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Influence of Dual Layer Silica Nanoparticles Coating on the Performance Enhancement of Solar PV Modules

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Abstract

The Porous silica nanoparticles deposited on the glass as well as bare silicon wafer substrate to obtain super hydrophilicity and antireflectivity. The coating is performed by using aerosol impact deposition system using silane, air and helium as precursor gases. The desired coating thickness over the substrate surface is achieved by tuning the RF power, pressures ratio of reaction to deposition chamber and maneuvering of silane flow rate, helium and air mixture. Scanning electron microscopy reveals the particle size of 12.6 nm, whereas, atomic force microscopy (AFM) is deployed to study the coated film surface topology. This indicates outstanding antifogging and super-hydrophilic properties due to surface roughness and nano-porosity. Moreover, the coated surface graded index increases the transmissivity from 90% to 99.2%. Such enhancements are much favorable for the solar PV applications.

Keywords: Nanoparticles, Antireflectivity, Aerosol deposition, Solar PV, SEM, AFM

I. Introduction

In today's modern era, solar energy is getting more attention due to high depletion rate of fossil fuels. A protective glass is use on the top of solar photovoltaics (PV) and solar thermal technologies to prevent the module from being in contact with outdoor severe environment [II] [III] [VI] [XVI] [XXII]. Mostly, boro-silicate glass is deployed over the first and second-generation solar PV technology, which reflects the light up to 16% due to the mismatch of refractive indices. This feature is devastating for glass applications such as lasers, lenses and other optoelectronics devices because all these devices need very high transmission [II] [VI] [XIII] [XVI] [XX]. Interestingly, solar PV modules are mostly placed in the outdoor environment where most of the time they are exposed to harsh environment and issues such as fogging, soiling and bird dropping. Due to soiling phenomenon, the performance demoted to 40% depending on factors like moisture in external environment, shape, size and area covered by dust particles [VIII] [XVIII]. In order to mitigate these losses, an antireflective coating is commonly applied on front glass of these devices. These antireflective coatings are also helpful in self-cleaning mechanism by making the surface super-hydrophobic or super-hydrophilic [XI]. The reflection Fresnel equation shows that, for air and glass having refractive indices of 1 and 1.52 respectively, the single antireflection film coating must have the following properties to obtain zero reflection from an interface: (i) refractive index of 1.23, and (ii) quarter wavelength thickness (120 nm at 590 nm). Magnesium fluoride is a material having lowest refractive index of 1.38, however, this is far beyond the desired value Mesoporous and nanoporous science has better solution to this problem, as these materials uses entraps air to decrease the refractive index of a material. Refractive index can be controlled by tuning the porosity of the material. Therefore, coating of nanoparticles, porous silica, has been emerged and rapidly used in technologies of thin film [VII] [IX]. Due to the optimized optical properties of porous silica, it can be used in different optoelectronics devices with ease.

Much research is going on the fabrication of antireflective nano-porous coating of silica which also helps in self-cleaning. Nonetheless, for self-cleaning ability, the film must have either photocatalytic ability or super-wetting ability to clean the dirt in the presence of ultra-violet light [XXIII]. Super-wetting is the ability of super-hydrophilic nature of the thin films. A thin layer of water forms when a water droplet is exposed on the front glass in case of super hydrophilic coatings as a result avoiding the scattering of light and dust particles are accumulated [IV]. Roughness in the thin film coating can also increase super-wetting ability that may be either in micro scale or nano scale [I]. Titanium nanoparticles are used as top layer self-cleaning ARC layer due to its excellent photocatalytic ability, nevertheless, refractive index of titania is very high which reduce the transmission of light inside in panel. Several efforts have been carried out to control the Titanium nanoparticles optimum level to balance out the self-cleaning properties and antireflective properties [XXIV].

Some research has been done by researchers and deposited both Titania and silica as multifunctional in succession, however, it is seen that the optical transmission become lowered due to use of Titania nanoparticles having high index [XIV]. In another research, etching processes is used to texture glass slides, which enhance transmission from 91% to 95% in broad wavelength of 300-1200 nm [XIX]. In another study [XII], sol-gel technique is used in fabrication of multifunctional silica nano-scale porous thin film as a result high transparency of 96% and having excellent antifogging properties when both side of glass is coated. Li et al. [V] studied the use of Titania nanoparticles with Silica nanoparticles, using TEOS/TIPT molar ratio having controlling parameters of Titania nanoparticles size. Sol-gel technique has been used for fabrication of silica nanoparticles, and the results are good in term of super-wettability and transmission [V][XXI]. However, there are various problems related with sol-gel or evaporation driven techniques for the self-assembly of nano-particles. When solvent is evaporated after suspension at high calcination temperature, then cracks are formed in the deposited coating and the mechanical stability is compromised. Furthermore, compatibility of nanoparticles with solvent and chemical solution is a big challenge with the solution treatment techniques [XVII]. This act is supported by the Prosser et al. [XV] finding on the coated film having thickness of 100 nm can exhibit inter connected cracking which destroy the coating after some time.

