Development of a Hydrophobic, Anti-soiling coating for PV Module Cover Glass

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***Abstract* — Soiling of photovoltaic modules is a serious problem that significantly reduces power output. The requirements for a hydrophobic anti-soiling coating are discussed and the development of a transparent hydrophobic coating with good durability is described. The performance of the coating has been assessed using optical transmittance, water contact angle and roll-off angle measurements. The durability of the coating is a key issue and the coating has been subjected to laboratory environmental stresses as described in IEC test standards for PV modules. These tests include UV exposure and damp heat exposure up to 1000 hours. Outdoor testing is now underway to confirm these results.**

***Index Terms* — anti-soiling coating, hydrophobic coating, water contact angle, coating degradation**

I. Introduction

Solar cells are semiconductor devices that convert light into electrical power [1]. Collection of dust/soiling on the cover glass of solar panels significantly reduces the power output by attenuating light into the active absorber. The use of a hydrophobic coating to create a low surface energy, non-adhering surface is a potential solution to this problem [2] However, solar panels are permanently exposed to the external environment and this produces very challenging conditions that vary in severity with location. It is therefore important that any degradation to the coatings is anticipated and where possible mitigated against. For example, previous studies on single layer sol gel anti-reflecting coatings have exposed a vulnerability to hot and humid conditions [3].

A world-wide effort is underway aimed at solving the problem of soiling on cover glass. Loss in energy yield due to soiling of the glass in dusty climates, collection of debris, continuous exposure to UV and infrared radiations, abrasion caused by conventional cleaning processes are all areas requiring attention [4] [5]. Soiling on cover glass can be removed with periodic cleaning procedures, e.g. dry wiping, use of water jets, cleaning detergents, etc. However, these measures require careful scheduling and can be costly. Cleaning may also cause damage to the cover glass surface. Discovery of the lotus leaf effect [6] motivated the development of artificial hydrophobic surfaces. Hydrophobic surfaces are prepared by employing rough micro/nanometer size structures on low surface energy materials [7].

Commercially, these coatings have found applications in various industries including self-cleaning of radar or satellite antennas, medical instruments, water proofing of fabrics, and easy to clean ophthalmic lenses. The benefits of these coatings depend on several factors, including the application methods and the chemical composition of the coatings. Methods of application include spaying, dipping, wiping, evaporation, chemical vapour deposition [8], self-assembly [9], chemical etching [10], electrospinning, sol-gel, and anodic oxidation [11]. The term hydrophobic means water-repelling, but these coatings are also oleophobic and generally easy to clean.

A benefit of applying hydrophobic coatings to cover glass is that it prevents the spread of water over the surface (when tilted) due to low adhesion forces between water droplets and the coating. The water droplets roll off the surface collecting organic and inorganic soiling materials. In practical terms, the coating must be low cost, highly transparent in the visible region, abrasion resistant, chemically stable, eco-friendly, UV resistant, damp heat resistant, easily curable and easy to apply and re-apply. The coating should be durable and provide functional benefit for periods of time comparable with the life- time of solar panels [7].

II. Experimental

A. Coating Formulations

A sol-gel coating consisting of trimethylsilylated silica from a tetraethoxysilane precursor [12], [13] and a siloxane adhesion promoting agent was deposited onto glass substrates using dip coating methods. Dipping with a withdrawal speed of 100mm/min resulted in a coating of ~2 micron in thickness. Curing of the coating was achieved at 65˚C at 85% relative humidity for 72 hours.

