The Origins of Condensation-Driven Degradation of Hydrophobic Thin Films

Jingcheng Ma[1,2], Nenad Miljkovic[1,2]

[1]Department of Mechanical Science and Engineering, University of Illinois at Urbana-Champaign

[2]International Institute for Carbon Neutral Energy Research, Kyushu University, Japan

Motivation

- Water vapor condensation is routinely observed in nature and has a large influence on the performance of industrial systems.
- 10X heat transfer enhancement compared to state-of-the-art filmwise condensation shown on hydrophobic condenser surfaces.
- Polymer coatings are not durable during dropwise condensation due to water blister formation beneath the coating and delamination.
- Mechanism governing the blister formation is not well understood.

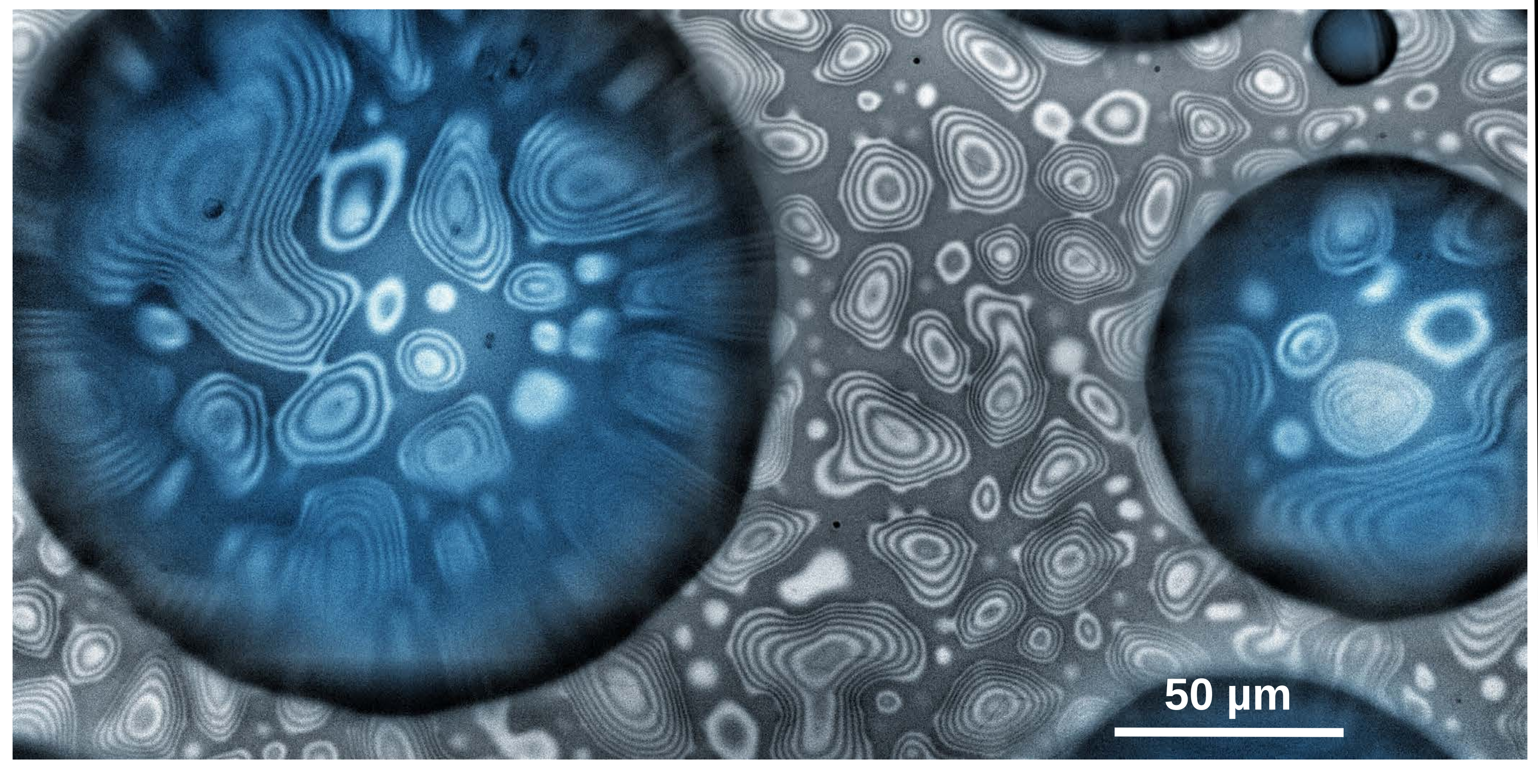

Figure 1. Water blisters on a 50-nm thick polystyrene film. The blisters are observable from the interferometric fringes. Water droplets on top of the coating are false colored blue.

Methods and Materials

- **Observation:** Optical microscopy, Atomic force microscopy
- **Condensation:** Peltier cold plate
- **Material:** Carbon-fluorine polymer (CFx) deposited by Plasma Enhanced Chemical Vapor Deposition
- **Important parameters:**
  1) Deposition rate: 117 ± 10 nm/min
  2) Chemical composition: C:F ~ 1
  3) Advancing contact angle: 116 ± 2º
  4) Young's modulus: 2.2 GPa
- **Substrates:** Polished silicon wafer (100), Thermally grown silica, Sputtered alumina