In this research, aerosol spray technique is used for the production and deposition of silica nanoparticles coating on the silicon wafer and glass substrate. Due to high average roughness and controlled porosity, coated films are super-hydrophilic having contact angle is near to zero. Aerosol deposition system uses gases precursors to synthesize as well as deposit silica nanoparticles with control porosity, thickness and refractive index. It has the advantage on other deposition methods and fabrication like PECVD, sol-gel, dip coating, spin coating, sputtering in comparison of better results, ease of parameters controls and stability in coating.

II. Experimental Details

The Borosilicate Glass slides and silicon wafer is cleansed with acetone solution for 10 min in ultrasonic bath then rinsed with deionized (DI) water and finally desiccated with nitrogen gas. In order to deposit nanoparticles coatings, the clean substrates were placed in the deposition chamber meeting rough vacuum conditions. Silica nanoparticle films were deposited using an aerosol impaction deposition assembly are demonstrated in Fig. 1 and experimental steps are presented in Fig. 2. The system has two main portions; (i) reaction chamber, where gases precursor are split into ion preceded by nucleation of silica nanoparticles, and (ii) deposition chamber for depositing synthesized particles with high impaction velocity. Impact velocity, film porosity and density are controlled with slit nozzle between reaction and deposition chamber of varying width. Particles were synthesized by igniting a plasma between two parallel rectangular electrodes with RF power supply of 14 MHz and a power density of 0.98W.cm-2. Precursors of SiH_4 and O_2 were introduced using a 5% SiH4 in air and Helium (He), respectively. Helium was then introduced additionally to control the impaction velocity and porosity of the deposited films. For the anti-reflection coatings used in this research, a refractive index of 1.15 and 1.30 at 600 nm with porosities of ~60% and 35% respectively, was targeted. Film thickness, porosity, and refractive index were measured on polished silicon wafers using spectroscopic ellipsometer (M-2000). Cauchy model and Bruggeman effective-medium-approximation was used to extract film thickness, refractive index and to determine porosity.