B. Assessment of Performance

The interaction between a liquid and a solid surface in terms of the ability of the liquid to wet is described by the Young equation [14];

$$\gamma_{SV} = \gamma_{SL} + \gamma_{LV}\cos\theta \qquad (1)$$

Where, γ_{SV}, γ_{SL} and γ_{LV} represent energies per unit area of the solid-vapour, solid-liquid and liquid-vapour interfaces. A surface is considered to be hydrophobic if the WCA exceeds 90º. However, it is more likely to be have useful durability and pass field trials if the initial WCA is greater than 105^0 [7]. Both the quasi-equilibrium static contact angle (θ) and the roll-off angle (RA) are widely used to measure hydrophobicity. When the liquid is water, a contact angle (WCA) greater than 90˚ demonstrates hydrophobicity, whilst 150˚ indicates superhydrophobicity. A roll-off angle (RA) of less than 10˚ is also recognized as a characteristic of super-hydrophobic surfaces [15]. Such characteristics are expected to yield self-cleaning behaviour as the water droplets collect dust and debris as they roll off the surface [16].

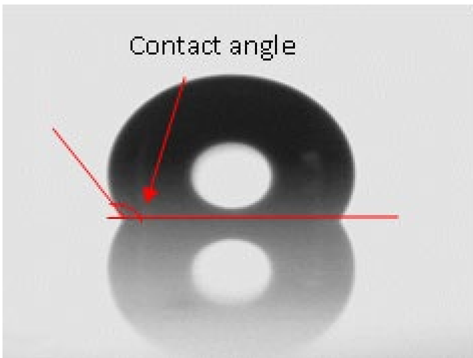

Fig. 1. Image captured by Dataphysics OCA 20 of a water droplet on a substrate measuring the WCA

C. Environmental Testing

The performance of the coating following exposure to various environmental stresses was studied. Coatings deposited on glass were exposed to UV and Damp Heat (DH) conditions as described in IEC16215-17 (MQT13 and MQT10 respectively) test standards. Samples were optically and morphologically analyzed before and after exposure to each test. Intermediate checks were performed to monitor any degradation. A Varian Cary® UV 5000 spectrophotometer was used for transmittance and reflectance measurements. Spectroscopic ellipsometry (SE) (Horiba, Jobin Yvon, UVISEL) provided information about the thickness, refractive index and extinction coefficient of the as deposited material. A Dataphysics OCA 20 contact angle measurement system was used for water contact angle measurements. A typical WCA measurement is shown in Figure 1. A Scanning Electron Microscope (SEM - Joel® 7100F and Leo 1530 VP FEG-SEM) and a Transmission Electron Microscope (TEM - Tecnai F20) were used to image the surface and cross sections of the coating before and after testing to assess the effect of each stress test on the coating.

III. Results and Discussion

A battery of laboratory tests is available to assess the durability of coatings. The most severe of these tests are the damp heat test and UV exposure each to 1000 hours of exposure. Previous work has shown that these accelerated tests can quickly reveal vulnerability to coating degradation [7].

The as deposited coating produces a consistent water contact angle of 106° (± 0.4^0). Figure 2 is an SEM image of the as- deposited coating surface. The coating thickness is approximately 2µm. This coating is applied by dip coating and the thickness is achieved by controlling the pull speed and the viscosity of the hydrophobic solution. The coating shows a homogeneous morphology, both through the thickness and across the surface of the coating, providing hydrophobic properties within the bulk. This is expected to provide long term protection should degradation occur through loss of the surface through abrasion or erosion.

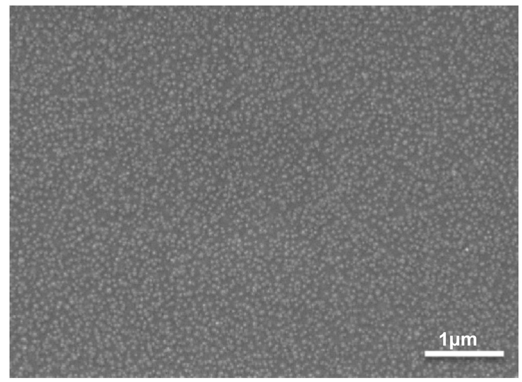

Fig. 2. SEM image of the as deposited hydrophobic coating surface.

