Photovoltaic module active self-cleaning surface using anisotropic ratchet conveyors fabricated with parylene-C stencil

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Abstract. This paper describes an active self-cleaning surface using an anisotropic ratchet conveyor (ARC) to move a water droplet under orthogonal vibrations. Two different ARC systems were designed and fabricated with self-assembled monolayers and hydrophobic Cytop thin films. A novel way to create micro-sized patterns on Cytop was developed without degrading the original Cytop hydrophobicity. Droplet transport speed is 20.5 mm/s at frequency 52 Hz and acceleration 3.3 g (g = 9.8 m/s²). Optical transmission measurements show Cytop can improve optical transmittance by 2.5~3.5% over the entire visible wavelength range. Solar cell module power output is measured to verify the output power efficiency gain. The self-cleaning function is demonstrated with ARC patterns.

1. Introduction

Photovoltaic (PV) modules are often installed in remote arid regions with high levels of sand and dust particles. Dust accumulation forms a non-uniform layer on solar panels that block the sunlight and degrade photovoltaic module efficiency over time. The composition of dust particles majorly consists of quartz and silicate minerals, with a distribution size in the 10~100 µm range [1]. In order to reduce maintenance costs and to minimize dust accumulation on the solar panel cover glass, methods have been proposed using superhydrophobic surface modification with micro textures [2], electrodynamic screens [3], photocatalytically active metal oxide to create superhydrophilic surfaces [4], among others.

The ideal properties of self-cleaning coatings and their system design include low adhesion of dust, optical transparency without degradation of light transmission, and the capability to remove dust particles from the top of the solar cell. Water droplets can be directed along the surface using chemical gradients [5], thermal gradients [6], electrowetting [7], and micro textures [8-9] while they are carrying away dust particles along their path and keeping the surface clean. In this paper, we design, fabricate and test an active self-cleaning surface system using anisotropic ratchet conveyors (ARC) by creating periodic micro-sized semi-circular hydrophilic rungs on a hydrophobic background. Two different designs and their corresponding fabrication processes are proposed here: a perfluoro-octyltrichlorosilane (FOTS, contact angle 108°) – trimethylsilanol (TMS, contact angle 53°) system and a Cytop (contact angle 110°)-TMS system. Mico patterning on hydrophobic surfaces (like Teflon, Cytop) is difficult using standard photolithography due to poor adhesion between the photoresist and substrate. Methods have been proposed [10] but the original surface properties will be damaged after treatment with decrease water droplet contact angle. By adopting parylene-C as a stencil mask, we create hydrophilic patterns on top of the Cytop surface without degrading the original surface properties.
2. System design
The design of the ARC surface is shown in Fig. 1. To introduce an anisotropic wetting force, the periodic, semicircular, chemically heterogeneous ratchet rungs are patterned on the silicon/glass surface. Each hydrophilic semicircular rung has 10 \( \mu \text{m} \) rung width and 50 \( \mu \text{m} \) centre to centre gap width between the adjacent rungs. The radius of curvature is 1000 \( \mu \text{m} \) and the curve angle is 120°. The remainder of the silicon wafer surface is treated with a hydrophobic coating. The whole substrate is mounted on a vibration stage.

As a sessile droplet is pipetted on the ARC surface, the water droplet wets the ratchet patterns along the rungs, creating an air-water-solid three-phase contact line (TPL) along its outer edge. We denote the portion of the water droplet edge that aligns with the rung curvature, which has a mostly continuous TPL, as the leading edge of the droplet, while the other portion, which has only intermittent TPLs across different rungs, is called the trailing edge of the droplet. During each vibration cycle, the leading edge provides higher pinning force than the trailing edge as the water droplet expands and recesses. This asymmetry in pinning forces causes water droplets to move toward the direction of the rung curvature [11].

2.1. Fabrication process
The patterning of FOTS-TMS system could be found from the reference [11]. As for the Cytop patterning process, after Si/glass wafer cleaning, diluted Cytop (Cytop CTL-809M: CTL-Solv.180= 3:1) was spin coated on a silicon wafer and baked under 180° C for 1 hour. Then 2.5 \( \mu \text{m} \) parylene was evaporated on the Cytop using a commercial parylene coater (PDS 2010, Specialty Coating Systems, Inc.) under vacuum. 6 \( \mu \text{m} \) photoresist (AZ9620) was coated and patterned. The parylene stencil mask and Cytop were etched through with O\(_2\) plasma using reactive ion etching (Vision RIE). Then the parylene stencil mask was peeled off with tweezers. The surface was treated with spin-on HDMS (MicroPrime MP-P20) and baked at 110° C for 2 min.

