Supporting Information.
Passive Anti-Frosting Surfaces Using Microscopic Ice Patterns

S. Farzad Ahmadi,[1] Saurabh Nath,[1] Grady J. Iliff,[1] Bernadeta R. Srijanto,[2]

C. Patrick Collier,[2] Pengtao Yue,[3] and Jonathan B. Boreyko[1,*]

[1]Department of Biomedical Engineering and Mechanics, Virginia Tech,
495 Old Turner Street, 222 Norris Hall, Blacksburg, VA 24061, USA
[2] Center for Nanophase Materials Sciences, Oak Ridge National Laboratory,
Oak Ridge, Tennessee 37831, USA
[3] Department of Mathematics, Virginia Tech, Blacksburg, VA 2406, USA
[*]To whom correspondence should be addressed; E-mail: boreyko@vt.edu.

Contents

1 Setup and concepts

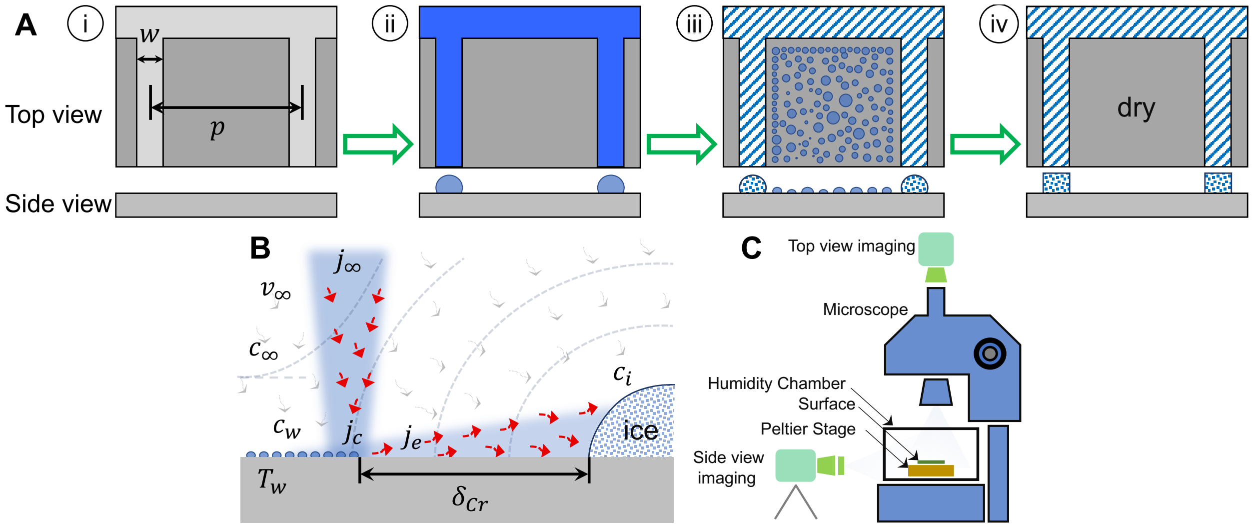

Figure S1: Schematics of the setup and concepts. (A) Bird's-eye-view (top cartoons) and side-view (bottom cartoons) of the chemically patterned surface used to obtain the proof-of-concept of the overlapping dry zones. (i) An interconnected array of thin hydrophilic stripes (light gray) with width of w is micropatterned against a hydrophobic backdrop (dark gray). (ii) Supercooled water deposited or condensed onto the surface will preferentially fill the hydrophilic stripes. (iii) At chilled temperatures, the interconnected water stripes will freeze before the supercooled condensation on the hydrophobic regions, both due to the lower nucleation barrier and the larger volume. (iv) The array of ice stripes will now serve as overlapping humidity sinks, which will evaporate any condensate already on the hydrophobic surface and subsequently keep it dry from dew or frost. (B) Schematic of the vapor flow around ice. The dry zone width (δ_{Cr}) can be found by balancing a droplet's in-plane evaporation flux, J_e, and out-of-plane condensation flux, J_c. (C) Experimental setup for characterizing frost growth.

