Dropwise Condensation on Structured Surfaces

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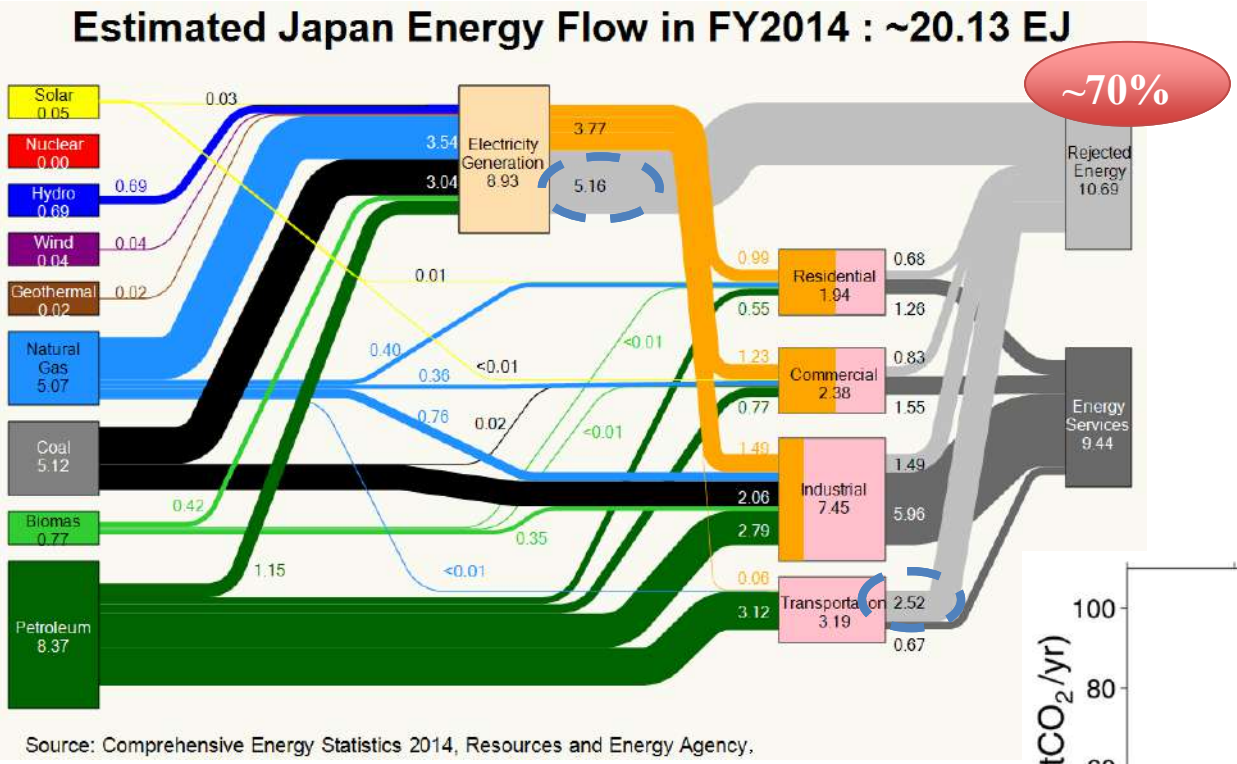
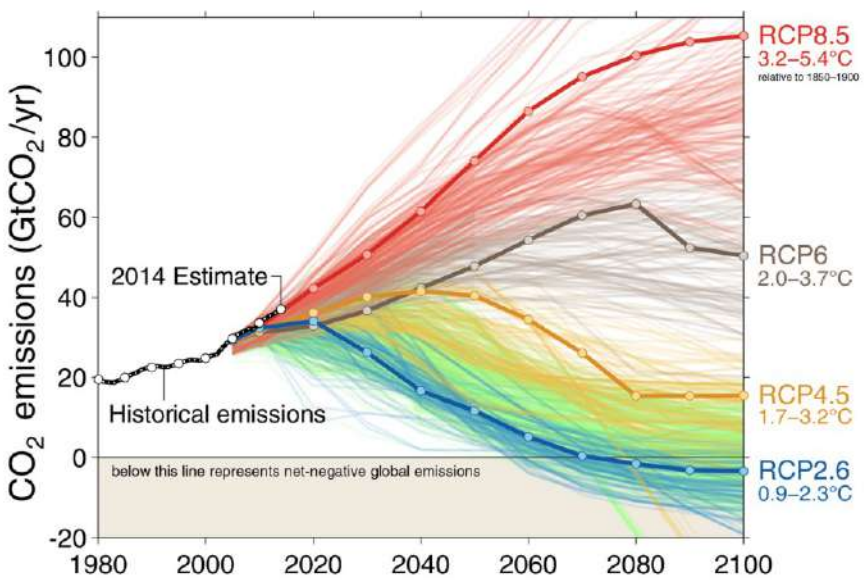
THERMASMART
Thermal Management of Microprocessors

Motivation I



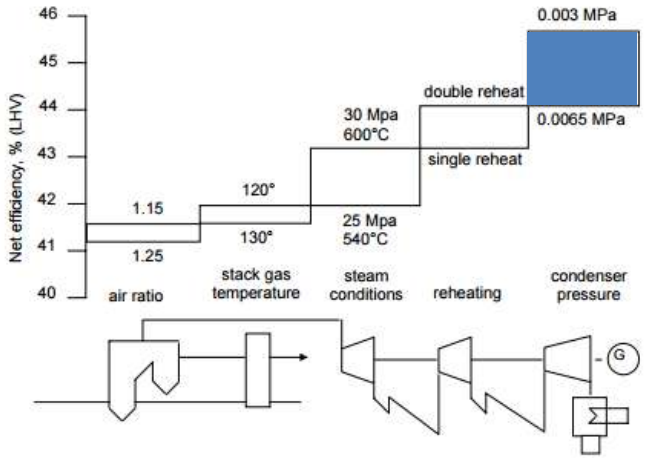
Source: Comprehensive Energy Statistics 2014, Resources and Energy Agency.



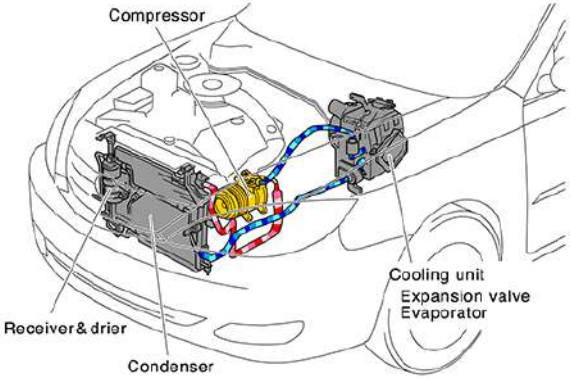
Fuss *et al.*, *Nature Climate Change* **4** (10), **2014**

Motivation II

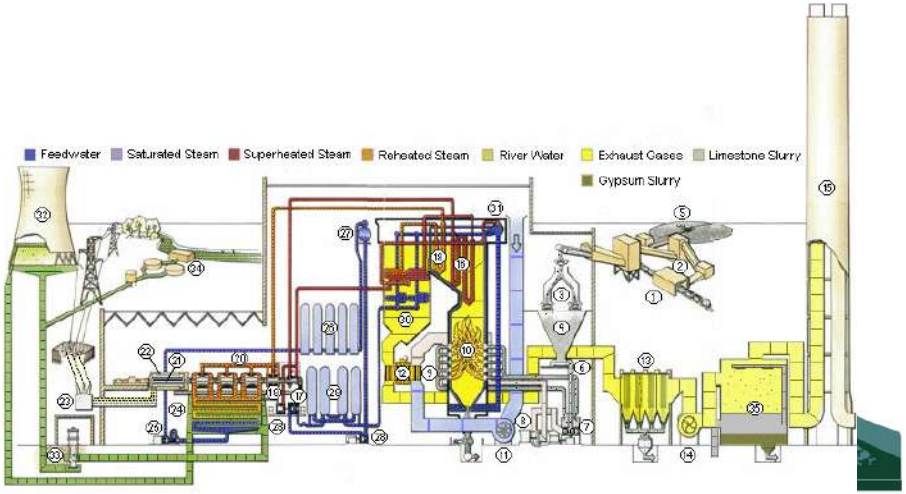
Management of I/T data servers without AC systems



Beér, *Prog. Energy& Combustion Sci.* **33** (2), **2007**



Reduction on car/planes/spaceships weight and dimensions



Coal-fired power plants can keep the same electricity production with less coal or fuel consumption

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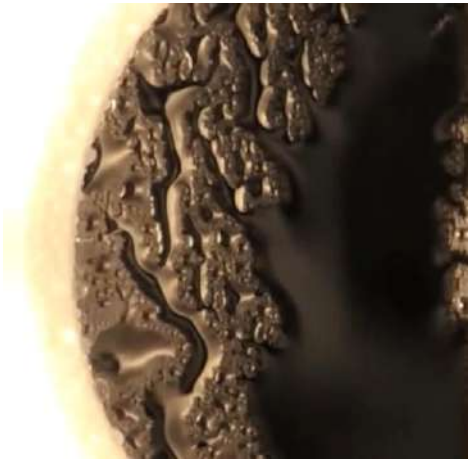
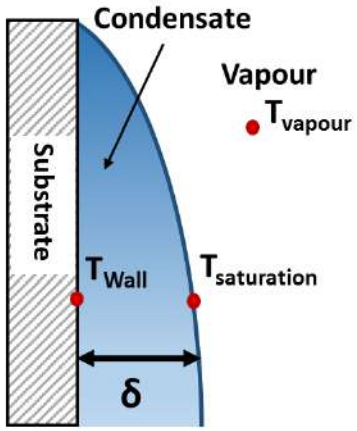
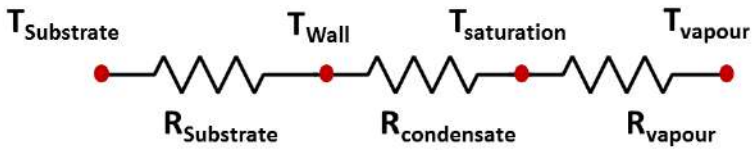
Condensation Heat Transfer



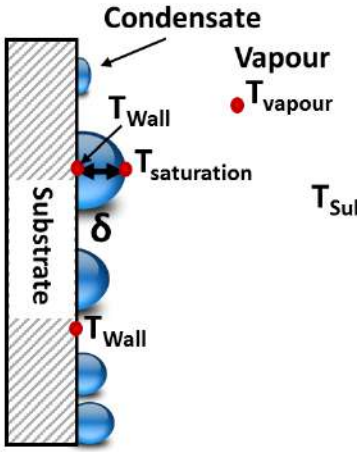


Filmwise Condensation

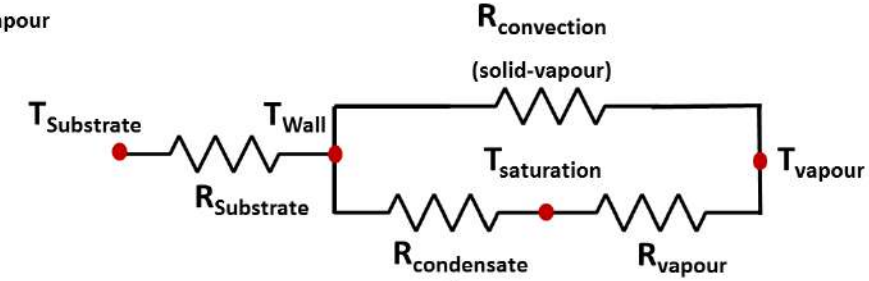


is

function of δ



Dropwise Condensation



is

function of δ

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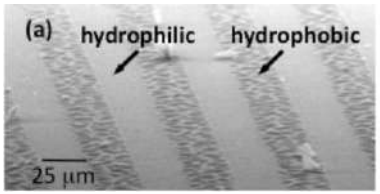
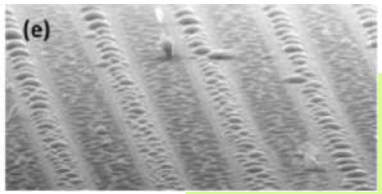
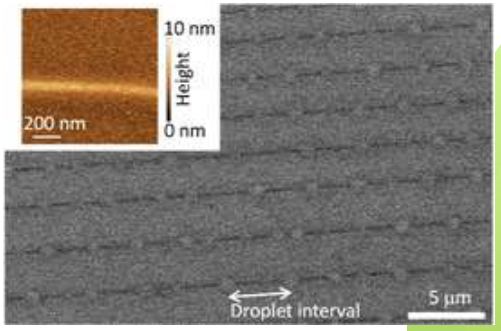
Condensation Logic

