Promoting Droplet Rapid and Explosive Jumping on Hot Engineered Surfaces without Leidenfrost Effect

Wenge Huang\textsuperscript{a}, Xukun He\textsuperscript{a}, C. Patrick Collier\textsuperscript{b}, Zheng Zheng\textsuperscript{c}, Jiansheng Liu\textsuperscript{c}, Jiangtao Cheng\textsuperscript{a, *}

\textsuperscript{a} Department of Mechanical Engineering, Virginia Tech, Blacksburg, VA 24061, USA
\textsuperscript{b} Center for Nanophase Materials Sciences, Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA
\textsuperscript{c} School of Electronic and Information Engineering, Beihang University, 37 Xueyuan Road, Beijing 100191, China

*Corresponding author. E-mail: chengjt@vt.edu; Phone: 540-231-4164
Abstract

Rapid removal of sessile liquid droplets from a substrate has thrilling applications in surface self-cleaning and anti-frosting/icing/corrosion. Yet, our understanding of interfacial phenomena including droplet wetting and phase changes on engineered surfaces remains elusive, impeding dexterous designs for agile droplet purging. Here we introduce a simple but effective method to modulate droplet jumping behaviors on micro-pillared substrates at moderate superheat of 20-30 °C by controlling vapor bubble growth thereon. For droplets in the Wenzel state, the micropillar matrix functions as fin array for heat transfer enhancement. Therefore, by tuning the feature sizes of micropillars, one can adjust the vapor bubble growth at the droplet base from the heat-transfer-controlled mode to the inertia-controlled mode. As opposed to the relatively slow vibration jumping in seconds on short-micropillared surface, the vapor bubble growth in the inertia-controlled mode on tall-micropillared surface leads to droplet out-of-plane jumping in milliseconds. Such rapid droplet detachment stems from vapor bubble explosion, during which the bubble expanding velocity can reach as fast as ~4 m/s. This study unveils the mechanisms of versatile jumping behaviors of droplet from a hot micro-structured surface and sheds lights on designing engineered surfaces mitigating potential damage of vapor explosion or alleviating condensate flooding.
Liquid droplet rapid detachment and facile removal\textsuperscript{1,2,3} from a surface has broad applications in various fields such as anti-frosting/icing\textsuperscript{4}, anti-corrosion\textsuperscript{5}, self-cleaning\textsuperscript{6}, evaporation desalination\textsuperscript{7} and thermal management\textsuperscript{8,9}. During the past two decades, many approaches to purging sessile droplets have been put forward by virtue of functional substrates with complex macro/micro/nanostructures\textsuperscript{10,11,12,13} or resorting to costly external stimuli such as electrical\textsuperscript{14}, photothermal\textsuperscript{15} or magnetic fields\textsuperscript{16}. As such, Leidenfrost effect\textsuperscript{17,18} can lead to droplet hovering over a heated substrate but requires the surface temperature maintained at a high level of 200 °C - 300 °C for water droplet. Nevertheless, our understanding of the interfacial phenomena including droplet wetting and phase changes at the solid-liquid interface remains elusive, impeding simple designs of engineered surfaces for droplet manipulations\textsuperscript{3,19,20,21}. In this respect, nucleate pool boiling on micro/nanostructured surfaces has been extensively explored in numerous studies\textsuperscript{22}, however, the vapor bubble growth within a sessile droplet and its influence on droplet actuations has been seldom studied. In this work, we introduce a simple but effective method to manipulate droplet jumping behaviors by tuning surface topographical features on micro-pillared substrates at moderate superheat. For droplets staying in the Wenzel state\textsuperscript{23}, the micropillars penetrate the droplet base and hence function as fin array for heat transfer enhancement. By simply increasing the micropillar height, one can adjust the vapor bubble growth at the droplet base from the heat-transfer-controlled growth mode\textsuperscript{24} to the inertia-controlled growth mode\textsuperscript{24}, which can be applied to significantly promote vapor bubble expanding velocity and hence droplet rapid jumping.

