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Dynamic characteristics of droplet impacting on prepared hydrophobic/superhydrophobic silicon surfaces

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ABSTRACT

Micro pillar arrays were fabricated on silicon surfaces based on the reactive ion etching technology. Low surface energy coatings were deposited on textured surfaces in order to prepare hydrophobic/superhydrophobic surfaces. After measuring the static contact angles and roll angles, the dynamic characteristics of droplets impacting on these hydrophobic/superhydrophobic surfaces were investigated in detail. Both the static contact angle and the roll angle increased with the increase of micro pillars' height. With the increase of micro pillars' spacing, the roll angle decreased, but the change of static contact angle was irregular. On superhydrophobic surfaces, the spreading coefficient of droplet was affected by both the static contact angle and the roll angle, and the rebounding coefficient of droplet was highly relevant with the roll angle. In addition, the bigger the incline angle of surface, the smaller the spreading coefficient and the smaller the rebounding coefficient of droplet.

1. Introduction

Understanding the impact dynamics of droplet on hydrophobic/superhydrophobic surfaces is of great importance in many industrial applications [1–3]. The droplet-surface interaction on superhydrophobic surfaces can prohibit liquid and freezing water-droplet retention on surfaces [4], which can be used to reduce the ice accumulation on wind turbines, aircraft, and power transmission lines [5,6]. Jin et al. [7] have experimentally investigated the impact process of a water droplet on cold surfaces. as for the freezing process, they think the cold surfaces affected not only the freezing time of the water droplets, but also the shape of the ice beads. Li et al. [8] have carried out an experimental study to identify the influence of solidification upon the impact process of a single water impacting on cold surfaces, their results indicate that solidification did not influence the impact process during the first spreading phase while it suppressed receding significantly for lower impact velocities. In addition, the droplet-surface interaction can enhance the heat transfer performance, which can make a contribution to improve heat exchangers and air conditioners [9,10]. Moon et al. [11] have studied the spreading and receding behaviors of droplets impacting on heated textured surfaces, they found the cooling effectiveness decreased with the increase of surface hydrophobicity. Negeed et al. [12] have investigated the effects of surface roughness and oxide layer on droplet impact behavior, they concluded that the maximum droplet spreading diameter increases with the increase of Weber number and the liquid-solid contact time increases with the increase of the surface roughness. Moreover, the droplet-surface interaction can remove the ash and dust on surfaces, which plays a great role in keeping the solar-grade silicon surfaces clean [13,14]. Matin et al. [15] prepared a superhydrophobic surface which can keep great self-cleaning property under a water-jet impact. Therefore, the understanding of droplet-surface interaction on hydrophobic/superhydrophobic surfaces is essential to optimize the efficiency of these applications. Although a lot of researchers reported on the dynamic characteristics of droplet impacting on different surfaces [16–20], there was a lack of systematic understanding of droplets' impacting characteristics on hydrophobic/superhydrophobic surfaces.

Hydrophobic/superhydrophobic silicon surfaces, because of their outstanding physical and chemical properties, have been extensively used in various fields [21–23]. Improving the hydrophobicity of silicon surfaces has aroused the worldwide interest. It has been proved that two processes should be taken to make the smooth silicon surfaces become superhydrophobic surfaces [24–26]. One is to construct the micro structure on surfaces [27–29], and the other process is to reduce the surface energy [30,31]. However, all the existed researches focus on the preparation of hydrophobic/superhydrophobic silicon surfaces, and the understanding of droplets impacting on hydrophobic silicon surfaces is not deep enough.

In this paper, the silicon surfaces with micro pillar arrays were fabricated by the reactive ion etching technology, and the self-assembled monolayer technology was used to reduce the surface energy. The moving processes of droplets impacting on these superhydrophobic surfaces

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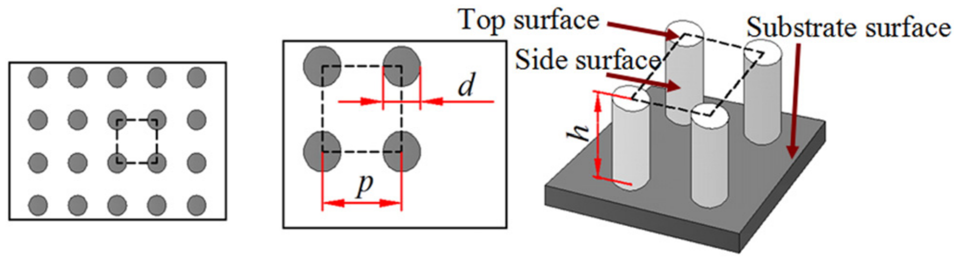

Fig. 1. Schematic diagram of micro-pillar arrays.

were recorded and analyzed using a high speed camera. The influences of the static contact angle and the roll angle on dynamic characteristics of droplets were expounded.

