Solar Energy Materials and Solar Cells 189 (2019) 188–196

Contents lists available at ScienceDirect

Solar Energy Materials and Solar Cells

journal homepage: www.elsevier.com/locate/solmat

Self-cleaning performance of superhydrophobic hot-embossed fluoropolymer films for photovoltaic modules

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ARTICLE INFO

Keywords:
Superhydrophobic
Self-cleaning
Anti-reflective coating
Photovoltaic
Fluorinated ethylene propylene
Hot-embossing

ABSTRACT

The soiling of photovoltaic (PV) modules can significantly reduce their energy yield unless a mitigation strategy is employed. One solution investigated in this work involves the implementation of a passive self-cleaning superhydrophobic top cover. To this end, superhydrophobicity was induced by hot-embossing random micro-textures on a highly transmissive and photostable fluorinated ethylene propylene (FEP) film. The impact of fabrication parameters (hot-embossing force and temperature) on achieving high contact angles (> 150°) and low roll-off angles (< 10°), which characterizes a surface as superhydrophobic, were investigated. It was found that a minimum threshold force of at least 15 kN and 5 kN must be used to achieve superhydrophobicity for processing temperatures of 270 °C and 280 °C respectively. Meanwhile at the highest investigated temperature of 290 °C, any force within the investigated range of 500 N to 50 kN suffices. The best fabrication parameters were identified (5 kN at 280 °C), resulting in a contact angle of 156 ± 1° and a roll-off angle of 8 ± 3°. When incorporated into a silicon PV mini-module, the addition of the textured FEP film enhances the short circuit current density (J_{SC}) by 1.1%. Moreover, the self-cleaning properties of the textured FEP films result in a recovery ratio of 93.6% (in terms of J_{SC}), which is significantly greater than that of the reference glass encapsulated PV mini-module (61.1%).

1. Introduction

The soiling of photovoltaic (PV) modules result in the shadowing of the underlying solar cells and thus significantly reduces the energy yield of the installed PV modules to be well below their expected capacity rating [1–6]. Soiling affects the photocurrent generation by reducing the photon flux reaching the solar cells via spectral losses (absorption and reflection) [4,7,8]. The reduction in PV power output can be anywhere between 2% and 50% depending on a range of factors, including local climate, dust composition and concentration, as well as whether a mitigation strategy is employed [3,9,10]. The impact of PV module soiling is prominent in arid or semi-arid areas, such as the Middle East and North Africa, where dust accumulation is very high due to high amount of suspended particles in air [9,11].

A wide range of soiling mitigation methods exist for PV and can be categorized into either preventive or restorative approaches [4,12]. These include: i) manual cleaning; ii) stowing of PV arrays [4]; iii) surface modification – both superhydrophobic [13] and superhydrophilic [14]; iv) automated or semi–automated mechanical cleaning [15]; and v) incorporation of electrodynamic screens to repel dust [16]. Manual cleaning, which is the most common method of cleaning, involves physically cleaning the PV modules – leading to high labour cost [4]. Semi-automated methods – including the stowing of PV arrays and mechanical cleaning systems – require less human attention, but in most cases the activation and operation are still operated manually [4]. Electrodynamic screens and automatic mechanical cleaning methods – including cleaning robots and scheduled wipers/water irrigations – are attractive since minimal monitoring is required but likely to be economic only for large installations [2]. An automatic cleaning system equipped with motorized brush and water flow consumes ~ 6% of the extra generated power, but when we also take the water consumption into consideration, the economic benefits of the system reduces even further [8]. In contrast, the development of passive self-cleaning surfaces offers a particularly attractive approach, which is

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https://doi.org/10.1016/j.solmat.2018.09.017
Received 15 May 2018; Received in revised form 9 August 2018; Accepted 14 September 2018

Table 1
Advantages and disadvantages of mitigation methods.

Mitigation method	Advantages (☑)	Disadvantages (☒)
Manual cleaning	☑ Fully restores PV module to as-clean condition [17]	☒ Labour and resource intensive [4,17,18] ☒ Requires frequent cleaning cycles. Typically weekly cycles, but also immediate cleaning for severe cases of soiling [19]
Stowing of PV arrays	☑ Protects from soiling when not in use (night time; dust storms)	☒ Ineffective during daytime if sudden dust storm approaches (insufficient stowage time) [4]
Surface modification	☑ Passive self–cleaning method	☒ Depends on rainfall to function [13,14]
Mechanical cleaning	☑ Performance not as good as manual cleaning, but little labour required	☒ High initial and maintenance cost; better suited for large systems [8] ☒ Electrical power required as the components are auxiliary systems [8] ☒ Potential abrasive damage [20]
Electrodynamic screens	☑ Removes 90% of soiling [21] ☑ Less power consumption; as low as 0.003% of generated power [21]	☒ Requires dry conditions to work effectively [21]

neither labour nor resource intensive [4,5]. The most suitable cleaning method has to be chosen considering specific applications and environmental conditions. The main advantages and disadvantages of each mitigation method are listed in Table 1.