We experimentally investigate the out-of-plane jumping behaviors of a sessile water droplet with diameter $D_d \approx 2 \text{ mm}$ on hot microstructured silicon-based substrates via high-speed cameras (Fig. 1). A water droplet is initially deposited on the substrate staying in the Wenzel state and then the sessile droplet is carefully translated to a preheated hot plate, which is maintained at 130 °C, for the jumping observation (see experimental setup in Supplementary Fig. 1). The substrates are engineered with an array of micropillars coated with a thin layer of fluoropolymer (Figs. 1a and 1d insets and Supplementary Fig. 2). The substrate in Fig. 1a consists of a micropillar matrix with uniform micropillar diameter ($D = 20 \mu\text{m}$), periodicity ($L = 120 \mu\text{m}$) and height ($H = 20 \mu\text{m}$), hereafter named as $[D, L, H] = [20,120,20] \mu\text{m}$. It is observed that the droplet vibrates periodically while boiling on the hot substrate with obvious prolate-to-oblate ellipsoid transformation as shown in Fig. 1a (Supplementary Movie S1). It takes about 750 ms for the vapor bubble to completely spread over the droplet base area as shown in the top-view snapshots in Fig.
The burst of the vapor bubble leads to the generation of capillary waves on the cap surface of droplet and then it takes about one more second (1034 ms) for the droplet to jump off the substrate. The slow vapor bubble growth indicates a small overpressure inside the vapor bubble, leading to the relatively long dwelling time before the sessile droplet completely jumps off the substrate.

![Image](image_url)

**Figure 1 | Droplet vibration jumping and explosion jumping on hot micro-pillared surfaces.**

a. High-speed images of droplet vibration jumping on substrate $[D, L, H] = [20, 120, 20] \mu m$ heated at 130 °C. Inset, scanning electron micrography (SEM) of micro-pillared substrate. Time-zero is set when droplet contact line depinning occurs and capillary waves emerge on the cap surface of the droplet. b. Slow vapor bubble growth at the droplet base on substrate $[D, L, H] = [20, 120, 20] \mu m$ heated at 130 °C. c. Diagram of a sessile droplet on a hot substrate decorated with 20-μm-tall micropillars. d. High-speed images of droplet explosion jumping on substrate $[D, L, H] = [20, 120, 80] \mu m$ heated at 130 °C. Inset, SEM of the micro-pillared surface. e. Rapid vapor bubble growth at the droplet base on substrate $[D, L, H] = [20, 120, 80] \mu m$ heated at 130 °C. f. Diagram of a boiling droplet on a hot substrate decorated with 80-μm-tall micropillars. For droplet in Wenzel state, the micropillars penetrate the droplet base functioning as fin array for heat transfer modulation. For more details, see Supplementary Movie S1.
Next, we consider promoting the droplet jumping behaviour, i.e., rapid detachment and facile removal from the substrate, by modulating the vapor bubble growth rate thereon. The underpinning mechanism is that increasing the substrate micropillar height can enhance the heat transfer between the droplet and substrate and thus incur a faster vapor growth. Specifically, the rise of the micropillar height from 20 μm to 80 μm causes substrate roughness $r = \frac{L^2 + \pi DH}{L^2}$ changing from 1.087 to 1.349, leading to a 24.1% increase of the solid-liquid contact area and hence ~35.9% enhancement of heat transfer rate (Supplemental Fig. 3). For droplet resting on the hot substrate $[D, L, H] = [20, 120, 80] μm$ at 130 °C with tall micropillars, it takes only 2 ms for the droplet to completely jump off the substrate as shown in Fig. 1d (Supplementary Movie S1), which is 500 times faster than the vibration jumping on the substrate of $[D, L, H] = [20, 120, 20] μm$. Essentially, the increase of the micropillar height (from 20 μm to 80 μm) incurs the explosive bubble growth at the droplet base, giving rise to the prompt jumping of the droplet in milliseconds, i.e., explosion jumping. Top-view of a typical explosive bubble growth process is shown in Fig. 1e. It takes only 0.4 ms for the vapor bubble to cover the droplet contact base (Supplementary Movie S1), which is about 1500 times faster than the bubble growth on the substrate $[D, L, H] = [20, 120, 20] μm$ as shown in Fig. 1b.