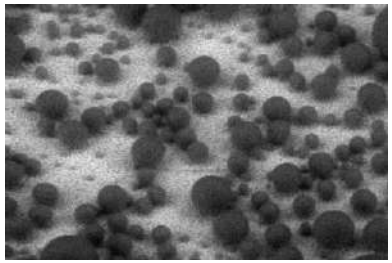




Varanasi *et al.*, *APL* **95**, 2009



Yamada *et al.*, *Langmuir* **30**, 2014



Miljkovic *et al.*, *Nano Letters* **13**, 2012

Nucleation

$t \approx 0 - 10$ s

$l \approx 0 - 0.1$ mm

Growth

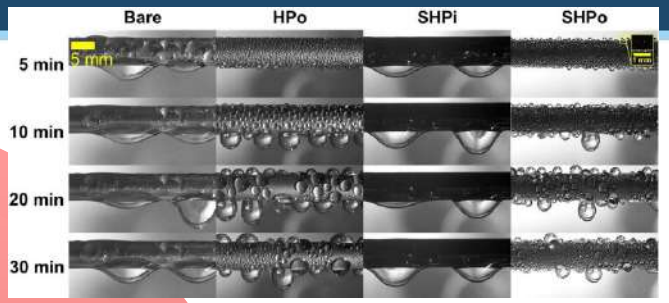
$t \approx 10 - 1000$ s

$l \approx 0.01 - 2$ mm

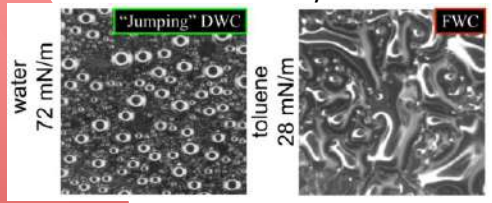
Detachment

$t \approx 0 - 1$ s

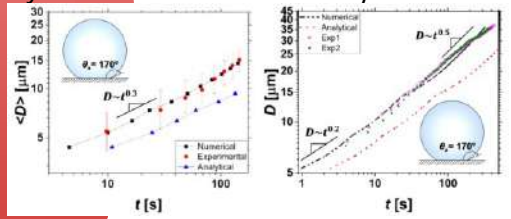
$l \approx 1 - 5$ mm



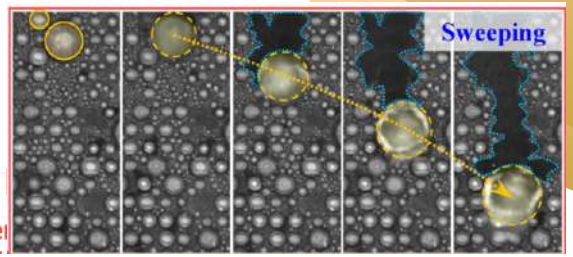
Seo *et al.*, *Sci. Rep.* **6**, 2016



Rykaczewski *et al.*, *Sci. Rep.* **4**, 2014

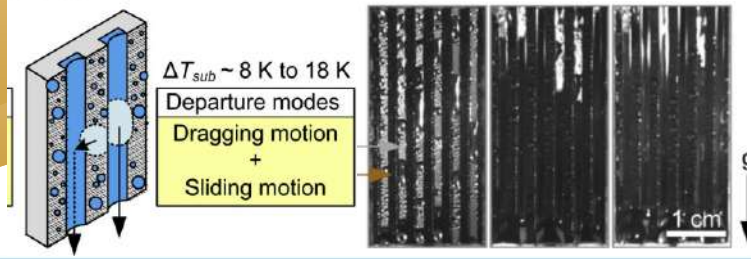


Chavan *et al.*, *Langmuir* **32**, 2016



Wen *et al.*, *ACS Appl. Matter Interfaces* **9**, 2017

Lo *et al.*, *Joule* **3**, 2019



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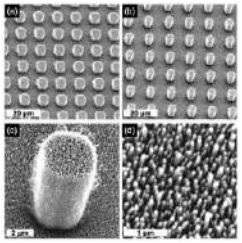
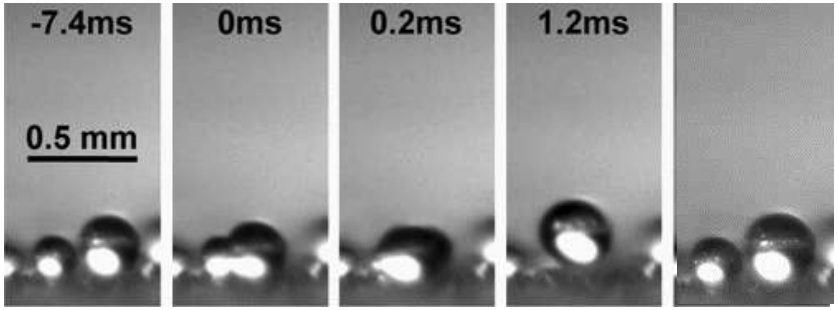
- **DWC on Un-Coated**

Superhydrophobic Surfaces SHSs

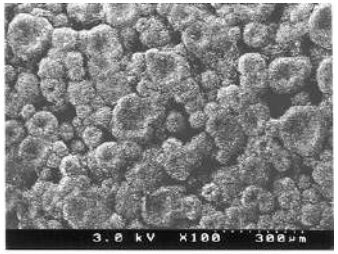
1. Surface Structure + Hydrophobic Coating

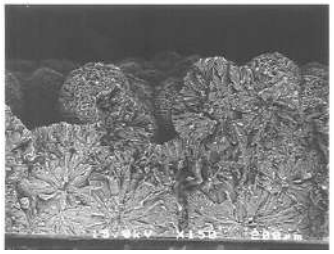


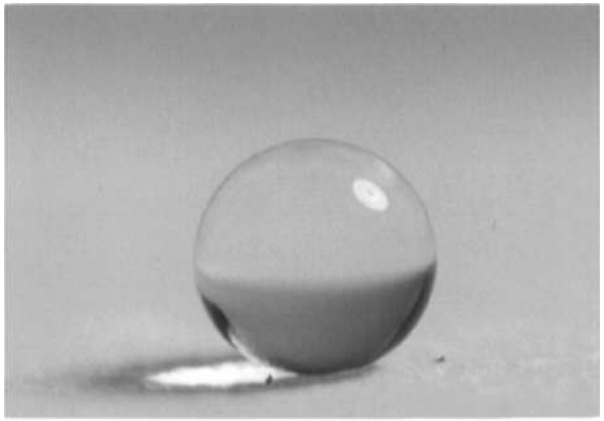


Boreyko & Chen, *Physics Review Letters* **103**, 2009

2. Structuring of an intrinsic Hydrophobic Material

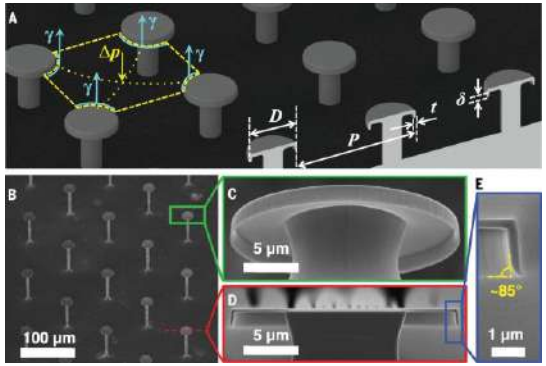


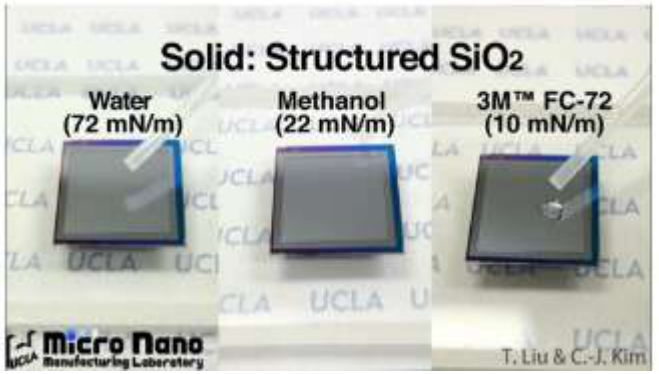




Onda *et al.*, *Langmuir* **12**, 1996

3. Presence of Re-entrant cavities





Liu & Kim, *Science* **346**, 2014

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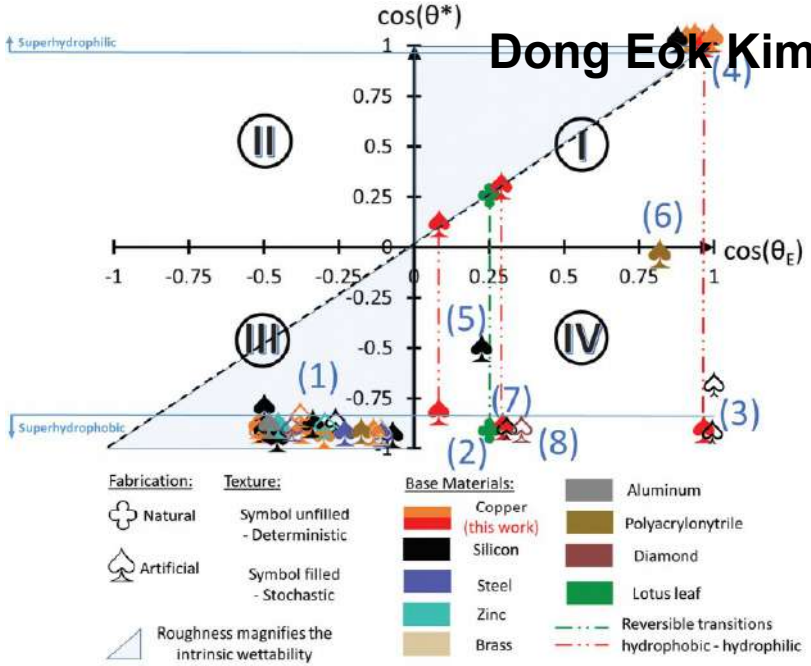
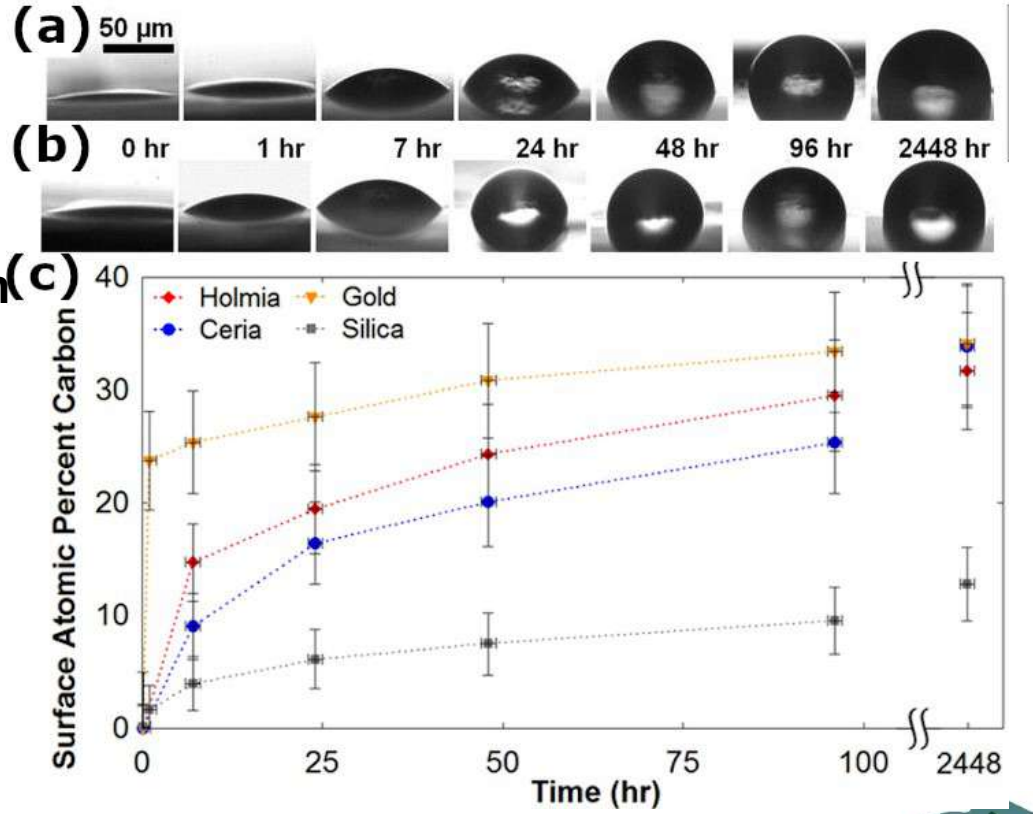
of Micr

