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EFFECT OF GLASS Na CONTENT ON ADHESIONAL STRENGTH OF PV MODULES

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ABSTRACT

Effect of reduction of soda-ash content and more effective fixing of sodium in superstrate sodalime glass surface on durability of PV modules was studied. Damp-heat acceleration-tested PV modules having higher soda-ash content glass or normal SO_2-treated glass were most severely stained. Their adhesional strength was the lowest and delamination was most severe. High concentrations of impurities correlated with regions of delamination. Increasing the intensity of SO_2 treatment reduced the surface roughness, degree of staining, powder formation, and delamination; and increased the adhesional strength. The best approach is to reduce the sodium content as well as to fix the remaining sodium by an adequate sulfur-dioxide treatment and having fixed it not to disturb it during subsequent processes.

INTRODUCTION

Over the last seven years, PV Materials Laboratory of Florida Solar Energy Center has been carrying out systematic and detailed study of the glass/encapsulant/ Si-cell/encapsulant/backing-layer composite with an objective to lay the scientific basis for further improvement of the manufacturing technology of PV modules. Through this study, wealth of data has been collected at FSEC on properties of new, acceleration-tested, and field-deployed PV modules fabricated by PV manufacturers in US, Japan and Europe. It included modules deployed in harsh coastal conditions, hot and humid, hot and dry, and moderate climates. Specifically, adhesional strength and impurity segregation at cell/encapsulant and glass/encapsulant interfaces, as well as on elastic properties of encapsulant samples extracted from PV modules have been studied [1-10].

Analysis of samples from delaminated regions in PV modules deployed in harsh coastal climates showed the highest surface concentrations of sodium and phosphorous. Often significantly high sodium and phosphorous concentrations were observed at the surface of crystalline silicon (c-Si) solar cells up to depths of few thousand angstroms. Phosphorous surface concentrations resulted from the n-type dopant while the very high surface sodium concentration was attributed to atmospheric sodium containing aerosols in the coastal climate [1,2]. However, very high surface sodium concentrations observed in modules deployed in Arizona as well as in damp-heat acceleration-tested modules during subsequent studies clearly pointed toward sodium out-diffusing from sodalime glass [9,10]. The Auger electron spectroscopy (AES) line-scans from c-Si cell samples usually showed correlation between concentrations of sodium and phosphorous. Often these were accompanied by proportionately larger concentrations of oxygen after discounting oxygen in the antireflection titanium-oxide layer [1,2,9,10]. The phenomenon of chemically-assisted diffusion seemed to be responsible for the excessively high sodium and phosphorous concentrations. This pointed to a strong probability of formation of compounds such as sodium phosphates and hydro-phosphates.

The high sodium and phosphorous concentrations both at the surface and throughout the depth of a few thousand angstroms always correlated with low adhesional strengths at c-Si/encapsulant interface. In fact, there was a correlation between low adhesional strength on the one hand and high sodium and phosphorous concentrations on the other [Figure 1]. EVA adheres to glass by attaching to silica bonding sites on the glass surface. The diffusion of active species such as sodium and phosphorous can satisfy some of the bonds at the EVA and silicon surfaces. This surface passivation, in turn, reduces the strength of the adhesional bonds. This indicated that the durability of PV modules could be improved if precautionary measures were taken to control the sources of impurities into the structure of PV modules, as well as, if the diffusion of inadvertent impurities was limited. The present study was undertaken to test this hypothesis.

PV manufacturers desire maximum light transmission through cover glass to optimize electricity production.

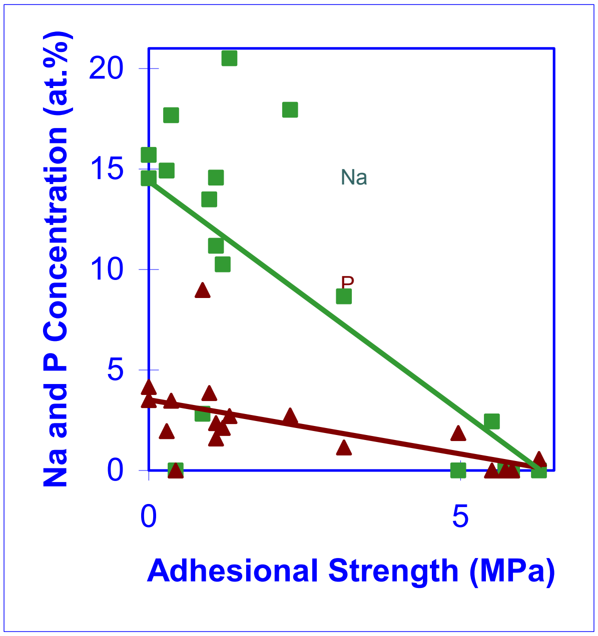

Fig. 1. Correlation between adhesional strength at c-Si cell/EVA interface with concentration of Na and P.