2.2. Experimental setup
The test wafer was mounted on an aluminum platform, which is attached to the vibration exciter (Brüel and Kjaer type 4809) with double adhesive tape. A sinusoidal wave signal was generated by the function generator and amplified by the power amplifier to drive the vibration exciter (Brüel and Kjaer type 2718). The vibration amplitude was monitored with a vibrometer (Polytec OFV) via an oscilloscope (Agilent Infinium). The water droplet movement was captured by high speed camera (FASTCAM Mini UX100) at 2000 fps. 2” by 2” solar cells were sandwiched between the cover glass and the support glass. After the surface treatment and patterning with FOTS-TMS and Cytop-TMS coatings, light transmission data was collected with a Cary 5000 UV-Vis-NIR spectrophotometer (Agilent Technologies, Inc.). Solar I-V curves were measured using the self-custom test bench. We used flood light as the light source and the distance between the solar cell modules and the light source was kept the same for each measurement.

3. Measurement results
3.1. Water droplet movement characterization
A water droplet was pipetted and the drop silhouette was monitored via high-speed camera. The progression of the leading and trailing edge position with time of both FOTS-TMS and Cytop-TMS system were characterized. The droplet transportation on the Cytop-TMS surface, plotted in Fig. 2(a), shows that the leading and trailing edge expanded at 0.57±0.09 mm and 0.36±0.14 mm, respectively, from the rest position during the expansion phase, while the leading and trailing edge recessed 0.28±0.05 mm and 0.74±0.17 mm during the contraction phase. This anisotropy of position change caused the droplet to move forward after each vibration cycle. Fig. 2(b) shows the water droplet contact angle change with time. Pinning anisotropy of the leading and trailing edge can be clearly observed during the recession phase from the contact angle change with time. Compared with the FOTS-TMS system, Cytop-TMS requires lower vibration amplitude and energy to drive the water droplet movement.

![Figure 2](image)

**Figure 2.** (a) Position change of the leading edge and trailing edge with time. The droplet center at rest is set as the origin. (b) Contact angle change of the leading edge and trailing edge. The water droplet (10 µL) moves forward from its initial position.

![Figure 3](image)

**Figure 3.** Optical transmittance measurement results with a wavelength range of 350 nm–800 nm. 4” soda lime glass wafers were used as the substrate baseline.

![Figure 4](image)

**Figure 4.** I-V curve measurement results of bare PV cells, PV cells with glass, FOTS-TMS, and Cytop-TMS system. [Insert] Solar cell module with cover glass treated with Cytop-TMS for measurements.

3.2. Light transmission and solar I-V output

Optical transmission measurements within the visible wavelength range are shown in Fig. 3. As for the FOTS-TMS system, the light transmission was degraded due to the added coating of monolayers, but within a range of less than 1%. The glass after FOTS-TMS treatment was transparent and optically flat. Meanwhile, the Cytop-TMS system improved the transmission with an enhancement of 2.5% ~ 3.5% over the visible wavelength range even with an added coating on top of the glass. The reason was that the refractive index of Cytop is ~1.34, which is between air (n<sub>air</sub>=1.0) and the glass substrate (n<sub>glass</sub> =
1.5), providing a refractive index match. Like Rayleigh's film, a portion of the incoming light reflects both at the interface of air/Cytop and Cytop/glass but has less reflection as compared to the single reflection at the air/glass interface with a larger refractive index mismatch. Fig. 4 shows the I-V curve measurements for assembled photovoltaic (PV) modules. The ARC structure was patterned in a zig-zag way covering a 2" by 2" area in the upper right of the solar cell. The Cytop-TMS coating generated larger optical output power compared with bare glass and FOTS-TMS surface treatment, in accordance with the light transmission measurements.

3.3. Self-cleaning surface demo

A self-cleaning surface should clean all randomly placed particles on the surface. Fig. 5 presents cleaning of sweetener particles by a droplet as a proof-of-concept. Through additional testing, sand particles, salt grains and airborne dust have all been cleaned by the ARC surface. 10 µL water droplets can carry up to 2 mg of sand particles, representing 20% of the water droplet’s original weight.

![Figure 5](image_url)

**Figure 5.** Surface cleaning performance for sweetener (dextrose, maltodextrin, and sucralose) contamination on ARC surface consisting of two ARC tracks. (a)-(f) are subsequent video frames of the experiment. All sweetener on the ARC areas is cleaned by the droplet.

4. Conclusions

In this paper, we demonstrate a proof of concept self-cleaning surface system with ARC tracks using both FOTS-TMS and Cytop-TMS systems. Cytop was successfully patterned using parylene as the stencil mask. Both optical transmission and solar cell power output I-V curves were measured. The Cytop-TMS system can combine both antireflection and self-cleaning functions, which provides an opportunity for PV module applications. For the future plan, we will perform outdoor field tests and explore large-scale, low-cost manufacturing processes creating ARC surfaces on solar panel cover glass.

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