Atmospheric-Mediated Transition

Frankiewicz & Attinger, *Nanoscale* **8**, 2016



Dong Eok Kim



Preston *et al.*, *APL* **96**, 2014

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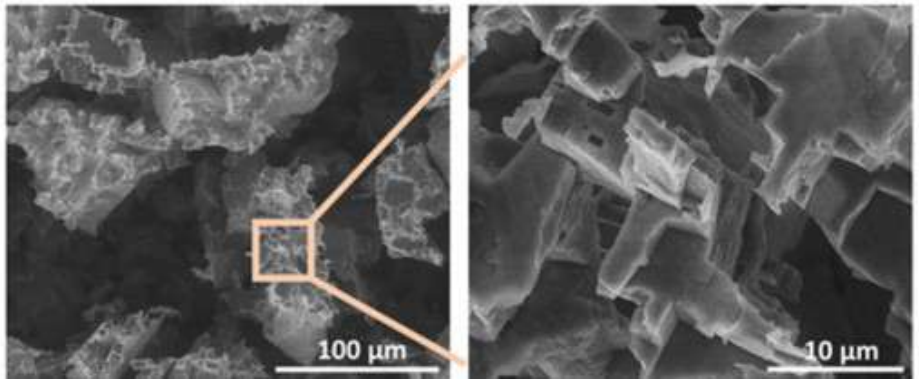
Bioinspired Metallic Surfaces I

Rose Petal



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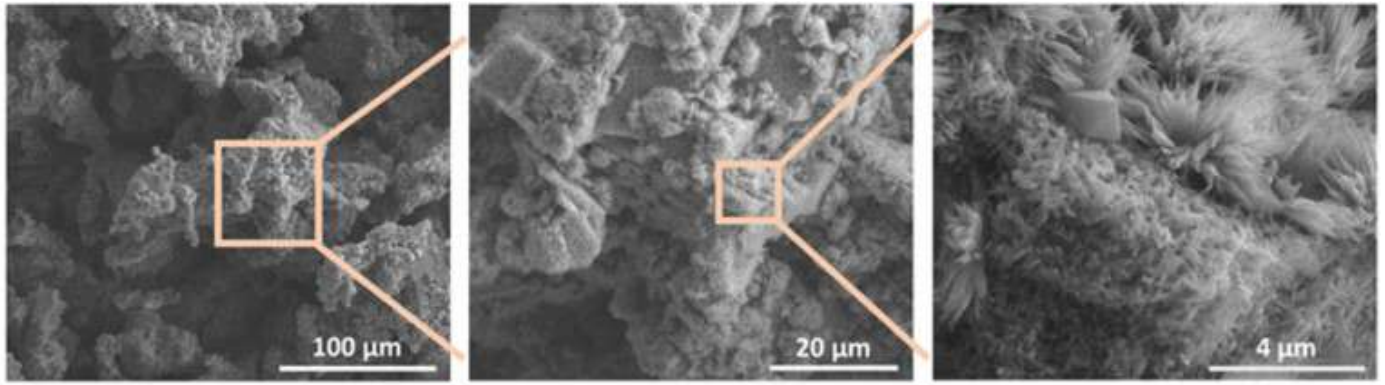
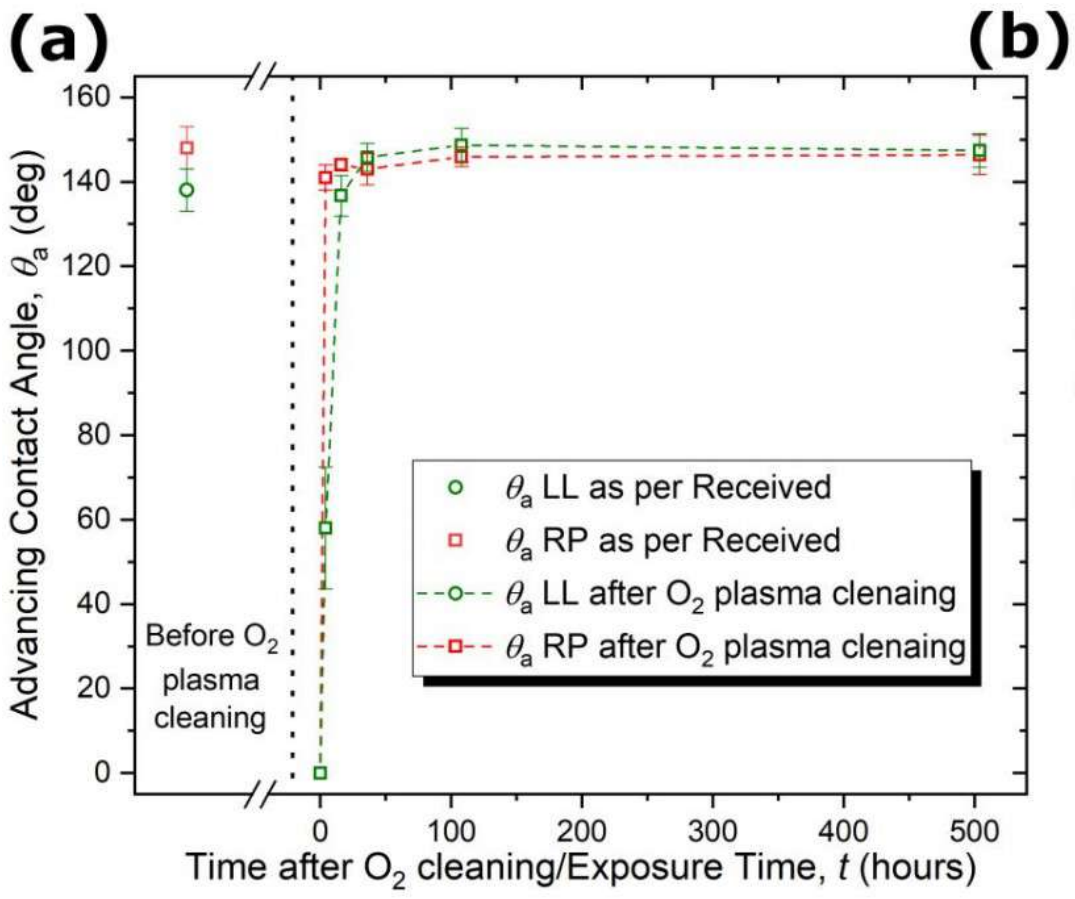
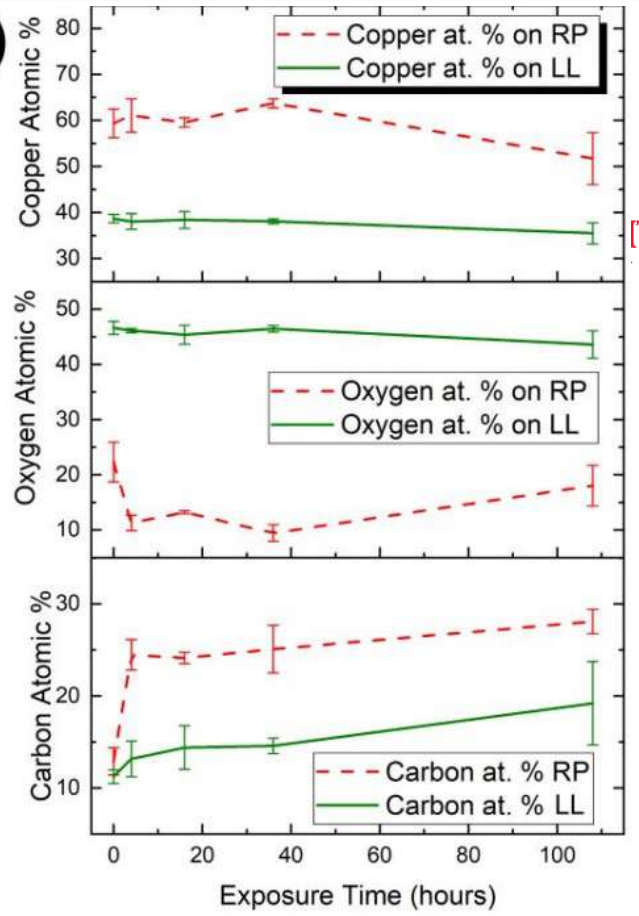
Lotus Leaf



Sample	S_a (µm)	Equilibrium, θ_0 (deg)	Advancing , θ_a (deg)	Receding, θ_r (deg)	Hysteresis, CAH
RP	26.2 ± 2	141° ± 3 °	148° ± 3 °	101° ± 3 °	47° ± 3 °
LL	24.4 ± 2	134° ± 3 °	138° ± 3 °	134° ± 3 °	4° ± 3 °

