An Anti-Reflective and Anti-Soiling Coating for Photovoltaic Panels

Q.F. Xu†, Y. Zhao‡, E. Kujan†, J.C. Liu† and A.M. Lyons†‡*

†ARL Designs LLC, Staten Island, NY alan@arldesignsllc.com
‡College of Staten Island and Graduate Center of the City University of New York

ABSTRACT

The electrical output of photovoltaic (PV) panels is limited because of several factors including reflections at the air-glass interface and scattering and/or absorption of light by dirt on the exterior surface. As semiconductor material efficiency increases, the impact of losses due to reflections and soiling on the overall solar harvest becomes more significant. To reduce losses, anti-reflection (AR) coatings are used on the exterior glass of the highest efficiency PV panels. However, soiling remains a challenge, especially as large PV arrays are deployed in arid, dusty climates.

To address these challenges, we developed a single high-performance polymeric coating on glass that imparts both anti-reflective and anti-soiling properties. Nano-scale surface features with hierarchical roughness are formed in the inherently photo-stable polymer during the coating process. This texture creates a graded index of refraction on the surface that reduces reflections throughout the visible spectrum. This same nano-scale texture also imparts superhydrophobicity, which provides the surface with anti-soiling properties. The process is scalable and suited to in-line processing.

In this paper we describe the properties and durability of this dual-functionality coating formed on glass coupons. Optical properties (% transmission and reflection) are reported from 300 to 900 nm and surface wettability is characterized by contact angle and sliding angle measurements. Mechanical durability, chemical stability and self-cleaning properties were tested to verify environmental robustness. The results indicate that the AR-SH coated glass increases transmission by 2% across the visible while exhibiting excellent self-cleaning properties under harsh weather and soiling conditions.

Keywords: superhydrophobic, anti-soiling, self-cleaning, transparent, anti-reflective

1 INTRODUCTION

Photovoltaic panels face two major challenges in maximizing and maintaining their electrical output – reflections and soiling of the outer glass surface.[1,2] Most of the anti-reflective technologies available commercially today for PV applications are oxides processed at high temperature. By nature, these coatings are hydrophilic, (i.e. a water contact angle <20°). As a result, many types of dust and dirt will adhere to these coatings. In some environments, soiling rates are so high that such PV panels are cleaned once per week. One approach to reduce the adhesion of such dirt is to coat the anti-reflective surface with a hydrophobic material. Such over-coating solutions can suffer from limited efficacy and short lifetimes. Frequent reapplications are often required. Hydrophobic layers, (water contact angle > 90°) can be made by specialized sol-gel processes[3], however the cost and process temperatures are not know. Low temperature processes, such as low surface energy polymer films, have been reported, but they require sandblasting of the glass surface to insure adequate adhesion. [4]

ARL Designs (ARLD) has developed a new coating technology that imparts both AR and self-cleaning properties through the formation of a superhydrophobic surface. Superhydrophobicity, where water contact angles exceed 150°, are known to enhance self-cleaning ability. As a result, these surfaces require less water or wind to remove soil. Furthermore, the ARLD process avoids cost adders required by other anti-soiling technologies, i.e. glass pretreatment, costly materials, long processing times or high temperatures.

Both anti-reflective and self-cleaning properties are achieved in one continuous process by applying a thin layer of an inherently photo-stable, commercially available polymer to bare glass and adjusting the morphology to create a coating with nano-scale features. Controlling the size and density of the features produces a graded refractive index AR coating with a maximum dimension of ~100 nm. Hence the films remain optically transparent throughout the visible spectrum. These nano-scale features also create a superhydrophobic surface. As a result water does not adhere to the exterior of the glass; small volumes form nearly spherical droplets as shown in Figure1.

Figure 1: ARL Designs' AR-SH coating on low-iron glass. Note that the film has no distortions at low angles of incidence; the underlying text is clear and easy to read.

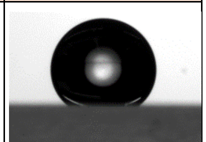
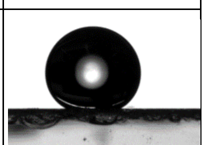
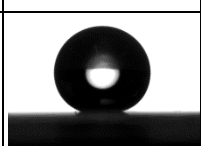
The AR-SH coating from ARLD was applied to 38 x 76 x 1.2 mm soda-lime glass microscope slides. Good uniformity and clarity was achieved across the substrate.

