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Experimental investigation of the anti-dust effect of transparent hydrophobic coatings applied for solar cell covering glass

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A R T I C L E I N F O

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A B S T R A C T

Transparent coatings with different hydrophobicity have been prepared by a cost-efficient and simple approach. These coatings possess two main properties: high transmittance and anti-soiling effect. Four experiments are designed to simulate the surface-dust interactions, one of which is a dust impinging experiment and the other three are dust removal experiments. A high-speed camera is used to capture the impinging and depositing process of dust driven by air stream. Different moving behaviors of dust particles can be observed on the bare and coated glass surfaces, which can be used to illustrate the different soiling phenomena. The anti-soiling effects of coated surfaces are reflected in two kinds of experiments. The first is the dust impinging experiments and the second is the dust removal experiments. It is found that the low surface energy and rough structures of coatings work together to lower the adhesion forces between the particles and surfaces. This anti-dust effect almost has no relations with the strength of hydrophobicity: both superhydrophobic surface and ordinary hydrophobic surface have anti-dust effect.

1. Introduction

Glass is widely used in solar modules to protect the active devices from harsh environmental conditions, for example, dust storms, humidity, heavy rains, wind, etc [1,2]. The high transmittance of glass surfaces enables the sunlight to reach the inside of the solar modules to the maximum extent. Then, the sunlight absorbed by the solar cells can be converted into electric energy effectively. However the outside environmental conditions are usually harsh. Dust in the environment poses a serious problem. The deposition of dust particles on the surfaces of solar modules will reduce the transmittance of the protective covers, which would then lower the photoelectric conversion efficiency due to the light reflection and absorption by accumulated dust particles. Also plastics have faster degradation of transmittance with respect to glass, that's why glass is preferred to be used in solar systems [2,3].

The phenomenon of soiling on photovoltaic systems is complicated. Air humidity, wind speed and direction, shape and composition of the dust particles will influence the deposition of dust particles [4]. Extra effort to remove the accumulated dust particles form the surfaces is required to keep a high solar efficiency. However, common cleaning methods have many problems, such as the high maintenance cost and the use of chemical detergents [5]. Therefore it will be an effective method to use anti-soiling coatings on the surfaces of photovoltaic modules [6–8]. These coatings can reduce the adhesion of dust. Piliougine [9] comparatively evaluated the energy produced by photovoltaic modules with and without anti-soiling coatings. He found that the coated modules had an average daily energy soiling losses of 2.5%, while for the modules without coatings this value is 3.3%. Sueto [6] coated an anti-soiling layer consisting of a WO_3 photocatalyst on a polymethylmethacrylate (PMMA) substrate (the primary material of Fresnel lenses for concentrator photovoltaics). The results shown that the mass of sand was more than 0.010 g for the sample without coatings and approximately 0.005 g for the sample with the coating.

The above findings motivate the investigation of anti-soiling coatings for solar modules. Superhydrophobic surface [10–13] is a common anti-foiling coating with excellent water repellent property and self-cleaning ability. However the mechanisms of anti-soiling are

Abbreviations: BGSs, bare glass surfaces; DA, dust aggregate; EDS, energy disperse spectroscopy; FTIT, Fourier Transform Infrared Spectra; HMDS, hexamethyldisilazane; PMMA, polymethylmethacrylate; SEM, scanning electron microscope; TEOS, tetraethoxysilane; XRF, X Ray Fluorescence; THCs, transparent hydrophobic coatings; TSCs, transparent superhydrophobic coatings

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still unclear. Droplets could readily roll on a superhydrophobic surface to carry the dust and dirt away. This can be considered as an anti-soiling ability of superhydrophobic surfaces. Water droplets play important roles in the cleaning process of dust particles. However, if there is no enough rain water in some places, such as in the desert, can the anti-soiling ability of superhydrophobic surfaces still be realized? What's the mechanism to realize the anti-soiling ability? How do the dust and coating interact with each other?

To answer the questions raised above, transparent nano-coatings with different hydrophobicity are prepared in this paper. To simulate the dust-coating interact conditions, four experiments are designed, including one dust impinging experiment and three dust removal experiments. The amount of adhered dust is evaluated with the reduction in transmittance. We comparatively investigate the adhering and removing processes of dust particles on bare glass surfaces and on coated glass surfaces. A high-speed camera (Pco, dimax hs) is used to capture the impinging and depositing processes of dust driven by air flows. Different impinging behaviors of dust particles can be observed by the camera on the bare and coated glass surfaces, which can be used to illustrate the different soiling phenomena.