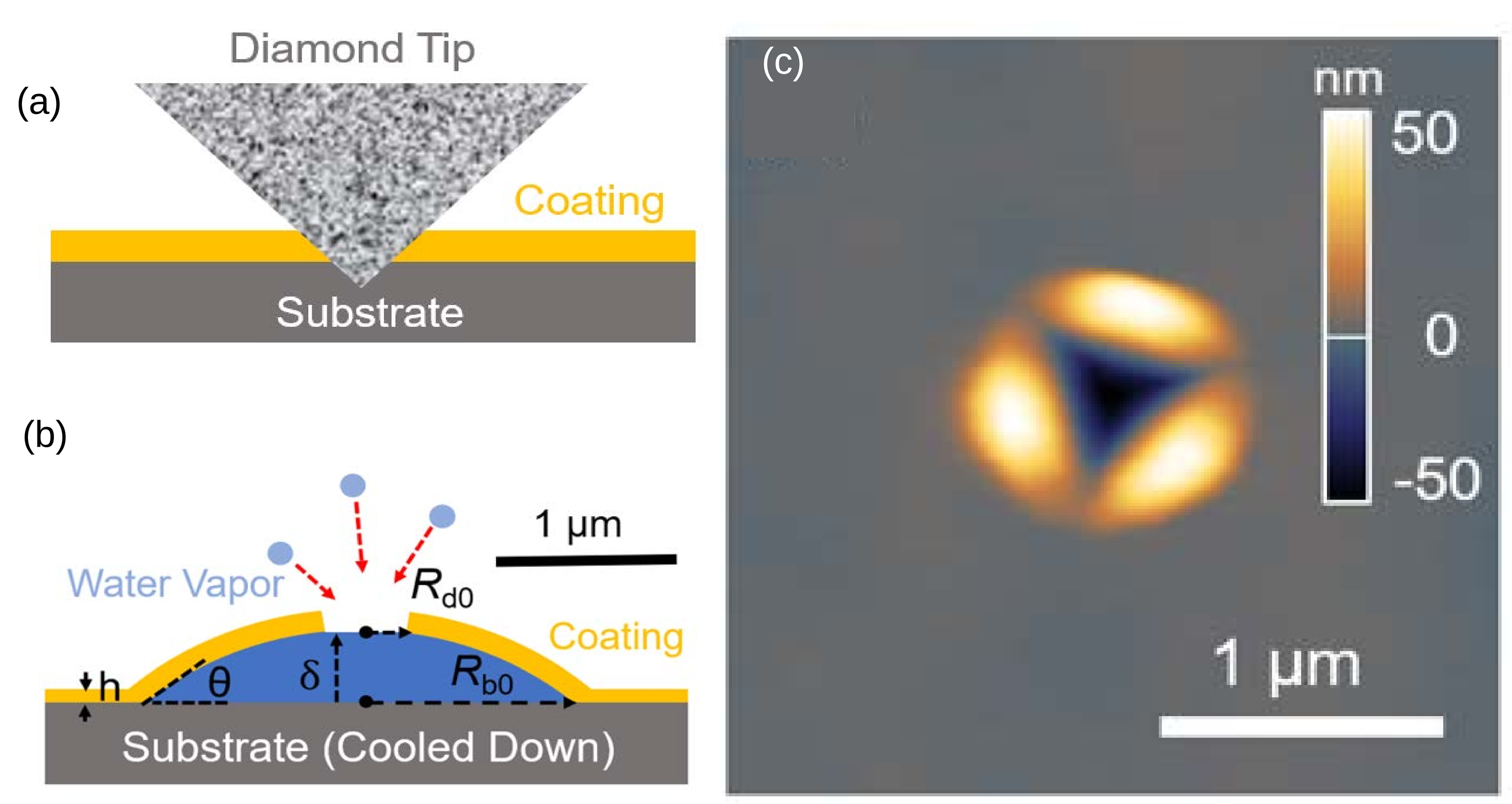

Figure 2. Schematic diagram of (a) indentation induced pinhole formation, and (b) pinhole induced blistering. (c) Height profile of the pinhole using AFM.