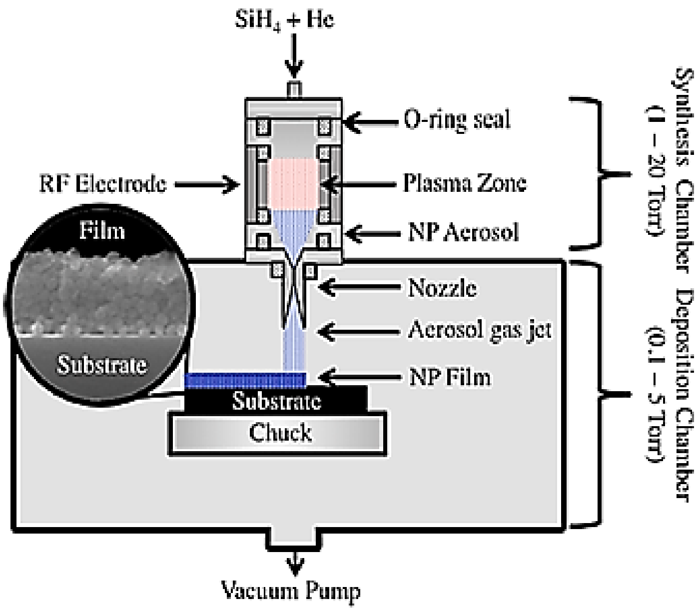

Fig. 1 Schematic of aerosol impact deposition system

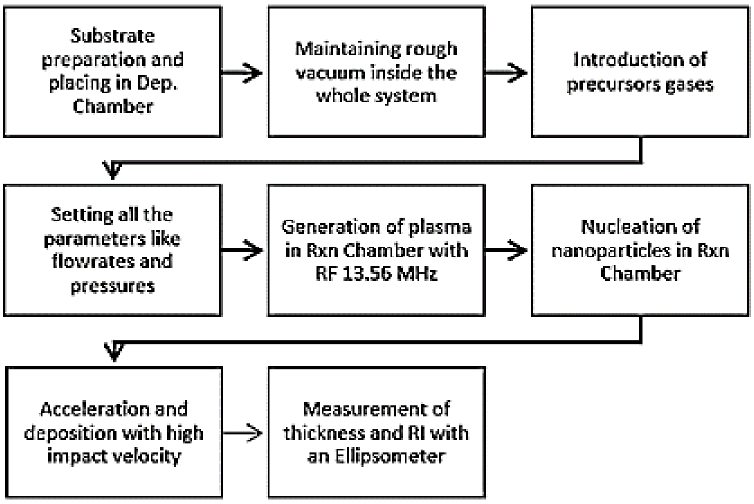

Fig. 2 Experimental steps

III. Characterization

Theoretical transmittance spectrum of uncoated and coated antireflective borosilicate glass was simulated with Module Ray Tracer software (Sunsolve) from PV lighthouse. Sunsolve uses Monte Carlo ray tracing with thin film optics. Transmission spectra were recorded experimentally using UV-NIR spectrophotometer (Lambda 950, Perkin-Elmer) for the broad range of 300-1200 nm. Film thickness, porosity, and refractive index were measured using spectroscopic

Ellipsometery (JA Woollam, M2000) on polished silicon wafers. The Cauchy model was used to extract film thickness and refractive index, whereas Bruggeman effective-medium-approximation [III] to determine porosity of the film. Surface topology were examined by atomic force microscope in tapping mode (Multimode, Brukers USA) using a silicon tip with a nominal radius of 10 nm. Frequency of scanning probe image was of 512 Hz and scanning size was selected 2 µ by 2 µ. To get surface roughness value (Root mean square, RMS), three positions were tested. Field Emission Scanning electron microscope (FESEM, Cross- beam 1540, Zeiss, Oberkochen, Germany) was used for the purpose of recording electron micrograph of surface and cross section of samples. Along with SEM images, Energy Dispersive X-ray spectroscopy (EDS) technique was used to confirm the elemental identification and quantitative compositional information. The operating parameters for EDS were set to the spot size 7 nm, distance 7.8 mm, magnification 46.1 k, and voltage 5.0 kV. Water contact angle (WCA) on the coated glass slides were measured at ambient temperature on OCA 15 Data Physics Instruments GmbH, USA, with angle precision of ±0.5o. A 4.2 µl drop of water was brought in contact with the surface of the substrate and video was recorded at 30 frames per second. The measurement was taken for three different areas on the sample surface.

IV. Results and Discussion

Antireflection

Fig. 3, show the transmittance of silica nanoparticles coated glass versus the wavelength. The objective of this study is to compare the spectrum of transmission and reflection of uncoated and coated glass. The coated glass slides have been layered with silica nanoparticles of both single and double. The UV-spectrophotometer (UV-3600 Plus, Shimadzu) has been used for recording the transmission and reflection spectrum. The spectrum is recorded in the broadband range of 300-1200 nm. The result shows that the uncoated glass covers 92% of transmission in the selected range of wavelength. The transmission boosts up in the range of 550-600 nm for single layer, the Fresnel equation of reflection has been used for designing the coating. The result clearly indicated that light transmission increases for single and double layer coated with respect to bare glass slide. The porosity has been introduced in both the films resulting decrease of refractive index, which enables to enhance the transmission of light, by 4%. By using silica nanoparticles for coating, single layer transmission is increased to 96.5%- and double-layer transmission is enhanced to 98%. The transmission of light got the peak of 98.8% for single layer at 600 nm of wavelength. The maximum transmission for single layer is recorded as 98.9% and this further increase for double layer. Two peaks of 98.2% and 98.4% were measured and recorded at 450 nm and 860 nm respectively. For single layer the transmission of light decreases in some part of a spectrum and this is because of the reason that the refractive indices remains constant for all the material in theoretical design and it was taken at 590 nm of wavelength. However, the values varies during experiment and the transmission get decreases in some part of the spectrum.

