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Condensed microdrops self-jumping based on flake-like nanostructures on a glass slide

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ABSTRACT

Condensed microdrops self-jumping (CMSJ) surfaces with specific nanostructure have been actively explored to promote favorable droplet dynamics for enhancement of condensation heat transfer efficiency. However, the CMSJ surfaces based on the glass itself are insufficient in the past, although it is significant in daily life and industry processes. Here, we report condensed microdrops with size of 20–30 μm could continuously self-jumping on the superhydrophobic glass slide with flake-like nanostructures and over 75% of dewdrops were maintained their diameter below 20 μm after condensed 1000 s. This work is expected to provide unique advantages in condensation heat transfer for enlargement of application of glass in various fields.

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1. Introduction

To enhance condensation heat transfer, superhydrophobic surfaces have been widely applied on the solid-gas interface in a cold and humid environment for decrease of formation and accumulation of condensed water [1,2]. However, the condensed microdrops do not always form Cassie state on the treated surface, although it shows favourable superhydrophobicity in room temperature [3], resulting that condensed water could not be drained timely. To resolve these issues, condensed microdrops self-jumping (CMSJ) behaviors were developed using the released surface energy to provide dynamics of merged microdrops [4,5]. CMSJ effects were successively developed on various nanostructures since it was published in 2009 [6]. Such as, nanograsped micropyramidal structures on a silicon wafer by anisotropic etching [7], hierarchically structured porous aluminum surfaces by a boiling process [8], knife-like nanostructures of CuO [9], carbon nanotubes array by chemical vapor deposition [10], ZnO nanoneedles by wet chemical crystal growth method [11], Co(OH)₂ nanocone by in situ grown [12], cerium oxide porous nanoparticle by in situ growth

[13], anodic alumina rod-capped nanopores [14], sprayable porous nanoparticle of SiO₂ [15] or CNT/SiO₂ [16].

However, it is still challenging to obtain CMSJ surfaces based on the glass itself, which are rarely studied despite they have important values in daily life and industry processes. In the past, superhydrophobic surfaces based on the glass itself were often prepared by selective etching [17] or wet chemical methods [18]. According to the cost-benefit principle and equipment accessibility, wet chemical nanocorrosion methods are more suitable for fabrication of CMSJ nanostructures on glass surfaces than selective etching. Therefore, it is significant to explore novel glass-based CMSJ nanostructures and wet chemistry processing methods. Here, inspired by the flake-like nanostructures on superhydrophobic aluminum surfaces with CMSJ functions [19], we propose that the jumping behaviors may be also observed on the glass surface with same construction. To verify this idea, we carried out an alkaline-tailored method to fabricate the flake-like nanostructures glass surface [18]. As expected, CMSJ property were observed on the transparent superhydrophobic glass slide and over 75% of condensed microdrops hold their sizes below 20 μm after 1000 s.

2. Materials and methods

1H, 2H, 2H-perfluorodecyltriethoxysilane (PFDTES) were purchased from Sikang New Material Co., Ltd. Glass slide, absolute

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ethyl alcohol (EtOH), acetone, deionized water, sodium hydroxide (NaOH), and other chemical reagents were purchased from Sinopharm Chemical Reagent Co., Ltd.

The typical superhydrophobic glass slide was fabricated by follow processes [18]: i) glass slide with size of $2 \times 2 \times 0.2$ cm was ultrasonically degreased in acetone for 5 min and then rinsed by deionized water and EtOH ordinarily; ii) after dried at 80°C , the sample was corroded in 0.1 M NaOH solution at 80°C ; iii) after 3 h, it was cleaned by deionized water and EtOH ordinarily; iv) after dried at 80°C again, the fluorination of the surface was carried out in a vacuum tank with oversaturated steam of PFDTES at 150°C for 2 h.

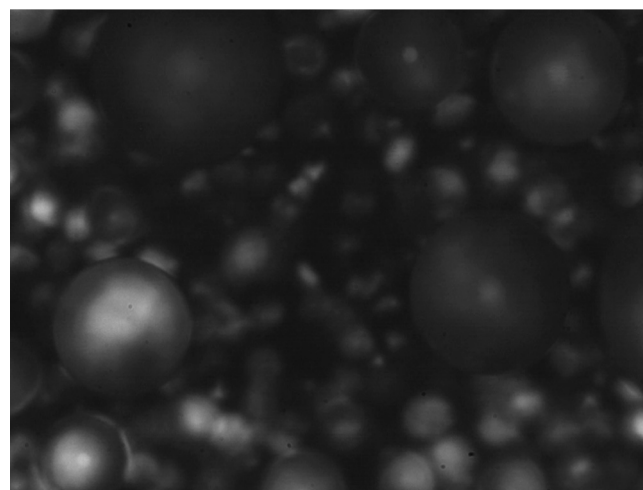
The microstructure of sample surface was observed by field-emission scanning electron microscopy (FESEM), which was conducted with Sirion instrument. Static water contact angels (SCAs) and roll-off angels (RAs) were observed at room temperature on an OCA 15Pro contact angle meter. The average CA value was determined by measuring the same sample at 3–5 different positions. Time-lapse images or videos were captured by a Photron FASTCAM Mini UX100 type high speed camera equipped with Navitar 6000 zoom lens.