Bioinspired Metallic Surfaces II





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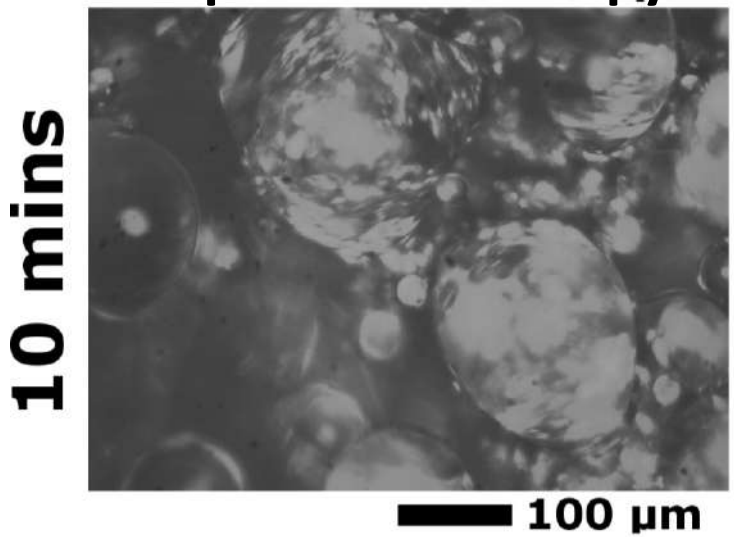
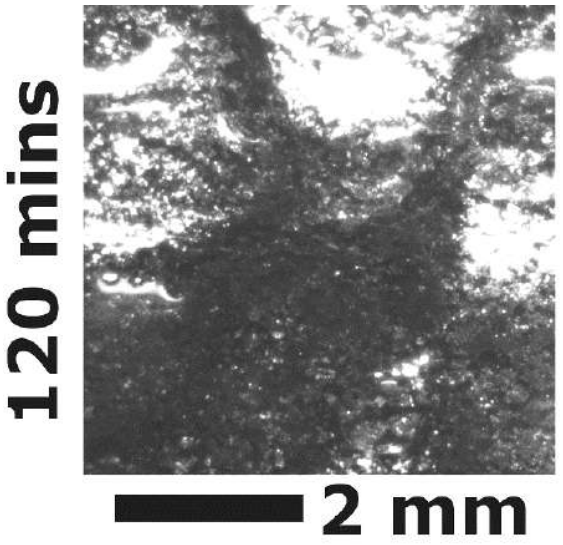
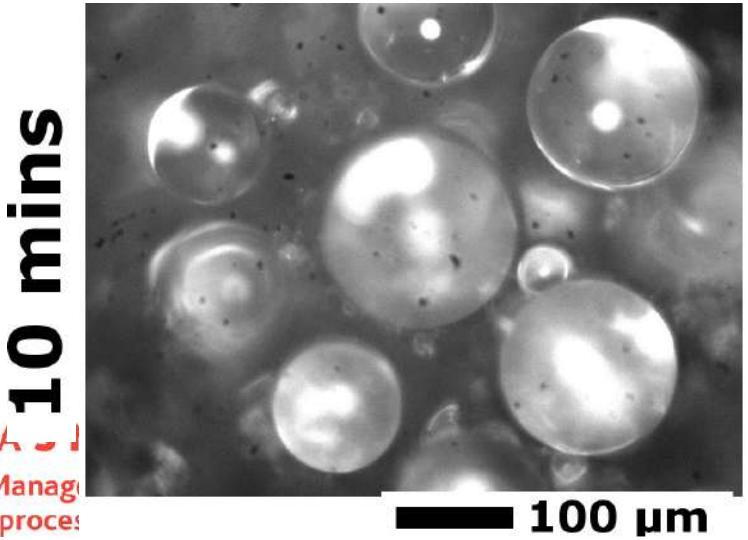
Condensation RP & LL

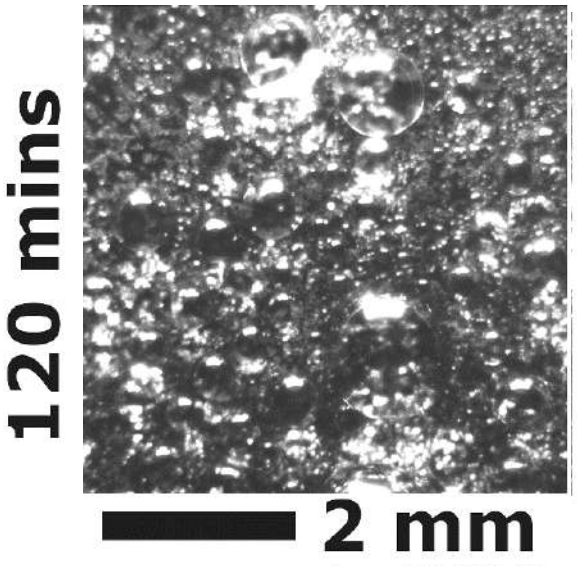
Optical Microscopy

Macroscopic Observations

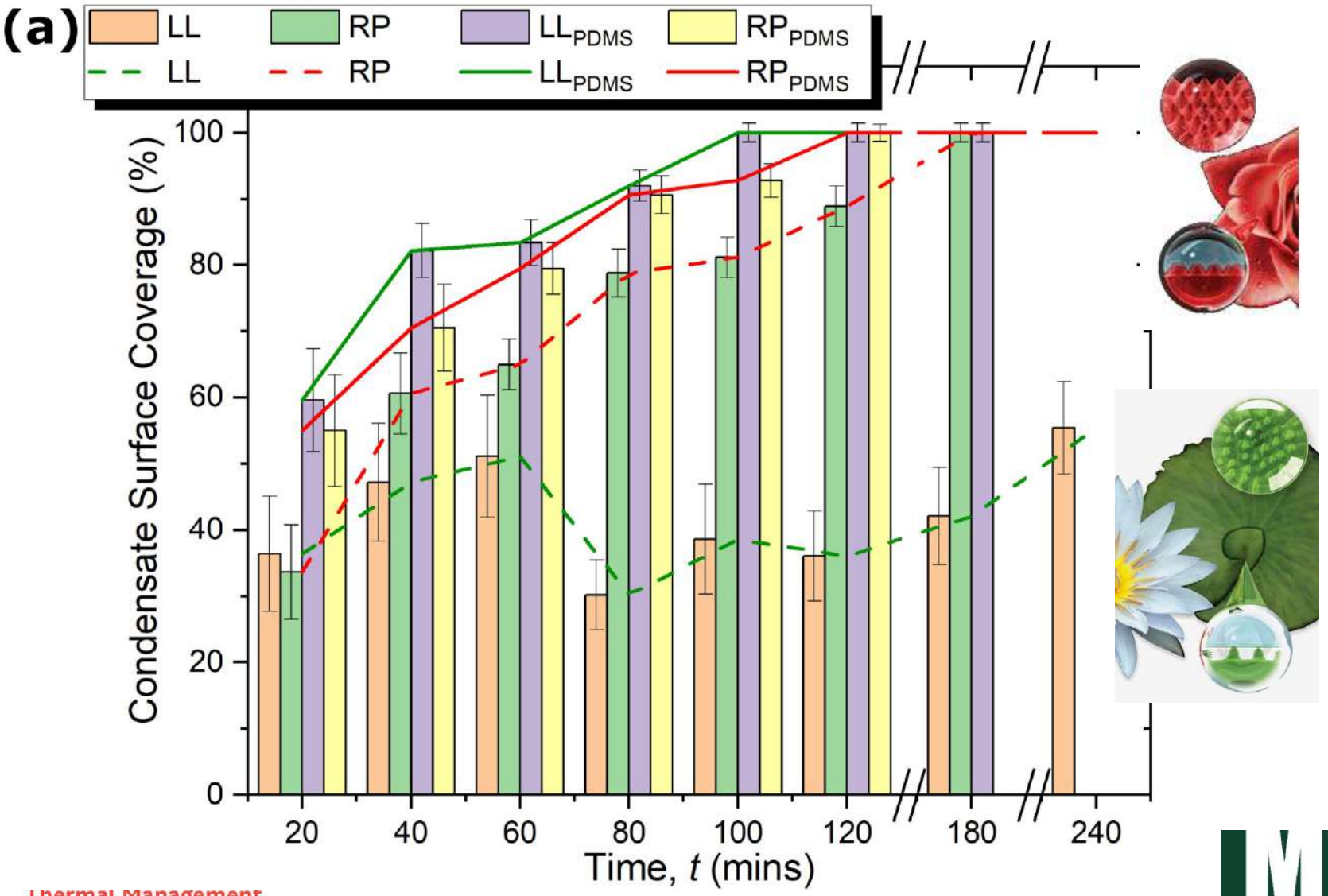




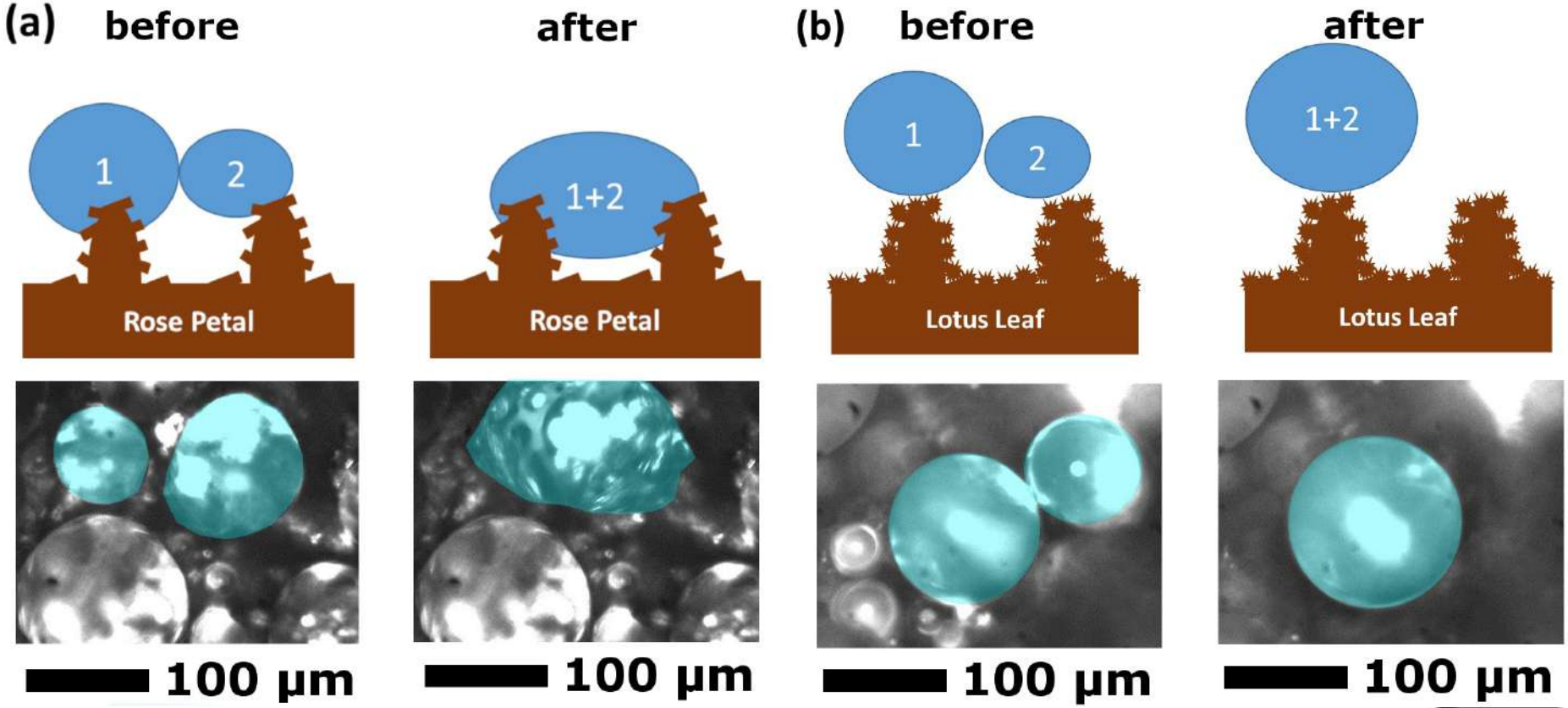




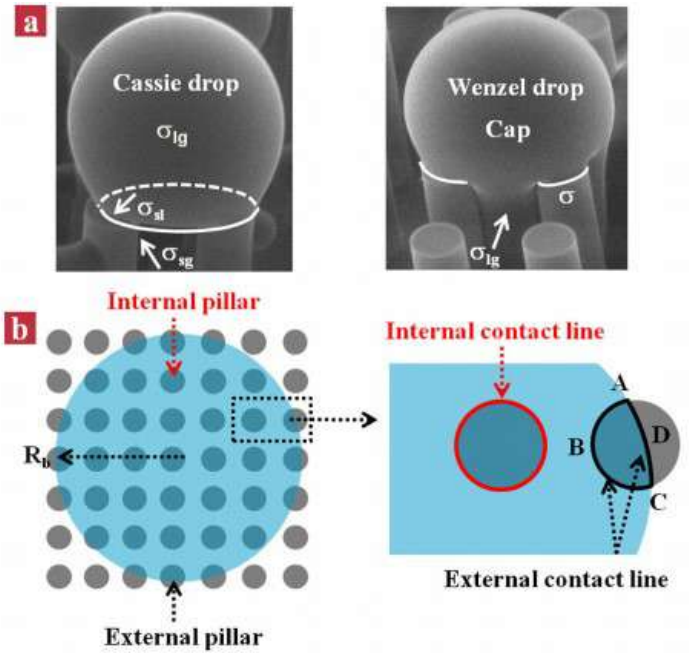
Surface Coverage on RP & LL



Characteristic Coalescence on RP & LL



Surface Energy Analysis on RP & LL



Chen *et al.*, *Physics Review Letters* **109**, 2012

$$E_{\text{adh,RP}} = \pi r_{RP} \gamma_{lg} (1 + \cos\theta_i) R_b^2$$

$$E_{\text{adh},LL} = \pi f_{LL} \gamma_{lg} (1 + \cos\theta_i) R_b^2$$

Table 2. Summary of the Energy of Adhesion, E_{adh}, Surface Energy, E_{surf}, and Excess of Surface Energy, $E_{ex\text{-}surf}$, of a Drop as a Function of Drop Radius, R, and Ratio $E_{adh}/E_{ex\text{-}surf}$ for Metallic RP and for Metallic LL Surfaces

	type of surface	
energy	rose petal (RP)	lotus leaf (LL)
E_{adh}(N)	$0.27R^2$	$0.015R^2$
E_{surf}(N)	$1.15R^2$	$1.005R^2$
$E_{ex\text{-}surf}$(N)	$0.862R^2$	$0.985R^2$
$E_{adh}/E_{ex\text{-}surf}$	0.31	0.015