2 Ice Bridges

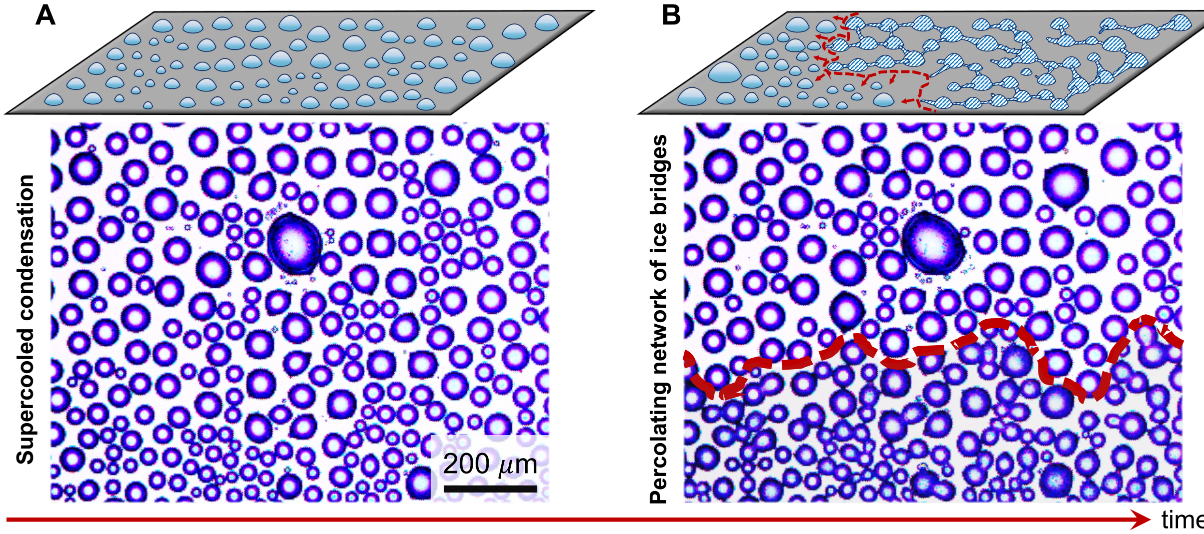

Figure S2: Frost growth via inter-droplet ice bridging. (A) Supercooled condensation formed on a hydrophobic substrate held at $T_w = -10°C$ in a supersaturated environment ($S = 2.7$). (B) As time goes by, one of the supercooled droplets will freeze (typically at defect or edge), which instigates a chain reaction of inter-droplet ice bridges that freeze the population of supercooled condensate. Image b is taken 34 s after the water droplet is frozen at the bottom part of the surface. These images illustrate why even non-wetting (i.e. hydrophobic or superhydrophobic) surfaces cannot prevent frost growth.

3 Surface Coverage

Let's define three modes of failure: i) Dry zone failure, where condensation/frost can nucleate in the areas between the ice stripes ($p > 4\delta_{Cr}$); ii) Branching failure, where the ice stripes are able to grow along the solid substrate to invade the dry zones; iii) Set-up failure, where frost initially formed between the grooves prior to the freezing of the ice stripes due to the hydrophilicity of the plasma-treated aluminum.

