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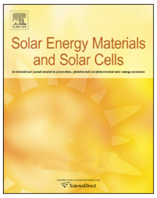

Anti-soiling coatings for solar cell cover glass: Climate and surface properties influence

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ABSTRACT

The objective of this study has been twofold: i) to investigate different strategies for CPV module glass surface modification, in particular preparing hydrophilic and hydrophobic coatings in order to reduce the dust accumulation (soiling) on the module surface; ii) to perform a joint comparative soiling testing in Italy, Spain and Brazil in order to understand the limit and advantages of the proposed anti-soiling coatings in different climate condition. Two TiO_2/SiO_2 films with different titanium content have been synthesized and benchmarked against pure TiO_2 in relation to transparency and hydrophilicity. Moreover, a hydrophobic antireflective material based on functionalized-SiO_2 thin film was also investigated. All these coatings have been deposited over low iron float glass substrates by sol-gel dip-coating and electron-beam evaporation technique. TiO_2/SiO_2 and functionalized-SiO_2 films showed higher transmittance in visible range than pure TiO_2. TiO_2/SiO_2 films showed a persistent superhydrophilic character with water contact angles near to 0°, while functionalized-SiO_2 presented hydrophobic property. The joint comparative soiling tests showed the importance of setting anti-soiling strategies in region characterized by more dry climate: in Brazil, which during the soiling test was characterized by a long dry period, the anti-soiling coatings were effective in reducing the soiling deposition and in the removal of the contaminants by rainwater; in Spain and Italy, the more frequent rain precipitation made the soiling effect less relevant, however, the deposition of anti-soiling coating on the module cover glass allowed to fully recover the initial transmittance after rain washing. A chemical and mineral characterization of the soiling has been carried out revealing the dependence of the contaminants from the environment conditions (e.g. car traffic, presence of industries, amount of rain and local minerals in the ground).

1. Introduction

The development of technologies for renewable energy is essential in the current world scenario that presents environmental problems and a shortage of fossil resources. The photovoltaic (PV) technologies stand out because they are renewable, safe and eco-friendly sources of electrical power [1]. Nowadays in order to increase the PV energy production the technological efforts are not only driven towards the development of high PV performance and reliable solar cells but also towards the means to mitigate the external factors that can reduce the conversion efficiency of the PV modules. One of these factors is the soiling effect caused by dust accumulation on module surface that reduces the transparency of the PV cover glass over time and consequently decreases the module PV energy production [2]. Dust usually deposits on the surface of the module cover glass as a thin layer of particles with less than 10 µm in diameter and its accumulation has a great dependence with the location/environment condition [2]. Soiling deposition on PV modules has been widely studied in literature [2–7], however, most contributions analyze the effect of dust accumulation in reducing the efficiency of PV modules or the transmission of glass

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Abbreviations: CPV, concentrator photovoltaic; PV, photovoltaic; LIFG, low iron float glass; TIPT, titanium isopropoxide; TEOS, tetraethyl orthosilicate; SDA, structure-directing agent; UV–Vis–NIR, ultraviolet-visible-near-infrared; BEMA, Bruggeman effective medium approximation; WCA, water contact angle; RMS, root mean square; AFM, atomic force microscopy; SEM, scanning electron microscope; EDS, energy disperse spectroscopy

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modules, while only fewer ones have evaluated different alternatives of anti-soiling coatings by testing them in different environmental outdoor conditions [8–11]. The possibility to prevent the soiling deposition is accomplished by the modification of the module glass with a self-cleaning and/or “easy to clean” surface [9]. Self-cleaning effect can be obtained by the deposition of TiO_2 thin films on cover glass. This material offers both photocatalysis, which is responsible of the decomposition of organic contaminants, and photo-induced superhydrophilicity, that makes easier the washing of the contaminants from the surface by rainwater [12]. However, TiO_2 reduces the glass transmittance and it rapidly loses the hydrophilicity, re-establishing the water contact angle in dark environments. TiO_2/SiO_2 composite films can overcome all these limitations [13]. TiO_2/SiO_2 films present high transmittance, enhanced photocatalytic activity and persistent superhydrophilicity in dark environments [1,13–17]. These coatings can be promising also for concentrating photovoltaic (CPV) applications whose modules make use of multijunction solar cells, and therefore need transparent anti-soiling coating in a wide wavelength region (typically between 300 and 1800 nm). “Easy to clean” surfaces can be obtained, for example, by hydrophobic functionalized silica, since this film has the property to produce moving spherical water drops which can collect the dust particles and eventually flow off the surface [9,18–20]. In this work, anti-soiling coatings based on TiO_2, TiO_2/SiO_2, and fuctionalized-SiO_2 films have been deposited on glass, characterized regarding their optical and structural properties and then compared in their performance in preventing the soiling deposition. The morphology and composition of the deposited dust has been analyzed and soiling dependence on weather conditions (humidity, rain precipitation) assessed. The soiling test has been performed in different locations, in particular in Italy, Spain and Brazil in order to understand the limits and advantages of the proposed self-cleaning surfaces under the different climate conditions.

2. Experimental details

2.1. Coatings preparation

The anti-soiling coatings used in this work were obtained by sol-gel and electron beam evaporation (e-beam) methods and were deposited at low iron float glass (LIFG, Pilkington Optiwhite Low Iron) substrates.

