The Hydrophil™ Difference

Introduction

The Lotus Leaf Coatings' solution based sol-gel approach is very attractive as a means to control structures and properties of materials at the nanoscale while still providing a synthetic route that is scalable and repeatable. By varying the components (monomers, alcohols, and/or water) present during the reaction, temperature, or pH, a number of different structural features can be obtained as is shown in Figure 1. Simply changing the reaction conditions at different stages of the process provides a vast number of possibilities for tuning the material's performance features.

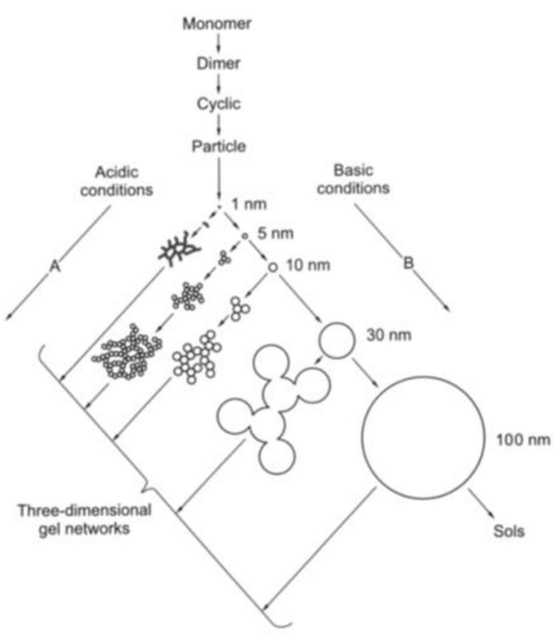

Figure 1. Synthesis-driven properties

Further property tuning can be accomplished by the incorporation of functional monomers during the synthesis of the material. The ability to incorporate chemical functional groups within the fine structure of the material offers a number of routes to optimize the performance of the final coating material. In this way, the surface functional properties of the Hydrophil™ coatings are controlled for specific applications. In addition, the coatings are commercially attractive since they can be applied using a number of low cost application methods such as spray coating, dip-coating, or spin-coating, and require significantly less capital equipment than, e.g., TiO_2 sputter treatment of glass during the manufacturing process. Application of the Patent Pending Hydrophil™ coating system requires no elevated temperatures for curing so heating up to 180^{o}C is possible to enhance the speed by which ultimate properties are achieved, and to increase throughput. This is much lower than the 400 – 600 ˚C required by classic SiO_2 sol-gel based systems, allowing for the treatment of polymeric substrates. Another consequence of the Lotus Leaf Coatings' sol-gel approach is that these coatings are optically clear and have a low refractive index (1.47 @600nm). Furthermore, they have the potential for higher light transmissions than other material systems.

Water Management – The Sheeting Effect

By maximizing the number of water-loving groups present in the final coating, we have developed a material that exhibits extreme and permanent hydrophilic properties. The surface energy can be engineered to be nearly identical to that of a water droplet, which results in extraordinary wetting properties. Figure 2 shows the low contact angle for a 2 microliter droplet on the surface of a Hydrophil™ coating.

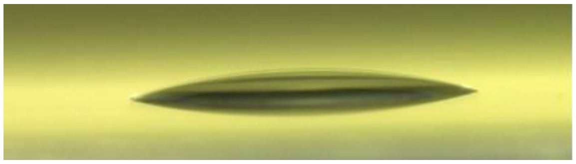

Figure 2. Contact angle of Hydrophil™ coating

Anti-Soiling Properties

Extremely low water contact angles give rise to a sheeting action, which leads to a hydrophilic self-cleaning mechanism. This feature of the technology also becomes useful in a number of high performance applications where the presence of beaded water droplets is not desirable. By inducing a sheeting effect, the light scattering effect from water droplets on a surface can be eliminated. This mechanism also allows for spot-free drying, which is very useful in applications where light scattering is not desired.

Testing of PV panels by the Frauenhofer Institute demonstrated the advantages of hydrophilic coatings even in an arid environment, as seen in Figure 3. According to the Frauenhofer Institute study, hydrophilic anti-soiling coatings can provide as much as a 3% efficiency gain as compared to uncoated PV panels.

