Supporting Information for

Condenensation of Satellite Droplets on Lubricant-Cloaked Droplets

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**S1 Condensation of satellite droplets captured with optical microscopy**

To ensure the observed satellite droplet formation in ESEM is not due to interaction between the electron beam and lubricant, we conducted optical microscopy experiments using a customized top-view optical light microscopy setup\textsuperscript{1,2}. Top view imaging was performed with a 10X (TU Plan Fluor EPI, Nikon) objective, capturing images at 5 s intervals. 1” x 1” flat coupon samples were horizontally mounted to a cold stage (TP104SC-mK2000A, Instec) and cooled to the test temperature of $T_w = 2 \pm 0.5 \degree C$, in a laboratory environment having air temperature $T_{air} = 22 \pm 0.5 \degree C$ and relative humidity $\phi = 40 \pm 1\%$ (Roscid Technologies, RO120). Illumination was supplied by an LED light source (SOLA SM II Light Engine, Lumencor). The LED light source was specifically chosen for its high-intensity, low-power consumption (2.5 W) and narrow spectral range (380−680 nm) in order to minimize heat generation at the surface due to light absorption. Furthermore, by manually reducing the condenser aperture diaphragm opening size and increasing the camera exposure time, we were able to minimize the amount of light energy needed for
illuminated and hence minimize local heating effects during condensation experiments. Figure S1 shows the top view of the condensed droplets on a CuO surface infused with Krytox1506 oil. Presence of satellite droplets is observed on almost all the visible host droplets.

Figure S1. Optical image for water condensation on Krytox1506-infused CuO surface, showing presence of satellite droplets.

S2 Ionic liquid: polarity and solubility

**Polarity.** According to the vOOG theory, surface tension for any liquid $i$ ($\gamma_i$) can be decomposed to a nonpolar component $\gamma_i^{LW}$ and a polar component $\gamma_i^{AB}$ as expressed in Eq. (S1). The polar component $\gamma_i^{AB}$ is defined as $2\sqrt{\gamma_i^+\gamma_i^-}$, where $\gamma_i^+$ and $\gamma_i^-$ are the acid and base components respectively. Accordingly, interfacial tension between liquid 1 and liquid 2 can be calculated with Eq. (S2).

$$\gamma_i = \gamma_i^{LW} + \gamma_i^{AB} \quad (S1)$$

$$\gamma_{12} = \gamma_1 + \gamma_2 - 2\left(\sqrt{\gamma_1^{LW}\gamma_2^{LW}} + \sqrt{\gamma_1^+\gamma_2^-} + \sqrt{\gamma_1^-\gamma_2^+}\right) \quad (S2)$$

Equation (S2) can be used to find the three surface tension components for BMIm-TFSI liquid as long as we have three different liquids, which have known surface tension components and are not miscible with BMIm. Here, we choose water, decane and ethylene glycol as the reference liquids, which have known surface tension components in the literature\(^3\). We measured the interfacial tension (IT) between BMIm and these reference liquids using the pendent drop method with a goniometer (Kyowa DM501). As all the
selected reference liquids are lighter than BMIm (densities are listed in Table S1), a pendent drop of BMIm is dispensed in a reservoir of each reference liquid to measure the interfacial tension. Figure S2a-c show the images of BMIm droplets hanging in the reference liquids during interfacial tension measurements. The surface tension components and interfacial tension are listed in Table S1. The last row of the table shows the calculated surface tension components data for BMIm, which indicates BMIm is slightly polar with polar component of 8.98 mN/m and nonpolar component of 25.02 mN/m. The molecular formula of BMIm-TFSI is illustrated in Fig. S2d.

**Table S1.** Surface tension components for the liquids involved and measured interfacial tension between BMIm and reference liquids

| Liquid | Density (g/cm³) | \( γ_i \) | \( γ_i^{LW} \) | \( γ_i^{AB} \) | \( γ_i^+ \) | \( γ_i^- \) | IT with BMIm |
|--------|----------------|-----------|----------------|----------------|----------|----------|--------------|
| Water  | 1.00           | 72.8      | 22.1           | 50.7           | 25.5     | 25.5     | 12           |
| Decane | 0.73           | 23.8      | 23.8           | 0              | 0        | 0        | 9            |
| EG     | 1.11           | 48        | 29             | 19             | 1.92     | 47       | 4            |
| BMIm   | 1.43           | 34.00     | 25.02          | 8.98           | 1        | 13.91    | -            |

**Figure S2.** Interfacial tension measurement for BMIm pendent drop in (a) water, (b) decane, and (c) ethylene glycol. (d) Molecular formula of BMIm.