A. Optical Analysis: Refractive Index and Extinction Coefficient

A simple single layer model was used to derive the refractive index and the extinction coefficient by using Ellipsometric Spectroscopy. Figure 3 shows the refractive index dispersion (n) and the extinction coefficient (k) of the as received hydrophobic coating measured in the wavelength range between 200 nm and 800 nm. The 2 µm coating thickness calculated using the model was consistent with SEM cross- sectional images.

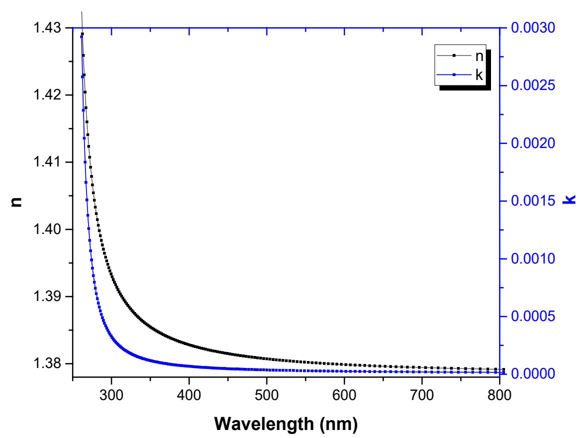

Fig. 3. The refractive index (n) and extinction coefficient (k) dispersions derived from the single-layer spectroscopic ellipsometry model.

The absorption (k) distribution has values lower than 0.03 and this is consistent with the high transparency of this coating. The refractive index (n) at 550 nm was measured to be ~ 1.38. This is lower than the refractive index of glass (n=1.50) so the coating has the potential to act also as an anti-reflection coating. Obtaining full surface uniformity and the precise thickness control necessary for an anti-reflection coating should be possible by dip coating.

B. UV Test

The WCA remained at 105.6° after 1000 hours of UV exposure confirming that the surface remains significantly hydrophobic. The roll off angle shows a 10° reduction after 200 hours of UV exposure and remains reasonably stable up to 1000 hours. The SEM image of the coating post 1000 hours of UV exposure is shown in Fig. 5. No change to the surface morphology is observed compared with Fig. 2(as deposited).

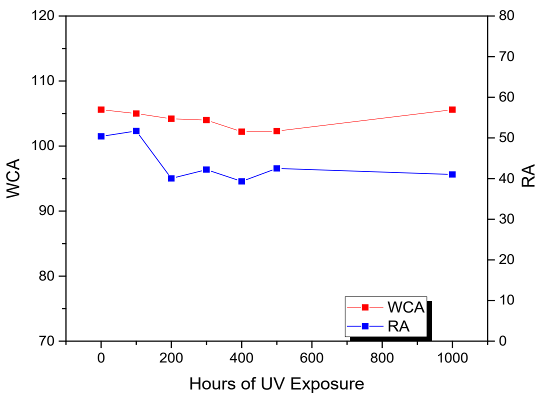

Fig. 4. The Water Contact Angle (WCA) and the Roll off Angle (RA)after 1000 hours of UV exposure.

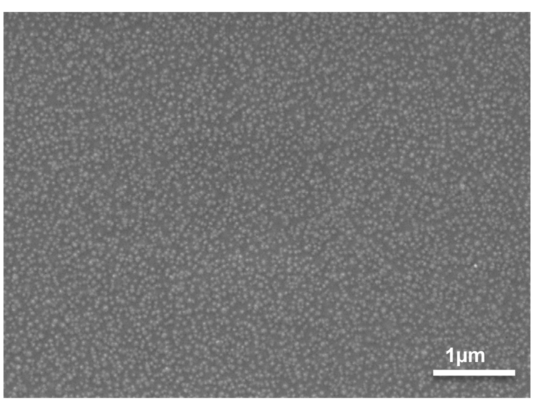

Fig. 5. SEM image of the hydrophobic coating surface after 1000 hours of UV exposure.