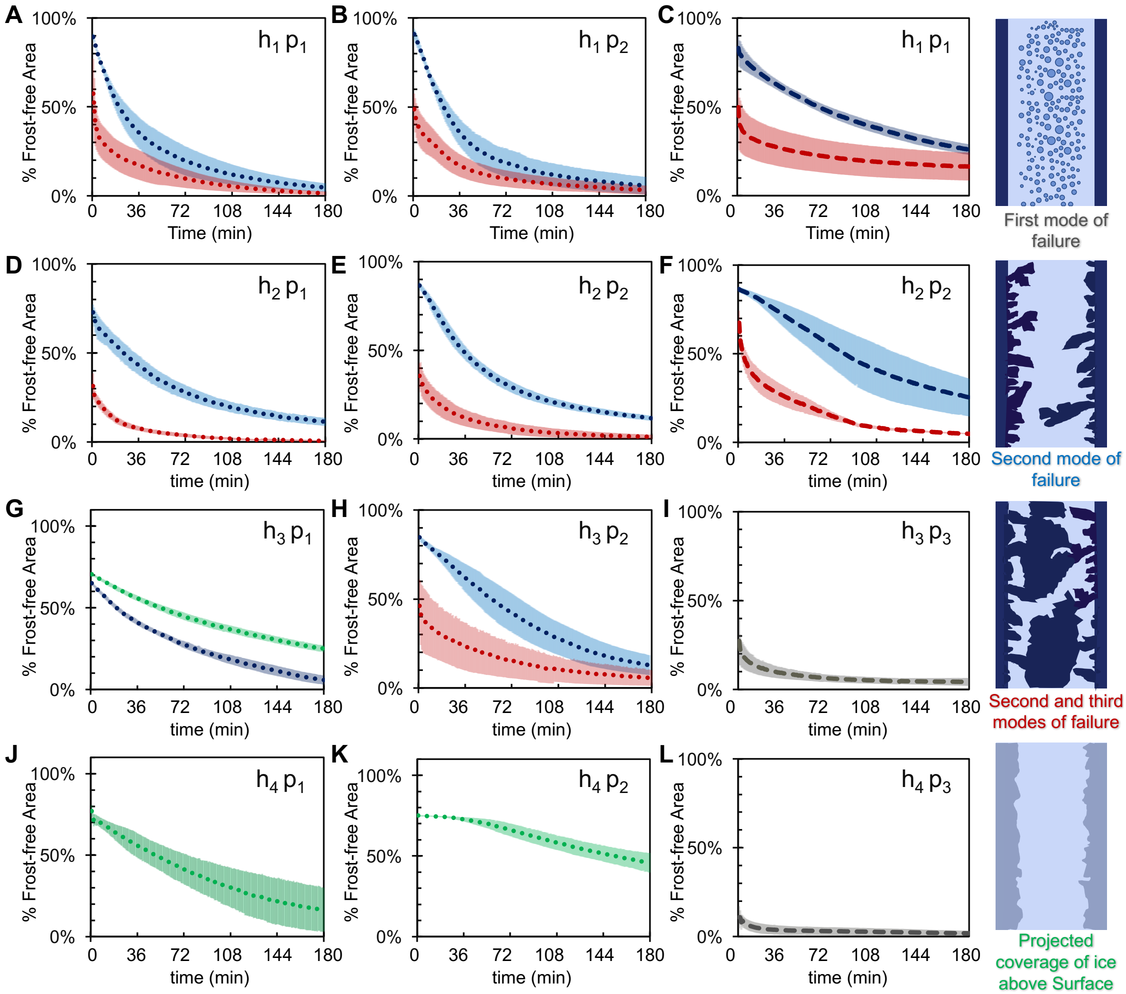

Figure S3: Mean experimental frost-free area vs. time for various physically patterned aluminum surfaces. The surface coverage of frost was defined here as the projected area of all frost visible from the top-down microscope, including the in-air coarsening of the elevated ice stripes above the floor (Fig. 5B). The three modes of failure are denoted by gray, blue, and red, respectively (see illustrations on right side of figure). For surfaces where the dry zones were maintained and the ice stripes were fully suspended in the air, the frost-free surface area is now signified by green data points. Dotted data points correspond to a supersaturation of $S = 1.5$ (A, B, D, E, G, H, J, and K), while dashed data points correspond to $S = 1.1$ (C, F, I, and L). The shaded region demonstrates one standard deviation between three trials.

