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Assessment of optical transmittance of oil impregnated and non-wetted surfaces in outdoor environment towards solar energy harvesting

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ABSTRACT

Self-cleaning of optically transmitting surfaces is important to improve the performance of solar harvesting devices in harsh environments such as dust and humid ambient. Non-wetting characteristics of surfaces can create self-cleaning effects while lowering efforts required to remove dust from surfaces. Non-wetting, in which the texture has been filled with some lubricant, have robust self-cleaning characteristics than surfaces with air pockets trapped between the textures. Consequently, non-wetting surface in which the textures are impregnated with silicone oil is examined in relation to solar energy harvesting applications. In this case, a hierarchal texture is generated first onto the transparent glasses by the convective assembly of silica particles. The resulting textures are characterized incorporating scanning electron and atomic force microscopes. The textures are then impregnated with silicone oil after functionalization with OTS (Octadecyltrichlorosilane). Non-wetting behavior, film thickness and transmittance of the resulting surface are assessed using contact angle goniometer, ellipsometer, and UV–Visible spectrophotometer. The resulting surfaces are tested in outdoor environments and transmittance reduction of UV–visible spectrum is assessed. It is found that silicon oil impregnation improves water droplet mobility at the surface; however, optical transmittance reduces significantly over the time due to dust particles settlement at the silicon oil film interface.

1. Introduction

Self-cleaning characteristics of optically transparent wafers is of interest in many applications, and it becomes critical for efficient harvesting of solar energy in harsh environments (Strauss et al., 2015). Generating self-cleaning characteristics of optically transparent wafer surfaces is one of the current challenges because the task of achieving durable surfaces in the harsh environmental conditions is extremely difficult. Self-cleaning of surfaces for solar energy harvesting is critical for efficient utilization of solar energy (Salvaggio et al., 2016). Studies on hydrophobic and antireflective films for photovoltaic applications were carried out previously (Yuan et al., 2016; Yang et al., 2015) and the findings revealed that surface hydrophobicity and antireflective coatings had a significant effect on the solar panel optical properties and their performances. Minimizing the adverse effects of environment, such as dust accumulation and mud formation on surfaces, on solar harvesting device is important for the efficient operation of these devices. The efforts were made to minimize the environmental dust adhesion and mud formation on optically transparent surface (Meng et al., 2014; Yilbas et al., 2016). A characterization study for self-cleaning and antireflective coating for photovoltaic panels was carried out previously (Arabatzis et al., 2018). Increased light transmittance in the visible light region and enhanced self-cleaning of the coated in comparison to the uncoated glass was demonstrated. The adhesion and the stability of the coating were tested in conditions of thermal fluctuations, UV weathering and sandblasting. The influence of mud drying temperature on surface characteristics of a polycarbonate PV protective cover was investigated in details for possible solar energy harvesting applications (Yilbas et al., 2017). The findings revealed that alkaline (Na, K) and alkaline earth metals (Ca) compounds in dust particles dissolved in condensed water while forming chemically active mud solution, which settled at the interface between mud and polycarbonate surface under the gravity. This had a detrimental effect on cleaning of dusted polycarbonate surface because of mud solution, upon drying, increased adhesion between dry mud and surface as well as modified microhardness and surface texture of polycarbonate surface. Generating the anti-dust effect of transparent hydrophobic coatings, which could be applied for solar cell covering glass, was challenging (Quan and Zhang, 2017). It was demonstrated that the low surface energy and rough structures of coatings worked together to lower the adhesion forces

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between the particles and surfaces. However, the anti-dust effect almost had no simple relations with the surface hydrophobicity. A study on the influence of snow and ice coverage on the energy generation from photovoltaic solar cells was one of the research interests in solar energy harvesting applications (Andenaes et al., 2018). In the study, some commonly understood effects of shading on photovoltaic panels performance, both in the form of uniform shading (weak light) and partial shading were explored.

On the other hand, nature has continued to inspire us to design and create surfaces with excellent functional properties (Rifai et al., 2016). One such superhydrophobic and self-cleaning surface is of lotus plant (*Nelumbo nucifera*) that has an intrinsic hierarchal structure, made by convex shaped epidermal cells *papillae* covered with hydrophobic wax tubules (Bhushan, 2009). Thus the presence of micro and nanoscale structures together with a low surface energy coating is required to make surfaces that are superhydrophobic and self-cleaning (Barthlott and Neinhuis, 1997; Oner and McCarthy, 2000) Many such surfaces have been fabricated using processes like soft lithography (Callies and Quéré, 2005), electron beam lithography (Liu et al., 2006), sol-gel (Feng et al., 2011), oxygen plasma etching (Bhushan, 2009), plasma enhanced CVD (Wu et al., 2006), and physical vapor deposition (Teshima et al., 2005). Such artificially made superhydrophobic surfaces continue to exhibit non-wetting behavior as long as stable air pockets are maintained beneath the droplet (Hozumi and Takai, 1997). These tiny air pockets, however, are unstable and collapse under conditions involving large wetting pressure, high temperature or humidity (Tavana et al., 2006; Lafuma and Quéré, 2003), or when damage occurs to the surface texture (Deng et al., 2009). A low surface tension liquid can also sometimes displace these air pockets and penetrate the texture (Reyssat et al., 2008). In all such cases, the droplet pins to the surface and the surface loses its self-cleaning ability.