 TechConnect Briefs 2015, TechConnect.org, ISBN 978-1-4987-4727-1

2 WETTING PROPERTIES

Superhydrophobic and optical properties of the dual functionality AR-SH films can be controlled by modifying process variables; hence they can be tailored to meet specific requirements. Samples were prepared with different levels of surface roughness and the corresponding water contact angles (CA), sliding angles (SA) and images of a 5 µL water droplet resting on the polymer coated glass substrates are shown are shown in Table 1. When the surface roughness was minimized, the coated glass substrate was superhdyrophobic with a CA value of 150 ± 3°. The sliding angle was relatively low, which enhances anti-soiling properties; a 5 µL water droplet could roll off when the surface was tilted to an angle of 20°. Increasing the roughness resulted in higher CA and lower SA values.

Table 1: Contact and slip angles of ARLD-coated glass with different surface roughness

Surface Treatment	Contact Angle (CA)	Slip Angle (SA)	Image
A & Method_1-2 low roughness	150 °	20°	
B-medium roughness	160 °	5°	
C- high roughness	165 °	~1°	

3 OPTICAL PROPERTIES

The fluoropolymer selected for PV applications is widely used in aerospace and other applications where UV stability and longevity is paramount. The selected resin also has an index of refraction (n = 1.34) that is well suited for anti-reflective properties. By creating hierarchical surface roughness on the polymer, a graded index of refraction between air (n = 1.00) and the glass surface (n = 1.52) is formed. As a result, more light is transmitted through the glass because less light is reflected.

The transparency of glass samples prepared under different process conditions is shown in Figure 2. Spectra were recorded using a Perkin-Elmer Lambda 650 uv/vis spectrophotometer. The surface with the lowest roughness (Sample A, blue curve) is transparent across the full spectrum from ~350 nm to 900 nm. The percent transmission is larger than the untreated glass (black curve) above 370 nm indicating that the surface is anti-reflective. Greater roughness increases scattering at shorter wavelengths. Surface roughness is one of several parameters used to optimize AR and SH performance.

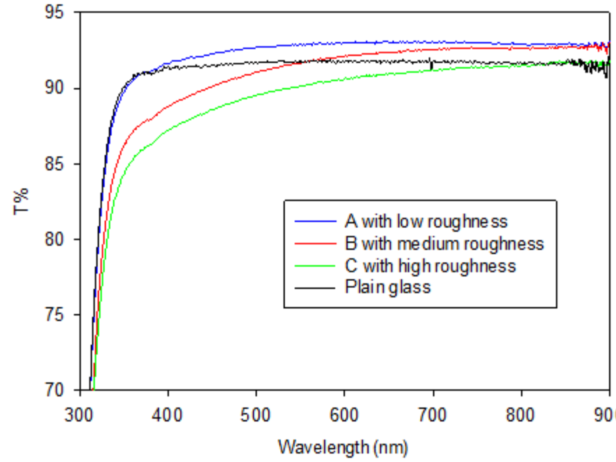


Figure 2: UV-vis transmittance of untreated glass and ARLD-coated glass prepared with different roughness values (normal incidence angle).

The incident angle of sunlight on a PV panel will also affect the amount of light reflected. By its nature, the sun does not remain at a fixed incident angle. Regardless of the orientation at which a solar panel is installed, most of the light will enter the panel at relatively high incident angles. Motorized racks that track the sun can mitigate the angular dependent reflectivity, but are very expensive to implement. The range of incident angles over which a coating can improve solar harvest is one of the distinguishing features of anti-reflective coatings such as ours. Coated glass samples were prepared and reflection spectra were recorded using the Perkin-Elmer 650 spectrophotometer equipped with a Universal Reflectance Accessory.

Figure 3 shows that the graded index of refraction of our anti-reflective coating is active at all incident angles; the percent light reflected is reduced by 2% over the range of incident angles measured from 8-60° compared to the untreated glass substrate. Process parameters have a relatively minor impact on the angular dependence as indicated by the similar performance of surfaces 1 and 2. Note that reduced reflection increases solar harvest. The reflection results in Figure 3 were recorded at a wavelength of 500 nm; a comparable 2% improvement was observed at all wavelengths across the visible spectrum.

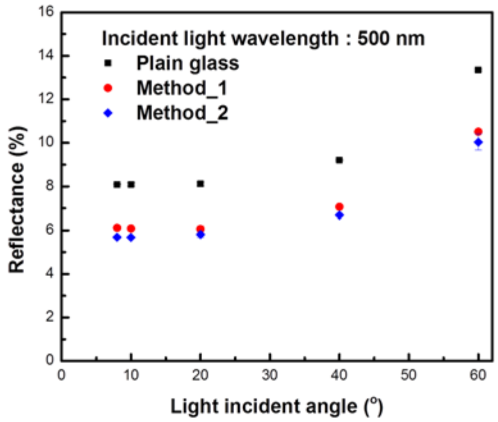


Figure 3: Reflectance of 500 nm light off untreated soda-lime glass and ARLD-coated glass as a function of incident angle

4 DURABILITY TESTING

Given severe weather and typical cleaning methods, we chose a set of tests involving water impingement and alkali exposure.[5] The UV durability of the fluoropolymer resin used in the ARLD process has been extensively characterized and conforms to the requirements for PV modules.