Blister Shape

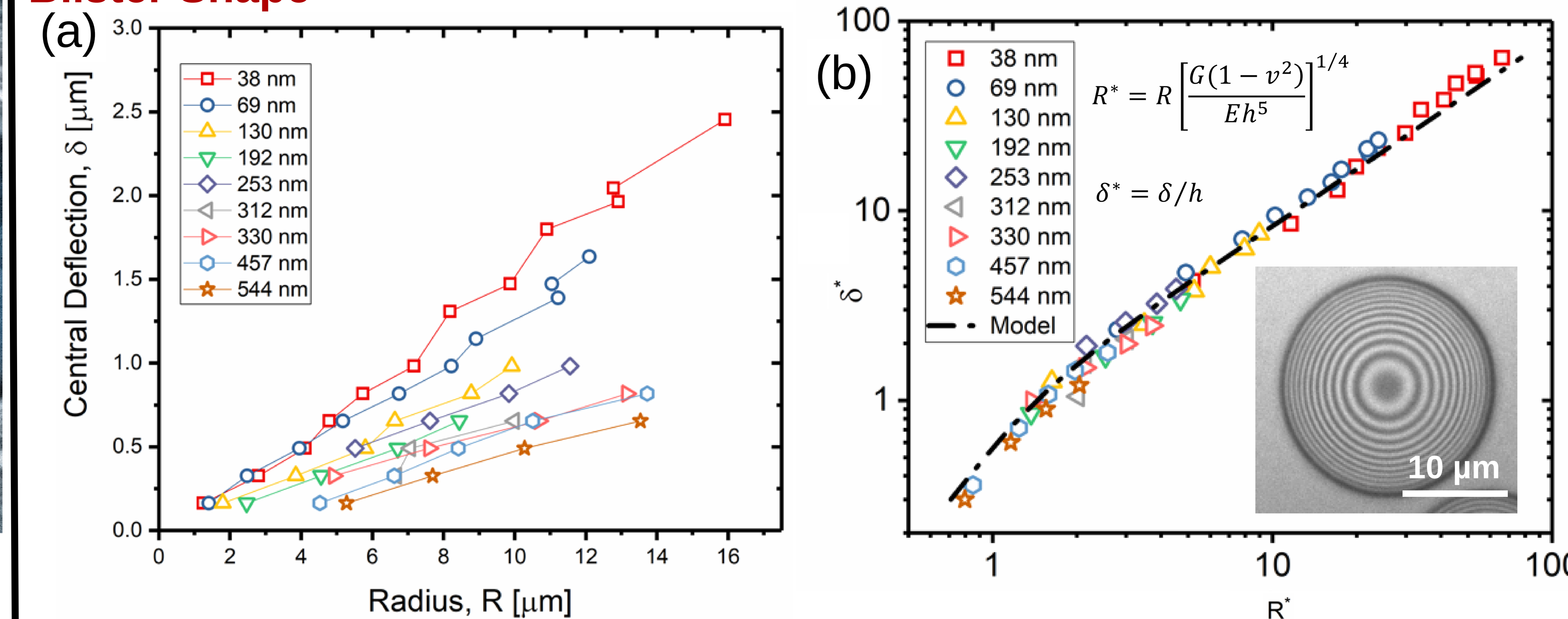

Figure 7. Radius and central deflection of blisters. (a) Raw data. (b) Normalized data. Dashed line: Plate and membrane theory. The shape of the blister is related to coating Young's modulus *E*, Poisson's ratio *ν*, thickness *h*, and interfacial adhesion *G*.