3. Results and discussion

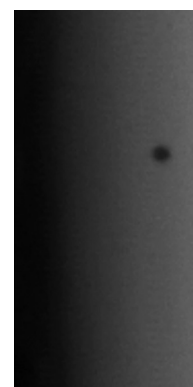
As shown in Fig. 1a, we demonstrate that the flake-like nanostructures were successfully obtained by alkaline-tailored method on the glass slide surface. After hydrophobization, the superhydrophobicity of the nanostructure surface was measured by macroscopic water droplet, which suggests SCA of over 160° and RA of under 5° (inset of Fig. 1a). To further exhibit the wettability, water droplet impacting test (Fig. 1b) was carried out by $5\ \mu\text{L}$ droplet perpendicularly impacts from 3 cm high. The droplet completely left the surface without wetted, contaminated, penetrated or damaged and the contacting time (Δt_c) between the droplet and the coating from encounter to separation is about 8.4 ms. As a comparison, we also examine the same water droplet impacting test on a hydrophobic glass slide surface, which was prepared by fluorination of the untreated plane glass slide (SCA is about 117°). The difference is that the droplet was completely stayed on the surface without bouncing (Fig. 1c).

To observe the condensation performance of the superhydrophobic glass slide, we place the sample on a cooling stage with the condition that substrate temperature is 2°C , ambient temperature is $25 \pm 1^\circ\text{C}$, relative humidity is $70 \pm 5\%$, and dew-point temperature is about $17\text{--}21^\circ\text{C}$. As shown in Fig. 2a, the coalescence and departure behaviors of three adjacent microdroplets with sizes of $20\text{--}30\ \mu\text{m}$ without any external force (Video S1, Supporting Information). We track a jumping droplet from the vertically placed surface in Fig. 2b to explore the jumping dynamics of the merged dewdrop. The results suggest that the dewdrop departed with a initial velocity of about $\sim 5\ \text{m/s}$ from the surface

(Video S2, Supporting Information). Based on this, the statistical parameters of microdroplets on horizontal cooling stage were examined under above condensation condition. As shown in Fig. 2c, the size distribution of microdroplets on the surfaces were displayed against times. Obviously, the number distribution of microdroplets with size of $20\text{--}50\ \mu\text{m}$ continues to rise at the early time ($0\text{--}400\ \text{s}$), which indicates that the nucleation and growth of the condensed droplets were mainly developed. And then a dynamic balance was sustained after 400 s, revealing that the jumping behavior was a continuously process on the nanostructures glass surface. In order to confirm and verify this inference, we capture the continuous self-jumping behaviors on the surface in Video S3 (Supporting Information).



Video S1.



Video S2.

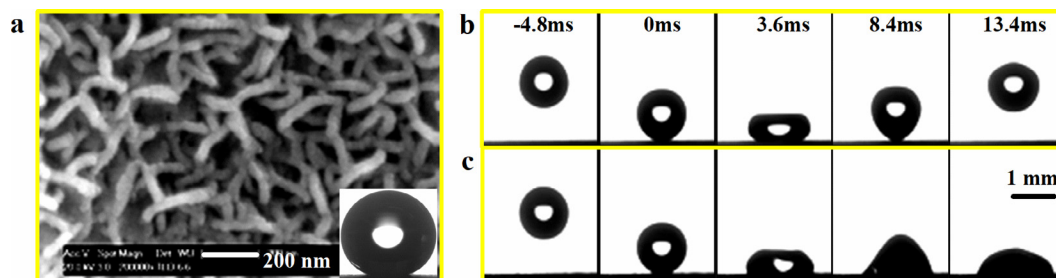


Fig. 1. a) FESEM image of the superhydrophobic glass slide. (Inset: Corresponding SCA image.) Water droplet bouncing tests on b) superhydrophobic and c) hydrophobic glass slide.

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