4.1 Rain Erosion

Rain erosion testing was used to evaluate the mechanical durability of the ARLD coating. Artificial rain droplets were generated with a UL-50 nozzle operated at a pressure of 5 psi. The resulting flow rate in the impact region is 120 mm/min. This accumulation rate over 10 minutes is equivalent to the average annual rain precipitation in Central Park, New York (1300 mm/year[6]). Droplets generated with this setup were recorded using a high speed camera (V 7.3 Phantom) at 6504 frames per second. Mean droplet diameter was calculated to be 1.5 ± 0.5 mm which correlates well with natural rain [6]. Average impact velocity of this droplets was 3.0 ± 0.1 m/s.

The coated glass surfaces remained thoroughly dry throughout the four (4) hours of test time. These conditions correspond to approximately 30 years of rain in New York City. The surface was removed from the simulated rain test hourly and the CA angle was measured. No change in CA was observed as a result of simulated rain erosion testing.

4.2 Chemical Immersion

A chemical immersion test was conducted to demonstrate strong adhesion of the coating to glass. The immersion test also demonstrates that the polymer coating process fully covers the glass surface without forming cracks or defects that could expose the underlying glass. Bare glass would attract dirt and reduce anti-soiling efficiency.

Samples were immersed in a 5% NaOH solution. After 9 hours of immersion at room temperature, the coating maintained its initial superhydrophobic properties; i.e. the coating functions as a strong liquid barrier. Previous studies in our lab have shown similar stability in strongly acidic solutions.

5 ANTI-SOILING BEHAVIOR

Solar harvest is diminished by soiling (e.g. dust, pollen and dirt buildup). Depending on conditions, the soiling effect can vary considerably, but can reduce energy output by as much as 50%.[7-12] Hence an anti-soiling coating that meets the stringent requirements of a solar module is very desirable to avoid a frequent cleaning regime or installing robotic cleaners.[2]

To assess the anti-soiling properties of our AR-SH coated glass samples, we developed a self-cleaning test to determine the amount of water consumed to remove a coating of dirt. Standard Arizona Road dust (ISO 12103-1, A2 Fine, Test Dust) was coated on each test coupon (13 ± 3 mg). The samples were fixed at a 20° tilt angle and droplets of water (1 ml) were placed at the top of the surface, allowed to roll across the dust-covered substrate and collected.

A comparison of our AR-SH coated glass substrates to untreated glass is shown in Figure 4. The AR-SH surface shown in this image is both superhydrophobic and anti-reflective at 500 nm. CA of 151 ± 3°, SA of 17 ± 2° and reflection of 5.7 ± 0.1 % at 8° light incident angle (vs 8.1 ± 0.1 % for untreated glass). On this AR-SH surface, a 1 ml water droplet rolls straight down across the surface imbibing dust particles as it progresses. The water droplet took ~1 second to roll across the treated glass surface. Since the droplet carried away the dust, a clean and highly transparent surface re-appeared. The width of the cleaned path varies slightly which is due to droplet bouncing. These oscillations cause variations in the contact area between droplet and glass. Essentially all of the water, along with the accumulated dust, could be collected after the drop leaves the surface.

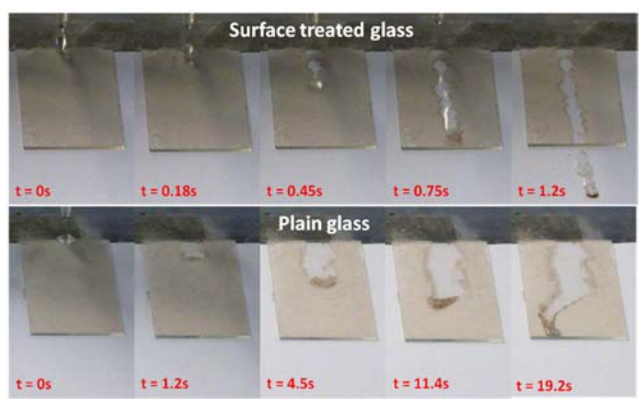


Figure 4: The comparison of anti-soiling behavior of surface treated glass and untreated glass by releasing a water droplet on the dusted surface with a 20° slope.

In contrast, a water droplet on the untreated surface took a longer time (~19 sec) to traverse the glass. Instead of rolling, the droplet spread out with the dust particles re-distributing themselves across the surface. Although most dust particles accumulated at the bottom edge of the glass, enough fine particles remained on the surface to cause a haze. If these fine particles are allowed to bake onto the glass, they will be more difficult for the next water drop to remove. None of the water could be recovered.