Blister Growth Rate

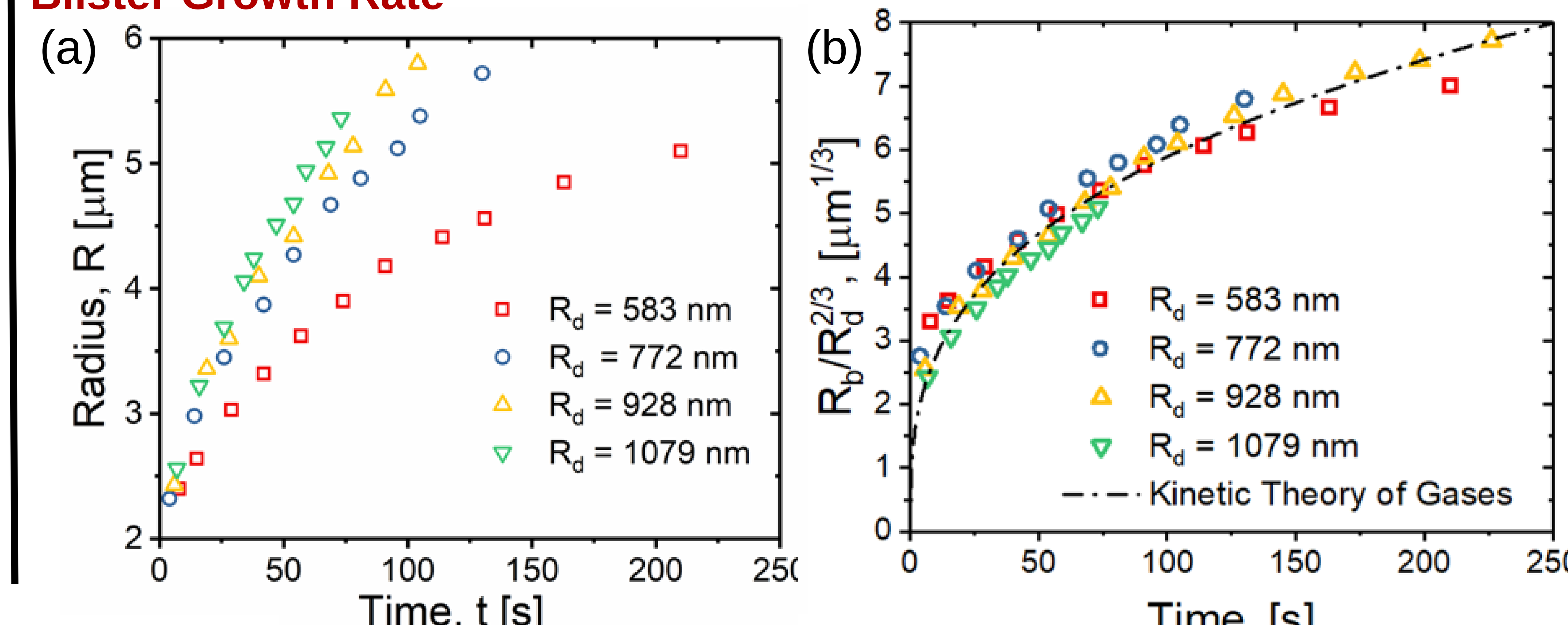

Figure 8. Blister growth rate as a function of pinhole radius. (a) Raw data.(b) Normalized data. Pinhole radius is the main factor governing blister growth. *E*, *h* and *G* play minor roles:

$$R \sim At^{1/3}$$

$$A \sim R_d^{2/3}(E\,h/G)^{1/12}$$

Initiation of Blisters

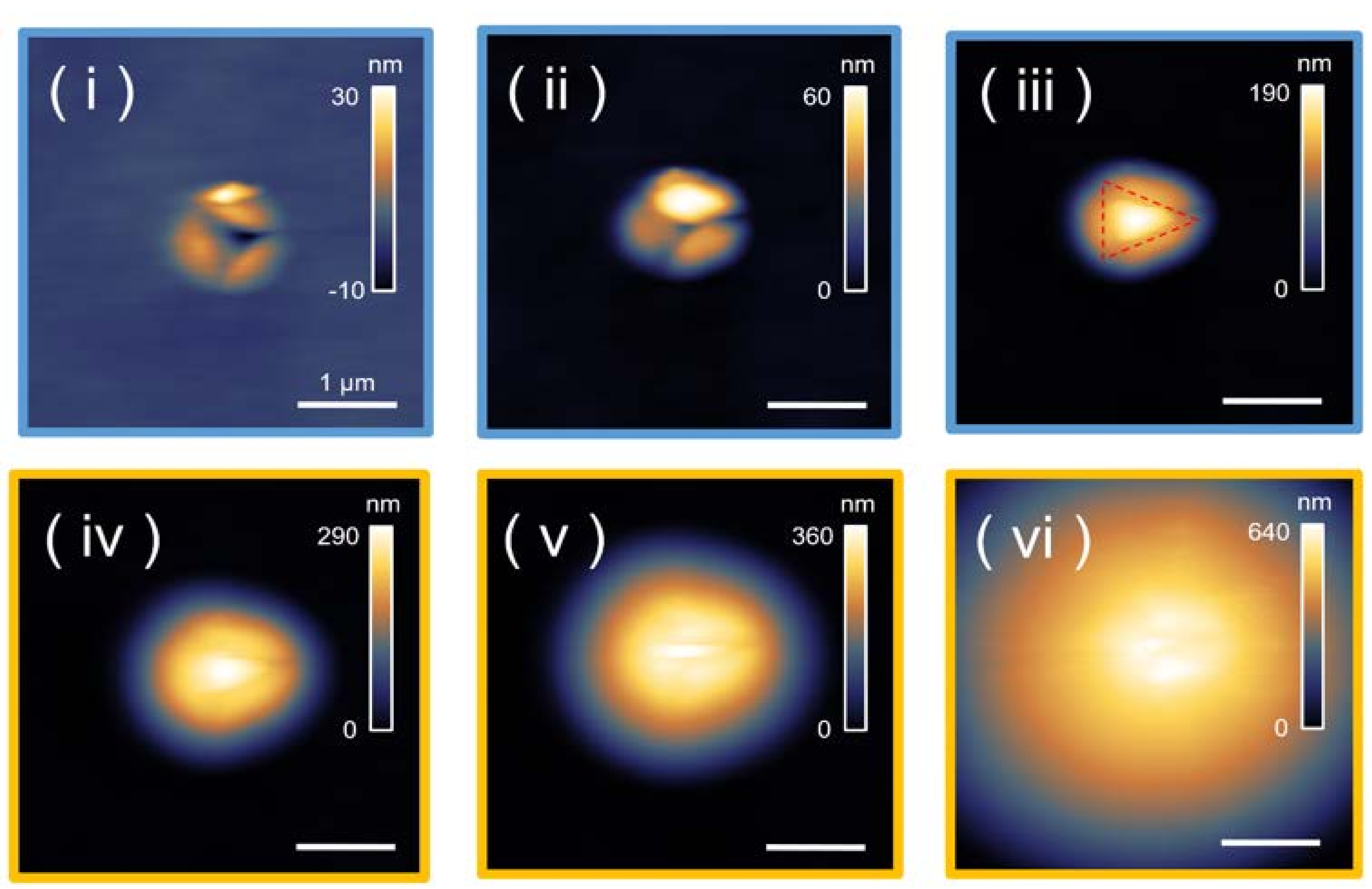

Figure 3. Two growth patterns of droplets beneath coatings observed by AFM. (i-iii) Growth with a fixed radius. (iv-vi) Growth with a fixed contact angle. The polymer used was a 33-nm thick CFx and the substrate was a polished silicon wafer (100).