**Solubility.** As BMIm is slightly soluble in water, it is possible that the interfacial tension between BMIm and water would change over time due to the dissolution. This may result in non-cloaking of water droplet on BMIm-infused surfaces. Here, to confirm that time scale of dissolution is much larger than that of lubricant spreading, we measured the BMIm-water interfacial tension over time. By using the same pendent droplet method described before, one BMIm droplet is dispensed in a water reservoir and kept undisturbed. The interfacial tension is measured every 2 mins for a period of 40 mins, as shown in Figure S3. Interfacial
tension data for Krytox oil and Fomblin oil are also included in the Figure as references. The interfacial tension for Krytox does not change over time as it is not soluble in water. For clear comparison, interfacial tension of Fomblin oil decreases with time due to its surface-active content. The constant water-BMIm interfacial tension indicates that dissolution between the two liquids did not happen within our experimental time period (over 40 minutes).

Figure S3. Measurements of interfacial tension between water and different liquids over time. Data for the case BMIm are measured in this work. Data for Krytox and Fomblin oil are taken from the reference4. The inset images show the BMIm pendent drop shape at time of 0 and 40 minutes respectively.

S3 Raman Spectrum Characterization

Figure S4 presents the series of Raman spectra of water droplet deposited on Krytox oil infused CuO surface recorded at different z values. The blue curve with open squares shows the characteristic Raman spectra of nanostructured CuO, where three Raman active modes $A_g$, $B_{g1}$, and $B_{g2}$ give peaks around 286, 330, and 620 cm\(^{-1}\) respectively, which matches well with those reported in literature5. This is also shown in Fig. S5a specifically for the substrate surface. The red curve with open circles show the characteristic peaks for Krytox oil. The Raman spectrum of pure Krytox oil contains intense peaks at 843 and 903 cm\(^{-1}\) (see Fig. S5b) corresponding to the stretching of peroxides and CF\(_3\) bonds in the fluoropropylene oxide groups of the perfluoro-poly(ether) backbone6,7. While, the peaks at 292 and 412 cm\(^{-1}\) are the torsional and deformation vibrations of CF\(_2\) bond8. Green curve with open diamonds in Fig. S4a shows the characteristic broad
absorption peak for water, where the shoulder at 3250 cm\(^{-1}\) corresponds to the asymmetric -OH stretch, and the most intense feature at 3410 cm\(^{-1}\) corresponds to the symmetric -OH stretch (see Fig. S5e)\(^9\).

First, we check the Krytox-oil-infused CuO surface. Starting from Position (1) in Fig. S4b, we observed strong signal for bare CuO surface. By moving sample stage in z direction down to Position (1), the weakest signal for CuO was observed and the distance of this position was marked as 0 µm in Fig. S4a. Moving sample stage in z direction above the Position (1), at around 25 µm to original position, the signal for CuO disappeared. By continuously increasing the z height, the signal for Krytox oil appeared with maximum around 85.5 µm. This is considered Position (2).

Then, the water droplet was dispensed on Krytox oil infused CuO surface. At this point, the Raman signal for water was also recorded at different z heights. The Raman shift at Position (3) shows very strong signal for water molecule with no signal for Krytox oil. At around 1025 µm which is Position (4), the water signal started to disappear. At this position by moving the z position to ± 5 µm with step size of 500 nm, we are able to record the signal for very thin cloaking layer of Krytox oil on water droplet. This shows that high resolution confocal Raman spectroscopy is unique way to get the characteristic vibrational information of thin layer of cloaking/non-cloaking lubricants on condensate droplets.

**Figure S4.** (a) The series of Raman shift of water droplet deposited on Krytox oil infused CuO surface recorded at different z values. (b) Schematics to present the different positions.
To evaluate the thickness of cloaking films, we first measure the thickness of the focal plane corresponding to the depth resolution of Raman spectrometer. The focal depth is measured by z-scanning the characteristic intensity of ultra clean silicon wafer around 520 cm$^{-1}$. Figure S6 shows the signal intensity profile collected by using a 0.55 NA, 50× objective. The full width at half-height is around 5 μm, which provides us information about the focal depth or depth resolution of Raman system$^{10}$.
Figure S6. (a) Signal intensity response of silicon Raman spectrum in z-scanning. The full width at half height (FWHH) implies that the “depth of focus” is 5 μm. (b,c) The signal intensity comparisons of infused and cloaking lubricants.