Orejon *et al.*, *ACS Appl. Mater. Interfaces*, 2019

Conclusions on RP & LL

- ✓ Demonstrated non-wetting and superhydrophobicity on Copper and Copper Oxide structured surfaces

- ✓ Dropwise Condensation on metallic LL

ACS APPLIED MATERIALS & INTERFACES

Research Article

www.acsami.org

Dropwise Condensation on Multiscale Bioinspired Metallic Surfaces with Nanofeatures

Daniel Orejon,[*,†,‡] Alexandros Askounis,[‡,§] Yasuyuki Takata,[‡,∥] and Daniel Attinger[⊥]

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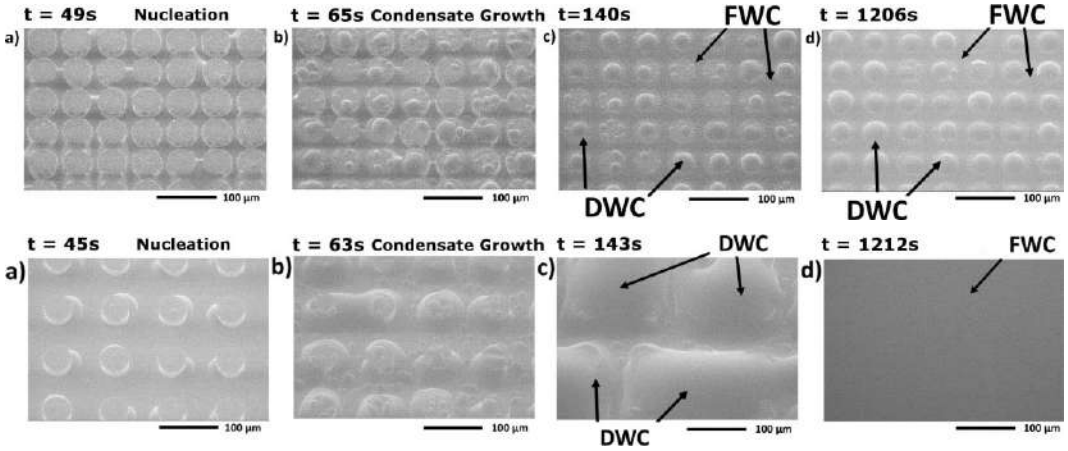
- DWC on Un-Coated SHSs
- **Nucleation & Sub-Cooling**

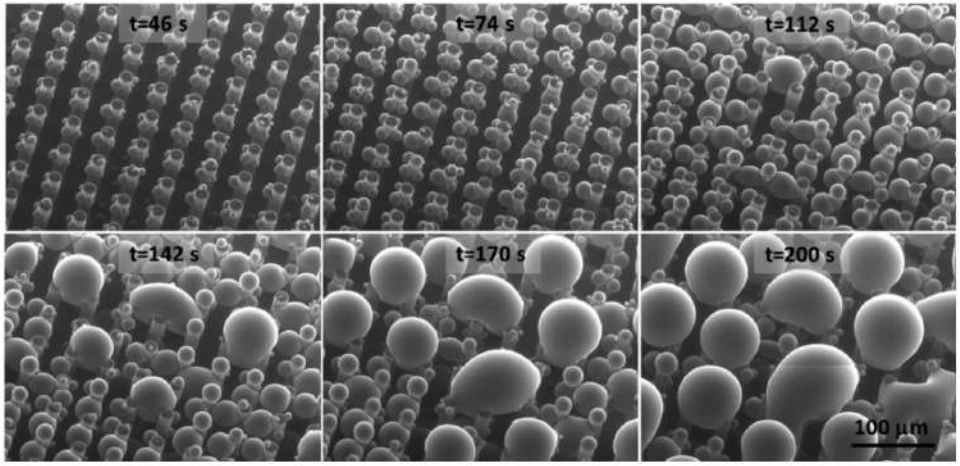
Nucleation & Growth on Structured Surfaces

- Hydrophilic Micropillars



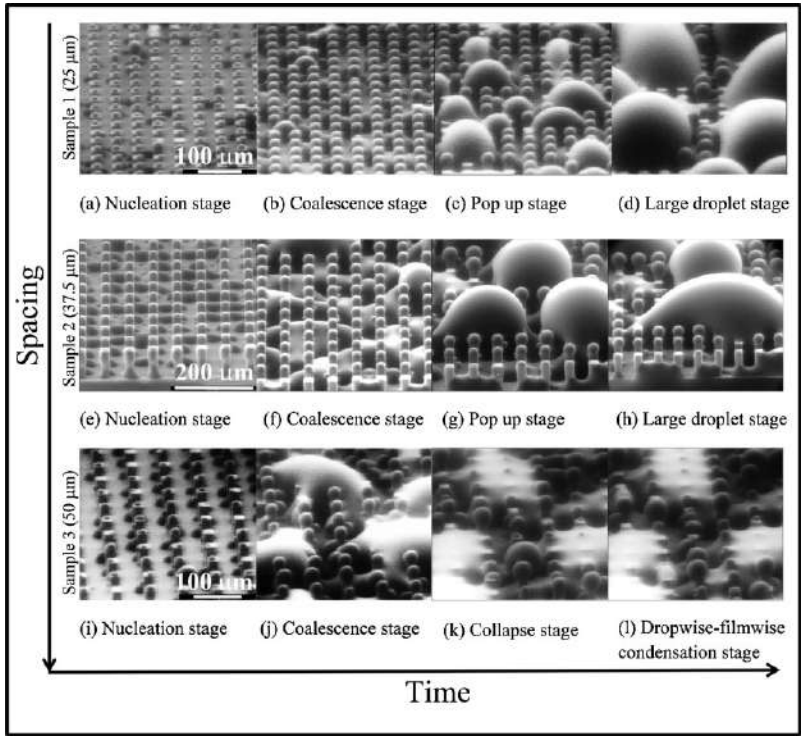
Orejon *et al.*, *IJHMT* **117**, 2017

- Hydrophobic Micropillars



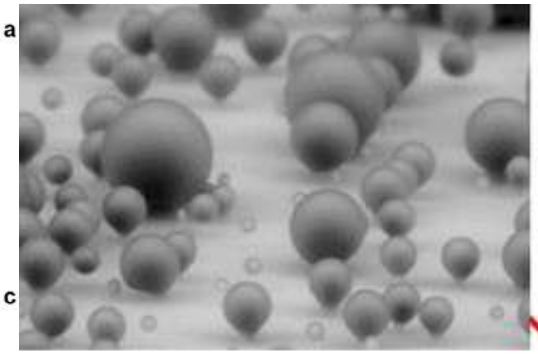
Zhang *et al.*, *PRF* **1**, 2016

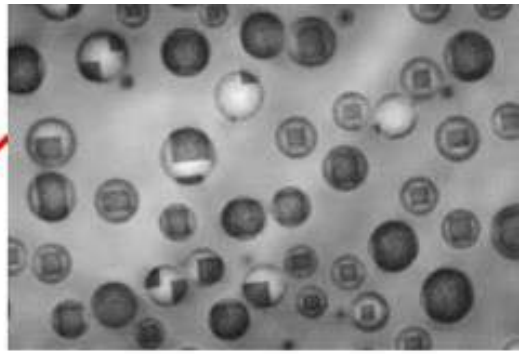
- Patterned Wettability Micropillars

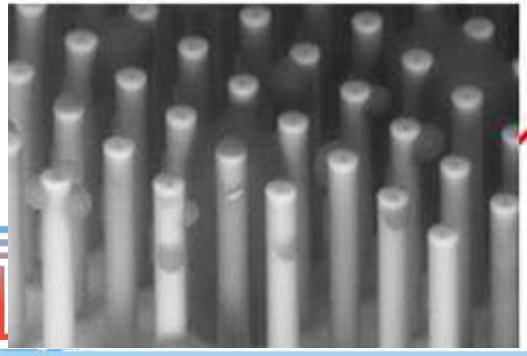


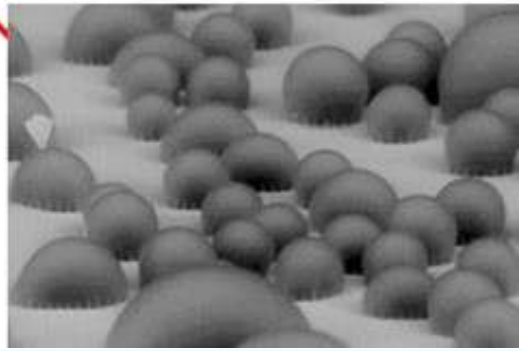
Yao *et al.*, *Appl. Surf. Sci.* **290**, 2014

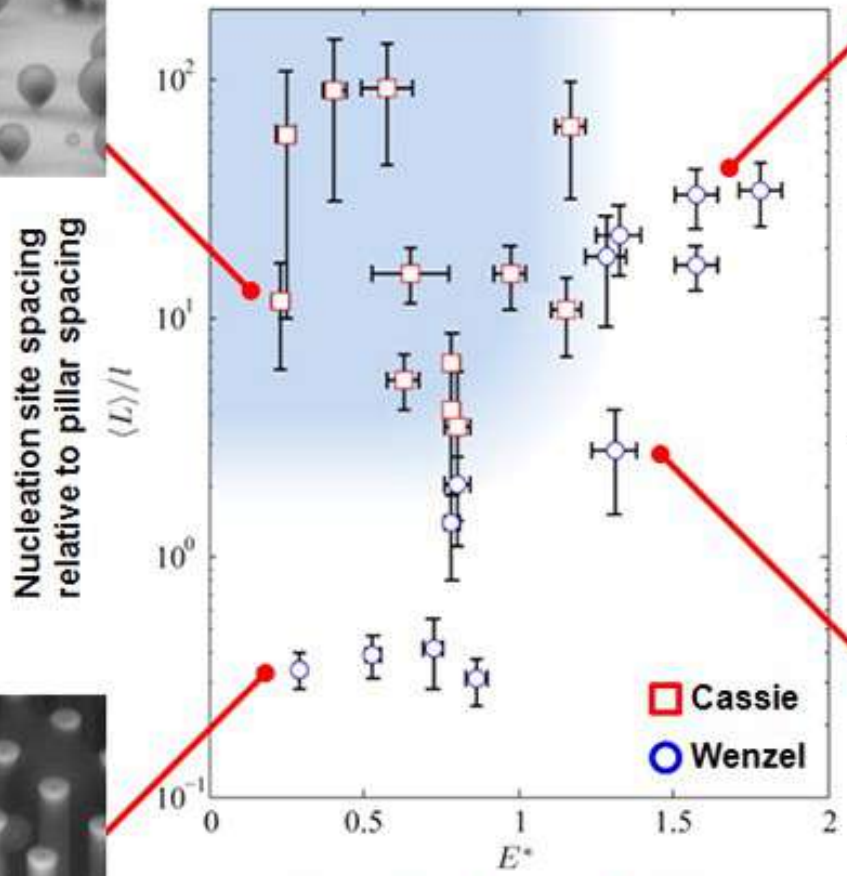
Structured Surfaces - Role of Length Scale