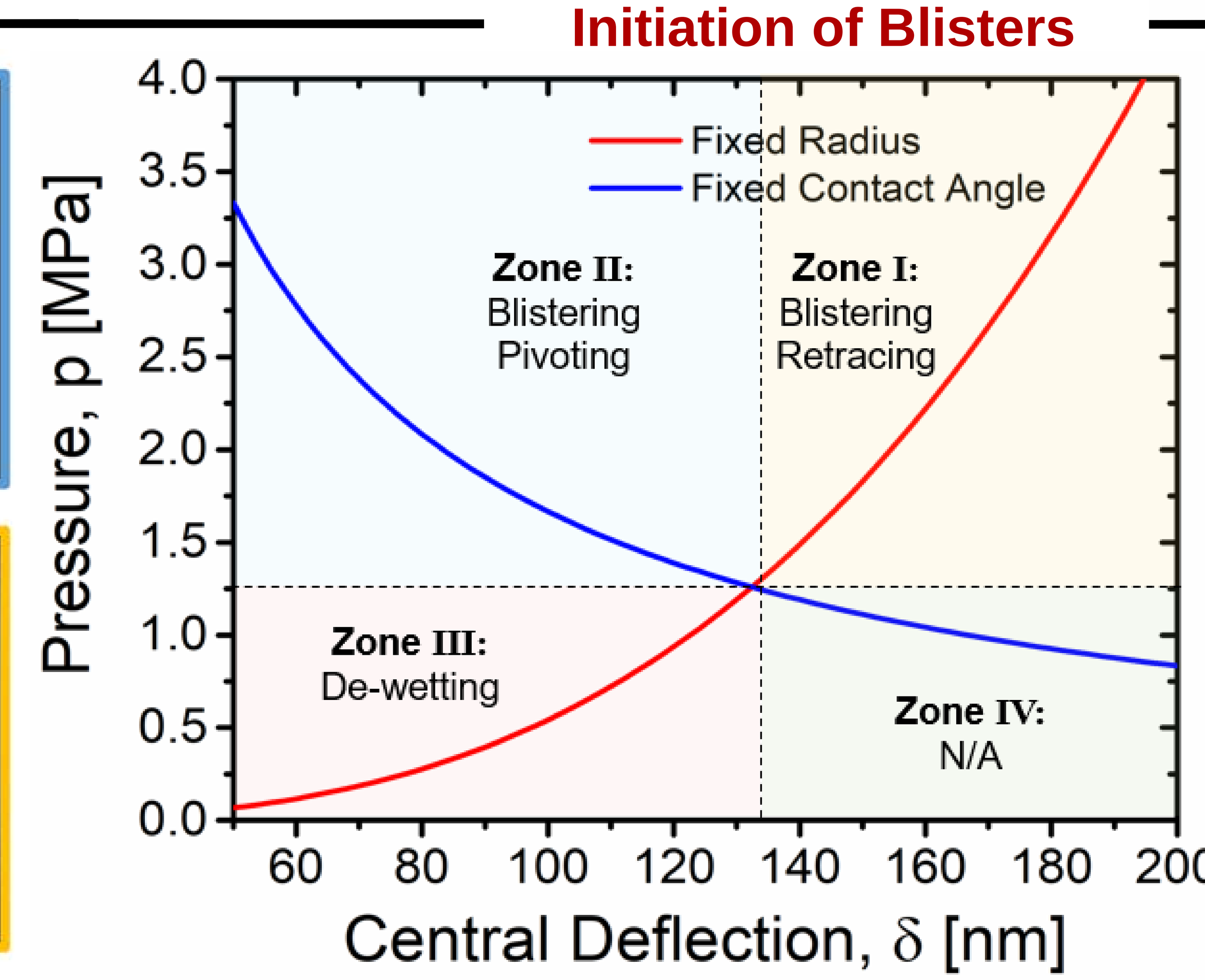

Figure 4. Theoretical elastic pressure applied on the coating during blister growth. A critical pressure barrier needs to be exceeded in order to delaminate the coating.

