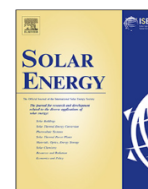




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Reducing the effect of dust deposition on the generating efficiency of solar PV modules by super-hydrophobic films

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ABSTRACT

Dust deposition on photovoltaic (PV) modules is related to environmental and weather conditions and results in a reduction in power generation efficiency over time. The effects of films on the transmittance can be obtained by testing sample glasses coated with silicon and fluorine super-hydrophobic films with a spectrophotometer. Red soil particles with a diameter of 25 μm were selected to simulate the process of natural dust deposition on PV module samples, and an incubator of constant temperature and humidity was used to simulate the condensation process. PV module samples were irradiated by a solar simulator after the aforementioned simulation process, and the effects of different amounts of sediment in unit areas on the photovoltaic properties and spectral characteristics were determined. The experimental results indicate that the influence of dust on the power generation efficiency of PV modules coated with fluorine super-hydrophobic film is smaller than that for PV modules coated with silicon super-hydrophobic film and that the super-hydrophobic films can not only greatly reduce the dust accumulation on the surface of PV modules but also increase the generating efficiency.

1. Introduction

Plateau desert areas are important areas for the development of photovoltaic (PV) power generation due to the long periods of light and large irradiation areas. However, the gales in plateaus make it easy for PV module surfaces to accumulate significant amounts of dust, reducing the power generating efficiency of PV components by 10–25% (Fan et al., 2015). Our research team conducted a practical investigation at the Qinghai, China PV power station and confirmed that dust deposition has a serious direct impact on PV power generation, as shown in Fig. 1.

Mekhilef et al. (2012) confirmed that temperature, humidity and dust in the external environment affected the power generating efficiency of PV modules but did not propose a solution. The influence of sand dust on the shielding of PV modules was analyzed from the spectrum perspective, and Hassan et al. (2014) proved that there is a relation between the dust density and spectral transmittance. By analyzing the force of dust on the plate surface, Meng (2015) designed a mechanical device to remove the dust, but the device installation caused a certain degree of panel sheltering. The cost and maintenance of the device are also significant, which indirectly increases the cost of

electricity. Outdoor installation of the PV modules made the dust deposition to be the most immediate problem about the efficiency loss. Paudyal and Shakya (2016) conducted the experiment in Kathmandu for 5 months, the result showed a negative correlation between humidity and dust accumulation. Relative humidity increased the dust particles adhesion force to a surface which increased the difficulty of removing dust. Therefore, a super-hydrophobic film with self-cleaning ability has been widely used in the automotive, construction, aviation, and PV industries among others (Zhang and Lv, 2015). Many experts have investigated improvements in the processing technology of super-hydrophobic films to improve the performance of other aspects and thus increase the range of applications of super-hydrophobic films (Yao et al., 2009; Gwon et al., 2014; Nayak et al., 2012; Strauss et al., 2015). Using nanosilica modified with FAS-17¹ as the filler, Guo et al. (2013) adopted different resins as a matrix to develop a super-hydrophobic coating for protecting the exterior surfaces of aircraft. Gwon et al. (2014) prepared a grass-like porous CaF_2 nanostructure with self-cleaning and antireflective properties on ITO² glasses via glancing angle deposition, which can be used for the industrial-scale production of solar cells. Li et al. (2012) formed porous silicon-nanoparticle (Si-NP) films on the solar cell surface to increase the light absorption rate,

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¹ Heptadecafluoro-1,1,2,2-tetradecyl)trimethoxysilane.

² Indium Tin Oxide.



Fig. 1. Dust deposition (Taken from PV power station).

thereby increasing the efficiency of their PV power generation, but did not reduce the impact of the external environment on the power generating efficiency of the panels. Many factors in the natural environment will lead to the reduction of PV power generation efficiency, Lappalainen and Valkealahti (2017) studied the mismatch losses caused by moving clouds, Topić et al. (2017) given out a shading factor which is calculated according to the given ratio of the sunny part and the total module surface that can be calculated using. Dust deposition plays a crucial role in obstructing the solar irradiance reaching solar cells and thus reduces the power generation. Therefore, this study focuses on developing a method to reduce the impact of the external environment, particularly dust deposition, on the efficiency of PV modules.

