High-Performance Solar Thermal Energy Conversion with Dry Cooling

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In collaboration with

Massachusetts Institute of Technology

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KHALIFA UNIVERSITY

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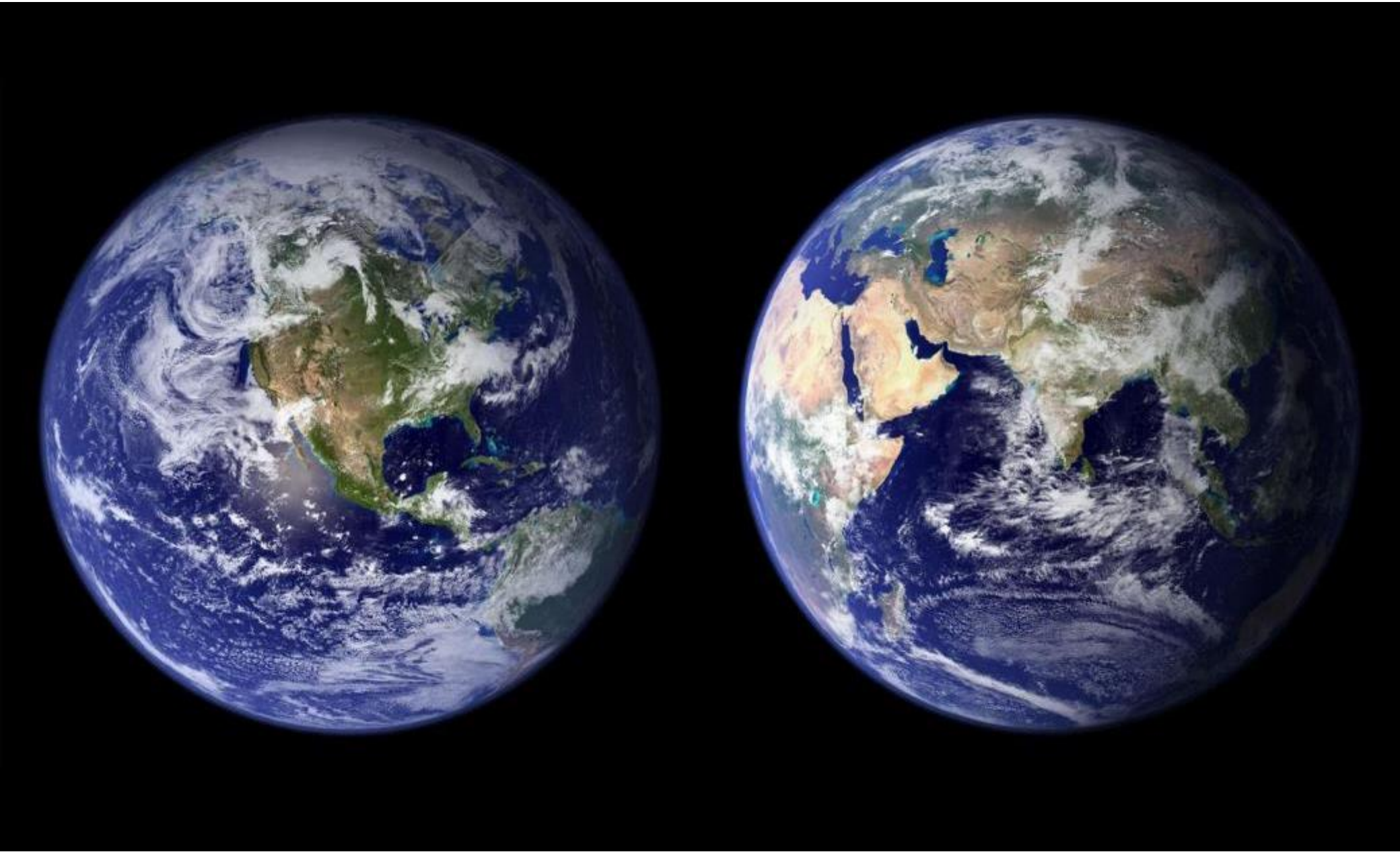
Picture of Earth – NASA