Light transmission in glass is reduced by iron contamination, which gives glass a greenish tint. Therefore, most PV manufacturers buy special low iron glass for cover plates for PV modules. Dolomite ($CaMg[CO_3]_2$) a mineral that was normally used in glass manufacturing typically contains excess iron, and is often unsuitable for low iron glass production. When dolomite was removed in order to fabricate low-iron glass, other compensating adjustments had to be made to the glass composition, such as increasing the sodium content. As a result, sodium oxide (Na_2O) concentration in low iron glass used in PV modules was typically raised to >15%. Sodium is a mobile ion that can cause a reactive surface layer. Usually SO_2 treatment is carried out during fabrication of sodalime glass to fix the sodium and thus to make the surface relatively inert. This paper presents a study of the effect of reduction of soda ash content and more effective fixing of sodium on the adhesional strength and staining of glass during damp-heat acceleration testing.

EXPERIMENTAL TECHNIQUE

Different types of glass superstrates were specially prepared by varying the soda-ash content or by increasing the intensity of SO_2 treatment. The formulation of specially prepared 1/8" thick, 1'x1' superstrate glass employed for preparation of PV modules were altered as follows: 1: Krystal Klear Float; 2: Krystal Klear Float with lower Na_2O; 3: Solite with normal SO_2; 4: Solite with high SO_2 (4scfh in annealing lehr and 30 psi in the tempering furnace); 5: Solite with very high SO_2 (5scfh in annealing lehr and 80 psi in the tempering furnace). PV modules were encapsulated using slow-cure ethylene vinyl acetate (EVA) and the above mentioned five types of glass. Each module contained four different types of crystalline silicon (c-Si) solar cells. Titanium oxide anti-reflection (AR) coating was deposited on two of the four cells. One AR-coated c-Si cell and one non-AR-coated cell were cleaned with isopropyl alcohol. AR-coated cells were labeled A and non-AR-coated cells were labeled N. Cells cleaned with isopropanol were labeled C and the cells that were not cleaned were labeled N. Thus the four cells were labeled AC, NC, AN, NN as follows: with (A) or without (N) AR-coat and with (C) or without (N) cleaning with isopropyl alcohol. Influence of bus lines and solder bonds was avoided by not attaching them. The modules were damp-heat accelerated tested at 85^0C and 85% relative humidity for 1000 hours. Accelerated-tested modules were inspected visually and photographed. Adhesional shear strength at the weaker of the two interfaces viz. glass/EVA or Si/EVA interfaces was calculated from the maximum torque required to extract samples using an extraction process initially developed by the Sandia National Laboratories and subsequently improved at FSEC. EVA and glass samples were examined by optical microscopy. The surface composition of EVA was analyzed by X-ray photoelectron spectroscopy (XPS).

RESULTS AND DISCUSSION

The surfaces of damp-heat acceleration-tested modules of type1 Krystal Klear Float glass and 3 Solite with normal SO_2 treatment were the roughest and most severely stained with powder non-uniformly sticking to the surface. Charles has studied water vapor corrosion ("stain") of sodalime glass [11]. In theses modules, delamination at the EVA/Glass interface was clearly visible especially at the EVA/Glass interface in the narrow strips between cells. At some places, delaminated portion also extended inside peripheral region of solar cells. White spots were observed in delaminated areas. The glass showed heavy chipping and degeneration into fine milky white powder with fine glass particles attached to the delaminated portion of EVA. EVA could be easily removed along with the backing sheet in the periphery and central portion of the module of type 1 using Krystal Klear Float glass. Delamination at EVA/Glass interface was observed all along the periphery and center of module in the case of type 3 module having Solite glass with normal SO_2 treatment.

Increasing the SO_2 flow rate in the annealing lehr and in the tempering furnace for Solite glass of type 4 and 5 PV modules progressively reduced the surface roughness, degree of staining, powder formation, and delamination. Delamination was observed at the glass/EVA interface all along the periphery of the modules 4 and 5 but not as prominently in the central region. Not much powder was observed on glass surface of module 5.