In the absence of other interference items (e.g., temperature, humidity, dust), this paper selects dedicated packaging glass for the PV module samples, placing plate samples coated with laboratory-prepared silicon, fluorine super-hydrophobic materials and substrates into a spectrophotometer instrument to test the differences in the transmittance. The samples were then placed in a device that simulated dust deposition to study the effects of the surface residual dust of different sand cover ratios on light transmittance after the same condensation process. Preparing three modules of the same type, a spray gun was used to coat silicon and fluorine super-hydrophobic materials on two of the samples, whereas the remaining samples were left uncoated as a reference. First, the sun simulator was used to irradiate the three models, and then, the solar module tester was used to test the PV characteristics of the three models. In this experiment, 25 μm red clay particles were used as a dust source to verify that the super-hydrophobic property can still ensure the efficient power generation of PV modules in such a harsh environment. After the dust deposition and condensation processes were simulated, we investigated the impact of changes in the sand cover ratio on the PV modules coated with super-hydrophobic films by monitoring their output power and I-V characteristic curves.

2. Experiment

2.1. Experimental reagent

The main reagents used in the experiment are shown in Table 1.

2.2. Experimental instruments

The main experimental equipment required in the experiment is shown in Table 2.

2.3. Coating preparation

Table 1
Main reagents used in the experiment.

Number	Reagent name	Manufacturer
1	Nanometer SiO ₂	Hefei Xiang Zheng Chemical Technology Co., Ltd.
2	Butyl Acetate	Hefei Xiang Zheng Chemical Technology Co., Ltd.
3	Fluorinated resin	Shandong Haihua Group Co., Ltd
4	Polydimethylsiloxane	Sichuan Daxing Pohua Chemical Co., Ltd
5	Ethanol	Shanghai Xiang Lan Chemical Co., Ltd.
6	Clean hydrochloric acid	Shanghai Xiang Lan Chemical Co., Ltd.
7	Nano polishing powder	Nanjing Baoning Chemical Co., Ltd

3.2 mm, used specially for PV modules. We first placed the glass into a clean hydrochloric acid solvent with a concentration of 10% for a 20-min ultrasonic cleaning to etch the surface oxide and rinse with water. Then, we polished the glass surface with nano polishing powder detergent. Next, we cleaned the glass in an ultrasonic cleaning machine for 20 min. Finally, we rinsed the sample substrate with clean water and performed a drying process in the drying oven.

2.3.2. Preparation of the coating

The transparent nanosilica material liquid was dispersed in butyl acetate solvent at a mass ratio of 11:20 and stirred with a sand mill at room temperature for 24 h to prepare a super-hydrophobic silicon film. It was then mixed with 10% fluorinated resin, 60% polydimethylsiloxane and 30% ethanol, stirred and mixed with a sand mill for 12 h, and the mixture was introduced into the nano-SiO₂ particles at a mass ratio of 55:12 to obtain a fluorine-based super-hydrophobic film.

The spray coating process in this experiment is simple, low cost and easy to operate. The super-hydrophobic material prepared as detailed above is filled into the container of the spray gun, and compressed air is injected to maintain a spraying pressure of 0.7 MPa and a spraying distance of 20 cm. The coating mixture is atomized into small liquid particles under the action of compressed air and deposited onto a clean glass surface. We changed the coating time and flow to control the coating thickness. To reduce the experimental operation error, we produced two samples for each type of super-hydrophobic film and numbered the samples as follows: S₁ and S₂ for the silicon class, S₃ and S₄ for the fluorine class, and S₅ and S₆ for the substrate.

2.4. Environmental simulation

2.4.1. Selection of the dust

The distribution data of dust particle size by volume percentage

Table 2
Main instruments used in the experiment.

Number	Instrument name	Model	Manufacturer
1	Experimental dispersed sand mill	SDF400	Shanghai Fu Lai Energy Technology Company
2	Ultrasonic cleaner	KQ-100B	Kunshan Ultrasonic Instrument Co., Ltd.
3	DHG Series Heating and Drying Oven	DHG-9023A	Shanghai Jinghong Experimental Equipment Co., Ltd.
4	Scanning electron microscope	SU-8000	Hitachi High-Technologies Corporation
5	Spectrophotometer	UV-3600	Shimadzu, Japan
6	Contact angle measurement	OCA40 Micro	Data physics Company, Germany
7	X photoelectron spectroscopy	PHI-5300	PE-PHI Company, USA
8	Spray gun	AB-17	Guangdong Andy Furniture Co., Ltd.