Solar Power Generation: Optical Concentration

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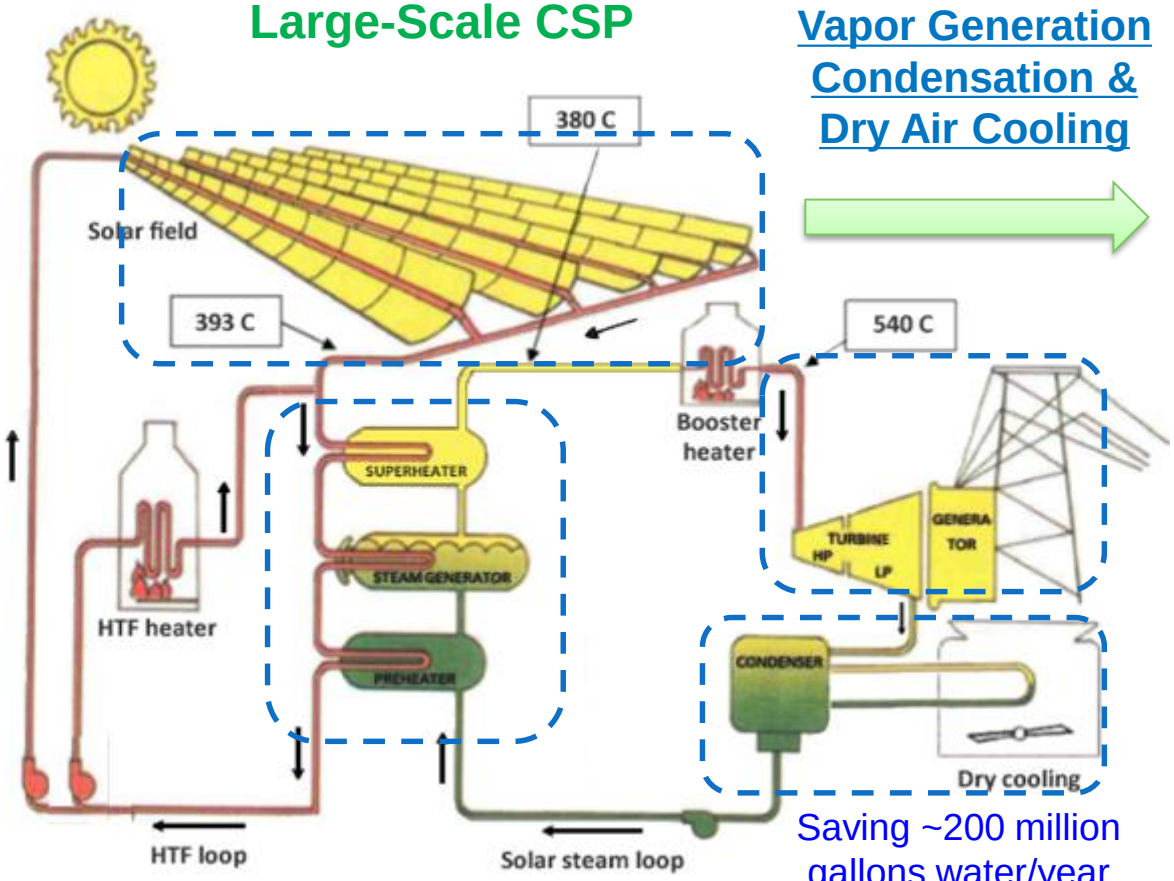
Large-Scale CSP