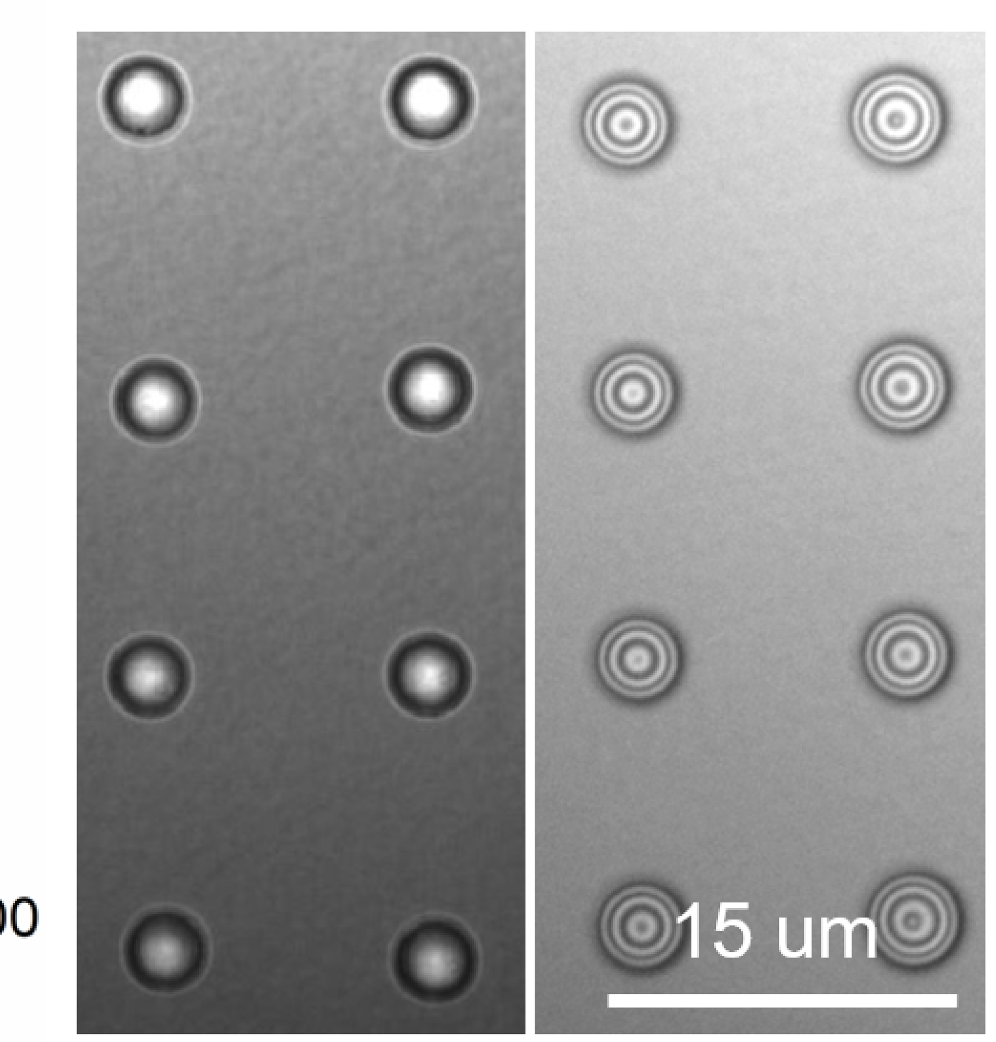

Figure 5. Top view optical microscopy images of blistering on a silica substrate (right) and de-wetting on an alumina substrate (left). $\Omega \equiv p_{L,\max}/p_{E,\max} > O(1)$