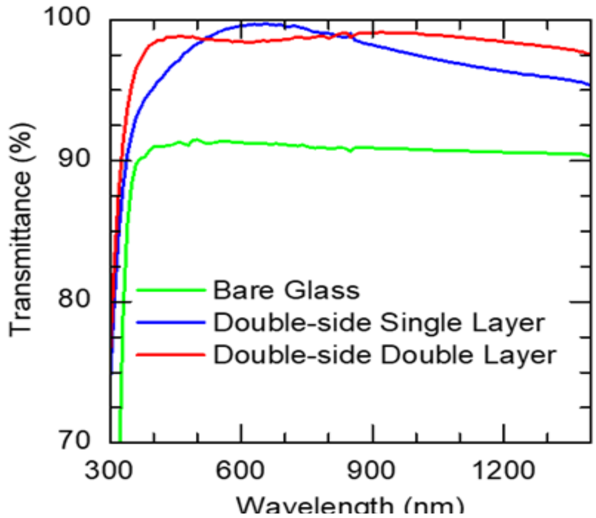

Fig. 3 Transmission spectra of double layer coating on glass substrate

V. FT-IR Result

The FT-IR spectra of coated thin films shows the absorption band with respect to the wavenumber in the range of 500 to 4500 cm-1 as presented in Fig. 4. The strong absorption band was assigned to Si-O-Si, while 1080 cm-1 related to the stretching modes of Si-O-Si groups. The strong band at 790 cm-1 was observed corresponds to the bending vibration of Si-(CH3)3. The stretching band of hydroxyl groups (Si-OH) got the portion at the spectrum of 3700-3200 cm-1 and assigned a peak of 1650 cm-1. It is infer from the FT-IR results that the spectrum of FT-IR contains the hydroxyl groups and got most of the portion in the spectrum. The presence of hydroxyl bonding tends to make the coated film a super hydrophilic in nature

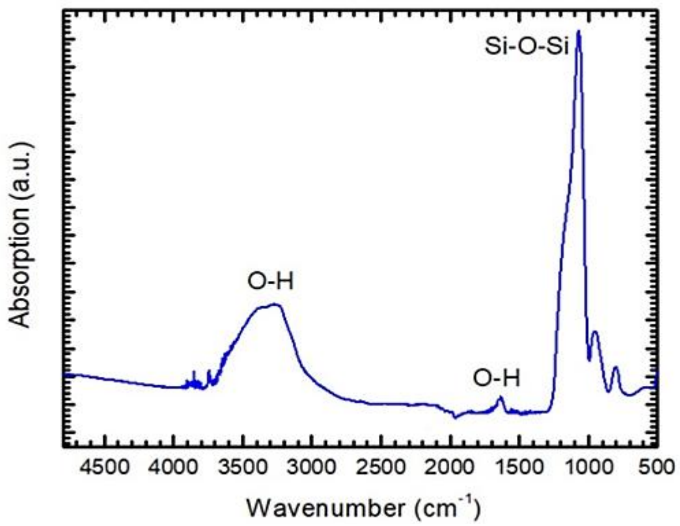

Fig. 4 FT-IR spectra of the coated film

VI. Water Contact angle and Antifogging

The contact angle of water is used to measure the super-wetting ability of the thin films. Materials are characterized according to the contact angle. Super-hydrophilic materials have a contact angle less than 10˚, which is important for self-cleaning of the surface. Super-hydrophilic surface resists the dust and contaminants by assisting in spreading of rainwater droplets. Goniometer is used to measure the contact angle of coated and uncoated glass by Rame-Hart 400. During the measurement 4 µl of water droplets were pour on a glass slide at five different areas and images of droplet spreading were captured with high resolution camera. For measuring the contact angle, a line has been drawn tangent to the air-water droplets on the surface. Glass contact angle was found around 50˚ while for nanoporous glass slide the water angle less than 5˚, showing super-hydrophilic nature of coated surface. The Wenzel theory [XII] states that the wetting ability of a surface depends on the roughness of the material. It is a matter of fact that the material with a high roughness as shown in Fig. 5 indicates that the hydrophilicity increases with the surface roughness.