The vapor bubble burst at the droplet base leads to the generation of capillary waves on the droplet cap surface as shown in Fig. 2a. When the bubble growth is slow, the overpressure between the vapor bubble pressure $P_2$ and the water base pressure $P_1$ is balanced by the surface Laplace pressure difference $\Delta P_{bw} : P_2 = P_1 + \Delta P_{bw}$. Similarly, a Laplace pressure difference $\Delta P_{wa}$ balances the water base pressure $P_1$ and surrounding air pressure $P_3 : P_1 = P_3 + \Delta P_{wa}$. The pressure difference between $P_2$ and $P_3$ causes the depinning of the droplet base contact line. That is, water entrapped on the micropillars around the contact zone, i.e., liquid bridge, could be detached from the substrate micropillars. The release of the pinned liquid bridge at the droplet contact line generates capillary waves on the droplet cap surface. This depinning process causes the shrink of droplet contact area and stretches the droplet into a prolate ellipsoid. Simultaneously, the momentum transfer during the capillary wave generation triggers the occurrence of droplet vibration. In the droplet vibration jumping process, the droplet mass loss during vibration plays a negligible role (Supplementary Fig. 4) and the droplet vibrates like a bumping spring with a relatively constant period of 24 ms (Fig. 1a), i.e., $T_v \sim \sqrt{\frac{m}{\sigma}}$, where $m$ is the droplet mass and $\sigma$ is
the surface tension. The vibration behaviours on the substrate can be modelled as a mass-spring-damper system\textsuperscript{3, 26} with continuous momentum input from the boiling-induced contact line depinning (Figs. 2a and 2b, more details see Supplementary Fig. 5). As shown in Fig. 2c, when the inertia force of the vibrating droplet is sufficient to overcome the adhesion force from the substrate, the droplet jumps off the micro-pillared surface\textsuperscript{27}. Assuming the adhesion force on each individual micropillar to be the same, the overall adhesion force from the substrate is proportional to the total number of the micropillars underneath the droplet. Therefore, the total adhesion force can be scaled as $F_a \sim \sigma D_d^2$. The inertial force of the droplet stems from the jumping velocity $v_j$ and can be scaled as $F_i \sim \rho_l D_d^2 \frac{v_j}{D_d/v_j}$, where $\rho_l$ is the liquid density. There should be a balance between the inertia and the adhesion force when the droplet is about to jump off the substrate surface with a take-off velocity $v_{jt}$:

$$\sigma D_d^2 \sim \rho_l D_d^2 \frac{v_{jt}}{D_d/v_{jt}}$$

(1)

Therefore, the take-off velocity is scaled as $v_{jt} \sim \left(\frac{\sigma}{\rho_l}\right)^{1/2}$, which is independent of the droplet diameter but depends on the liquid properties. Droplets with different volumes (different diameters) exhibit a relatively constant take-off velocity as shown in Fig. 2d, which matches well with our scaling analysis.
a) Liquid bridge, Micropillar top, Capillary wave, Contact line pinning, Contact line depinning, Wave generation, Capillary waves

b) Mass-spring-damper system

c) Inertial force, Adhesion force

d) Take-off velocity (mm/s) vs. Volume (μL)

- 120 °C
- 130 °C
- 140 °C
- 150 °C
- 160 °C
- 170 °C

- 40 mm/s

e) Bubble expanding velocity (m/s) vs. Vapor bubble diameter (mm)

- Inertia-controlled mode velocity: 3.55 m/s
- Heat-transfer-controlled mode velocity: 1.5 mm/s

- Various parameters shown for different bubble diameters and liquid volumes.
Figure 2 | Droplet take-off velocity and vapor bubble expanding velocity. a, Diagram of contact line depinning at droplet base due to vapor bubble burst and capillary wave generation. The snapshot shows the capillary waves on the cap surface of a vibrating droplet. b, Diagram of the droplet mass-spring-damper system. The vibrating droplet is modeled as two mass points connected with a spring and a damper. c, Inertia-adhesion force balance of the vibrating droplet. When the inertia force is sufficient to overcome the adhesion from the substrate, the vibrating droplet is about to jump off the substrate surface. d, Take-off velocities of vibrating droplets with different volumes of 2-16 µL on substrate $[D, L, H] = [20, 120, 20] \mu m$ heated at 130 °C. The take-off velocity is defined as the instantaneous velocity of the droplet mass center when the droplet is about to take off the substrate. e, The vapor bubble expanding velocities for water droplets dwelling on a variety of micro-pillared substrates with 20 µm, 60 µm and 80 µm tall micropillar arrays, respectively. The substrates were placed on a hot plate with surface temperature maintained at 130 °C. The vapor bubble expanding velocity in the inertia-controlled growth mode is theoretically predicted to be 3.55 m/s and the theoretical prediction of vapor bubble expanding velocity in the heat-transfer-controlled mode is 1.5 mm/s. When the bubble gets larger, i.e., bubble diameter $D_v > 0.7$ mm, the bubble cannot be approximated to be hemispherical and surface tension starts playing a more influential role, leading to the deviation of bubble expanding velocity from the theoretical prediction.

