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EVAPORATION AND CONDENSATION ON TWO-TIER SUPERHYDROPHOBIC SURFACES

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ABSTRACT

Superhydrophobic surfaces exhibit large contact angle and small hysteresis which promote liquid transport and enhance heat transfer. Here, liquid-vapor phase change behavior is reported on superhydrophobic surfaces with short carbon nanotubes deposited on micromachined posts, a two-tier texture mimicking the surface structure of lotus leaves. Compared to one-tier microtexture which energetically favors the Wenzel state, the two-tier texture with nanoscale roughness favors the Cassie state, the desired superhydrophobic state. During droplet evaporation, the two-tier texture delays the transition from Cassie to Wenzel state. Using two-tier texture with hexadeconethiol coating, continuous dropwise condensation was demonstrated for the first time on engineered superhydrophobic surfaces.

Keywords: Superhydrophobic, Two-Tier Texture, Evaporation, Condensation, Biomimetics

INTRODUCTION

Superhydrophobic surfaces with large contact angle (>150º) and small hysteresis (<5º) are nearly frictionless for water drops, and can therefore promote liquid transport [1] and potentially enhance heat transfer. A natural example of superhydrophobic surface is a water-repellant lotus leaf. Its two-tier texture with nanoscale roughness on top of microstructures, discovered a decade ago [2], yields very stable superhydrophobic surface properties. On lotus leaves, the Cassie mode where liquid drops sit on top of air-filled cavities is preferred over the Wenzel mode where liquid penetrate into the cavities in the textures [3,4]. Here, we report a lotus-mimicking superhydrophobic structure with two-tier texture consisting of carbon nanotubes (CNTs) deposited on micromachined posts, and discuss the effects of superhydrophobicity on liquid-vapor phase change behavior at the interface.

FABRICATION

Figure 1 shows images of a two-tier texture. On a silicon (Si) substrate, squarely positioned micropillars were formed by deep reactive ion etching (DRIE). The etched Si substrates were coated with a thin layer of nickel as catalyst, and CNTs were grown by plasma enhanced chemical vapor deposition (PECVD) [5]. The micropillars were 3.9 μm in diameter, 8.0 μm in height, and spaced 12.0 μm center to center. The nanopillars were approximately 0.4 μm in height with a 25% surface coverage. The substrate was then hydrophobicized, either by a 10 nm-layer of parylene N coating, or by a 10 nm-layer of gold coated with a monolayer of 1-Hexadecanethiol. For comparison purposes, one-tier microtextures were prepared by skipping the step of CNT deposition, but were otherwise processed in the same manner. Compared to one-tier microtexture without nanotubes, the two-tier texture is more stable for the preferred Cassie mode as it increases surface roughness and decreases solid-liquid contact, both decreasing the critical physical contact angle above which Cassie state is energetically favorable [6].

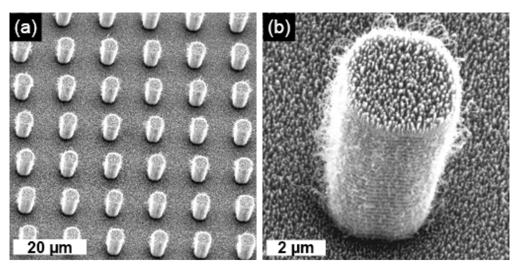

Fig. 1 Two-tier structure consisting of carbon nanotubes on micromachined pillars.

EVAPORATION

Figure 2 shows the evaporation process of a 1μL drop on one-tier (Fig. 2a) and two-tier (Fig. 2b) structures, both coated with parylene. For the one-tier texture, care was taken to gently deposit the drop so it landed in the Cassie state. In contrast,

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pipetted drops always landed in the Cassie state on a two-tier texture, an indication of the stability of the Cassie state. The evaporation process in ambient air under laboratory conditions appeared almost identical in the first 12 minutes. However, in the 13th minute (Figure 2), the two-tier surface (Fig. 2b) was superior to one-tier surface (Fig. 2a). On the one-tier surface, the apparent contact angle dropped below 90º in the last 10s (critical drop diameter d_c ~ 160µm); In contrast, on the two-tier surface, the transition to below 90º happened only in the last 5s (d_c ~ 90µm). Therefore, the inclusion of the secondary roughness on the two-tier texture delays the transition from Cassie to Wenzel state during droplet evaporation.