C. Damp Heat Test

The damp heat test exposes the coating to 85^{0}C and 85% relative humidity. Figure 6 shows the coating remains hydrophobic after 1000 hours of exposure to Damp Heat, although the WCA decreased from ~108^0 to 93.5°. The decrease only begins to occur after 500 hours of damp heat exposure. The roll-off angle (RA) increased to ~90^0 after 1000 hours of exposure. This is likely to be associated with the increased roughness induced in the coating surface. The changes in surface morphology are shown in the SEM images in Figure 7. Circular features are formed on the surface of the coating with a diameter of approximately 10-12 µm. They are a variation of concave and convex circular features. This is due to the formation of bubbles which develop into crater-like features. These crater-like features are initially observed after 100 hours of Damp Heat exposure as shown in Figure 7(c). However, this feature is relatively small with a diameter of approximately 700 nm. The formation of these defects is due to solvent/moisture entrapment. The nature of the coating requires elevated humidity and temperature curing conditions.

The elevated humidity and temperatures used in the Damp Heat exposure experiment activates the curing of any uncured deposited coating (typically from within the bulk of the coating). The solvent/moisture from the curing reaction appears at the surface. These surface defects have a gradual deleterious effect on the roll off angle and after 500 hours also have an effect on the water contact angle. The features become larger and more spread across the surface as the exposure time increases.

This type of degradation can be avoided by ensuring the full cure of the coating. This can be achieved by controlling the curing conditions or by depositing a thinner coating layer. The coating is designed for PV module cover glass which will experience varying weather conditions dependent on location. It is likely that if the local environmental conditions do not exceed the curing conditions of temperature and humidity, then the coating will not release the solvent/moisture.

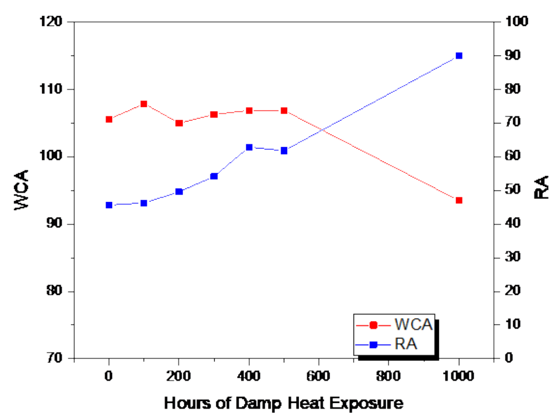

Fig. 6. Water Contact Angle (WCA) and Roll off Angle (RA) of the hydrophobic coating after damp heat, DH, exposure up to 1000 hours.

The different initial conditions (WCA and RA values) between Figure 4 and Figure 6 are due to tests performed on coupons coated with different formulations.