In essence, there exist two limiting vapor bubble growth modes: one is the inertia-controlled growth mode whose bubble growth rate is only limited by how fast it can push away the surrounding liquid and the other one is the heat-transfer-controlled growth mode whose relatively small bubble growth rate is mainly limited by the heat transport through the bubble interface. We attribute the observed relatively slow bubble growth on $[D, L, H] = [20, 120, 20] \mu m$ (Fig. 1b) to the heat-transfer-controlled mode and the explosive bubble growth on $[D, L, H] = [20, 120, 80] \mu m$ (Fig. 1e) to the inertia-controlled mode. The evolutions of inertia-controlled bubble expanding velocities on high-micropillared substrates and the evolution of a typical heat-transfer-controlled bubble expanding velocity on a short-micropillared substrate with the lateral diameter of bubbles are presented in Fig. 2e, respectively (Supplementary Movie S2). For a vapor bubble with a small diameter ($D_v < 0.7$ mm), the inertia-controlled bubble growth exhibits a relatively constant expanding velocity of ~4 m/s whereas the heat-transfer-controlled bubble expanding velocity is orders of magnitude smaller, i.e., only ~1.5 mm/s.

The temporal evolution of the radius $R_v$ of the inertia-controlled vapor bubble can be expressed as:

$$R_v(t) = \left\{\frac{2}{3} \left(\frac{T_{\text{sup}} - T_{\text{sat}}(P_\text{a})}{T_{\text{sat}}(P_\text{a})}\right) \frac{h_{\nu_\text{v}} \rho_v}{\rho_l}\right\}^{1/2} t$$

(2)
where $T_{\text{sup}}$ is the temperature of the superheated water; $T_{\text{sat}} = 373$ K is the saturation temperature of water under the ambient pressure $P_a = 101$ kPa; $h_{lv}$ is water specific evaporation enthalpy; and $\rho_v$ is the water vapor density. Accordingly, the inertial-controlled bubble interface velocity $dR_v/dt$ is independent of the bubble radius and time as observed in our experiments. The temperature measurement by an IR camera indicates that the maximum superheat of water is $\sim 5$ °C at the droplet contact line before the droplet jumps off the substrate (Supplementary Fig. 6). As a result, it is reasonable to assume that the temperature at the droplet base is between $103$ °C to $105$ °C during the vapor bubble growth period. The expanding velocities of the vapor bubble interface at temperatures of $103$ °C and $105$ °C are $2.16$ m/s and $3.55$ m/s, respectively, which agree well with our experimental observations as shown in Fig. 2e. The high expanding velocity of the inertia-controlled growth bubble stems from the rapid pressure increase during the vapor explosion. On the other hand, the temporal evolution of the bubble radius $R_v$ during the heat-transfer-controlled growth can be calculated as$^{24}$:

$$R_v(t) = 2 \sqrt{\frac{3k_l \rho_l c_{pl}}{\pi} \frac{(T_{\text{sup}} - T_{\text{sat}}(P_a))}{\rho_v h_{lv}}} \cdot \sqrt{t}$$

where $k_l$ is the liquid water conductivity and $c_{pl}$ is the liquid water specific heat. The typical expanding velocity of a bubble in the heat-transfer-controlled growth mode with a $105$ °C superheat and at time $t = 1$ s is in the order of $1$ mm/s. As evidenced in Fig. 2e, the experimental results of the bubble interface expanding velocities in both the inertia-controlled mode and the heat-transfer-controlled mode match well with the theoretical predictions.
Figure 3 | Water droplet jumping height variation on different substrates at 130 °C.  

a, Jumping height variation on substrate \([D, L, H] = [40, 120, 40] \mu m\).  
b, Jumping height variation on substrate \([D, L, H] = [20, 120, 20] \mu m\).  
c, Jumping height variation on substrate \([D, L, H] = [20, 160, 20] \mu m\).  
d, Jumping height variation on substrate \([D, L, H] = [20, 120, 60] \mu m\).  
e, Jumping height variation on substrate \([D, L, H] = [20, 120, 80] \mu m\).  
f, Diagram of capillary pressure resistance at the micropillar tips.  
g, Side-view snapshots of droplet wetting state transition in a.  
h, Side-view snapshots of droplet vibration in b.  
i, Side-view snapshots of droplet trampolining in c.  
j, Side-view snapshots of droplet vibration and capillary jumping in d.  
k, Side-view snapshots of droplet explosion jumping in e.