Light Absorption
Vapor Generation
Condensation &
Dry Air Cooling

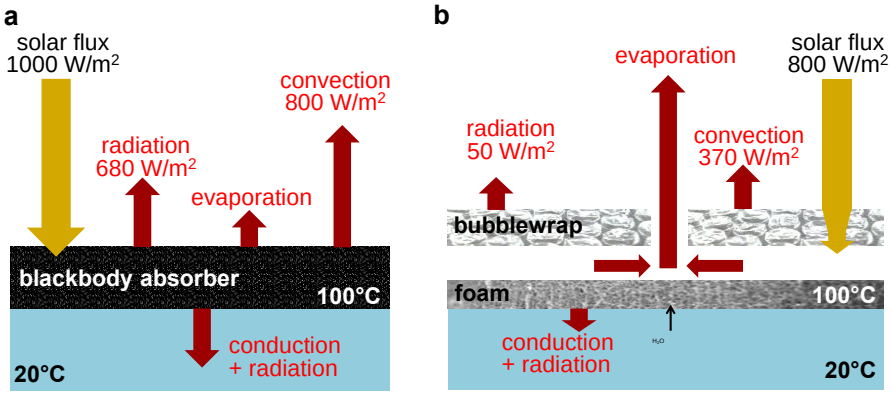


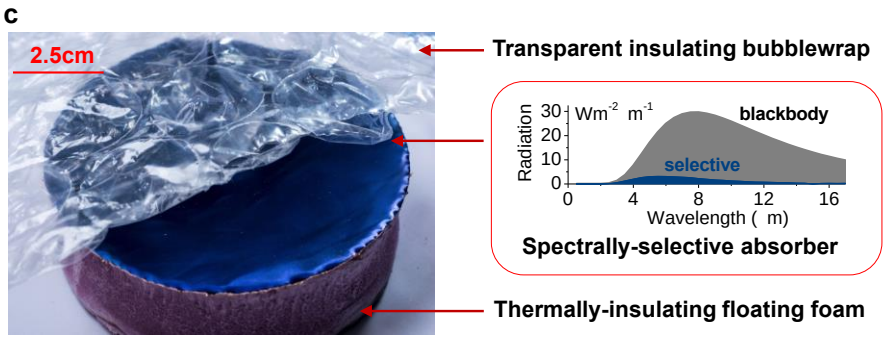
Saving ~200 million gallons water/year

100-MW Shams-1 Concentrated Solar Power Plant in Abu Dhabi

- A. Almasabai, A. Alobaidli, T.J. Zhang, “Transient Characterization of Multiple Parabolic Trough Collector Loops in a 100 MW CSP Plant for Solar Energy Harvesting”, *Energy Procedia: SolarPACES2014*, vol.69, pp.24-33, 2015.
- W.L. Yang, J.W. Gao, G. Feng, T.J. Zhang, “An Optimal Approach to Output-feedback Robust Model Predictive Control of LPV Systems with Disturbances,” *International Journal of Robust and Nonlinear Control*, vol.26, pp.3253-3273, 2016.

