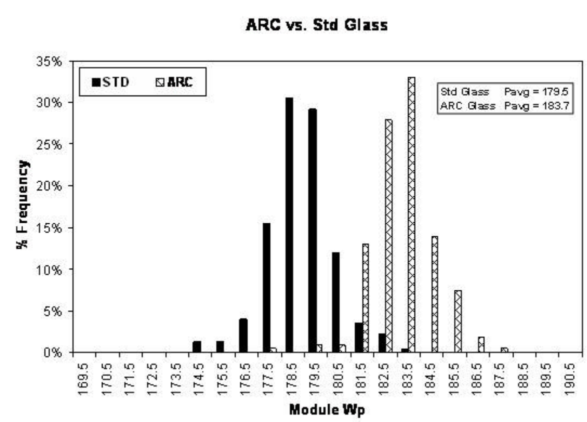

Figure 4: Distribution of module power from pilot run

The modules built in the pilot run will now be installed in two identical 40 kW systems in Germany. The performance of the two systems will be monitored to determine the energy production of each over an extended period of time.

When manufacturing modules with standard glass, the front of the glass is often placed down on the equipment or the transport system. For the AR glass such handling can result in scratching of or contamination of the AR coating. Therefore, manufacture of modules with AR coated glass will require improved handling, likely requiring that the AR coated surface be protected during at least part of the module production process.

SUMMARY

Laboratory and pilot runs of AR coated glass resulted in significant (2.4 to 3%) increases in STC power output. Preliminary outdoor exposure tests indicate that the energy gain may be in excess of the STC gain. Implementation in production may require modification to the module handling procedures to protect the coating. Ultimately, use of AR coated glass for commercial products will depend upon the economic trade-off of the added glass cost versus the value of the increased power produced. The AR coated glass yields a defined increase in output power. The additional cost of the coating on the glass must be less than the value of the added power produced.

REFERENCE

[1] IEC 61215 “Crystalline Silicon Terrestrial Photovoltaic Modules – Design Qualification and Type Approval”

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[3] S. Ransome and J. Wohlgemuth, “An Overview of 4 Years of kWh/kWp Monitoring at 67 Sites Worldwide”, **WCPEC-3,** Osaka, Japan, 2003.

[4] S. Ransome and J. Wohlgemuth, “A Summary of 6 Years Performance Modelling from 100+ Sites Worldwide”, 31st IEEE PVSEC, Orlando 2005.