The variations of droplet height \(h\), which is defined as the distance from the substrate surface to the droplet apex, and the droplet jumping snapshots on a variety of substrates are shown in Fig. 3. A typical Wenzel-to-Cassie transition\(^{28}\) on substrate \([D, L, H] = [40, 120, 40] \mu m\) happens after the sessile droplet is translated on the hot plate as shown in Figs. 3a and 3g (Supplementary Movie S3). The relatively large micropillar diameter \((D = 40 \mu m)\) and short micropillar periodicity \((L = 120 \mu m)\) generate a high capillary pressure resistance\(^{29}\) \(P_{Ca} = \frac{4 \pi D \sigma \cos \theta}{4L^2 - \pi D^2} = 286 \text{ Pa}\) at the micropillar tips (Fig. 3f), where \(\theta\) is the intrinsic contact angle of water droplet on the fluoropolymer coating, inhibiting the replenishment of the dried cavities between the micropillars after evaporation and leading to the smooth Wenzel-to-Cassie transition \((P_{Ca} \gg P_h\), where \(P_h = \rho_l g h = 18 \text{ Pa}\) is the hydrostatic pressure at the droplet base).
Obvious vibrations of the boiling droplet appear on the substrate of \([D, L, H] = [20, 120, 20]\)µm with a smaller capillary pressure resistance \(P_{Ca} = 133\) Pa as shown in Figs. 3b phase 4 and 3h. The relatively lower capillary pressure resistance \(P_{Ca}\) makes it easier for the bulk liquid to replenish the droplet base cavities. Moreover, when a wetted cavity exists at the droplet base, the capillary pressure resistance of the neighbouring empty cavity would be reduced by half as illustrated in Fig. 3f. The vibration motion of the droplet generates an additional wetting pressure \(P_W = 0.002C\rho_l v_{\text{fall}} + \rho_l gh\), where \(v_{\text{fall}}\) is vibration velocity and \(C\) is the speed of sound in water\(^9\). On the substrate of \([D, L, H] = [20, 120, 20]\)µm, \(v_{\text{fall}} \cong 20\) mm/s and \(P_W \cong 75\) Pa, which can overcome the reduced capillary pressure resistance, i.e., \(P_W > \frac{1}{2}P_{Ca}\), so that the droplet is apt to dwell in the Wenzel state. Capillary waves are triggered by the depinning of droplet contact line\(^{30}\) (Fig. 2a) when the expanding vapor bubble approaches the droplet contact line. In general, the generation of capillary waves is accompanied by the shrink of droplet contact radius, leading to the gradual increase of the droplet height as shown in phase 3 of Fig. 3b. The droplet in this phase is unstable with a prolonged height\(^{31}\) (prolate ellipsoid) and starts to vibrate periodically with a relatively constant period and an increasing vibration amplitude as shown in phase 4 of Fig. 3b as well as in Fig. 3c \((D, L, H) = [20, 160, 20]\)µm. The droplet continuously gathers energy from the successive depinning at the droplet base to achieve the jump-off eventually. Once the droplet body jumps off the substrate, there are no refilled wet cavities in the substrate and the complete capillary pressure is high enough to withstand the subsequent gentle falling of the same droplet \((P_{Ca} > P_W)\). After landing on the substrate again, the droplet would stay in the Cassie state and vibrate with decaying amplitude due to viscous dissipation as shown in phase 5 of Fig. 3b and Fig. 3h. On substrate \([D, L, H] = [20, 160, 20]\)µm, however, the even smaller capillary pressure resistance of \(P_{Ca} = 74\) Pa is insufficient to endure the gentle impact of the falling droplet. The micropillars would puncture into the landing droplet again and the droplet recovers to the Wenzel state for subsequent vibration jumping. In this way, the droplet would trampoline\(^{32}\) on the hot substrate due to the depinning-induced momentum exchange at the droplet base as shown in Fig. 3c phase 6 and Fig. 3i (Supplementary Movie S4).