The ability to recover the dust-laden water droplet on the ARLD treated superhydrophobic surface provides two significant advantages. First, the dirt is removed from the surface, thereby preventing a build-up of particulates that can scatter light and adhere strongly to the glass. The ability of water to promote adhesion between dust and glass is well known [11].

A second important aspect is the ability to recover the water used to clean the glass. Water is precious in arid climates and the ability to recover and reuse the water used for cleaning reduces costs and improves environmental compatibility. Such a water recovery system could be integrated into the panel installation reducing the need for human intervention. This process would also eliminate the need for robotic cleaning systems that are expensive, difficult to maintain, and abrasive to anti-reflective coatings.

6 CONCLUSION

A scalable process for depositing a dual functionality, anti-reflective and superhydrophobic (AR-SH) coating on glass substrates was designed and tested. Properties of treated glass surface (e.g. transparency, reflectance and wetting properties) can be tailored by controlling the polymer processing conditions. Anti-reflectivity was demonstrated over the full visible spectrum, from 370 to 900 nm. The anti-reflective properties increase the percent light transmitted through the glass over all incident angles measured (8-60^{o}). Our coating proved to be very robust under harsh conditions, surviving the equivalent of 30 years of rain and nine hours of alkali solution immersion.

The ARLD coated glass also demonstrated remarkable anti-soiling (i.e. self-cleaning) behavior in the laboratory. Future studies will document is field performance.

Most importantly, our dual-purpose coating technology is intrinsically low cost and the process is compatible with high-volume manufacturing. The process is amenable to many polymer resins; the one chosen for these PV studies has an index of refraction that is well matched to solar glass and is has well established photo-oxidative stability when exposed to sunlight.

With these promising results, we believe solar panels with the ARL Designs' anti-reflective, anti-soiling coating will out-perform standard panels especially in dusty, high-soiling environments.

REFERENCES

[1] The International PV Quality Assurance Task Force at PVQAT.org, Soiling and Dust: Task Group 12.

[2] S. Ghazi, A. Sayigh, K. Ip, Dust Effect on Flat Surfaces – A Review Paper; *Renewable and Sustainable Energy Reviews* 33,742–751, 2014

[3] Z.R. Abrams, P. Gonsalves, B. Brophy, J. Posbic, "Field and Lab Verification of Hydrophobic Anti-Reflective and Anti-Soiling Coatings on Photovoltaic Glass" in *Procedings of the European Photovoltaic Solar Energy Conference and Exhibition (EU PVSEC)* 2759 - 2764 ,2014.

[4] M. Barletta, M. Puopolo, V. Tagliaferri, S. Vesco, "Retrofitting of solar glasses by protective anti-soiling anti-graffiti coatings", *Renewable Energy* 443-453, 2014

[5] E. Kujan, B. Farshchian, Q.F. Xu, M. Feldman, A.M. Lyons, "Superhydrophobic Thermoset Elastomers with Excellent Stability to Rain Erosion and Water Immersion," *TechConnect World Technical Proceedings 2015*, paper 435.

[6] T. Iserloh, J. Ries, J. Arnáez, et. alia, European small portable rainfall simulators: A comparison of rainfall characteristics ,*Catena*, 2013 100–112

[7] CSN EN 1096-2;"Glass in building - Coated glass - Part 2: Requirements and test methods for class A, B and S coatings"

[8] A. Kimber, et al., "The Effect of Soiling on Large Grid- Connected Photovoltaic Systems in California and the Southwest Region of the United States," in *Conference Record of the 2006 IEEE 4th World Conference on Photovoltaic Energy Conversion*, Waikoloa, HI, 2006.

[9] S. Canada, "Quality Assurance: Impacts of Soiling on Utility-Scale PV System Performance," *SolarPro Magazine*, no. 6.3, pp. 14–20, May-2013.

[10] J. R. Caron and B. Littmann, "Direct Monitoring of Energy Lost Due to Soiling on First Solar Modules in California," *IEEE Journal of Photovoltaics*, vol. 3, no. 1, pp. 336–340, 2013.

[11] M. Corn, "The Adhesion of Solid Particles to Solid Surfaces, a Review" *Journal of the Air Pollution Control Association*, 11:11, 523-528, 1961.

[12] L.L. Kazmerski, M.A. Jardan, Y.A. Jnoobi, Y.A. Shaya, and J.J. John, Ashes to Ashes, Dust To Dust: Averting a Potential Showstopper for Solar Photovoltaics; *Proceedings of Photovoltaic Specialist Conference (PVSC), 2014 IEEE 40th*, 2014.