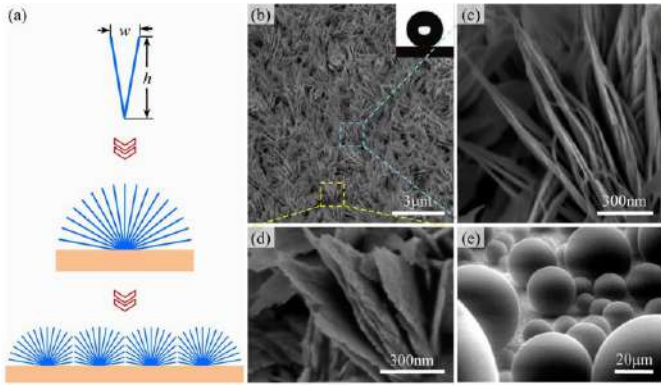




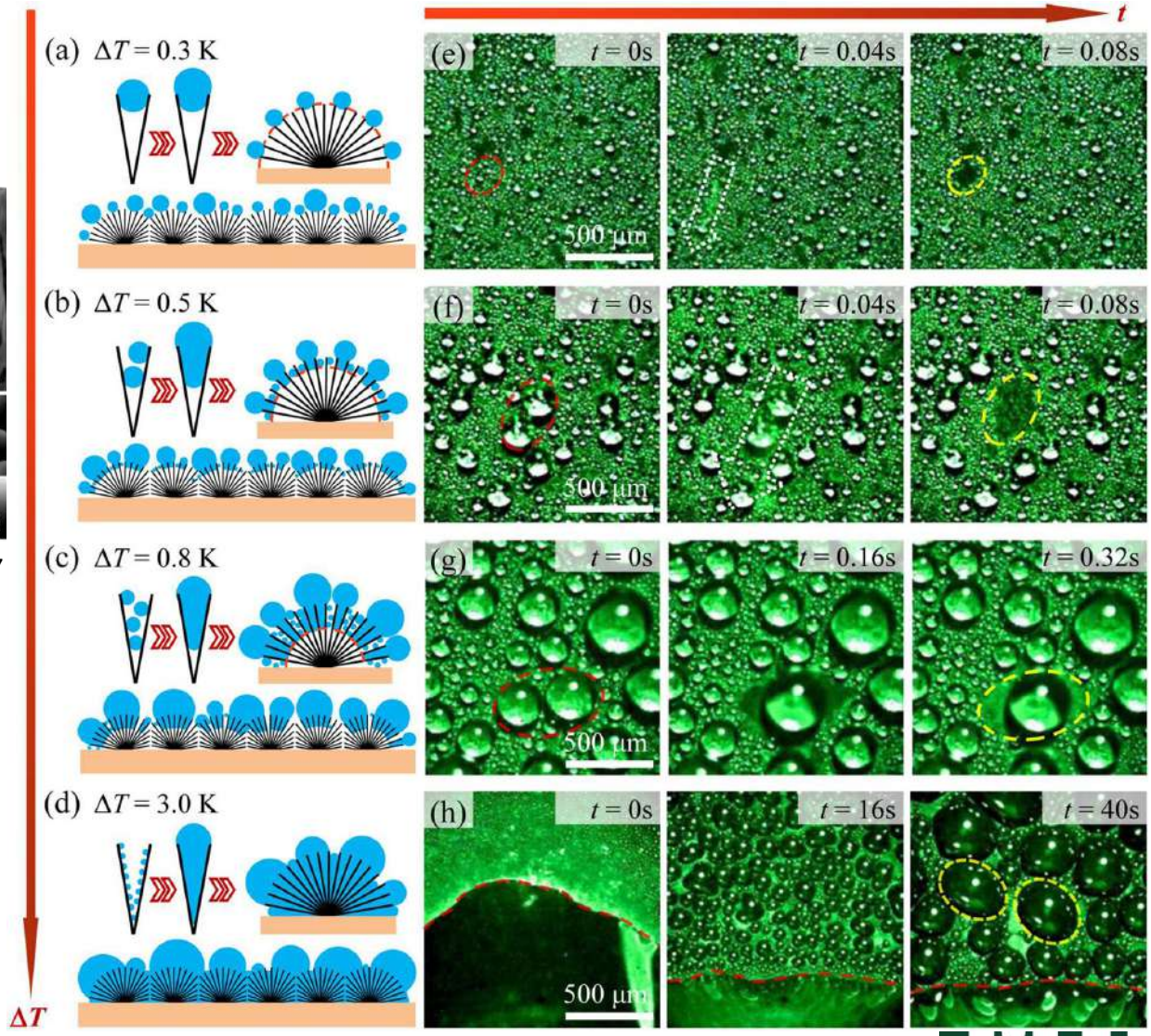
$$E^* = \frac{\cos\theta_a^{CB}}{\cos\theta_a^{W}} = \frac{-1}{r\cos\theta_a},$$

Enright *et al.*, *Langmuir* **28**, 2012

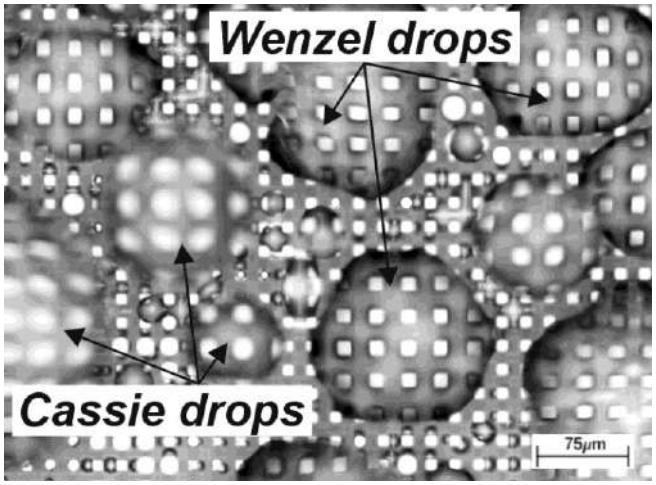
Nucleation vs. Subcooling



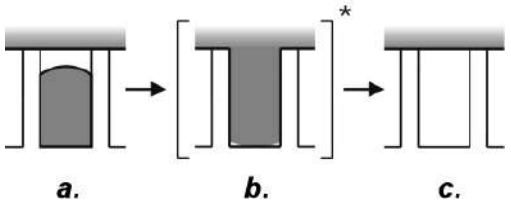
Wen *et al.*, *ACS Appl. Matter Interfaces* **9**, 2017