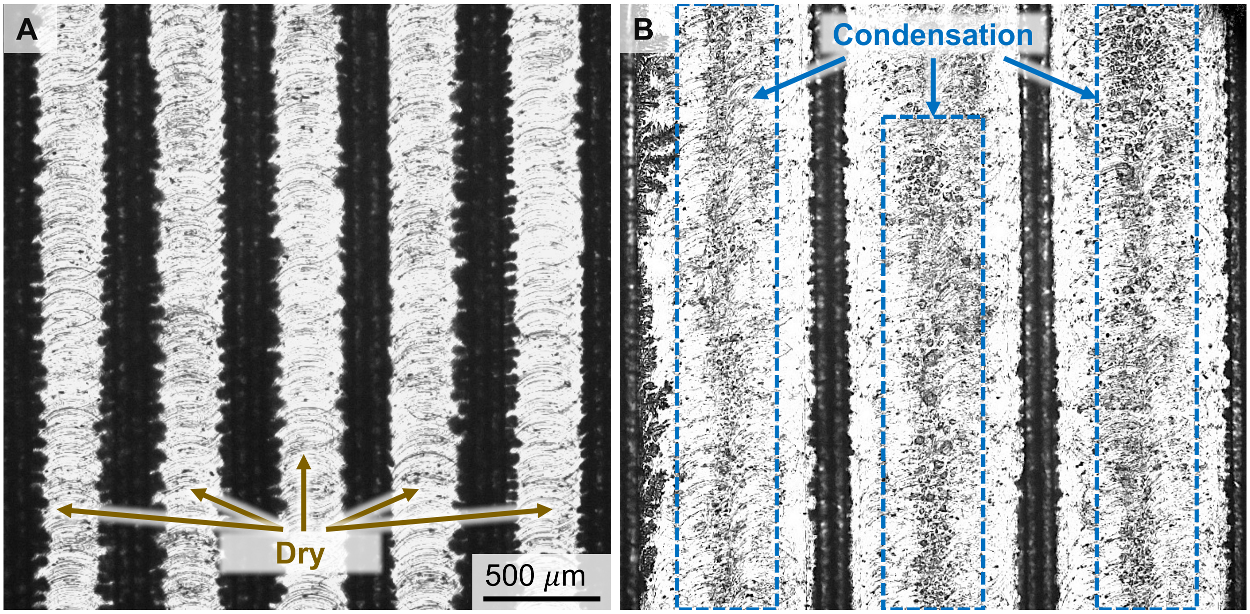

Figure S4: Experimental demonstration for success and failure of the overlapping dry zones. (A) For surface h_3p_1, the regions between ice stripes remain dry as indicated by the visible machine marks of the aluminum floor. (B) In contrast, for a surface where the ice stripes exhibit a larger pitch, h_3p_2, the formation of supercooled condensation is easily observed which subsequently frosts over. Conditions were $T_w = -10\,°C$ and $T_\infty = 15.1\,°C$ in both cases, with $RH = 92\%$ for a and $RH = 53\%$ for B.

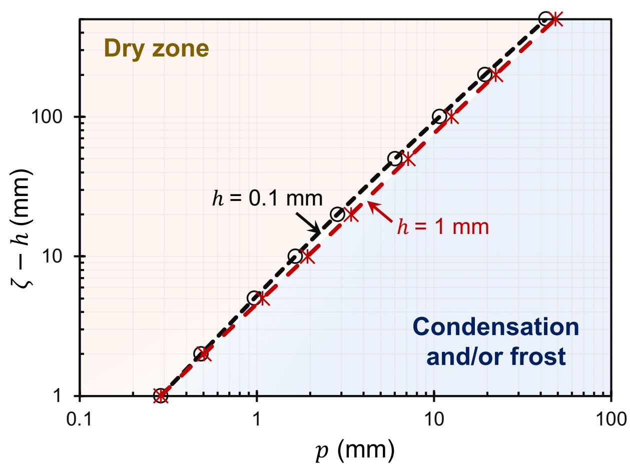

Figure S5: Computational phase map. This phase map shows that the domain size is linearly proportional to the dry zone, while the height (h) of the micro-fins elevating the ice stripes plays a secondary role.

4 Video Captions

Movie S1

Proof-of-concept experiment on the chemically micro-patterned substrate that shows the condensation between the ice stripes completely evaporating, despite the supersaturated conditions of $T_w = -8\,^{\circ}\mathrm{C}$ and $S = 1.2$. However, in-plane coarsening of the ice stripes occurs over time.

Movie S2

Frost formation on a smooth, untreated aluminum surface (on the left) and aluminum treated with a superhydrophobic nanostructure (on the right) under supersaturated conditions of $T_w = -10\,^{\circ}\mathrm{C}$ and $S = 1.5$. The bare aluminum surface is completely frosted over in under 1 hr. The superhydrophobic surface promotes jumping-droplet condensation which delays frost growth, but still ends up frosting over.

Movie S3

Unlike the control surfaces (Movie S2), our physically patterned aluminum surface remains predominantly dry from condensation or frost under the same test conditions. Therefore, barring the sacrificial ice stripes, which comprise 10% of the projected surface area, the other 90% of the surface is anti-frosting.

Movie S4

Even after 24 hr, our anti-frosting surface remains 90% dry for test conditions of $T_w = -10\,^{\circ}\mathrm{C}$ and $S = 1.1$.