2. Experimental section

2.1. Materials

Tetraethoxysilane (TEOS) is purchased from Guangzhou Chemical Reagent Factory. Hexamethyldisilazane (HMDS) and SiO_2 nanoparticles of approximately 30 nm are purchased from Aldrich and Adamas, respectively. Ethanol is purchased from Sinoparm Chemical Reagents Co., Ltd. Distilled water is prepared by a Purescience water purification system.

2.2. Fabrication of silica sol

Hydrophobic silica sol (SS) is prepared first [14]. TEOS (2.1 ml) is dripped into ethanol (30 ml). After being vigorously stirred for 10 min, HMDS (2.0 ml) is slowly added to the above mixture and stirred for 0.5 h. Then deionized water (3.0 ml) is dropped into the mixture with the same stirring rate at room temperature (25 °C). Then the reaction of the mixture is carried out with a constant stirring rate for 2 h to form a transparent sol. The aging of SS is necessary before it is used [14].

2.3. Fabrication of transparent coatings with different hydrophobicity

The procedure for the preparation of transparent hydrophobic coatings (THCs) is described as follows. First, glass slides are cleaned by acetone, ethanol and deionized water in an ultrasonic cleaning bath for 10 min, sequentially. Second, SiO_2 (0.2 g) nanoparticles are added in the silica sol (10 ml, aged for 10 days) with magnetic stirring until a homogeneous sol mixture is formed. Then, different drops of the sol mixture (1–50 drops calculated by squeezing a dropper pipette) are dropped into 1 ml ethanol with ultrasonic vibrating for 5 min. A homogeneous sol solution is formed, named as $(SS\text{-}SiO_2)_x$, where x is the number of drops of the sol mixture. The THCs are formed by dripping the $(SS\text{-}SiO_2)_x$ onto glass substrates to form uniform coatings. The hydrophobicity of THCs can be controlled by adjusting the number of x.

2.4. Characterization and instruments

The surface morphology of THCs are observed by scanning electron microscope (SEM, S-3700N, HITACHI, Japan). Copper foils are used as the substrate for observation, because copper foils can be easily cut into small pieces, which will be convenient for the SEM observations. Thus, the SEM images are obtained by observing the coatings coated on copper foils. The wettability of THCs is measured by a Dataphysics OCA 20 contact angle system at ambient temperature with a 10 μl droplet. The slide angles are measured by tilting the samples after depositing a static droplet of 10 μl, when the water drop starts to roll from the surface, when it is recorded. The optical transmittance is measured using a UV spectrometer (U-3010, Japan). The electrostatic potential of the sample is measured by an electrostatic measurement instrument (SIMCO-fmx003).

2.5. The dust particles

The dust particles used in this paper are collected from a building site in Guangzhou, China. These dust particles are closely related to our daily life. The investigation of the anti-dusting effects for these particles has practical significance. The properties of the dust particles are analyzed by a variety of analyzing methods, including the SEM (Fig. S1), EDS (Energy-dispersive X-ray spectroscopy, Table S1), FTIR (Fourier transform infrared, Fig. S2) and XRF (X Ray Fluorescence, Table S2).

The dusty surfaces are formed by two ways. The first one is by dust impinging experiments. Sample surfaces are placed vertically on the

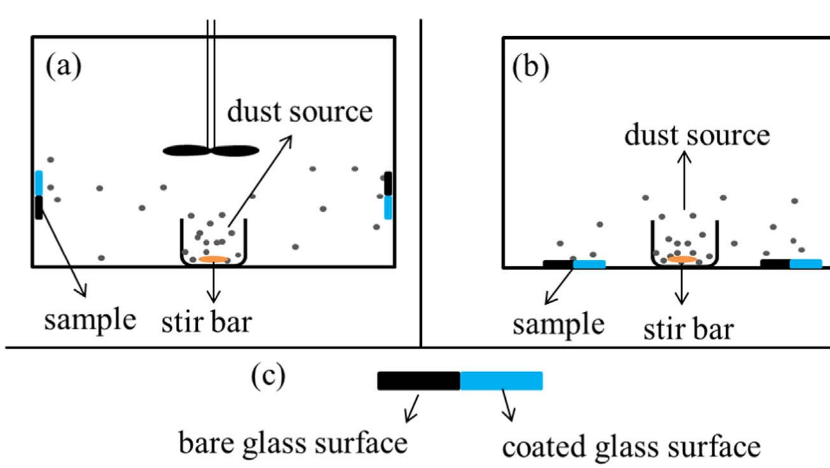

Fig. 1. Schematic of the experiments to obtain dusty surfaces with different methods. (a) Particles impinging driven by air stream, (b) free settling method. (c) Sample surface. It is divided into two parts, the black color means bare glass surface and the blue color represents coated surface. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).