There was no powder formation and the staining was

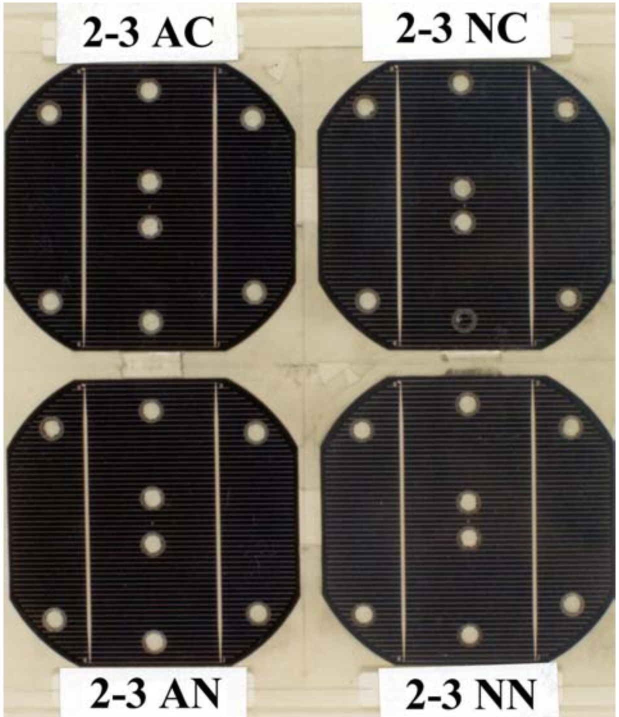

Fig. 2. Images of cells AC, NC, AN, and NN of the module of type 2: Krystal Klear Float with lower Na_2O

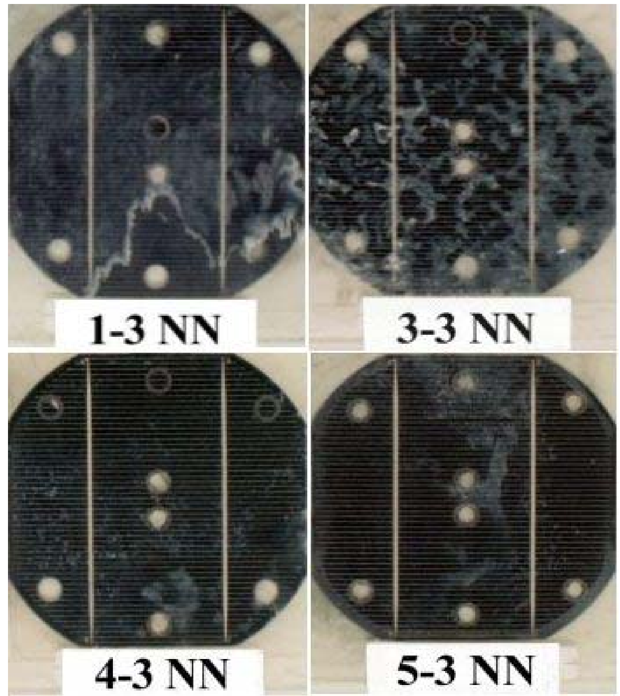

Fig. 3. Images of cells NN of modules of type 1: Krystal Klear Float; 2: Krystal Klear Float with lower Na_2O; 3: Solite with normal SO_2; 4: Solite with high SO_2 and 5: Solite with very high SO_2.

the least showing interference colors at an inclined angle in module of type 2 Krystal Klear Float with lower Na_2O. Also delamination was very low as compared to other modules. Figure 2 provides a photograph of a damp heat-tested module of type 2, with the four types of c-Si cells. Photographs of type NN cells of modules of type 1, 3, 4, and 5 in Figure 3 clearly depict varying degree of staining in different modules.