To overcome the problems associated with lotus leaf inspired surfaces, a new type of pitcher-plant (*Nepenthes*) inspired surfaces called SLIPS (stable liquid infused porous surfaces) have been reported (Wong et al., 2011). These surfaces do not rely on trapped air pockets inside the texture to repel liquids. The texture is instead filled with a lubricant thus providing a surface with an over-lying liquid interface that is ultra-smooth, chemically homogeneous, continuous and provides an extremely low contact angle hysteresis for a broad range of liquids (Wong et al., 2011). The lubricant infused surfaces, however, become more complex due to the introduction of an additional phase and such a system has far more possible thermodynamic states which may exist when a droplet is placed on such surfaces. Kim et al. (2013) investigated the effect of surface roughness on lubricant loss under high shear conditions and found out that nano structured surfaces were best at retaining a thin layer of lubricant because of the capillary forces. It was also concluded that two tiered roughness is not necessary and that a single level of roughness is sufficient enough to hold the lubricant in place. Smith et al. (2013), however, reported that water droplet pinning was significantly reduced for BMIM (an ionic non-wetting liquid) impregnated silicon micro post arrays when a second level of roughness was added. Anand et al. (2012) studied droplet condensation on lubricant impregnated surfaces and found out that the droplets stayed mobile and didn't pin to the substrate whereas significant droplet impalement was observed in conventional superhydrophobic surfaces. Kim et al. (2012) demonstrated that lubricant infused surfaces can be used as ice-repellent coatings because of their ability to resist ice and frost formation at low temperatures.

Although oil impregnation of surfaces towards self-cleaning applications has been introduced previously (Wong et al., 2011; Kim et al., 2013; Smith et al., 2013), the main focus was to examine water droplet mobility on the oil impregnated surface. The outdoor testing of such surfaces in relation to solar energy harvesting was left for future studies. Consequently, in the present study, outdoor testing of the hydrophobic surface generated from the method of colloidal silica particles deposition and silicon oil impregnated surface is carried out. The UV–visible transmittance of the resulting surfaces is assessed and the influence of environmental dust settlement on the transmittance loss is determined incorporating the outdoor data. Lubricant impregnated surfaces are a new class of non-wetting surfaces that offer several advantages over conventional superhydrophobic surfaces. We report a simple method for obtaining such surface on glass. To impart roughness to the smooth glass substrate, we deposit silica particles via a process called convective assembly which is governed by the evaporation of solvent in the meniscus region of the substrate being pulled slowly out of the colloid solution (Anand et al., 2012). The replacement flux carries the particles from the solution to the drying part of the meniscus. Strong capillary attractions cause the particles to pack into mono/multi layers as the meniscus thickness becomes less than the particle diameter (Dimitrov and Nagayama, 1995). The formation of mono or multi layers depend upon a variety of parameters like substrate withdrawal speed, colloid volume fraction and diameter, solvent evaporation rate etc. (Kralchevsky and Denkov, 2001). After deposition of silica particles, the surface is functionalized with OTS (Octadecyltrichlorosilane) followed by impregnation with silicone oil.

2. Experimental

The materials used in deposition and functionalizing of colloidal silica particles included OTS (n-Octadecyltrichlorosilane) (90%) and silicone oil (380 mPas viscosity), which were obtained from Sigma Aldrich, USA. Acetone (99.8%), Ethanol (99%), n-hexane (96%), H_2SO_4 (97%), 30%w/w H_2O_2 were used, which were received from Scharlau, Spain. FUSO PL-20 (220 nm diameter silica particles) (20 wt%), PL-7 (75 nm diameter silica particles) (23 wt%), and PL-3 (35 nm diameter silica particles) (20 wt%) colloidal silica were obtained from FUSO Chemicals, Japan. The glass slides were received from Fisher Scientific, USA. Milli-Q water with resistivity greater than 18.2 MΩ·cm was used.

Glass slides were first cleaned by a soap solution to remove grease and dirt and then immersed in Piranha solution (H_2SO_4 and 33% H_2O_2 in 5:1 volume ratio) for 30 min. After rinsing thoroughly with DI water, the glass slides were then sonicated in ethanol, acetone and then ethanol again, followed by a final rinse in DI water and drying under Nitrogen gas. The glass slides were used immediately to avoid contaminants buildup. Colloidal silica particles in three different sizes (220 nm, 75 nm and 30 nm) were mixed in equal volumes. Ethanol was then added to the mixture to achieve a volume ratio of 15:1 (ethanol to colloidal silica mixture). The mixture was sonicated for 15 min to homogeneously distribute the particles. Glass slides were then immersed into this colloidal silica mixture and then withdrawn vertically at a velocity of 150 µm/s using MTI Dip Coater. The silica-coated glass slides were then baked in an oven at 200 °C for 2 h to dry out the solvent and then air cooled.

The silica particles deposited onto the glass slides were functionalized using OTS. Briefly, 0.01 M solution of OTS in n-hexane was prepared, and the silica coated glass slides were immersed in that solution for 4 h. The surfaces were then taken out of the solution, rinsed with acetone and chloroform three times each, and baked in an oven at 125 °C for 15 min. Silica coated glass slides were then impregnated with silicone oil using dip coating technique. The surfaces were withdrawn vertically from a silicone oil container at a controlled velocity of 1 mm/min.

SEM imaging was performed on LYRA Tescan 3 Field Emission Scanning Electron Microscope. AFM by NanoMagnetics was used in Dynamic mode to analyze the surface texture. The tip was made of silicon nitride probes (r = 20–60 nm) with a manufacturer specified force constant, k, of 0.12 N/m. The wetting experiment was performed using Kyowa (model – DM 501) contact angle goniometer. A sessile drop method was considered for the contact angle measurements and 7 µL droplets were deposited onto the surface using an automated dispensing system. UV–VIS Spectrophotometer (Jenway 67 series) was used to measure the transmittance of the workpieces.