2.1.1. Superhydrophilic sol-gel TiO_2/SiO_2

These composite films were obtained by previous established procedure [13]. LIFG substrates 4 mm thick were ultrasonically cleaned with ethanol (EtOH) and air dried. TiO_2 precursor solution was prepared using titanium isopropoxide (TIPT), isopropanol (IspOH) (99% w/w) and water (H_2O) with TIPT:IspOH:H_2O molar ratio equal to 1:97:0.5. Similarly, SiO_2 precursor solution was prepared using tetraethyl orthosilicate (TEOS) with TEOS:IspOH:H_2O molar ratio equal to 1:47:2. TiO_2/SiO_2 composite films were prepared with different Si/Ti molar rate mixed solutions. The abbreviations $Si_{86}Ti_{14}$ and $Si_{40}Ti_{60}$ mean the Si/Ti molar rate used to prepare the TiO_2/SiO_2 composite films by the mixture of SiO_2 and TiO_2 precursor solutions. One side of the glass was recovered with the film using the dip-coating equipment Marconi (MA 765) at room conditions (20 °C, relative air humidity lower than 30%) with a withdraw speed of 3.6 mm/s. Then, films were treated in muffle furnace at 500 °C for 2 h under air $Si_{86}Ti_{14}$ composite film is referred in this study as ST1 sample while the $Si_{40}Ti_{60}$ film as ST2 sample.

2.1.2. Superhydrophilic e-beam TiO_2

As a benchmark, TiO_2 film sample was deposited onto one side of the glass by e-beam evaporator Kenosistec® UHV Thin Film Equipament - using solid Kurt J. Lesker® TiO_2 - USA, 99.99% purity and particle size of 1–4 mm. This TiO_2 film was referred as T sample.

2.1.3. Hydrophobic sol-gel SiO_2

These films consisted of multilayer stacks of graded refractive index SiO_2 sol-gel films deposited by dip-coating technique and functionalized by an ‘easy to clean’ post-treatment based on silylating agents to provide the hydrophobicity. The substrates were ultrasonically cleaned with ethanol (EtOH) and air dried. Tetraethyl orthosilicate (TEOS), poly (oxyethylene) cetyl ether, and ethanol (EtOH) (99%w/w) were used as precursor, structure-directing agent (SDA) and solvent for sol-gel solution. Two different sols containing or not SDA were prepared in order to obtain multi-layer stack composed by films with different refractive indexes. The multi-layer stack is composed by an inner denser (D) film of higher refractive index and an external porous (P) film of lower refractive index. Film deposition was performed onto one side of the glass substrate using homemade dip-coating equipment at controlled conditions (22 °C, relative air humidity 60%). LIFG substrates were first immersed and emerged in the non-containing SDA sol-gel with a speed of 0.83 mm/s and then films were treated in muffle furnace at 550 °C for 1 h under air. Subsequently these coated substrates were immersed and emerged in the containing SDA sol-gel with a speed of 0.83 mm/s and were treated in muffle furnace at 550 °C for 1 h under air. A post-treatment with hexamethyldisilazane (H) solution was then performed. This silylating treatment allows reducing the number of free silanol groups (Si-OH) in the surface and substituting them by methyl groups attached to Si thus permitting to obtain hydrophobic surface, the obtained sample was referred in this study as SM sample (Patent EP17382016) [21].

All samples prepared in this work are summarized in Table 1.

2.2. Characterization of the coatings

Transmittance (%T) spectra were measured with a UV–Vis–NIR spectrophotometer Jasco V-670 (with integrating sphere) in 300–2000 nm wavelength. Integrated transmittance was calculated by weighting transmittance values with mean hemispherical solar spectral irradiance incident on surface tilted 37° toward the sun (ASTM G173-03) according to equation:

$$\tau = \frac{\int_{\lambda_1}^{\lambda_2} \mathrm{T}_\lambda \cdot S_\lambda \, d\lambda}{\int_{\lambda_1}^{\lambda_2} \mathrm{S}_\lambda \, d\lambda} \tag{1}$$

Where T_λ is the transmittance spectrum of the covered glass, S_λ is the hemispherical solar spectral irradiance for absolute air mass of 1.5 (ASTM G173-03) and λ_1 and λ_2 define the wavelength range in which τ is calculated.

Ellipsometric parameters ψ and Δ of the SM film were recorded by Variable Angle spectroscopic ellipsometer. Spectra were recorded at wavelength comprised from 300 nm to 1000 nm at three angles of incidence (65°, 70°, 75°). The data analysis was performed with WVase32 software. The spectra were fitted using the dispersion Cauchy model for obtaining spectral refractive index n and film thickness. The Bruggeman effective medium approximation (BEMA) model was adopted for void fraction calculation. The void fraction of each film was calculated considering polarization factor of 0.33 with respect to pure dense silica, thus value of absolute porosity in % was provided.

A VARIAN CARY 50 spectrophotometer was used in the soiling test and the transmittance was measured in the range of 200–1100 nm. An

Table 1
List of samples prepared with their composition and classification.

Sample references	Composition	Classification
ST1	$Si_{86}Ti_{14}$	Hydrophilic
ST2	$Si_{40}Ti_{60}$	Hydrophilic
T	TiO_2	Hydrophilic
SM	Functionalized-SiO_2 bi-layer	Hydrophobic