The concept of a self-cleaning, superhydrophobic surface originated from nature and is commonly described as the “Lotus-effect” [22]. Wenzel as well as Cassie and Baxter [23,24] had previously provided the fundamental analysis of water repellence due to multiscale roughness and porosity of solid surfaces. Different wetting states exist depending on the liquid-solid interface; namely the interfacial surface energy and the surface contact area [25]. Therefore, introducing multiscale textures on the surface can significantly alter the wetting behaviour of a surface. Wetting behaviour on a structured surface can be classified into i) the Wenzel state; and ii) the Cassie-Baxter state [25,26]. The critical difference between the Cassie-Baxter and Wenzel state is whether water penetrates into the structures or whether air is trapped inside the structures of a surface. In the Wenzel state, a droplet sticks to the surface, while in the Cassie-Baxter state, the droplet usually rolls off [23,25]. A surface is classified as superhydrophobic if it exhibits a water contact angle of $> 150^\circ$ [25,27]. Several different effects are apparent in a superhydrophobic state such as the”Lotus-effect” and the “rose petal effect”. For the “Lotus-effect”, water rolls off easily and cleans the surface of soiled lotus leaves [22]. In the case of “rose petal effect”, a high contact angle is observed but the water droplets will stick to the surface even if the surface is tilted $> 90^\circ$ [28,29]. To further define superhydrophobicity, other characteristics such as contact angle hysteresis [30], roll-off angle [28] or bouncing of water droplets [30–32] were also taken into account. In this work, a surface needs to exhibit both a contact angle $> 150^\circ$ as well as a roll-off angle $< 10^\circ$ in order to be classified as superhydrophobic, because self-cleaning highly depends on water droplets rolling off the surface.

The strategy to achieve a superhydrophobic top surface has been studied previously via various approaches, which include: i) modifying the bulk material to become superhydrophobic [33]; ii) applying a superhydrophobic coating on the top surface [34]; and iii) introducing textures to modify the liquid-solid surface contact area [35–38]. As this work will involve achieving a superhydrophobic surface from texturing, some notable results are highlighted below where various textured superhydrophobic coatings have been studied for PV applications. It was shown that applying superhydrophobic polydimethylsiloxane (PDMS) microshell arrays, exhibiting a contact angle of $\sim 151^\circ$, on a monocrystalline silicon solar cells achieved a 71.8% recovery rate in term of solar cell efficiency after washing with water droplets ($\eta = 6.6\%$ when soiled to $\eta = 9.8\%$ after self-cleaning compared to initial $\eta = 11.2\%$) [39]. Another work achieved a 1.1% efficiency improvement by adding PDMS nanocones on perovskite solar cells. The authors realized a superhydrophobic contact angle of $\sim 155^\circ$ and a roll-off angle of $\sim 13^\circ$ [40]. A more recent study used inverted micro-pyramidal structures (IMPS)-PDMS on perovskite solar cells, where a 3.3% improvement was achieved ($J_{SC} = 21.3\,\mathrm{mA/cm^2}$) compared to a reference device ($J_{SC} = 20.6\,\mathrm{mA/cm^2}$), while a flat PDMS cover exhibited a J_{SC} of $20.9\,\mathrm{mA/cm^2}$. However, the IMPS-PDMS requires a fluoro-octyltrichlorosilane treatment for it to achieve superhydrophobicity (CA $> 150^\circ$) [41]. Vüllers *et al.* have shown that using a higher surface energy material, it was also possible to achieve superhydrophobicity where bioinspired nanofurs were textured on polycarbonate films, achieving a 5.8% relative gain in terms of J_{SC} compared to a bare multicrystalline silicon solar cell. The work also exhibited a superhydrophobic behaviour with a contact angle of $\sim 166^\circ$ and a roll-off angle of $< 6^\circ$ [42]. In another work, FEP microcavity arrays were applied to a multicrystalline silicon solar cell that results in a 4.6% enhancement in the electrical output compared to a bare reference device. The superhydrophobic surface exhibited a contact angle of $\sim 158^\circ$ and a roll-off angle of $\sim 5^\circ$ [13]. These previous achievements demonstrate that the application of self-cleaning superhydrophobic cover films will improve PV device performance, but there were not many reports on the self-cleaning performance itself. The present study focuses on the development of a superhydrophobic top cover for PV modules that exhibits self-cleaning properties via microtexturing of a fluorinated polymer.

With regards to the targeted application as a front cover for PV modules, the proposed polymeric film must also satisfy a list of additional requirements. First, it must exhibit very high transmittance, which is challenging with superhydrophobic microtextured surfaces as texturing usually results in opacity [43,44]. Further requirements are mechanical strength and prolonged photostability (> 20 years) under sunlight [43]. Fulfilling those requirements, fluoropolymers have always been known for their durability, chemical inertness and environmental resistance [45,46]. The energy of photons at $\lambda = 300\,\mathrm{nm}$, corresponding to an energy of 397 kJ/mol, is not sufficient to break the bonds between carbon and fluorine molecules, which has a bond dissociation energy varying between 452 and 544 kJ/mol [46]. These requirements can also be met by using fluorinated ethylene propylene (FEP), which is chosen for this work and is already a common fluoropolymer studied for PV applications [44,47–50]. The DuPont datasheet for Teflon FEP compared the solar transmission of FEP to low iron float glass over a 20 year period [51]. The results indicated that FEP exhibited: i) a higher transmittance (afforded by its low refractive index); and ii) was also stable over a 20 year period, retaining over 90% of its initial transmittance [51]. The FEP manufacturer also guarantees high stability against outdoor exposure up to 20 years [50]. These factors justify the choice of FEP for PV applications. In previous work, it was also already demonstrated that highly transmissive, superhydrophobic films can be fabricated using microtextured FEP [13].

This work focuses on the impact of fabrication parameters (hot-embossing force and temperature) on the self-cleaning performance and a subsequent optimization thereof. The concept of a self-cleaning top cover is illustrated in Fig. 1. The impact of soiling was shown to significantly reduce the short-circuit current density (J_{SC}) of a PV module, as shown in Fig. 1a. A superhydrophobic cover film placed on top of the