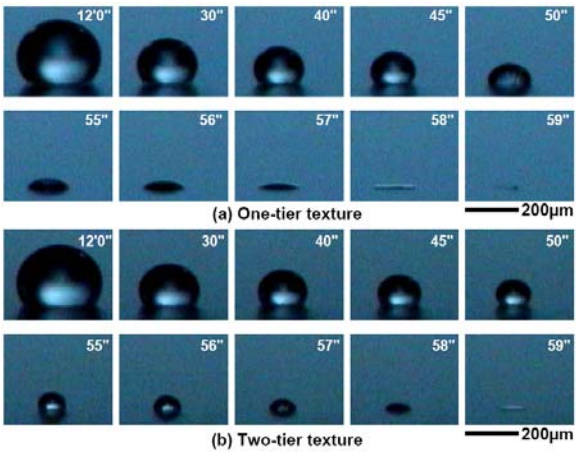

Fig. 2 Evaporation of a Cassie drop on one- and two-tier textures coated with parylene.

CONDENSATION

Condensation of water vapor from ambient air was also tested on both one-tier and two-tier textures. The substrate was cooled below the dew point, and the condensation process was visualized on textured surface (Figure 3). On the one-tier texture with only micro-pillars (Fig. 3a-b), the condensed drops penetrated into the interstitial cavities as shown by the flattened and irregular drop shape before and after coalescence, at 9min and 10min respectively. In contrast, on a two-tier surface with nano-pillars on top of micro-pillars (Fig. 3c-d), the condensed drops stayed in the Cassie state as indicated by the almost spherical drops. Except for drops with a diameter comparable to the micro-pillar separation (i.e. ~20µm), the coalesced drops (some after a series of coalescence) remained in the Cassie state on a two-tier texture during an experimental test spanning 1 hr.

Although in the Cassie state, the drops had limited mobility on a parylene-coated two-tier texture, as evident from the nearly stationary drops around the coalescing drops in Fig 3c-d. To achieve rapid droplet removal, the surface energy of the coating material was lowered by using hexadecanethiol (physical contact angle ~ 101º) instead of parylene (91º). The rapid drop motion, usually triggered by coalescence, is apparent by comparing Fig. 3e-f to Fig. 3c-d, both taken at 9 and 10 min after condensation started. Compared to the parylene-coated surface, it was no longer possible to track most of the drops on the thiol-coated surface after one minute. Continuous dropwise condensation was therefore enabled by maintaining the Cassie state and ensuring high droplet mobility.

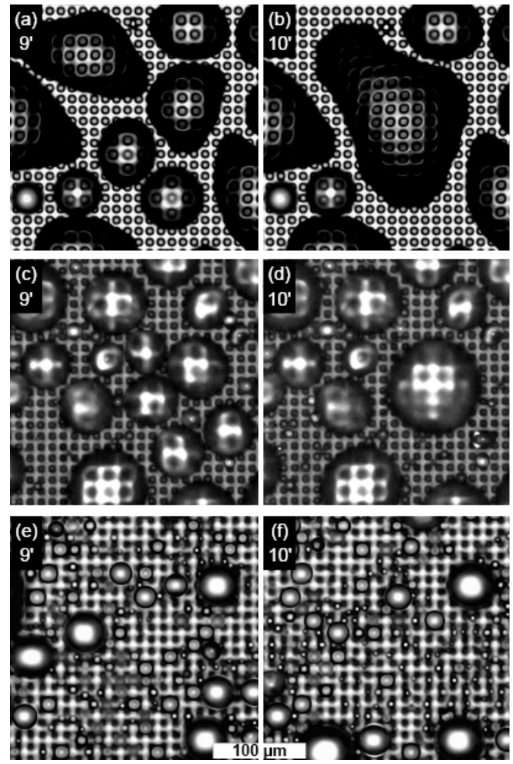

Fig. 3 Condensation processes on (a-b) One-tier texture with parylene coating; (c-d) Two-tier texture with parylene coating; (e-f) Two-tier texture with hexadecanethiol coating.

CONCLUSION

Compared to its one-tier counterpart, the lotus-mimicking two-tier superhydrophobic surface is energetically favorable for the Cassie state. The two-tier texture delays the transition from Cassie to Wenzel state during droplet evaporation. With low energy surface coating on two-tier texture, continuous dropwise condensation was demonstrated for the first time on engineered superhydrophobic surfaces.

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