ACTIVE SELF-CLEANING SURFACES ON SOLAR MODULES

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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. The ARC system was fabricated by creating hydrophilic micro-sized patterns on hydrophobic Cytop thin films, successfully developed by utilizing parylene as a stencil mask. Droplet transport speed is 20.5 mm/s at frequency 52 Hz and acceleration 3.3 g ($g = 9.8 \text{ m/s}^2$). 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 efficiency can be improved from 69% to 92% after cleaning contaminants on top of the solar module with surface dimensions of 30 mm by 24 mm.

INTRODUCTION

The power generation efficiency of photovoltaic (PV) modules can be affected by the accumulation of dust and environmental contaminants over time [1]. This problem, which is often called soiling, has become a growing concern in the effort to improve PV module efficiency and reliability. The composition of dust particles majorly consists of quartz and silicate minerals, with a distribution size in the 10~100 μm range [2]. Researchers have been exploring self-cleaning surfaces to clear the surface contaminants away and improve efficiency. 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 a surface using chemical gradients [3], thermal gradients [4], electrowetting [5], and micro textures [6-7]. Earlier, we developed an active self-cleaning surface system using anisotropic ratchet conveyors (ARC) with trimethylsilanol (TMS, contact angle 53°) and perfluorooctyltrichlorosilane (FOTS, contact angle 108°) self-assembled monolayers (reported in Transducers'17 [8]). Unlike that system, where the substrate was first treated with a hydrophilic TMS layer and patterned with lithography, we developed a new process to pattern directly on hydrophobic Cytop thin films. Cytop is an amorphous fluoropolymer with good transparency over the visible and UV wavelength range, good chemical resistance, excellent water repellence and low surface tension. Micro-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 using a metal buffer layer [9-10] or plasma pretreatment of the surface, but the original surface properties will suffer after treatment and exhibit decreased water droplet contact angle. Parylene can be etched with oxygen plasma, making it compatible with standard lithography processes. It has been used to create biomolecular stencil arrays [11] and patterns on soft substrates [12]. By adopting parylene-C as a stencil mask, we create hydrophilic patterns on top of the Cytop surface without degrading the original surface properties.

In this paper, we demonstrate an active self-cleaning surface system using water droplets to clean surface contaminants on solar module cover glass. A hydrophobic thin film is successfully patterned using parylene-C as a stencil mask. Droplet transportation performance and solar module level cleaning effects is characterized

and discussed.

SYSTEM DESIGN

Theory Background

To initiate transport of a sessile droplet sitting on a horizontal surface, force anisotropy needs to be created at the boundary of the solid-liquid-gas interface, which is termed the three-phase line (TPL). As the droplet is agitated by external forces (*e.g.* vibration, alternating electric field, *etc.*), the contact angle at the TPL will be different from the equilibrium status according to Young's equation during the droplet expansion and recession phase. The difference of the droplet TPL contact angle during expansion and recession phase is termed as contact angle hysteresis (CAH). Shown in Fig. 1, at equilibrium state, at the infinitesimal length of TPL (noted as ϵ), the net forces can be expressed as:

$$(\gamma_{SG} - \gamma_{SL} - \gamma_{LG} \cos\theta_e)\epsilon = 0 \quad (1)$$

where γ is surface tension between solid, liquid and gas phase.

In the advancing and receding state, the contact angle will change because of external forces. The net forces can be expressed respectively as:

$$(\gamma_{SG} - \gamma_{SL} - \gamma_{LG} \cos\theta_a)\epsilon = F_{ex,a} \quad (2)$$

$$(\gamma_{SG} - \gamma_{SL} - \gamma_{LG} \cos\theta_r)\epsilon = F_{ex,r} \quad (3)$$

where $F_{ex,a}$ and $F_{ex,r}$ are the portion of the external driving forces that are opposed by pinning on the substrate during advancement and recession, respectively, and θ_a and θ_r are the contact angles during advancement or recession. By combining equation (2) and (3), as for a complete cycle of TPL advancement and recession processes, it is useful for us to define a contact line hysteresis force (F_{hys}) to express the average force on the TPL during each expansion and recession cycle:

$$F_{hys} = F_{ex,a} - F_{ex,r} = (\cos\theta_r - \cos\theta_a) \gamma_{LG} \epsilon \quad (4)$$