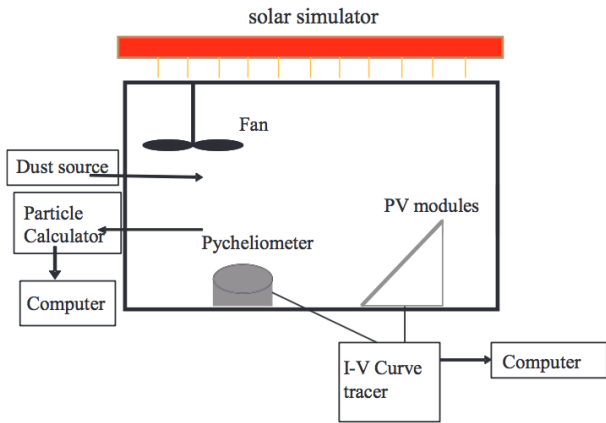


Fig. 2. Simulation of the natural dust falling device.

and Al₂O₃ (Fan et al., 2015). Therefore, red clay with the same composition is selected, and 25 μm red clay particles were screened by a standard screen.

2.4.2. Simulation of dust falling and condensation

The device for simulating natural dust falling is shown in Fig. 2. First, we placed samples S₁, S₃, and S₅ into the simulator after measuring their net weights. After 38 h in the dust device, the samples were removed and weighed, yielding a dust content per unit area of 5.5 ± 0.1 g/m². Samples S₂, S₄ and S₆ were placed in the apparatus in the same manner. After 103 h, the dust content per unit area was determined to be 17.5 ± 0.1 g/m². The six samples covered with sand were placed in the three integrated experimental temperature-humidity-vibration boxes (CH500 CVTH) at Chongqing University to simulate the natural condensation process. Considering that the tilt angle affects both the properties of the super-hydrophobic film and the force of the dust (Shen, 2013), the samples were placed in a rack with an inclination angle of 40° and then placed in the test chamber.

The results show that the hydrophobic characteristics of the super-hydrophobic film are not affected by temperature when the humidity is below 60% (Yu et al., 2014); thus, the instrument humidity is set to 50%. Natural condensation is mainly a process of hot vapor encountering the cool surface of objects and condensing into water droplets. Thus, the instrument temperature was set to −10 °C for 3 h, after which the temperature was raised from −10 °C to the room temperature and kept stable for 1 h before being removed to simulate the condensation process.

3. Experimental results and discussion

3.1. Characterization of super-hydrophobic films

resin is the main component in fluorine-based super-hydrophobic materials. The molecular structure is dense due to the introduction of fluorine atoms. Carbon and fluoride atoms are closely arranged around the main chain of the resin, causing the structure to be more stable and extending the life of super-hydrophobic film while increasing its durability.

In addition, the contact angles of the water droplets on the substrate and the two films were measured with a contact angle meter to determine the hydrophobicity difference between them. As shown in Fig. 4, the water droplets of the substrate have a contact angle of 44.6°, which indicates hydrophilicity. The contact angles of the water droplets for the silicon and fluorine films made in this experiment are 158.7° and 153.5°, respectively, which indicates that the film has better hydrophobicity. Therefore, with these protective films, the PV module can utilize the surface self-cleaning function of the super-hydrophobic film to improve its power generating efficiency.

3.2. Analysis of the spectral characteristics of super-hydrophobic films

The process for preparing ultra-hydrophobic film has a high demand for light transmittance to protect the power generating efficiency of PV modules from being affected by the super-hydrophobic coating film. The contribution to the efficiency of PV modules is mainly light waves with wavelengths of 200–1100 nm (Shen, 2013). The sample light transmittance was measured with a spectrophotometer at wavelengths between 200 and 800 nm. Fig. 5 illustrates that there is a significant fluctuation in the 300–400 nm band caused by the spectrophotometer being switched from the UV detection gear to the position of the visible light detection (which is a problem with the instrument itself); however, the test results were essentially unaffected by these fluctuations. At a wavelength of 600 nm, the light transmittances of the silicon, fluorine and substrate samples were 92.5%, 92.2% and 87.6%, respectively.