Periodic vibration disappears for droplet boiling on the substrate of \([D, L, H] = [20, 120, 60]\)µm with a relatively large micropillar height \((H = 60\) µm) and there appears large capillary waves on the cap surface of the droplet as shown in Figs. 3d and 3k (Supplementary
Movie S3). Since the capillary waves are generated by the depinning of droplet contact line, i.e., the depinning of the liquid bridge as shown in Fig. 2a, the initial amplitude of the capillary waves should be proportional to the length of the liquid bridge, which is mainly determined by the height of the micropillars. Thus, the capillary wave amplitude $A$ should be proportional to the micropillar height $H$, i.e., $A \sim H$. The total energy of capillary wave on the droplet surface can be estimated as $E = 2\pi \sigma k^2 A^2 R_d^2$ where $k$ is the wavenumber and $R_d$ is the radius of the droplet (Supplementary Fig. 7). The taller the micropillar height, the larger the capillary wave amplitude and the more energy contained in the capillary waves. Conceivably, the more the energy contained in the capillary waves, the less the energy stored in the droplet bulk. Therefore, the prolate-to-oblate ellipsoid deformation becomes less obvious, and the droplet can eventually achieve jumping due to the released capillary wave energy, i.e., capillary jumping.

On the substrate of $[D, L, H] = [20, 120, 80] \mu m$ with even taller micropillars ($H = 80 \mu m$) and hence even larger heat transfer area between the droplet and the substrate, the explosive bubble growth adjacent to the droplet base intensely pushes the surrounding fluid in the droplet and eventually gives rise to the fast droplet jump-off as evidenced in Figs. 3e and 3k. A sessile droplet of $D_d \approx 2 \text{ mm}$ with a contact angle of $150^\circ$ can achieve $\sim 180 \text{ mm/s}$ jumping velocity triggered by the explosive bubble, which is much faster than the maximum take-off velocity $v_{jt} \sim 40 \text{ mm/s}$ (Fig. 2d) of vibrating droplets. The large jumping velocity indicates sufficiently strong inertial force to overcome the adhesion on the substrate so that prompt droplet detachment from the substrate can be achieved within only several milliseconds.
The diverse out-of-plane jumping behaviors, i.e., Cassie state maintaining, Wenzel to Cassie transition, vibration jumping, capillary jumping, explosion jumping, Cassie state hovering and Wenzel state trampolining, of a boiling water droplet have been identified. If the jumping-off droplet falls in the Wenzel state again, the droplet would trampoline on the hot substrate, i.e., Wenzel state trampolining. In case of Cassie state, the falling droplet will hover over the hot substrate, i.e., Cassie state hovering. This phase map is valid for water droplet boiling on substrates heated at 120 °C - 170 °C.

Our observations indicate that besides droplet properties the jumping modes of the boiling droplet are highly dependent on the substrate topography. The phase map of droplet jumping on substrates with different micropillar diameter $D$, micropillar height $H$ and micropillar periodicity $L$ is shown in Fig. 4. The occurrence of droplet jumping is principally determined by the substrate...
micropillar periodicity $L$. No out-of-plane jumping is observed for droplet boiling on substrate with a short micropillar periodicity ($L < 100 \, \mu m$) due to the large $P_{ca}$ thereon and the droplet prefers to stay in the Cassie state, i.e., Cassie state maintaining\textsuperscript{34} or the Wenzel to Cassie transition\textsuperscript{28}. The micropillar diameter $D$ would only slightly affects the threshold value $L$ for the occurrence of droplet jumping due to its secondary influence on $P_{ca}$. Obvious and versatile droplet jumping behaviours take place on substrates with a large periodicity ($L > 120 \, \mu m$) due to the small $P_{ca}$ and the easily replenished cavities underneath the droplet. In particular, the droplet jumping modes are mainly determined by the substrate micropillar height $H$, which dominantly affects the vapor bubble growth modes and the generation of capillary waves. Droplet jumping mode gradually changes from the vibration jumping or the capillary jumping to the explosion jumping with the continuous increase of the substrate micropillar height. After jumping off the substrate, the falling droplet would impact on the surface again either hovering in the Cassie state when the substrate has a large $P_{ca}$ (large $D$ and small $L$) or trampolining in the Wenzel state when the substrate has a small $P_{ca}$ (small $D$ and large $L$).

In this study, the versatile out-of-plane jumping behaviors, i.e., Cassie state maintaining, Wenzel to Cassie transition, vibration jumping, capillary jumping, explosion jumping, Cassie state hovering and Wenzel state trampolining, of a boiling water droplet have been observed and investigated on microstructured substrates at a temperature much lower than the typical Leidenfrost point. Different modes of vapor bubble growth and hence droplet detachment can be achieved by simply modulating the feature sizes, i.e., micropillar height, of the engineered surfaces. In essence, the enlarged contact area between the droplet and the substrate with relatively taller micropillars leads to enhanced heat transfer, providing the necessitated energy for the rapid commence of explosive vapor bubble growth. The phase map presents a comprehensive view of distinct vapor bubble growth modes and diverse droplet jumping behaviors contingent on the topology of the surface microstructures and paves the way for designing engineered surfaces preventing the potential damage of vapor explosion\textsuperscript{35, 36} or alleviating condensate flooding\textsuperscript{37}.