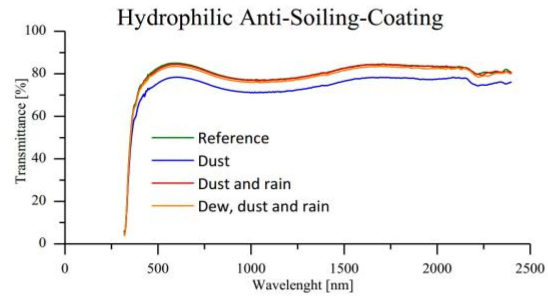

Figure 3. Spectral graphs of hydrophilic anti-soiling coated glass substrates after soiling tests and artificial rain[1]

Anti-Soiling: Hydrophobic or Hydrophilic

In comparison, hydrophobic cleaning mechanisms rely on the beading up of water droplets followed by roll-off. The hydrophobic cleaning mechanism relies on a steep substrate angle, which may not be ideal for some applications, including solar. For the current commercially available fluoro-alkyl-silane (FAS) systems, water droplets must reach a critical size before any sliding can occur. Smaller droplets that are left behind will accumulate dust, dry onto the substrate as a dirt crust, and such contribute to light scattering and loss of transmission. This is especially noticeable in areas with dew point transitions like coastal areas, especially in the Middle East. Dew forms on up to 40% of days, leading to a rapid build-up of dirt that is difficult to remove by dry cleaning, especially if the area lacks occasional heavy rain storms. Table 1 provides a comparison of hydrophilic and hydrophobic performance factors.

Factor	Hydrophilic	Hydrophobic

[1] Klimm, E., T. Lorenz, and K. A. Weiss. "Can anti-soiling coating on solar glass influence the degree of performance loss over time of PV modules drastically?" *the 28th EUPVSEC* (2011).

Technology	Sol-Gel SiO2	FAS (Enki)
Water Contact Angle	<20°	≈100°
UV Stable	Stable	Degrades with UV light exposure
Slope	Works on surfaces with low tilt angle	Required high tilt angle for water movement
Water Spots	Sheeting Effect eliminates water spots	Requires droplets to reach critical size or water spots will form.
Anti-Reflective Compatible	Yes	Yes

Table 1. Comparison of hydrophilic and hydrophobic materials

Environmental Stability

One of the drawbacks inherent to some of the other approaches to solve the anti-soiling problem is UV stability. This is especially a problem for FAS type and other hydrophobic materials employed for this purpose. Existing FAS materials show a significant decrease in performance with exposure to ultraviolet light. According to Dow Corning water contact angles on FAS standard FAS materials degrade after 500 hours in a Sunshine Weather-O-Meter, which equates to slightly more than 1 year outside UV exposure.

Hydrophil™ properties were maintained after accelerated weather testing per QUV weathering test ASTM 4329. Unlike surfaces treated with FAS's, any organic incorporation into the Hydrophil™ material is restricted to only a few carbon atoms between silicon oxide bonds. This molecular confinement generally leads to less susceptibility to UV degradation.

Furthermore, for areas with a high build-up of organic contaminants, the cleaning ability of Hydrophil™ based systems can be enhanced by the incorporation of TiO_2 nanoparticles. This enhances the photocatalytic activity of the coating, similar to that of expensive vacuum sputtered TiO_2 coatings.

The weathering performance of the coatings is matched by the mechanical stability. Linear abrasion testing according to ISO 9211-4:2012 (cheesecloth, 5N) shows sub 20˚ contact angle after 5000 rubs.

Other tests performed included resistance to acidic salt spray, hydrolysis and hot-wet cycles.

Anti Reflective Compatibility

According to a study by DSM, 75% of PV panels were coated with antireflective (AR) coatings in 2015 with the percentage coated expected to rise to over 90% by 2017. The development of Hydrophil™ for the ophthalmic industry required that the coating be part of an antireflective (AR) coating package. Since the chemistry of Hydrophil™ and those of AR coatings are similar and compatible, Hydrophil™ is able to chemically bond with these types of materials. Figure 4 shows that the reflectivity of an antireflective stack for the ophthalmic application can be tuned both by the alternating layers applied and the thickness control of the Hydrophil™ coating as the top functional layer in the AR system. For solar applications transmission gains of 3% per side is considered premium performance. Using these unique features of the technology, there can be a multitude of applications for Hydrophil™ where cleanability and light management are key components to system performance. Hydrophil™ is advantageous in AR systems since TiO_2 based materials generally are not applied as the top functional layer in AR coating systems due to processing limitations.