The transmittances of the two super-hydrophobic films are both higher than that of the substrate because when the light reaches the surface of the super-hydrophobic film, the micro-nanometer column-like antireflective structure reflects only part of the sunlight, and the majority of the light is multi-refracted to the inside of the PV module, the actual micro-nanometer column-like antireflective structure that as shown in Fig. 6. Fig. 7 gives a schematic diagram of the antireflection that helps the reader understand better. The light transmittance of the fluorine-based super-hydrophobic film is lower than that of the silicon-based super-hydrophobic film. Two reasons for this phenomenon are an error in the production of fluorine-like coating, causing it to be thicker than the silicon, as well as the different refractive indexes between the fluorine- and silicon-based super-hydrophobic films.

3.3. Using the solar simulator to evaluate the current and voltage characteristics

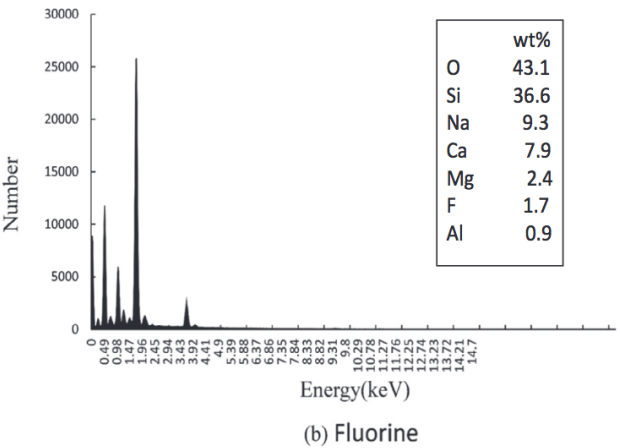
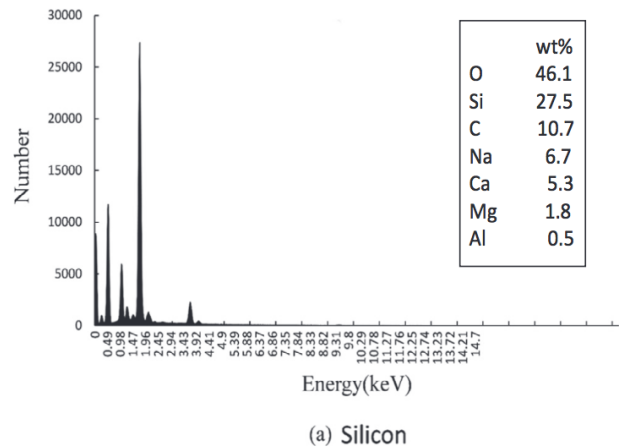


Fig. 3. Energy spectrum analysis.

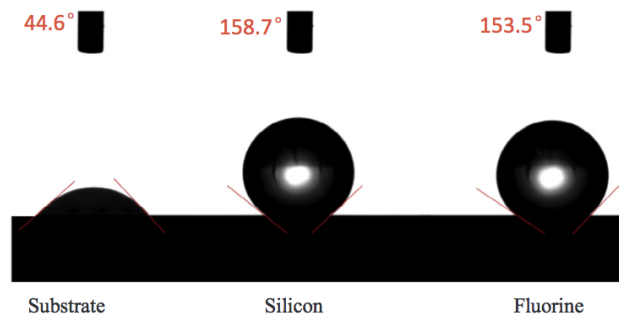


Fig. 4. Contact angle diagram.

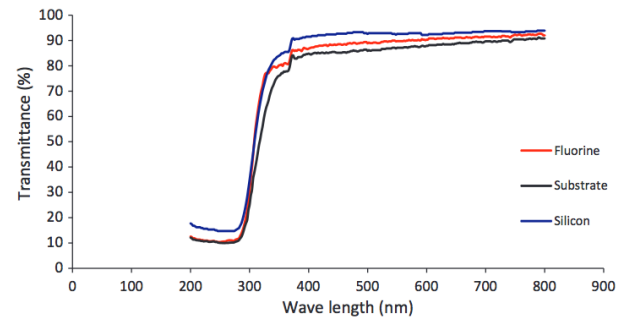


Fig. 5. Transmittances of the samples.