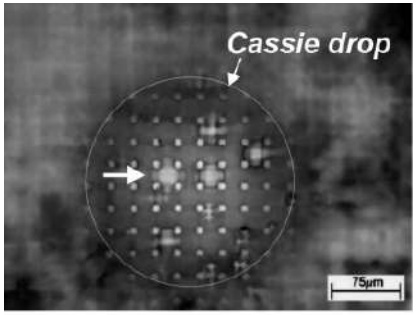


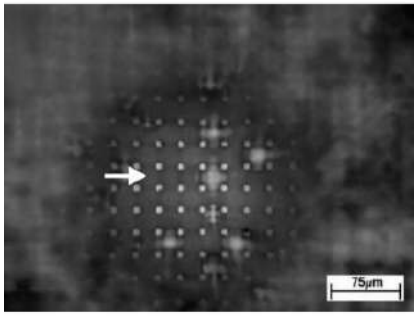
Dewetting Strategies I

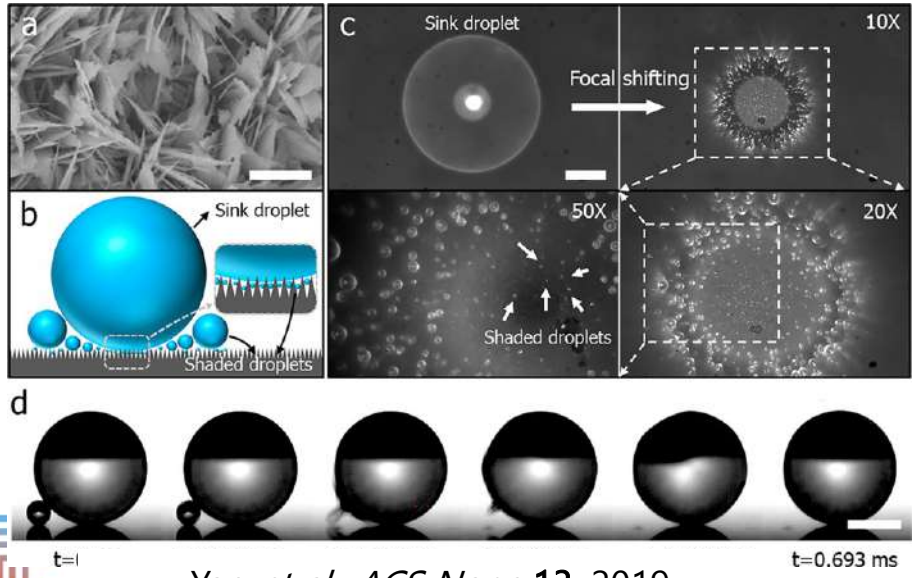


Dorrer & Ruhe, *Langmuir* **23**, 2007

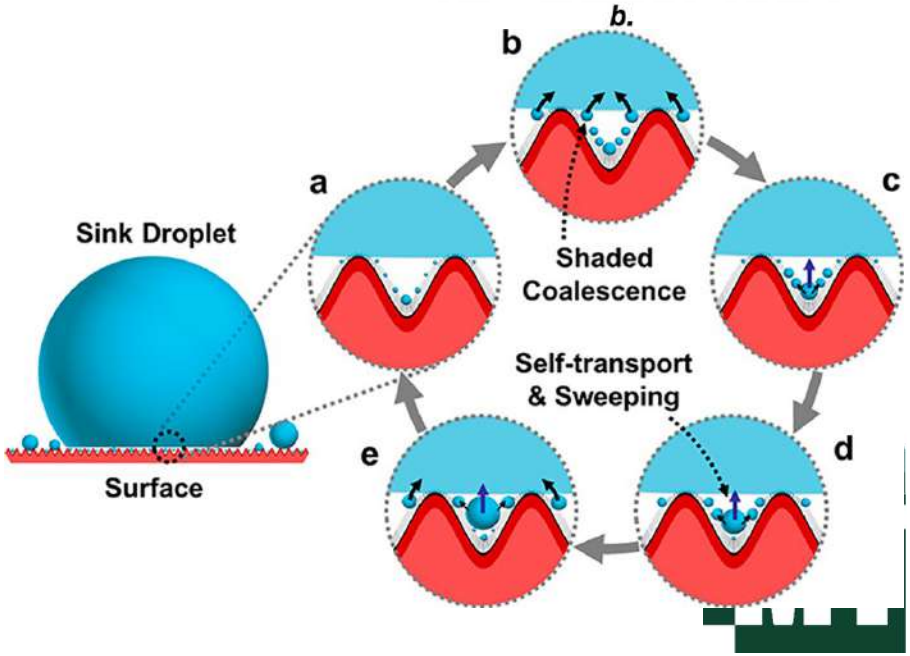




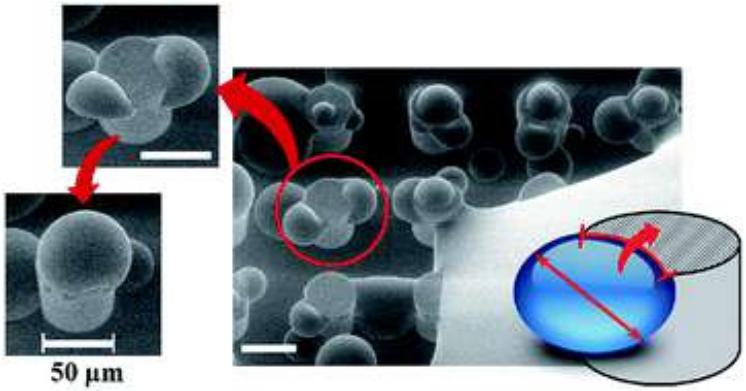




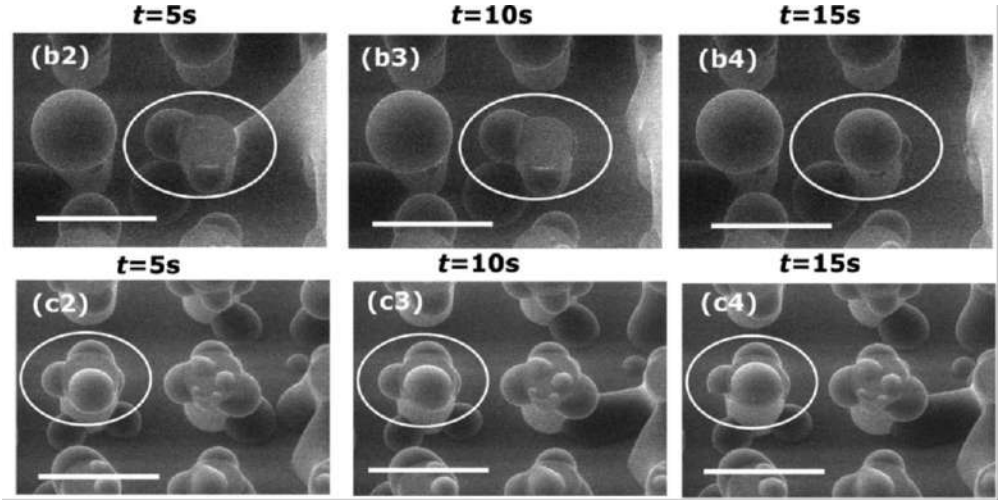
Yan *et al.*, *ACS Nano* **13**, 2019

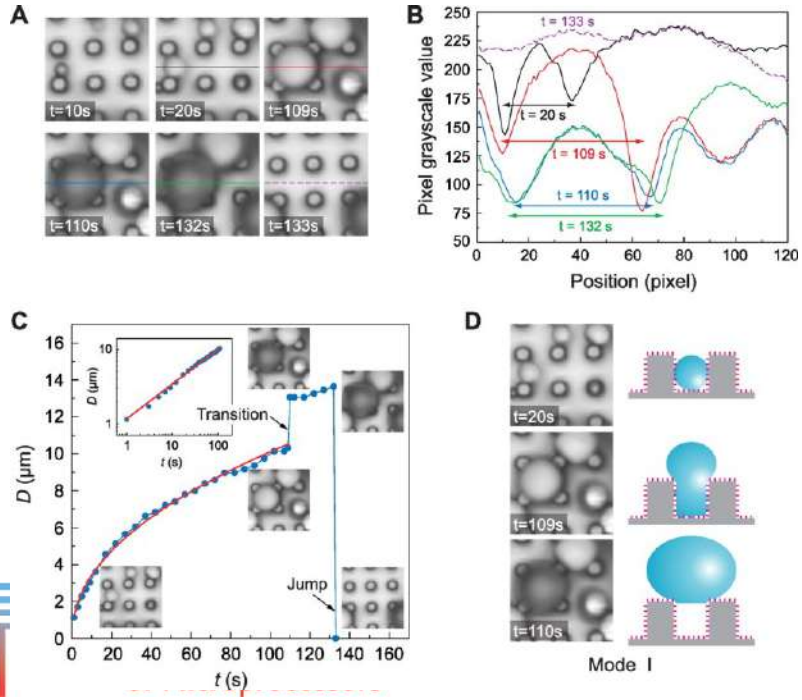


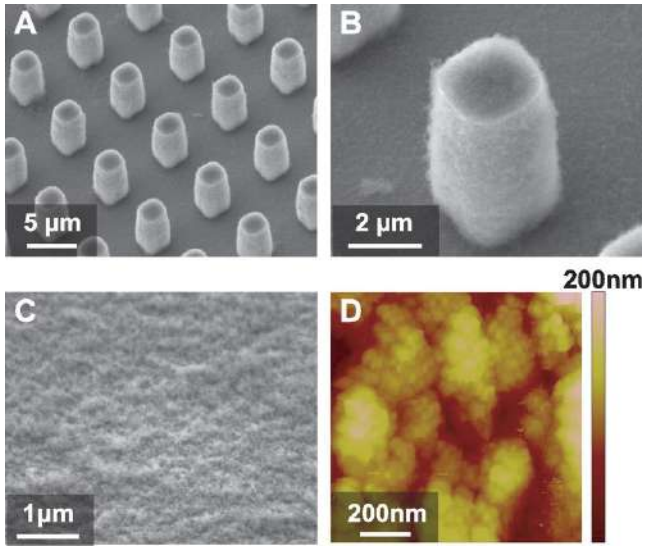
Dewetting Strategies II



Orejon *et al.*, *RSC Advances* **43**, 2016

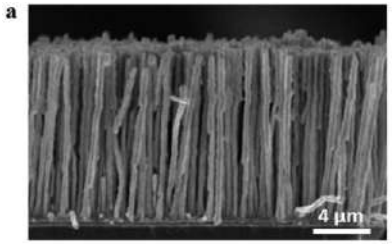


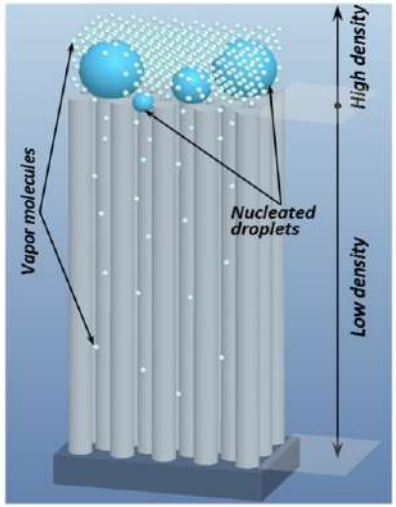


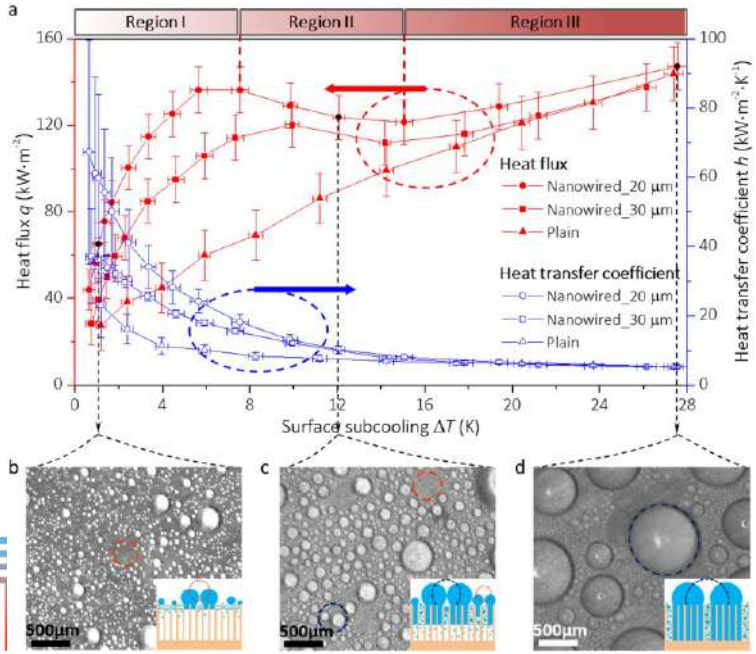


Lv *et al.*, *ACS Nano* **9**, 2015

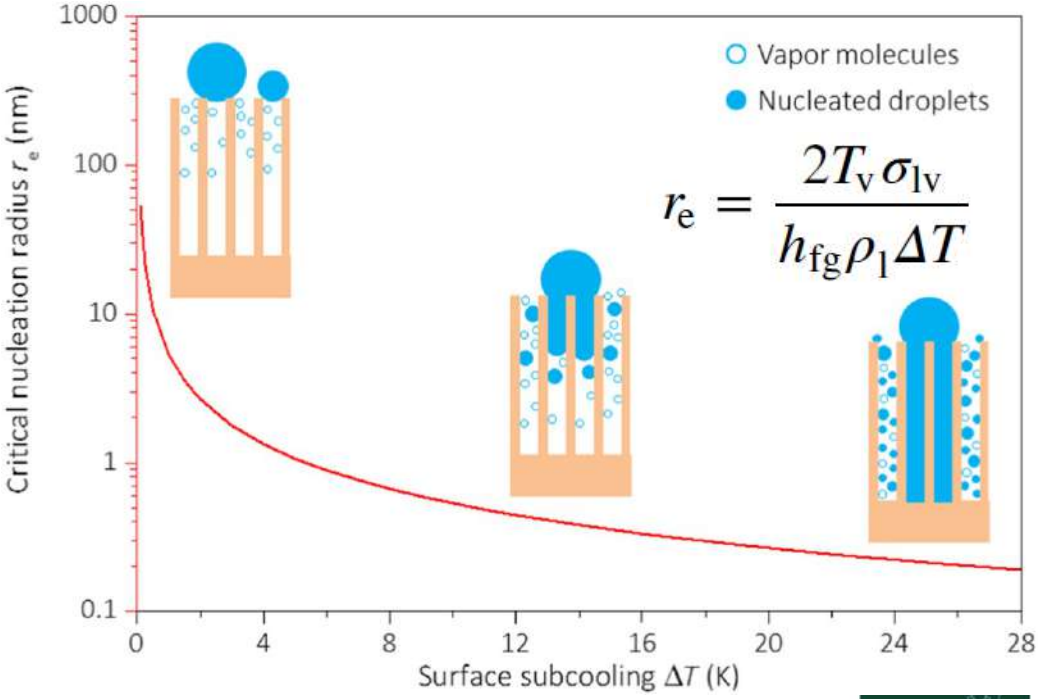
Subcooling – Nano-confinement





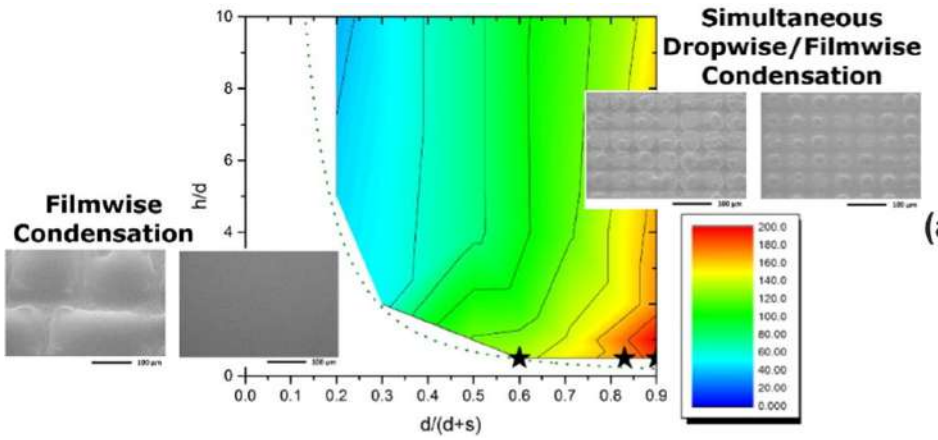


$$\Delta G(r_e) = \frac{\pi \sigma_{lv} r_e^2 (2 - 3\cos\theta + \cos^3\theta)}{3}$$