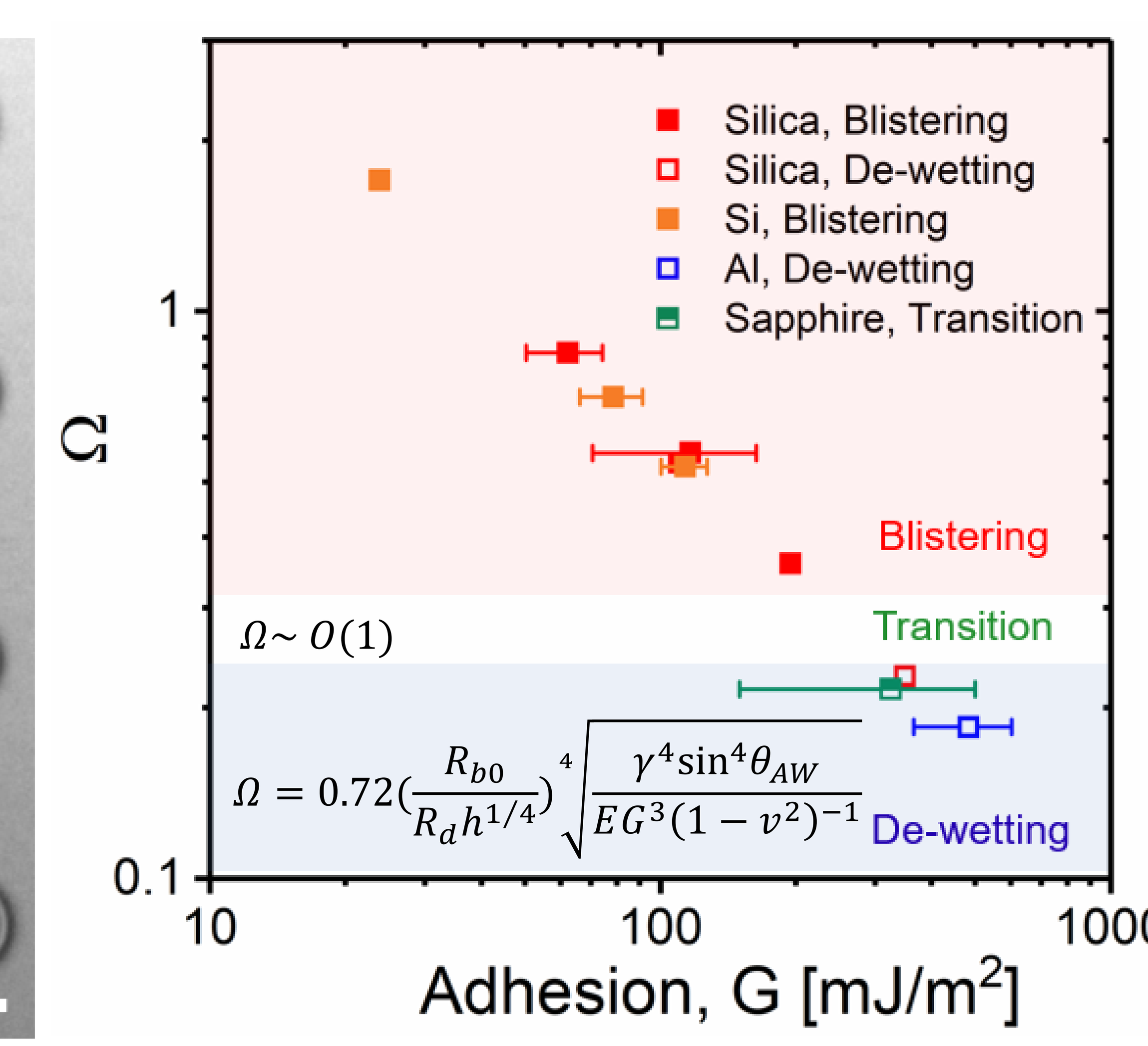

Figure 6. Blistering criteria map. With the same coating and pinhole geometry, substrate having high adhesion with the coating (sapphire, aluminum) showed de-wetting, while others showed blistering.