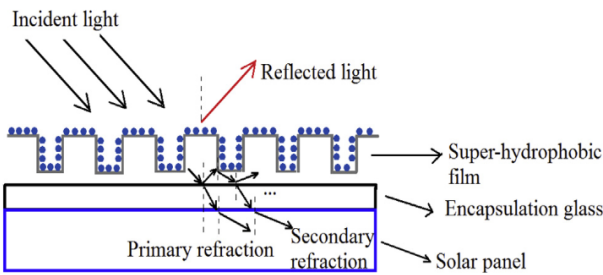
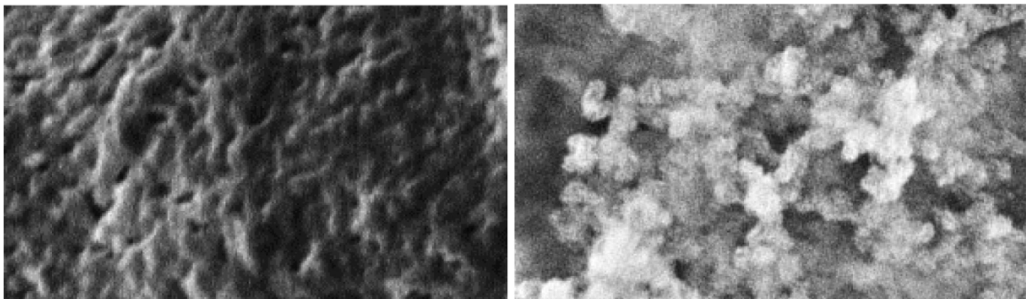


Fig. 7. Schematic diagram of the minus reflection structure.

Table 3
P6-50 parameters.

Number	Parameters	Numerical value
1	Maximum power generation (P_{max})	50 W
2	MPP voltage (V_{mp})	17.6 V
3	MPP current (I_{mp})	2.84 A
4	Open circuit voltage (V_{oc})	21.5 V
5	Short-circuit current (I_{sc})	3.12 A
6	Length $\times$ width $\times$ thickness	550 mm $\times$ 600 mm $\times$ 30 mm

solar simulator and then tested the current and voltage characteristics and output power of the PV modules coated with super-hydrophobic films and substrates using the solar module tester (Prova 200A) manufactured by Taiwan Taiyi Co., Ltd. The parameters of the solar simulator were set to be identical for each measurement. The light intensity was set at 950 W/m^2 , the tilt angle of the PV module bracket was set to 40° according to the actual installation effect, and the I-V and power



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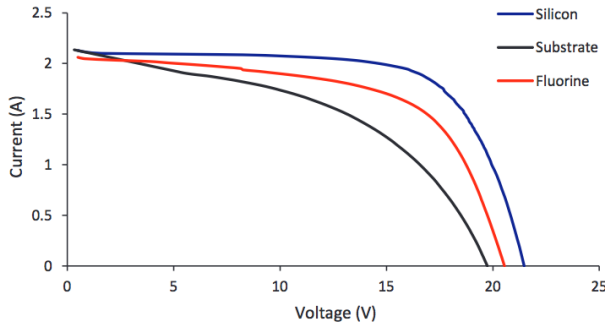


Fig. 8. I-V curves of the samples.

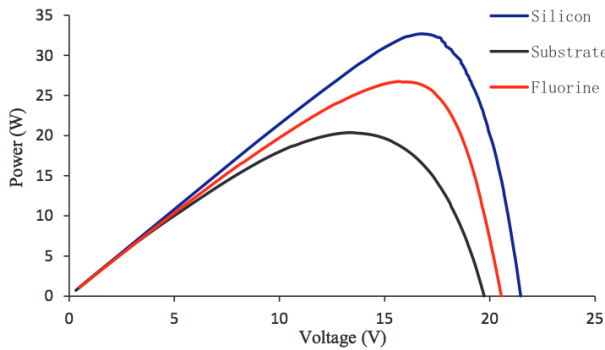


Fig. 9. Output power P (W) curve of the samples.

curves obtained in the same period are shown in Figs. 8 and 9, respectively. The measurements of I-V and P-V curves in this paper are all performed in a closed solar simulator at room temperature.

All electrical data are obtained at standard test conditions: Irradiance of 1000 W/m², spectrum AM 1.5 and cell temperature of 25 °C.