S4 Prediction of Surface Temperature

In order to characterize the nucleation processes for satellite droplets and mother droplets, the temperature at different interfaces should be predicted, especially for the infusing lubricant-vapor and cloaking lubricant-vapor interfaces. Growth dynamics of condensate droplets on flat and micro/nano-textured superhydrophobic surfaces has been studied with a thermal resistance model previously11,12. This model considers thermal resistances of all contributing components from saturated vapor through the droplets to the cold condensing surface. In this work, the droplets are cloaked with a thin lubricant oil layer, which will alter the total thermal resistance and thus affect growth rate of the droplets. The original thermal resistance model is extended with additional terms to take into account of the cloaking lubricant layer. Figure S7 shows a schematic of one single cloaked water droplet on lubricant-infused surface with regular pillars and the respective thermal resistance diagram. The water droplet has a radius of \(r_d\), which is dependent on time.
The solid condensing surface is textured with pillars of dimensions: diameter $d$, height $h$, spacing $l$ and coated with hydrophobic coating with thickness of $\delta_c$. Thickness of the infusing layer on the solid surface is $\delta_{o,i}$, while the cloaking lubricant layer thickness is represented by $\delta_{o,c}$. The radius of cloaked water droplet $r_{d,c} = r_d + \delta_{o,c}$, which is approximated to $r_d$ as the thickness cloaking layer is much smaller than radius of the droplet. Temperatures at the saturated vapor $T_{sat}$, vapor-cloaking lubricant interface $T_{i,1}$, cloaking lubricant-water interface $T_{i,2}$, droplet base $T_b$, coated pillar top $T_{c,1}$, pillar top below the coating $T_p$, coated spacing between pillars $T_{c,2}$, and the cold surface $T_s$ are all as illustrated in Figure S7(a). Heat is transferred from the saturated vapor to the droplet base through thermal resistances of the vapor-cloaking lubricant interface $R_{i,1}$ by convection, and cloaking lubricant layer $R_{o,c}$, and water droplet $R_d$ by conduction. Then the heat conduction continues through the combined lubricant-coating-pillar system with thermal resistance of $R_{o,1}$ and $R_{o,2}$ for lubricant layer on the pillars and spacings, $R_{c,1}$ and $R_{c,2}$ for the coating layer on the pillars and spacings, and $R_p$ for the pillars, respectively. Convection through the lubricant layers and droplets is neglected due to their nano scale for condensation. Contact resistance at cloaking lubricant and water droplet interface is also neglected.

![Figure S7](image)

**Figure S7.** (a) Schematics of a single cloaked water droplet on lubricant-infused condensing surface; (b) Thermal resistance diagram.

With addition of the infusing and cloaking lubricant layers to the thermal resistance model for condensation on superhydrophobic surface, the heat transfer rate through a single droplet can be predicted,

$$ q = \frac{\Delta T}{R_{tot}} = \frac{T_{sat} - T_s - \Delta T_c}{R_{i,1} + R_{o,c} + R_d + R_{bs}} $$

(S3)

where,

$$ \Delta T_c = \frac{2T_{sat}y_w}{h_{fg}r_d\rho_w} $$

(S4)
Given surface temperature $T_s$, saturation temperature $T_{sat}$ and apparent contact angle $\theta_a$ measured in condensation experiment, the heat transfer rate is predicted with Eq. (S3) for various droplet size. Then, by using the definition of thermal resistances in Eq. (S5-S8), we can calculate the temperature at different interfaces, including $T_{i,1}$, $T_{i,2}$, and $T_b$. The predicted results are presented in Fig. 6d in the main manuscript.

### S5 Prediction of Nucleation Energy Barrier

To analytically understand the nucleation process of the satellite droplets, the classical nucleation theory (CNT) is used to estimate nucleation energy barrier as a function of surface temperature. According to the CNT$^{13}$, the normalized nucleation energy barrier,

$$W^*/k_B T = \frac{16\pi \gamma_0 \nu_0^2 \gamma^3}{3(k_B T)^3 (\ln S)^2}$$

where, $\psi(\theta) = (2 + \cos \theta)(1 - \cos \theta)^2$, $\theta$ is the contact angle; $\gamma$ is interfacial tension between water and the condensing media (vapor or infusing lubricant), $\gamma = \gamma_w = 72\text{mN/m}$ for condensation on un-infused surface, $\gamma = \gamma_{wo}$; $\nu_0 = 3 \times 10^{-29} \text{m}^3$ is the volume for an individual water molecule; $S$ is supersaturation.

By setting $P_v = 750 \text{Pa}$ (experimental condition) and varying condensing surface temperature, the nucleation energy barrier in the case of Krytox and BMIm infused surfaces are plotted as functions of the temperature in Figure 6e of the main manuscript. Apparently, nucleation energy barrier on BMIm-infused surface is lower that on the Krytox-infused surface. Moreover, the energy barrier increases with condensing surface temperature. As temperature at infusing lubricant-vapor interface is always lower than that at
cloaking lubricant-vapor interface, droplet nucleation happens preferentially at the infusing lubricant-vapor interface and nucleation of satellite droplets starts after the infusing lubricant-vapor interface is fully occupied by mother condensates.

**S6 Spreading dynamics of cloaking and non-cloaking lubricants on water droplets**

Spreading dynamics of Krytox, BMIm and Dodecane lubricants on water droplets are shown in Fig. S8.

![Figure S8](image)

**Figure S8.** Spreading of cloaking and non-cloaking lubricants on water droplets. Side-view time-lapse images of water droplets (left) approaching and contacting (a) Krytox oil, (b) BMIm, and (c) dodecane lubricant films residing on a hydrophobic polished Si wafer.

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