Reference

1. Richard D, Clanet C, Quéré D. Contact time of a bouncing drop. *Nature* 2002, **417**(6891): 811-811.

2. Bird JC, Dhiman R, Kwon H-M, Varanasi KK. Reducing the contact time of a bouncing drop. *Nature* 2013, **503**(7476): 385-388.
3. Schutzius TM, Jung S, Maitra T, Graeber G, Köhme M, Poulikakos D. Spontaneous droplet trampolining on rigid superhydrophobic surfaces. *Nature* 2015, 527(7576): 82-85.

4. Stone HA. Ice-Phobic Surfaces That Are Wet. *ACS Nano* 2012, 6(8): 6536-6540.

5. Chen X, Yuan J, Huang J, Ren K, Liu Y, Lu S, *et al.* Large-scale fabrication of superhydrophobic polyurethane/nano-Al2O3 coatings by suspension flame spraying for anti-corrosion applications. *Appl Surf Sci* 2014, 311: 864-869.

6. Blossey R. Self-cleaning surfaces—virtual realities. *Nature materials* 2003, 2(5): 301-306.

7. El-Dessouky H, Alatiqi I, Bingulac S, Ettouney H. Steady-state analysis of the multiple effect evaporation desalination process. *Chemical Engineering & Technology: Industrial Chemistry - Plant Equipment -Process Engineering -Biotechnology* 1998, 21(5): 437-451.

8. Cheng J-T, Chen C-L. Active thermal management of on-chip hot spots using EWOD-driven droplet microfluidics. *Experiments in fluids* 2010, 49(6): 1349-1357.

9. Kim J. Spray cooling heat transfer: The state of the art. *International Journal of Heat and Fluid Flow* 2007, 28(4): 753-767.

10. Liu Y, Moevius L, Xu X, Qian T, Yeomans JM, Wang Z. Pancake bouncing on superhydrophobic surfaces. *Nature physics* 2014, 10(7): 515-519.

11. Huang C-T, Lo C-W, Lu M-C. Reducing Contact Time of Droplets Impacting Superheated Hydrophobic Surfaces. *Small* 2022, 18(13): 2106704.

12. Song M, Liu Z, Ma Y, Dong Z, Wang Y, Jiang L. Reducing the contact time using macro anisotropic superhydrophobic surfaces — effect of parallel wire spacing on the drop impact. *NPG Asia Materials* 2017, 9(8): e415-e415.

13. Abolghasemibizaki M, Mohammadi R. Droplet impact on superhydrophobic surfaces fully decorated with cylindrical macrotextures. *Journal of Colloid and Interface Science* 2018, 509: 422-431.

14. Lee SJ, Hong J, Kang KH, Kang IS, Lee SJ. Electrowetting-induced droplet detachment from hydrophobic surfaces. *Langmuir* 2014, 30(7): 1805-1811.

15. Chen XX, Wu TL, Huang DM, Zhou JJ, Zhou FX, Tu M, *et al.* Optothermally Programmable Liquids with Spatiotemporal Precision and Functional Complexity. *Adv Mater* 2022, 34(38).

16. Qian C, Zhou F, Wang T, Li Q, Hu D, Chen X, *et al.* Pancake Jumping of Sessile Droplets. *Advanced Science* 2022, 9(7): 2103834.

17. Bernardin J, Mudawar I. The Leidenfrost point: experimental study and assessment of existing models. 1999.

18. Kwon H-m, Bird JC, Varanasi KK. Increasing Leidenfrost point using micro-nano hierarchical surface structures. *Applied Physics Letters* 2013, 103(20): 201601.

19. Eberle P, Tiwari MK, Maitra T, Poulikakos D. Rational nanostructuring of surfaces for extraordinary icephobicity. *Nanoscale* 2014, 6(9): 4874-4881.
20. Jung S, Dorrestijn M, Raps D, Das A, Megaridis CM, Poulikakos D. Are superhydrophobic surfaces best for icephobicity? *Langmuir* 2011, **27**(6): 3059-3066.

21. Bouillant A, Mouterde T, Bourrianne P, Lagarde A, Clanet C, Quéré D. Leidenfrost wheels. *Nature Physics* 2018, **14**(12): 1188-1192.