The open-circuit voltage, short-circuit current, filling factor efficiency and total conversion efficiency of the substrate were 19.737 ± 1%V, 2.205 ± 1%A, 46.78% ± 1% and 6.17%, respectively. The open-circuit voltages of the PV module coated with silicon- and fluorine-based super-hydrophobic films were 21.468 ± 1%V and 20.546 ± 1%V, respectively. The short-circuit currents were 2.23 ± 1%A and 2.132 ± 1%A. The filling factor efficiency was 68.26% ± 1% and 61.1% ± 1%, and the total conversion efficiency was 9.9% ± 1% and 8.1% ± 1%, respectively. Fig. 8 illustrates that the short-circuit current of the PV module coated with the super-hydrophobic film does not differ from that of the substrate, but the open-circuit voltage increases and the open-circuit voltage of the silicon is the largest. This trend mainly occurs because due to the exposure of the simulator, the temperature of the PV module coated with protective film increases faster than the substrate, and the fluoride-based super-hydrophobic film has a certain heat resistance compared to the silicon sample, leading to the lower open-circuit voltage than that of the silicon sample.

In the absence of other interference factors, the data obtained in Fig. 9 illustrate that the PV module coated with the silicon-based super-hydrophobic film can reach a maximum output power of 32.67 ± 1% W, whereas those coated with the fluoride-based super-hydrophobic film and substrate reach 26.75 ± 1%W and 20.36 ± 1%W, respectively. The total conversion efficiency of the PV modules coated with super-hydrophobic film is increased because the micro-nanostructures of the films reduces the refraction of the surface light and increases the light transmittance, resulting in a higher power generating efficiency.

3.4. Impact of dust

3.4.1. Effect of dust on the spectral characteristics of the sample

The dust accumulation on the PV module surface will result in a decrease in light transmittance, resulting in a reduction in the power generation efficiency. Dust accumulation causes the shielded parts of the PV module to be of electric resistance, which can lead it to heat up and generate hot spots (Paudyal and Shakya, 2016), reducing the lifespan of PV modules.

In the early 1960s, Lifshitz proposed the theory of macromolecules (Meng, 2015). Due to the small electrostatic force of dust particles, studies on the adhesion force of dust particles mainly focuses on Van der Waals' force and gravity. The macroscopic intermolecular force of dust acting on the sample surface is the Van der Waals' force.

Generally, without considering the contact deformation and external forces, the Van der Waals' force between the dust and PV modules is

$$F = -\frac{h\omega}{8\pi} \left[\frac{R}{Z_0^2} + \frac{R}{(Z_0 + 2R)^2} - \frac{2R}{Z_0(Z_0 + 2R)} \right] \quad (1)$$

In Eq. (1), R is the dust particle radius; Z_0 is the molecular separation between dust particles; and $h\omega$ is the Lifshitz constant.

Because $R \gg Z_0$, Eq. (1) can typically be simplified to

$$F = \frac{h\omega R}{8\pi Z_0^2} \quad (2)$$

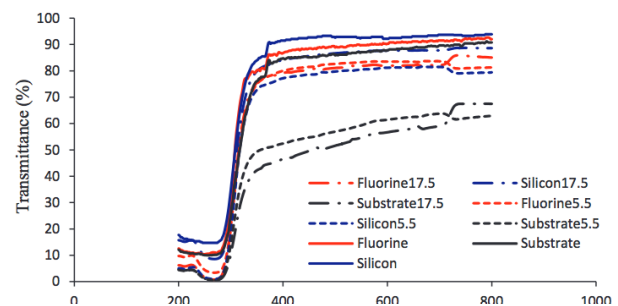
In addition to the Van der Waals' force, dust particles are also affected by their own gravity as follows:

$$G = \frac{4\pi(\rho - \rho_0)gR^2}{3} \quad (3)$$

In Eq. (3), ρ is the dust particle density and ρ_0 is the air density.

Fig. 10 shows that the light transmittance tested from the sample after sand covering and condensation decreased by several degrees. The substrate transmittance decreases with an increase in the sand covering rate. The change in the sand covering rate of the fluorine sample has no effect on its light transmittance, whereas the transmittance of the silicon sample is higher at a sand covering rate of 17.5 ± 0.1 g/m² than at a rate of 5.5 ± 0.1 g/m².