The contact line hysteresis force serves as the pinning force to prevent the droplet boundary from moving. In order to transport the water droplet, we have designed anisotropic ratchet conveyors, which are abbreviated as ARCs. As shown in Fig. 1 (b), hydrophilic semicircular rungs are patterned on a hydrophobic background and a sessile droplet is dispensed on the ARC tracks. Because of the surface ratchet pattern design, the TPL of the droplet leading and trailing edge has different line fraction overlaps at the hydrophobic and hydrophilic region boundaries. We denote the line fraction lying on the hydrophobic-hydrophilic boundary as χ_b , which provides the anisotropy at the leading and trailing edges of the water droplet. We define the anisotropy force of the water droplet on the ARC surface as $F_{anisotropy}$, which can be expressed as:

$$F_{anisotropy} = F_{hys,leading} - F_{hys,trailing} \quad (5)$$

We assume that recession occurs when $\theta_r = \theta_1$ and advancement occurs when $\theta_a = \theta_2$, where θ_1 and θ_2 are contact angles for hydrophilic and hydrophobic regions, respectively. We integrate the hysteresis force over the contact line at the surface hydrophobic and hydrophilic boundaries. The anisotropy force can then be expressed as [7]:

$$F_{anisotropy} = (\chi_{b,leading} - \chi_{b,trailing})w(\cos\theta_1 - \cos\theta_2) \gamma_{LG} \quad (6)$$

where w is the contact line width of the droplet and χ_b is the line fraction. $\chi_{b,leading}$ is larger than $\chi_{b,trailing}$. The contact angle hysteresis is larger for the leading edge than the trailing edge by measurement. The water droplet will be driven forward and moved along the surface.

Figure 1: (a) Force analysis of the droplet at advancing, equilibrium, and receding phases. At advancing and receding phases, the external forces to change the contact angle at the TPL boundary can come from vibration or electrical agitation. (b) Top view of TPL movement during one vibration cycle of expansion phase and recession phase. The black highlighted regions are contacts between the water droplet TPL and the substrate. The red semi-circular curves are hydrophilic regions.

Fabrication Process

To fabricate the ARC surfaces, a silicon wafer was first cleaned with piranha solution at 110°C for 10 min, rinsed with deionized (DI) water and dried with nitrogen gas using a spin rinse dryer (ClassOne Technology). 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 μm parylene was evaporated on the Cytop using a commercial parylene coater (PDS 2010, Specialty Coating Systems) under vacuum. 6 μm 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 TMS (MicroPrime MP-P20) and baked at 110°C for 2 min.

Figure 2: Cytop-TMS system using parylene as a stencil mask. Cytop will keep its hydrophobicity after peeling off parylene coating.

Experimental Setup

We use a vibration stage setup to characterize droplet transport on the ARC surface. The test wafer was mounted on an aluminum platform, which was attached to the vibration exciter (Brüel and Kjær 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 Kjær type 2718). The vibration amplitude was monitored with the vibrometer (Polytec OFV) on the oscilloscope (Agilent Infiniium). The water droplet movement was captured by high speed camera (FASTCAM Mini UX100) at 2000 fps. The video was processed with MATLAB custom code. We also measured light transmission data of the two ARC surface coatings on soda lime glass substrate with a Cary 5000 UV-Vis-NIR spectrophotometer (Agilent Technologies). A custom source meter was used for the I-V curve output of the solar modules. 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.

CHARACTERIZATION RESULTS

Droplet transport on ARC

The patterned Cytop is shown in Fig. 3 with ~ 70 nm thickness. Cytop hydrophobicity was not degraded after peeling off parylene. Each hydrophilic semicircular rung has 10 μm rung width and 100 μm center to center gap width between the adjacent rungs. The radius of curvature is 1000 μm and the curve angle is 120°.

Figure 3: SEM images of ARC patterns on Cytop. For each semi-circular rung, the radius of curvature is 1000 μm , the etched linewidth is 10 μm , and the period between adjacent rung centers is 100 μm .

The wafer was mounted on a vibration platform. A range of 5–15 μL water droplet was pipetted on the surface. The vibration amplitude was monitored by vibrometer. We tested the minimum required vibration acceleration to drive a water droplet over the frequency bandwidth of 35–100 Hz. As a comparison to FOTS-TMS surfaces, Cytop-TMS surfaces directed the droplet movement with lower stage vibration amplitude as shown in Fig. 4. The minimum acceleration to drive the water droplet on Cytop-TMS surfaces was as low as ~ 0.7 g at a frequency of 55 Hz, 5 times lower than on the FOTS-TMS surface (~ 3.6 g).

Optical transmission measurements within the visible wavelength range are shown in Fig. 5 (a). 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% $\sim$ 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 ($n_{\text{air}} = 1.0$) and the glass substrate ($n_{\text{glass}} = 1.5$), 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. 5 (b) 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.

Figure 4: Minimum vibration acceleration required to move the water droplets along the ARC surface for both systems.

