Atmospheric Plasma Surface Preparation of Solar Glass

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Introduction

The primary purpose of glass in the construction of PV modules is "clear" – to maximize transmittance of light at any angle of incidence while minimizing absorbance to generate energy. The use of anti-reflective coatings on photovoltaic glass also serves to enhance the efficiency and performance of the modules. Another major requirement is that PV glass must provide protection from the extremes of environmental conditions, as well as to meet building safety codes and safety glass specifications. Furthermore, the unexposed side of the glass must bond securely to encapsulant resin materials such as ethyl vinyl acetate (EVA), as well as plasticized polyvinyl butyral (PVB) interlayers to prevent moisture ingress and retention, among other module performance requirements.

Given the critical nature of these surface performance requirements of PV glass, the application of surface modification techniques which can optimize PV glass performance can enable new levels of efficiency and performance. This paper analyzes the use of atmospheric plasma technology as a potential key process technique in achieving optimized PV glass performance.

Background – The Role of PV Glass

PV glass is typically either of the float or rolled variety. Float glass is produced by mixing sand and sodium carbonate, heating this mixture to a temperature of over 1,500 °C and 'floating' it in molten state over a tin bath in a continuous ribbon. On-line chemical vapor deposition (CVD) of a metal oxide coating (such as titanium dioxide), for example, can then directly applied to the glass, while the glass is still hot, in the annealing lehr at less than a micron thick to reflect visible and infrared wavelengths. It is in the lehr where the glass is ultimately cooled (for later reference, titanium dioxide has a surface tension of approximately 1588 mN/m relative to PV glass with a surface tension of 500 mN/m). Rolled glass is manufactured whereby a continuous stream of molten glass is poured between water-cooled rollers. Thickness of rolled glass is controlled by adjustment of the gap between the rollers. The continuous glass ribbon leaves the rollers at about 850 ºC and is supported over a series of water-cooled steel rollers to the annealing lehr. After annealing the glass is cut to size. Antireflective coatings are also applied to either float or rolled PV glass to create interference between two reflected waves from the top and bottom of a thin film coating for the purpose of increasing light transmittance over the full solar spectrum and the sun's incident angles. If these waves are out of phase, they will cancel each other and minimize the reflected light. Optimum cancellation occurs when the refractive index of the thin film is tuned for the particular glass used, and the thickness of the thin film is controlled to one-quarter of the targeted wavelength.

PV glass can represent a majority percentage of the total material cost in PV thin film-based modules. As such, optimizing the performance of the glass component is crucial. Increases in glass quality is necessary in order to reach higher efficiencies (about 91% transmittance rate necessary), longer module lifetimes, and in order to increase competitiveness of thin film technology. Downstream manufacturing processes such as laser scribing, edge isolation and transparent conductive oxide (TCO) deposition will in-turn only add value to the module if the glass meets flatness and transmittance specifications. Outdoor glass performance as measured by accelerated aging, surface corrosion and overall module degradation relative to glass surface adhesions are also key factors in the glass performance equation.

Plasma treatment

Atmospheric plasma treatment (APT) devices allow for completely homogenous surface modification without filamentary discharges (known as streamers), because a uniform and homogenous high-density plasma at atmospheric pressure and low temperature is produced (in Fig.1, a comparison between corona discharge and plasma is shown).

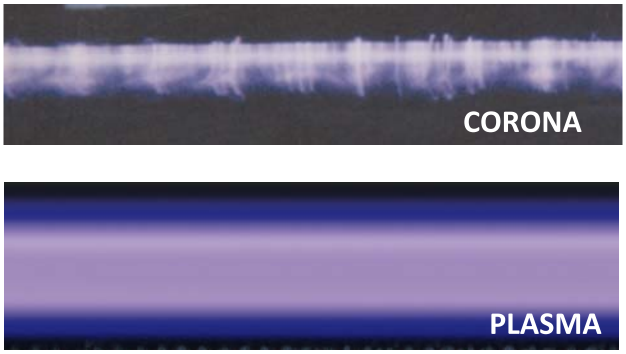


Fig.1 Corona Discharge compared with Atmospheric Plasma between planar electrodes.

The APT process modifies material surfaces similarly to vacuum plasma treatment processes - the surface energy of treated materials increases substantially, corresponding to enhancements in surface cleanliness, wettability, and adhesion properties. The APT process consists of exposing a surface to a low-temperature, high-density glow discharge (i.e., plasma). The resulting plasma is a partially ionized gas consisting of a mixture of neutral molecules, electrons, ions, excited atomic and free radical species. Excitation of the gas molecules is accomplished by subjecting the gas to an electric field, typically at high frequency. Free electrons gain energy from the imposed high frequency electric field, colliding with neutral gas molecules and transferring energy, dissociating the molecules to form numerous reactive species. Interaction of electrons, UV radiation and excited species with solid surfaces placed in opposition to the plasma results in the chemical and physical modification of the material surface.