For the same sand covering rate, the low-free-energy surfaces of silicon and fluorine play the role of self-cleaning during the condensation process such that the dust on the sample surface with super-hydrophobic film flows with dew, leaving only a small amount of dust and decreasing less light transmittance. After the dust on the substrate surface absorbs a small amount of water, the molecular spacing of Z_0 becomes smaller. Formula (2) shows that for a given particle diameter R , the Van der Waals' force will increase when the molecular spacing becomes smaller; however, water molecules increase the capillary force between the sand and glass plate, thereby increasing the adhesion of sand to the substrate; thus, a large amount of dust remains on the



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substrate surface, resulting in a substantial decline in light transmittance.

Under the same conditions of condensation, the silicon sample has a higher light transmittance with a sand covering rate of $17.5 \pm 0.1 \text{ g/m}^2$ than with a rate of $5.5 \pm 0.1 \text{ g/m}^2$. Eq. (3) illustrates that when the sand covering rate is high, the water-sand mixed particles with greater gravity can form more rapidly during the condensation process, generating a sufficiently strong glide force. In the course of gliding, the continuous adsorption of dust and water forms a larger mixture of water and sand, which rapidly removes the majority of the dust.

Fluorine-based super-hydrophobic film has a lower decrease in light transmittance than the silicon sample and is largely independent of changes in the sand covering rate. Because the surface tension and friction coefficient of the added fluorinated resin is low and the roughness is positively correlated with the hydrophobicity (Gwon et al., 2014), the surface roughness of the fluorine-based super-hydrophobic film is lower than that of the silicon-based super-hydrophobic film. When the sand covering rate is $5.5 \pm 0.1 \text{ g/m}^2$, the amount of residual dust on the sample surface of the fluorine-based super-hydrophobic film is lower than that on the silicon-based super-hydrophobic film; thus, the light transmittance of the fluorine sample does not decrease as much. When the sand covering rate is $17.5 \pm 0.1 \text{ g/m}^2$, it is easier to form a sufficient water and sediment mixture to remove most of the dust because of the increase in dust density. Therefore, only a small amount of dust remains on the sample surface, and the light transmittance is largely the same as for the sand covering rate of $5.5 \pm 0.1 \text{ g/m}^2$. In conclusion, the micro-nanostructures on the surface of the fluorine super-hydrophobic films are fairly stable even though the light transmittance and hydrophobicity are slightly lower than those of the silicon super-hydrophobic films. They have excellent abrasion resistance and stain resistance; are suitable for sandier situations; and have more stable light transmittance.

3.4.2. Effects of dust on the PV properties of PV modules

Current research on PV modules is attempting to improve the power generating efficiency. There is a near-linear relationship between the sand covering rate and power generating efficiency of the PV module (Jiang et al., 2011), expressed as follows:

$$E_1/E_2 = K \cdot \rho \quad (4)$$

where E_1 is the output power after sand covering, E_2 is the output power before sand covering, K is the filling factor and ρ is the sand covering rate.

Eq. (4) illustrates that the power generating efficiency of PV modules installed outdoors shows an approximately linear downward trend. In this experiment, the silicon- and fluorine-based super-hydrophobic films and the film-free PV modules were placed in simulated dust-fall laboratories. We repeated the above condensation process when the sand covering rates of the three boards were 5.5 ± 0.1 and $17.5 \pm 0.1 \text{ g/m}^2$. Next, we used the sun module tester to test and

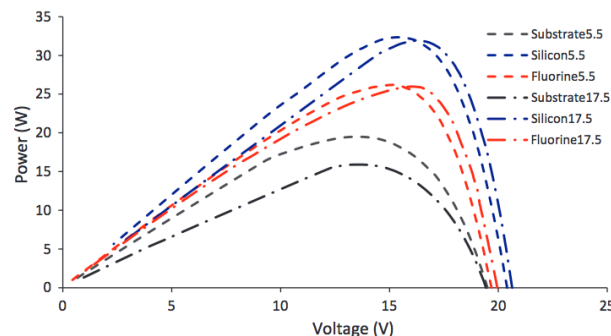


Fig. 12. P(W) for sand covering rates of 5.5 and 17.5 g/m^2 .