Figure 5. (a) Optical transmittance measurement results with a wavelength range of 350~800 nm. 4" soda lime glass wafers were used as the substrate baseline. (b) I-V output of solar module assembly with coated cover glass.

Self-cleaning Surface Design

We assembled solar modules with the patterned cover glass on top. As shown in Fig. 6, a piece of solar cell cut to the size of 30 mm by 24 mm was assembled with a Cytop-TMS ARC patterned glass. Silicon nitride particles (with a total mass of 10 mg) were evenly applied on the surface through polyester mesh. A 13.5 μ L droplet was pipetted atop and followed the zig-zag ARC track while cleaning the surface contaminants. The solar module output

efficiency response was monitored in real-time. It increased by more than 23 percentage points, rising from 69.1% after contamination to 92.1% after 15 s of cleaning.

Figure 6. [top] Real-time power output response of solar module during the cleaning process. The solar module was connected with a resistive load for power monitoring. [bottom] Top view of cleaning process with continuous 3 cleaning cycles. The droplet is 13.5 μ L in volume at a vibration frequency of 50 Hz. The droplet zig-zag path is shown at T=0 ms with the red dotted line.

We tested the surface cleaning function with different categories of typical contamination, including dust and dirt particles, soluble and insoluble contaminations, summarized in Table I. From the table, most water-soluble materials (like salt and sweetener) plus low surface adhesion insoluble particles (like sand, SiO_x , SiN_x , carbon powers) can be effectively cleaned with the droplet from the self-cleaning surface. Hydrophobic surface contaminants like polytetrafluoroethylene (PTFE) cannot be cleaned with the droplets. The hydrophobic particles tended to stay at the boundary of the water droplet instead of being trapped inside the droplet. The droplet surface was gradually covered with solid powder so that the surface tension at the TPL was reduced. Eventually a “droplet marble” was formed jumping on the surface as agitated by vibration. We also tested pepper and dry soil. However, these contaminants contained contents with a tendency of adhering to the surface and preventing the droplet from moving.

Table 1: Materials tested on the self-cleaning surface.

Material	Sand (< 600 μ m)	Salt	Sweetener	SiO_x and SiN_x	Carbon powder	PTFE
Can be cleaned or not	Y	Y	Y	Y	Y	N

To understand the cleaning mechanism, silicon nitride powder was deposited on top of the Cytop-TMS surface. The droplet silhouette was monitored by high-speed camera. When an air-water interface is in contact with dust particles, the interfacial force can be decomposed into vertical and horizontal components. The vertical component detaches the dust particles from the surface and the horizontal component pushes the accumulated particles to another location (Fig. 7). The droplet was able to carry the SiN_x particles along. Similar phenomena could also be seen with the carbon powder.

Figure 7: (a)-(d) demonstrates how the bulk hydrophilic SiN_x powder is detached from the surface and relocated by the interfacial surface tension. When the droplet expands, the water-air interfacial force removes powder particles from point A to point B location. (e)-(f) show the particles (highlighted in the dotted line circle) captured by the droplet at the interface. Eventually, they will be trapped inside the droplet and carried away with the droplet movement.

CONCLUSIONS AND FUTURE PLAN

In this paper, we demonstrate a proof of concept self-cleaning surface system with ARC tracks using Cytop-TMS coatings. Cytop was successfully patterned using parylene as the stencil mask. Solar module level optical transmission and solar cell power I-V measurements were performed, demonstrating Cytop coating can provide antireflection properties on the soda lime cover glass and improve solar output efficiency. Different surface contaminants including water soluble, insoluble, hydrophobic and hydrophilic dust particles were characterized. Our system relies on the surface tension anisotropy at the TPL of the droplet boundary to move the droplet along while dislodging and removing surface contaminants during droplet expansion and recession phases under vibrations. Compared with hydrophobic surfaces utilizing the lotus effect, our system has the advantage of systematically transporting the droplet to designated locations compared with uncontrolled droplet rolling by gravity on hydrophobic surfaces. The cleaning process only utilizes a sessile droplet with minimized water usage.

As for the future plan, we will explore the large scale patterning process. Printing is a promising option. By combining flexographic and gravure printing techniques, a high resolution ($10\ \mu\text{m}$) Cytop patterning was achieved [13]. Meanwhile, the power consumption is another concern for the fielding application. A high quality factor vibration motor optimized at the droplet resonance frequency is required to minimize the system power consumption. The cleaning time of the system can be limited to a short period of time depending on the local dust accumulation rate so that the solar module power gain from the cleaning processes can compensate for the cleaning power consumption.

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