The effect of plasma on a given material is determined by the chemistry of the reactions between the surface and the reactive species present in the plasma. At the low exposure energies typically used for surface treatment, the plasma surface interactions only change the surface of the material; the effects are confined to a region only several molecular layers deep and do not change the bulk properties of the substrate. The surface is subjected to ablation and activation processes (See Figure 2). Activation is a process where surface functional groups are replaced with different atoms or chemical groups chosen to react within the plasma.

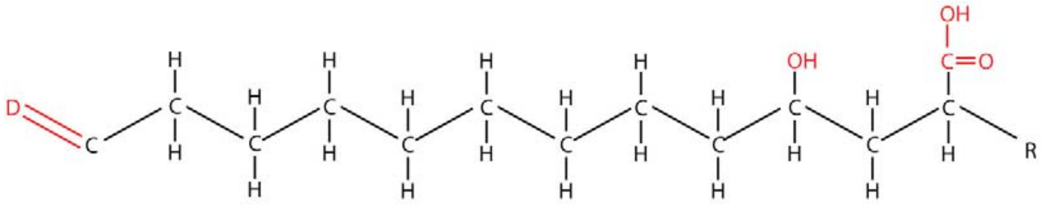


Fig.2 Plasma activation of polymer surface by creation of free radicals through substitution.

The bombardment of the material surface with energetic particles and radiation of plasma produces the ablation, and micro-etching effects where organic materials are introduced. The bombardment by plasma species is able to create a nano-roughness on a polymeric film, for example, that does not modify the mechanical bulk properties of the film but removes low molecular weight surface organics and thereby strongly increases surface adhesion (See Figure 3). Where bond strength is required, atmospheric plasma's highly reactive species significantly increase the creation of polar groups on the surface of materials so that strong covalent bonding between the substrate and its immediate interface (i.e., coatings, adhesives) takes place.

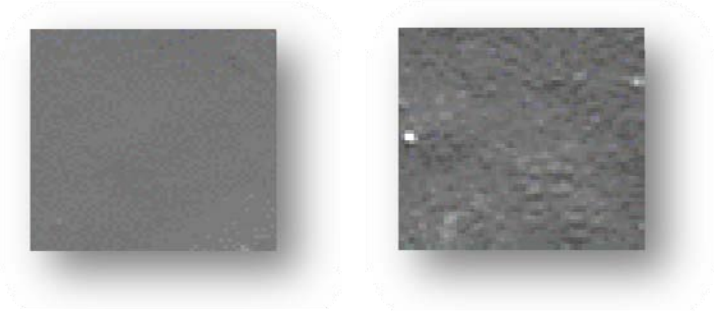
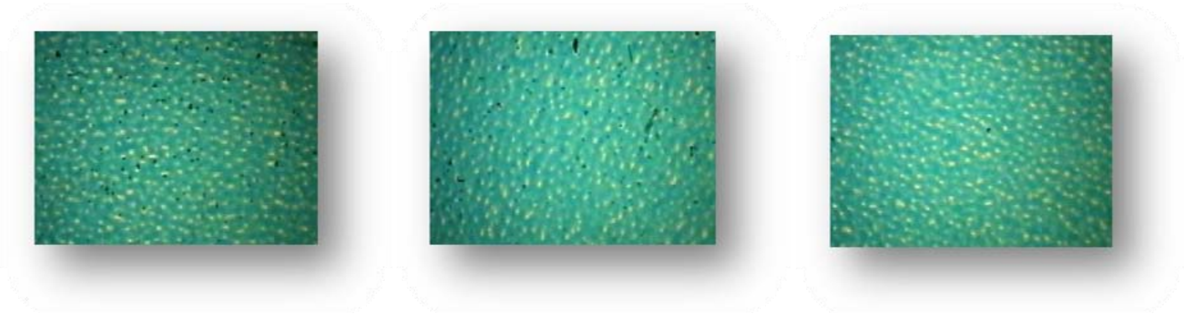


Fig. 3 Atmospheric plasma micro-etching effect of PE film, 30,000 SEM magnification

Surface cleaning via atmospheric plasma techniques reduces organic contamination on the surface in the form of residues, anti-oxidants, carbon residues and other organic compounds. Oxygen-based atmospheric plasmas in particular are effective in removing organics whereby mono-atomic oxygen (O+, O-) reacts with organic species resulting in plasma volatilization and removal (See Figure 4).