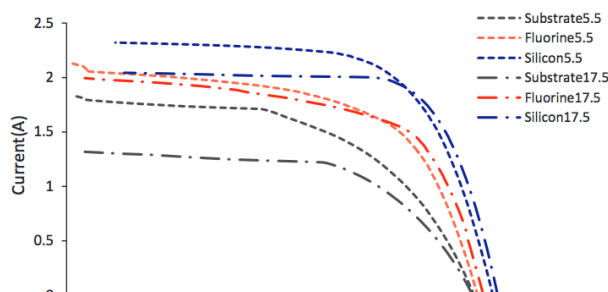
obtain the I-V curve and output power curve after the solar simulator irradiation. Fig. 11 illustrates that the sand covering rate on the surface of the PV module has no effect on the open-circuit voltage of each sample, but the short-circuit current has decreased significantly, which is consistent with the conclusion in Zang et al. (2014).

Fig. 12 shows that the maximum output power efficiency of the uncoated substrate decreases from $19.48 \pm 1\%$ W to $15.91 \pm 1\%$ W, the maximum output efficiency of the PV module coated with the silicon super-hydrophobic film decreases from $32.34 \pm 1\%$ W to $31.9 \pm 1\%$ W, and the maximum output efficiency of the PV module coated with the fluorine super-hydrophobic film decreases from $26.2 \pm 1\%$ W to $25.96 \pm 1\%$ W when the sand covering rate increases from 5.5 ± 0.1 to $17.5 \pm 0.1 \text{ g/m}^2$. Although the super-hydrophobic material of silicon has a higher light transmittance at a high sand covering rate than at a low sand covering rate, the efficiency is decreased by $(1.36 \pm 0.07)\%$ with an increase in the sand covering rate, mainly because the PV module is heated by the light source. In contrast, at a high sand removal rate, the surface of the PV module is mainly covered with a water-sediment mixture, which is dried before slipping off the surface. According to the overlapping model, it can be determined that the dust remaining on the PV module surface is comparatively collective compared to a low sand covering rate, resulting in reduced heat dissipation and a lower power generating efficiency. The fluorine-based super-hydrophobic film has no change in light transmittance, but the maximum output power decreased by $(0.92 \pm 0.08)\%$ due to the fluoride super-hydrophobic film having a certain heat resistance in addition to the antifouling properties of the silicon-based super-hydrophobic film. Thus, after the same period of irradiation, the power generating efficiency of the PV module coated with the fluoride-based super-hydrophobic film decreases less than that of the PV module coated with the silicon-based super-hydrophobic film.

4. Conclusions and prospects

This paper investigated the influence of dust on the light transmittance, power generating efficiency and I-V characteristic curve of PV modules with and without super-hydrophobic film coatings. The following conclusions can be drawn:

- In the absence of other interference items, the PV modules coated with super-hydrophobic films have increased transmittance due to their micro-nano-antireflective structures, which in turn increases the power generating efficiency. Coating with super-hydrophobic films has no effect on the short-circuit current of the PV module, but the open-circuit voltage increases.
- After the simulated dust and condensation process, the sand covering rate increased from 5.5 ± 0.1 to $17.5 \pm 0.1 \text{ g/m}^2$ and the



than at $5.5 \pm 0.1 \text{ g/m}^2$.

- Dust accumulation has an impact on the PV characteristics of the PV modules with and without films. For a given open-circuit voltage, the short-circuit current shows a significant decline; specifically, the maximum output power of the substrate decreases by $(18.33 \pm 0.1)\%$, that of the PV modules coated with the silicon-based super-hydrophobic film decreases by $(1.36 \pm 0.07)\%$, and that of the PV modules coated with the fluorine-based super-hydrophobic film decreases by $(0.92 \pm 0.08)\%$.

In general, after the simulation processes of dust deposition and condensation were carried out on the surface of PV modules coated with super-hydrophobic, we can find that the super-hydrophobic films can not only greatly reduce the accumulation of dust on the surface of PV modules, but also improve the efficiency of photovoltaic power generation. Silicon-based super-hydrophobic film has a higher light transmittance than the fluorine film, but the fluorine light transmittance is more stable to the external environment, and the power generating efficiency of PV modules coated with fluorine-based super-hydrophobic films is the least affected by the sand covering rate.

At present, this paper studied only the sediment characteristics and power efficiency of PV modules covered with super-hydrophobic film on the surface in central and western regions of China; however, the dust compositions of different regions are different (Mehmood et al., 2017). Therefore, the adhesion mechanism between different types of dirt and the surface of PV modules and the influence on the power generation efficiency should be regarded as the main focus of further research.

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