2. Experimental procedure and numerical simulation

2.1. Fabrication of surfaces

Twelve kinds of surfaces were fabricated on silicon substrate with electrical resistivity ranged between 0.010–0.015 Ω cm. At first, all the specimens were heated to generate 500 nm thick layer of silicon dioxide (SiO_2), and each substrate was coated with positive photoresist at 3000 r/min by a spin coater (SUSS 80RC, Germany). Immediately after this, specimens were baked at 90 °C for 20 min. Secondly, UV exposure was performed by the Suss MA6/BA6 (Germany). Alkali (NaOH) solutions were used for saw damage removal and then specimens were baked at 120 °C for 30 min. Thirdly, specimens were immersed in HF solution ($HF:NH_4F:H_2O = 3:6:10$, V/V/V) to remove SiO_2 layer and then cleaned with DI water. Fourthly, specimens were immersed in KOH solution ($C_3H_8O:KOH:H_2O = 1:2:6$, V/V/V) to remove Si. At last, the photoresist and SiO_2 were removed [32,33].

Fig. 1 shows the schematic diagram of micro-pillar arrays, the diameter of each micro pillar (d) was 5 μm, the height of the micro pillar (h) was 5, 10 and 15 μm, and the spacing of micro pillars (p) was 15, 25, 35 and 45 μm, respectively. In order to distinguish all the surfaces, we named them by their heights and spacing. For example, the height and the spacing of micro pillars on surface 5–15 are 5 μm and 15 μm, respectively.

After constructing the textured structure, the surfaces were deposited with low surface energy coatings by the self-assembled monolayer technology. The process contained two steps. One was the hydroxylation process, the specimens were immersed in piranha solution ($H_2SO_4:H_2O_2 = 7:3$, V/V) for 60 min. The other one was the deposition process, the specimens were immersed in 1H,1H,2H,2H-perfluorinatedalkyltrichloro- silane (FOTS) solution ($CH_3C_6H_5:FOTS = 200:3$, V/V) for 60 min. Fig. 2 shows the mechanism of depositing the low surface energy. Firstly, hydrolysis reaction happened between FOTS molecules, which followed by the condensation reaction. Secondly, the polymerization reaction took place and then the monomolecular film formed on the substrate surface. At last, the hydrophobic/superhydrophobic surfaces were obtained.

2.2. Experimental set-up

With the use of contact angle meter (KRÜSS Easy Drop, Germany) and the self-designed roll angle meter, the static contact angle (SCA) and roll angle (RA) were separately measured. The static contact angle is the angle, conventionally measured through the liquid, where a

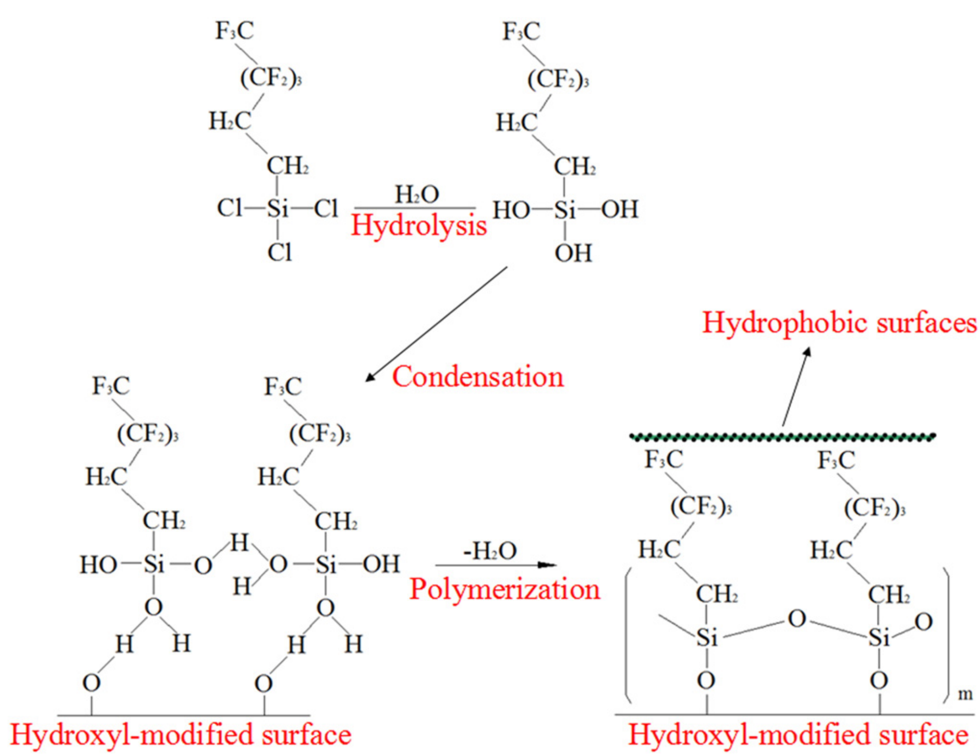

Fig. 2. Process of depositing the low surface coating.