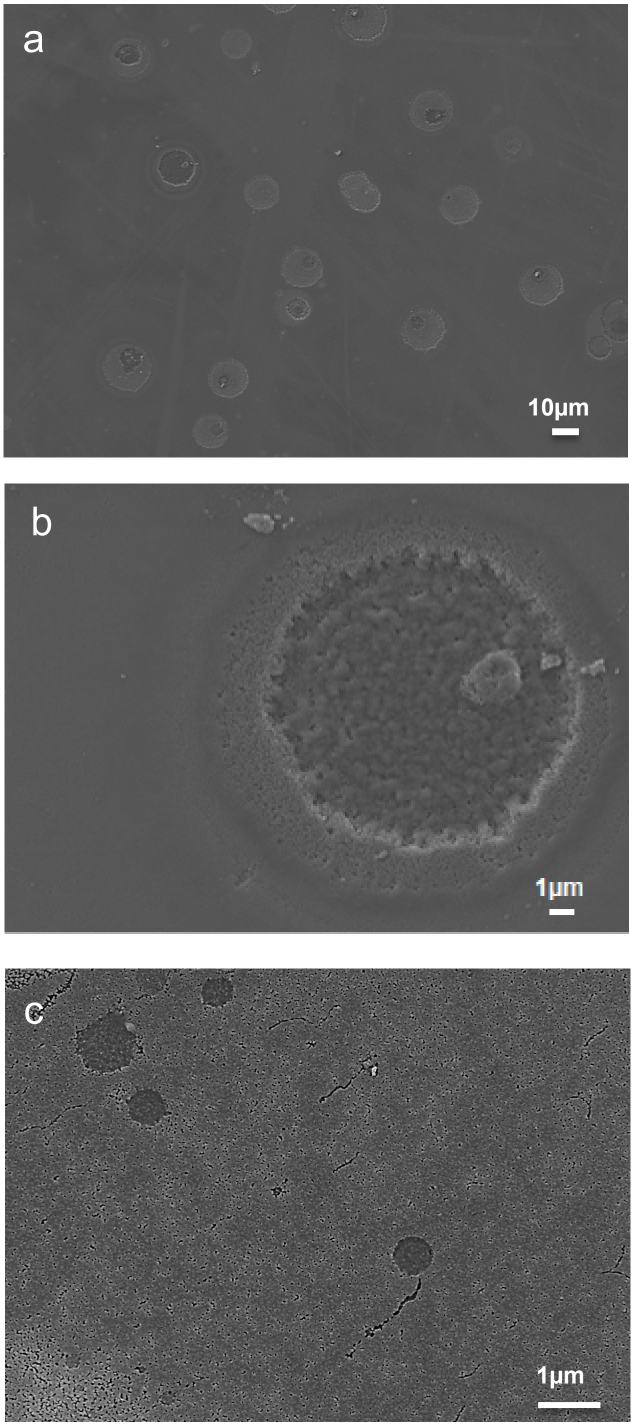

Fig. 7. SEM images of 1000 hours (a and b) and 100 hours (c) of DH exposure

D. Optical Measurements

The optical performance of the coating was assessed by measuring transmittance (%T) and reflectance (%R). The Transmittance decreased after UV exposure. There is a red shift of the absorption edge from 320 to 360 nm. However, this remains within the visible region and within the wavelength range used by a PV module. The reflectance drops slightly with exposure; however, a significant change is not observed. Under Damp Heat exposure there is no shift in the absorption edge. However, the transmittance increases at 570nm wavelength, as shown in Figure 8. This is attributed to the formation of craters due to blistering which thins the coating and may lead to an anti-reflection effect. This change is observed as a decrease in reflectance (see also Figure 8).

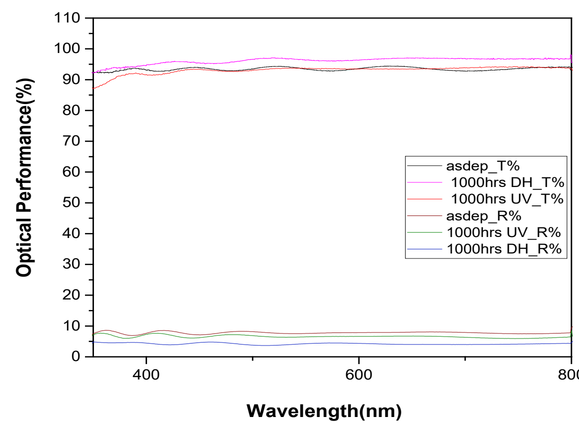

Fig. 8. Optical performances (T% and R%) of the as deposited coating and post 1000 hours of DH and UV exposures.

IV. Conclusion

A novel coating has been prepared and applied to glass substrates. The coating has a low refractive index of 1.38 at 550nm. This could be exploited as an anti-reflective coating if the thickness is controlled. The coating also shows high levels of hydrophobicity.

Environmental testing shows the static water contact angle is $\sim106^{0}$ and remains approximately constant even after 1000 hours of UV exposure. Damp heat testing indicates a reduction in repellence as measured by the static water contact angle after 500 hours exposure although the roll-off angle indicates an earlier onset as a result of the solvent/moisture entrapment from residual curing reactions activated by the extreme Damp Heat conditions.

The development of effective hydrophobic coatings for solar cover glass applications requires both new materials and more effective assessment methods. The work presented here indicates routes forward in both directions.

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