As expected, AR coated cells appeared dark blue whilst the non-AR-coated cells appeared dull gray. Adhesional failure at the glass/EVA interface was observed in more samples in the peripheral region than in the middle region. In the middle region, the average adhesional strength at the cell/EVA interface was the least (3.89-3.94 Mpa) in modules of type 1 Krystal Klear Float glass and 3 Solite with normal SO_2. The average adhesional strength at the glass/EVA interface in the peripheral region was the least (3.2 Mpa) for module of type 3 Solite with normal SO_2. Increasing SO_2 flow rate to 4 scfh in the annealing lehr and pressure in the tempering furnace to 30 psi for module of type 4 Solite glass with increased SO_2 showed low to moderate improvement in the adhesional strength. High adhesional strength (4.89-5.3 Mpa) was obtained in the case of the modules of type 2 Krystal Klear Float with lower Na_2O and 5 Solite with very high SO_2. The data on high adhesional strength for the module of type 5 Solite with very high SO_2 does not take into consideration delamination observed in one corner. Therefore, relying totally on very high SO_2 treatment would not be effective.

XPS energies and atomic concentrations of elements identified on the glass-side surface of a typical EVA sample (13NNP) from the peripheral area of module of type 1, were as follows: C (1s), 284.5 eV, 73.1%, O (1s), 532 eV, 20.7%, Si (2p3), 101.5 eV, 2.6%, Na (1s), 1072 eV, 3.6% (Fig. 4). Sodium atomic concentration on the glass-side surface of a typical EVA sample measured by XPS in the other modules 2, 3, 4, and 5 respectively were 1.4%, 2.2%, 3.9%, 3.6%. The high concentrations of precipitated impurities correlated with regions of complete delamination.

Excessive amounts of sodium are detrimental to adhesion. The high concentration of sodium on EVA surface is from sodalime glass. Such impurity precipitation would deplete the sites of adhesional bonds between EVA and silicon cell surface.

It may be noted that voids resulting from the delamination provide a preferential location for accumulation of moisture and precipitation of active impurities. These impurities can greatly increase the possibility of corrosion failures in metallic contacts.

Based on the above study, AFG completely redesigned their low iron glass composition and lowered the sodium content to ~13% for the PV industry. This constitutes a reduction of ~2%. Subsequently, low-Na glass is being supplied to all PV manufacturers.

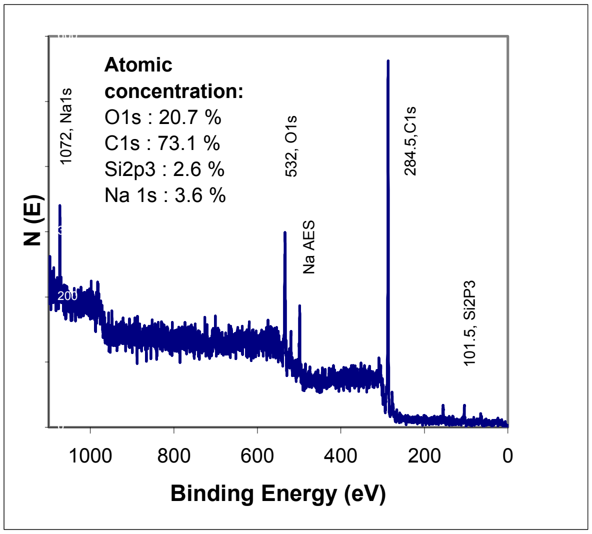

Fig. 4. XPS spectrum of EVA on glass side of module of type 1: Krystal Klear Float glass.

The reduction in the soda ash content by ~2% would certainly improve the PV durability of PV modules. As discussed above, high surface sodium concentration can result from atmospheric sodium containing aerosols in the coastal climate. Therefore, the concentration of dopant and other impurities must be carefully monitored and controlled.

So_2 treatment of glass tends to fix sodium and thus to neutralize the active layer on the surface of sodalime glass. However, glass surface can be damaged during some thin-film module manufacturing processes, such as edge delete by sand blasting. This seems to have resulted in sodium migration and severe delamination of SnO_2:F layer from glass surface together with the remainder of the thin films cells in high-voltage bias and damp-heat tested thin-film PV modules [3,12].

CONCLUSIONS

High concentrations of precipitated impurities at Si/EVA and glass/EVA interfaces correlated with complete delamination in PV modules. Surface roughness, staining, powder formation, and delamination of superstrate glass and surface Na concentration of EVA in damp-heat tested PV modules can be reduced with lower sodium content and by increasing the intensity of sulfur dioxide treatment in the lehr and in the tempering furnace. Very high SO_2 treatment by itself would not be sufficient. The best approach is to reduce the sodium content as well as to fix the remaining sodium by an adequate sulfur dioxide treatment and having fixed it not to disturb it during subsequent processes. It is also essential that the concentration of dopant and other impurities should be carefully monitored and controlled.

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