22. Liang G, Mudawar I. Review of pool boiling enhancement by surface modification. *International Journal of Heat and Mass Transfer* 2019, **128**: 892-933.

23. Zhao L, Cheng JT. Analyzing the Molecular Kinetics of Water Spreading on Hydrophobic Surfaces via Molecular Dynamics Simulation. *Scientific Reports* 2017, **7**: 10880.

24. Carey VP. *Liquid-vapor phase-change phenomena: an introduction to the thermophysics of vaporization and condensation processes in heat transfer equipment*. CRC Press, 2020.

25. Okumura K, Chevy F, Richard D, Quéré D, Clanet C. Water spring: A model for bouncing drops. *Europhysics Letters (EPL)* 2003, **62**(2): 237-243.

26. Okumura K, Chevy F, Richard D, Quéré D, Clanet C. Water spring: A model for bouncing drops. *EPL (Europhysics Letters)* 2003, **62**(2): 237.

27. Boreyko JB, Chen C-H. Restoring superhydrophobicity of lotus leaves with vibration-induced dewetting. *Phys Rev Lett* 2009, **103**(17): 174502.

28. Liu G, Fu L, Rode AV, Craig VS. Water droplet motion control on superhydrophobic surfaces: exploiting the Wenzel-to-Cassie transition. *Langmuir* 2011, **27**(6): 2595-2600.

29. Kwon H-M, Paxson AT, Varanasi KK, Patankar NA. Rapid deceleration-driven wetting transition during pendant drop deposition on superhydrophobic surfaces. *Physical review letters* 2011, **106**(3): 036102.

30. Nguyen T-V, Tsukagoshi T, Takahashi H, Matsumoto K, Shimoyama I. Depinning-induced capillary wave during the sliding of a droplet on a textured surface. *Langmuir* 2016, **32**(37): 9523-9529.

31. Rimbert N, Escobar SC, Meignen R, Hadj-Achour M, Gradeck M. Spheroidal droplet deformation, oscillation and breakup in uniform outer flow. *Journal of Fluid Mechanics* 2020, **904**.

32. Graeber G, Regulagadda K, Hodel P, Küttel C, Landolf D, Schützus TM, et al. Leidenfrost droplet trampolining. *Nature communications* 2021, **12**(1): 1-7.

33. Tulin MP. On the transport of energy in water waves. *Journal of Engineering Mathematics* 2007, **58**(1): 339-350.

34. Huang W, He X, Liu C, Li X, Liu Y, Collier CP, et al. Droplet Evaporation on Hot Micro-Structured Superhydrophobic Surfaces: Analysis of Evaporation from Droplet Cap and Base Surfaces. *International Journal of Heat and Mass Transfer* 2022, **185**: 122314.

35. Berthoud G. Vapor explosions. *Annual Review of Fluid Mechanics* 2000, **32**(1): 573-611.

36. Lee H, Merte Jr H. The origin of the dynamic growth of vapor bubbles related to vapor explosions. 1998.

37. Cheng JT, Vandadi A, Chen CL. Condensation heat transfer on two-tier superhydrophobic surfaces. *Applied Physics Letters* 2012, **101**(13): 131909.
Methods

Substrate preparation
Polished P-type silicon wafers of 150 mm diameter and 550 ± 25 μm thickness were used as substrates in this work. Standard photolithography process was performed with a SUSS MicroTech Contact Aligner. Then the substrates were etched with Oxford PECVD to fabricate the well-defined micropillar arrays. The micro-pillared substrates were conformally coated with fluoropolymer (PFC 1601V, Cytonix Corporation) using a spin coater at 3000 rpm for 30 s and then baked at 100 °C for 1 hour. Substrate micropillar diameter, height and periodicity (pitch-to-pitch distance) are donated with $D$, $H$ and $L$, respectively. More detailed information about the substrates is given in Supplementary Fig. 2.

Data availability
The data that support the findings of this study are available from the corresponding author.

Acknowledgements This work was supported by NSF CBET under grant number 2133017 and NSF ECCS under grant number 1808931. Device fabrication, and a portion of the analysis and manuscript preparation were performed at the Center for Nanophase Materials Sciences, which is a US DOE Office of Science User Facility.

Author contributions W.H and J.C conceived the research. J.C. supervised the research. W.H. designed and carried out the experiments, W.H. and J.C. analyzed the data and wrote the original manuscript. W.H., X.H., P.C. and J.C. prepared the samples. All authors wrote and edited the manuscript.

Competing interests The authors declare no competing interests.