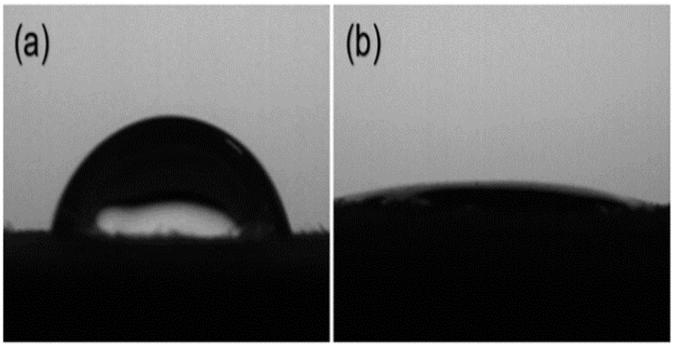

Fig. 5 Water droplet on (a) uncoated, and (b) silica coated glass

VII. Surface Morphology of the film

The study of particle analysis and surface topology was carried out by Bruker Nano Atomic Force Microscopy (AFM) in a tapping mode by using a 10 nm tip. The frequency of the image was 512 Hz with the size of 2µ by 2µ. Fig 6 shows the AFM image of surface topography. Ellipsometer was used to measure film thickness, refractive index and porosity. The nano porous silica roughness is found to be 28.5 nm. This roughness is measured in the scale of root mean square value. Porosity was 52% and refractive index was 1.24 at a wavelength of 600nm. If the roughness of the surface is less than the 200 nm then there will be no light scattering at the surface. Interestingly, the best part of nano-porous silica is the roughness that is less than the 200 nm and this has no bad effect on transmittance. The research indicates that the roughness of thin films can be affected by porosity in thin films, so the roughness increases by formation of porosity. The increase of surface roughness has some impact on the wettability as define by the Wenzel equation [V].

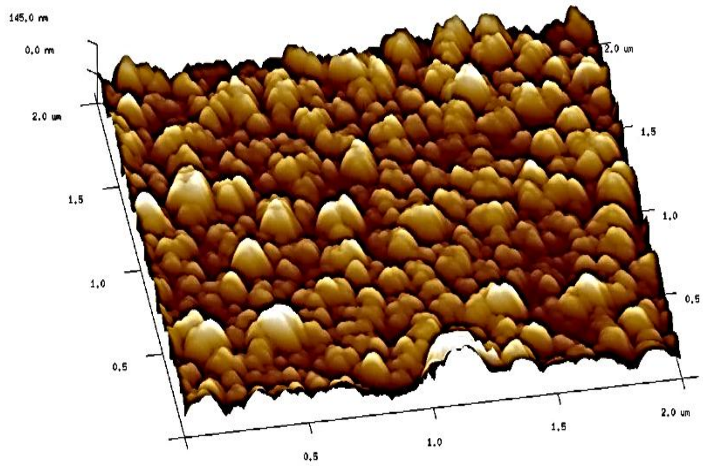

Fig. 6 Surface topology of coated surface by atomic force microscope

The cross section and surface structure of silica thin film was investigated by SEM as shown in Fig 7a and 7b. The Fig. 7a shows the porous nanostructure having 12.5 nm sizes of scattered nanoparticle and nanopores. The size of most of the pores between the particles is around 20 nm and both are dispersed evenly. Due to the fast speed of particles, an unusual shape of silica particle is formed in the chamber. During experiment, the thickness calculated by ellipsometer confirms the findings of SEM image. The thickness for double layer was around 240 nm as demonstrated in Fig. 6b. High transparency and optical transmission depends on high porosity and space between nanoparticles, which results in less refractive index [X].

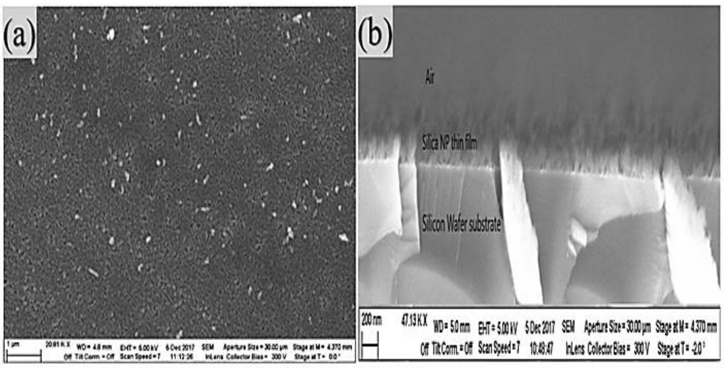

Fig. 7 SEM image of (a) SNP and (b) cross section of coated film

VIII. Conclusions

Nano-particulate coating is deposited on the substrate to control reflection, soiling losses and dust accumulation on protective glass of PV module. Aerosol impact deposition system coupling with RF power enables the coating thickness and refractive index to be controlled more precisely. Pressure ratio in reaction and deposition chamber, flow rates of precursors gases and substrate distance from the nozzle are the parameters used for the tuning of porosity and refractive index of the film. The prepared coating shows high optical enhancement of 7% in the wavelength range of 300-1400 nm. Due to high roughness and porosity, the surface shows high transparency and super-hydrophilicity. In addition, the coated glass surface shows excellent antifogging properties due to the low refractive. Such type of coating has potential to be used for solar PV, optoelectronics devices, lenses and lasers.

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