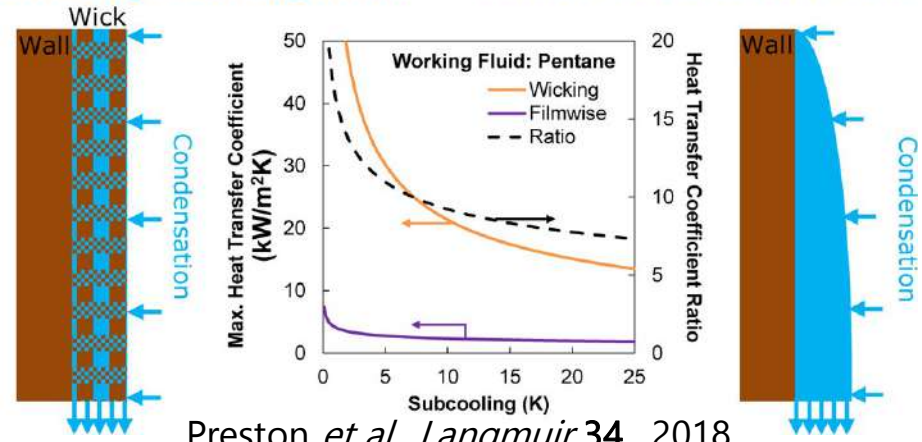


Wen *et al.*, *Nano Energy* **33**, 2017

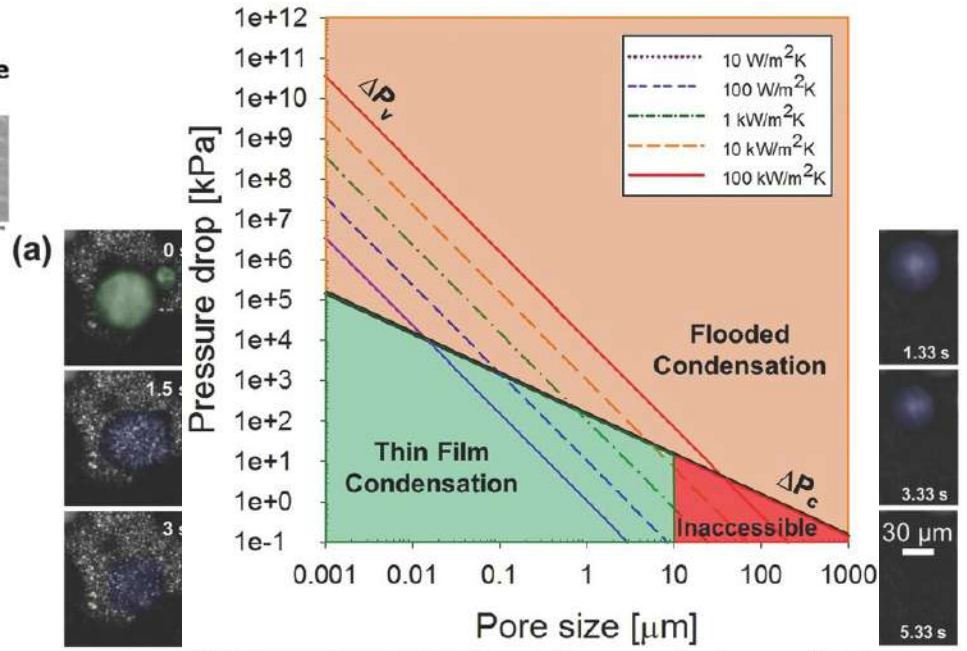
Overcome Sub-cooling – Other Strategies I

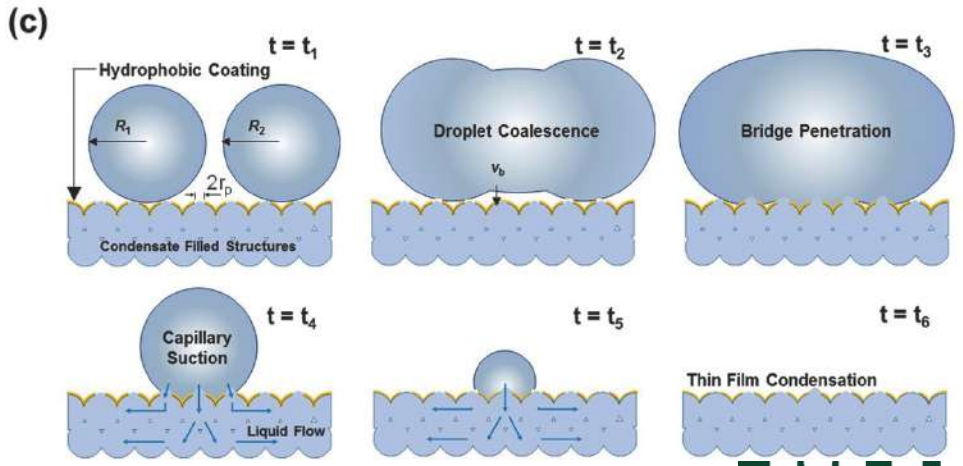


Orejon *et al.*, *IJHMT* **117**, 2017



Preston *et al.*, *Langmuir* **34**, 2018



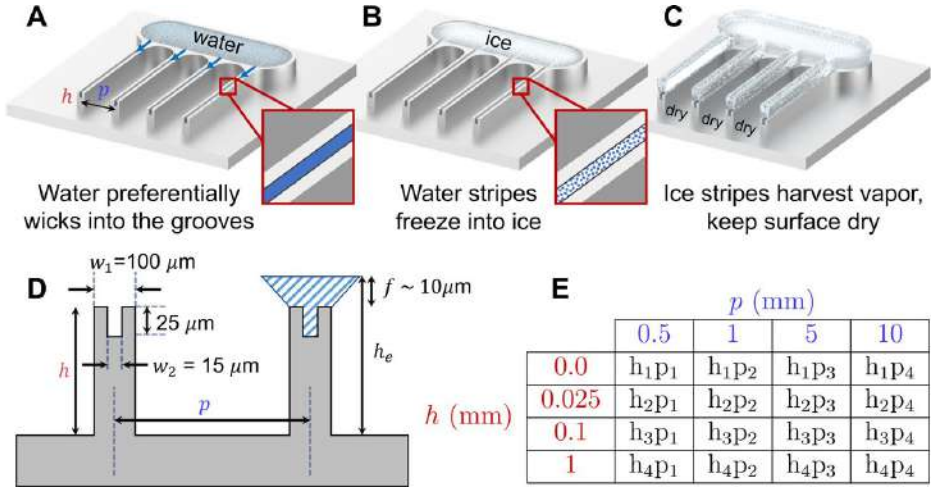


Oh *et al.*, *Appl. Functional Matter* **28**, 2018

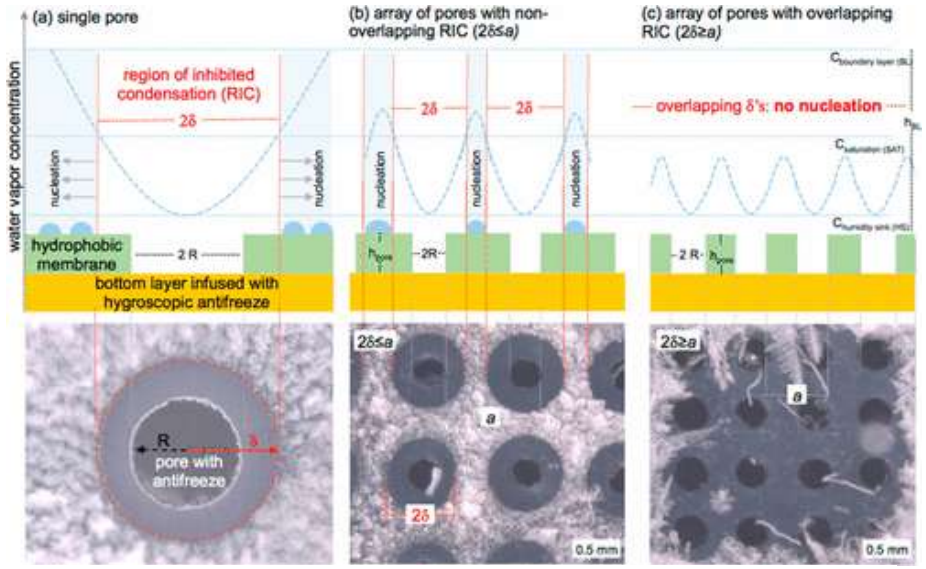
THERMASMART
Thermal Management of Microprocessors

Overcoming Sub-cooling – Other Strategies II

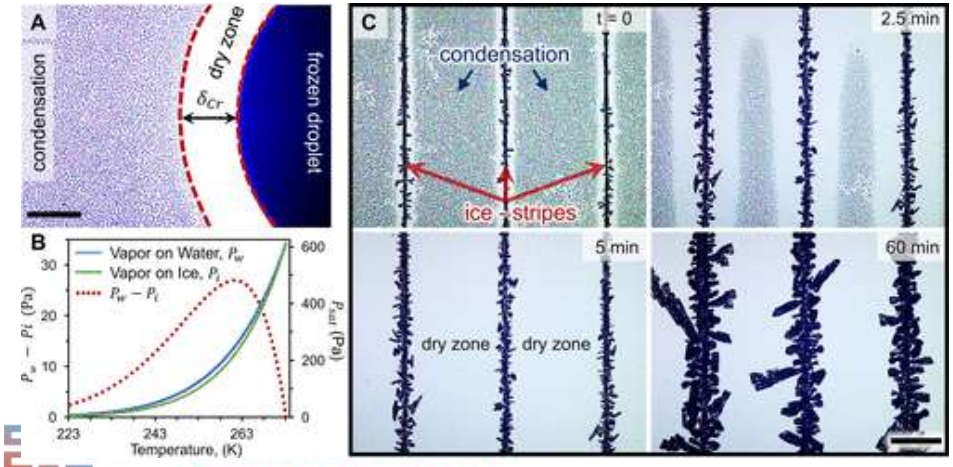
- **Hygroscopic Ice Micropatterns**



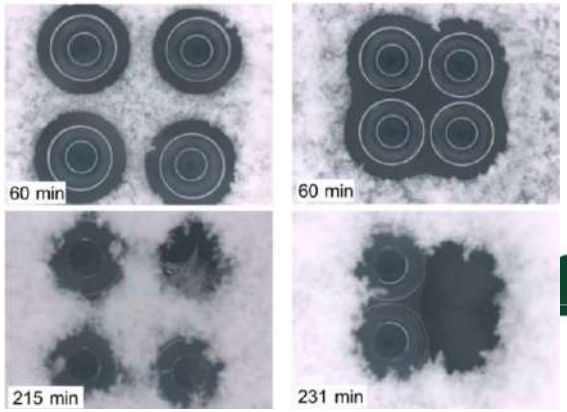
- **Use of Liquid Desiccants**



Sun & Rykaczewski, *ACS Nano* **11**, 2017



Farzad Ahmadi *et al.*, *ACS Appl. Matter. Interfaces* **10**, 2018



Sun *et al.*, *Langmuir* **31**, 2015

Conclusions & Concerns

- ✓ Dropwise Condensation on metallic structured surfaces without hydrophobic coating achieved
- ✓ Condensation mode highly dependent of sub-cooling
- ✓ Control of nucleation independently of sub-cooling conditions to avoid droplet attachment?
- ✓ Are structured surfaces better than smooth ones?
- ✓ When are we going to be able to use of the beautiful imaging techniques available for boiling or phase flow?

Acknowledgments

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Thank you very much
for your attention
Any Answers are Welcome

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JP18K13703