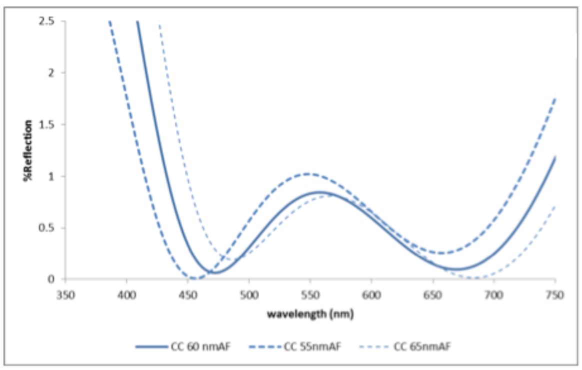

Figure 4. Influence of coating thickness on reflectivity

Sub-nanometer Porosity

Although it is common for sol-gel based materials to be porous, Hydrophil™ has been designed to provide a solid coating. This solid coating enables greater bonding to the underlying substrate and minimizes the risk of material failure. The presence of pores in coatings subject to environmental exposure tend to induce material failure as moisture is able to condense in the pore network and create a state of stress, which can lead to cracking and unwanted light scattering. The scanning electron micrograph of a thinly deposited layer of Hydrophil™ deposited on a silicon wafer and cleaved for cross-sectional viewing (Figure 5) shows that any porosity would be sub-nanometer at most. Additional optical data, i.e. a refractive index not less than that of dense silica (1.47 vs. 1.45), indicates that there is not a significant porosity, which would lead to a lower refractive index.

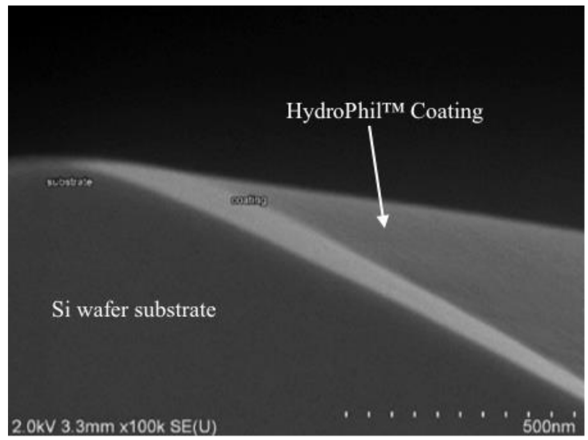

Figure 5. SEM of solid Hydrophil™ coating on Si-waver

Multi-functionality - Cleanable Coating Design

Most recently, the Hydrophil™ coating series has featured an easy to clean functionality. This has been accomplished by the incorporation of chemical groups that tailor the surface energy so that dirt and oils can be removed effectively. Essentially, the cleanable version of Hydrophil™ has been engineered to neither like nor dislike oils, which prevents the smearing effect that is observed for the hydrophobic and oleophobic approaches to the cleaning problem. The Hydrophil™ approach differs from the traditional use of hydrophobic materials, which typically involve the application of FAS.

An example of how this technology has been used is in ophthalmic lens industry, where lens cleanability is a key customer pain point. The market leading coatings, sold as part of anti-reflective coating packages, are designed to have as high of a water contact angle as possible (normally around 110-115^{o}). Despite the marketing influence on highlighting hydrophobic coatings as the most cleanable, the data shown in Figure 6 provides evidence that leads to the conclusion that hydrophilic coatings show the most promise for solving the cleaning issue. The test data shown in Figure 6 compares the cleanable properties of Hydrophil™ as compared to Essilor's Crizal *Avance™* lens treatment. In this test, artificial skin oil is applied to the coating surface, and the percent haze (light scattering or opacity) is measured before and after simulated cleaning cycles. It can be seen that the repellency effect from the FAS treatment prevents effective removal of the contaminants since the oils and dirt are just smeared around rather than being removed. When the test is conducted with water based cleaners, the effect is even more dramatic. This cleanable function has significant applicability to the solar and other markets.

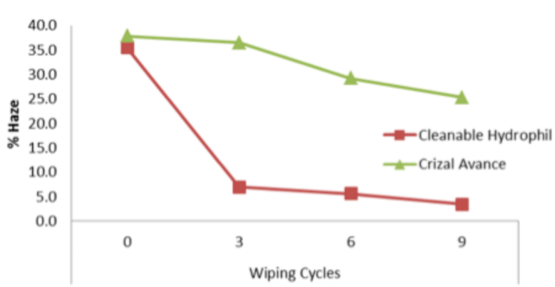

Figure 6. Cleanability comparison of Hydrophil™ coating vs. market leading FAS-coating

Low Cost Manufacturing

Most of today's coatings, whether based on sputtering, chemical or physical vapor deposition, require application during the original glass manufacturing process. These coatings require extremely high capital costs. Hydrophil™ coatings are provided as stable solutions, typically in alcohol or alcohol/water mixtures and can be applied at any stage of the production, e. g. at a solar manufacturer on any uncoated glass or on finished modules. The result is a much lower capital requirement and a very low cost of goods sold. In addition, the wide compatibility with substrates allows treatment of all exposed surfaces. The low-temperature cure makes it compatible with not only glass but also a variety of polymer-based substrates like carbonate, acrylic or polyethylene. This makes the approach future-proof against potential changes in technology.

Conclusion

The Hydrophil™ technology differentiates itself strongly from any other system on the market. No other system offers the performance, ease of property tuning, environmental stability, and cost advantages combined in the Hydrophil™ coating.