(a) (b) (c)

Fig. 4 Micrograph of PET film (a) untreated with low molecular weight organic contamination, (b) after corona discharge cleaning, and (c) after oxygen-based atmospheric plasma cleaning.

Solar cell processes transferred to atmospheric pressure plasma processes include dry etching, surface cleaning, and activation. Layer reductions using hydrogen-based atmospheric glow discharge plasmas has also been an employed aspect of the technology.

APT and PV Glass

As mentioned above, the surface of cleaned PV glass is typically 500 mN/m. However, glass is typically found with surface contaminations of low molecular weight organics and other particles which can dramatically reduce its surface tension to <35 mN/m, or equivalently a contact angle > 70 degrees. This is why elaborate, two-sided “wet” glass cleaning systems have employed alkaline cleaners, followed by nylon brushing, ultrasonic immersion/venturi-type spray (high flow rate/low pressure) rinse modules, and finally air blower drying to restore intrinsic surface tension and cleanliness.

As illustrated in Figure 5 below, the use of in-line, continuous atmospheric plasma technology (Enercon Industries) as a dry glass cleaning process can, by reduction and ablation, effectively remove glass surface contaminations uniformily and homogenously as a single stage process.

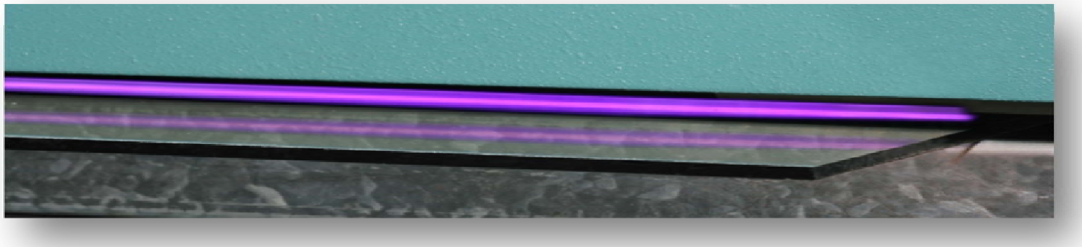


Fig. 3 Atmospheric plasma cleaning of float glass, from 85 degree contact angle to <5 degree contact angle, by Enercon plasma system

This level of cleanliness forms the critical interfacial basis for adhesions between PV glass and polymeric encapsulants such as EVA. Delamination of EVA from PV glass on in-field crystalline-Si modules has been experienced, particularly after being subjected to hot, humid weather where moisture ingress, retention and condensation become evident. Pertinent to the interfacial adhesion issue, it has been reported by Pern and Glick that, relative to EVA delaminations, glass type, surface texture, cleaning method, and priming treatment are prime considerations. Their study also concluded that not only was the surface affinity properties for EVA, which involved siloxane and hydrogen bonding and cross-linking through Z-6030 silane, appeared to be critical, but also that direct priming on the glass surface did not improve and sometimes even worsened the EVA adhesion to the PV glass substrate [1]. The effectiveness of glass surface priming is directly dependent upon the intimacy of the interfacial bond with the glass, so it is imperative that the surface cleaning process is effectively uniform and creates a strong bond. Table 1 above relates peel adhesion force before and after atmospheric plasma treatment using helium as the process gas on an Enercon Industries plasma treatment system. The single stage process treatment indicated a 29% increase in mean peel force adhesion, and a 34% increase in peak value peel force adhesion, prior to any previous surface pre-cleaning process.

	Un-Cleaned	Plasma-Cleaned	Peel Force Increase
Peel Adhesion Force - Mean	1060.3 grams	1368.7 grams	29%
Peel Adhesion Force - Peak	1103.2 grams	1482.0 grams	34%

Table 1. Improvement in peel force adhesion on float glass following helium-based atmospheric plasma cleaning.

Summary

The pre-cleaning of PV glass is critical to solar module performance. The presence of minute traces of ionic particles on solar glass can compromise energy transference, directly affecting module efficiency. These ions may be deposited by previous module fabrication processes or transferred as a result of machine component corrosion, abrasive wet washing processes, ineffective drying or imprecise machine function.

The benefits associated with the use of atmospheric plasma cleaning as an alternative or adjunct process to wet cleaning protocols are many, including the removal of organic contaminations by chemical reaction and physical ablation, the elimination of the use of chemical solvents as well as the storage and disposal of solvent waste, a significant increase in surface wettability, and a subsequent increase in surface adhesion. As a single stage process, advantages relative to a reduced process footprint may also be realized.

References

[1] F.J. Pern and S.H. Glick, "Adhesion Strength Study of EVA Encapsulants on Glass Substrates," National Renewable Energy Laboratory, May (1996) p. 5.

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