Solar Steam Generation: Thermal Concentration

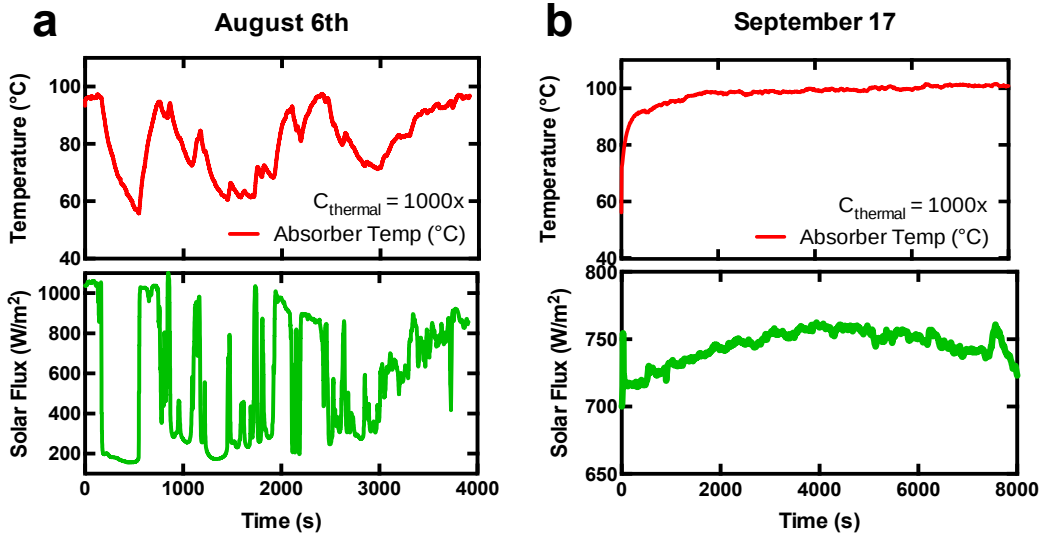


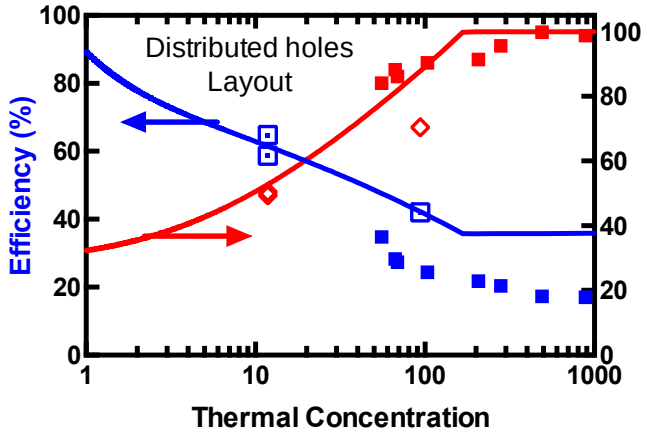


Floating solar receiver for steam generation @ 1 Sun

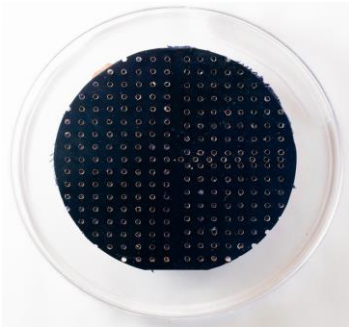
G. Chen (MIT) & T.J. Zhang (Masdar Inst.)

Light Absorption → Vapor Generation → Condensation → "Water" Cooling





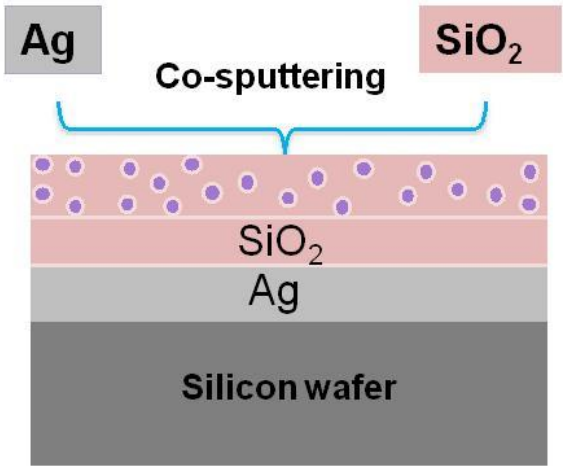
Up to 85% solar-vapor efficiency



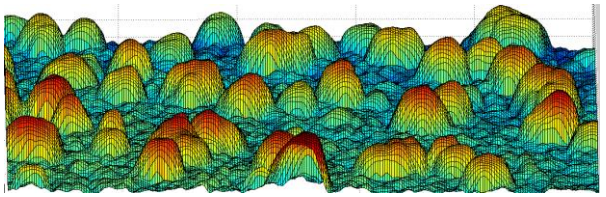
Distributed holes
12x concentration

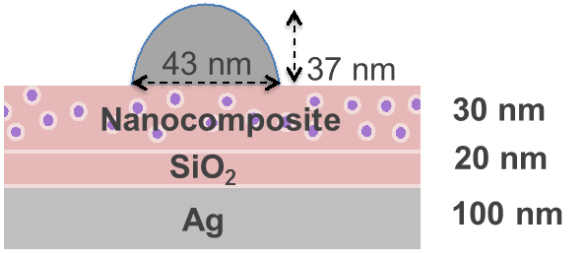
G. Ni, …, T.J. Zhang, G. Chen, "Steam Generation under One Sun Using a Floating Structure with Thermal Concentration", *Nature Energy,* vol.1, 16126, 2016. **(MIT News, Scientific American, Fox News, Science, IEEE/ASCE Magazine)**

Light Absorption: Nanocomposite Morphology

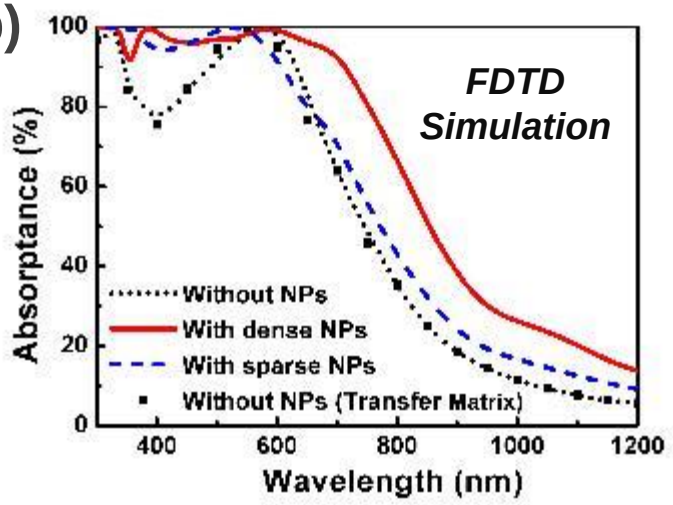


(a) AFM surface profile



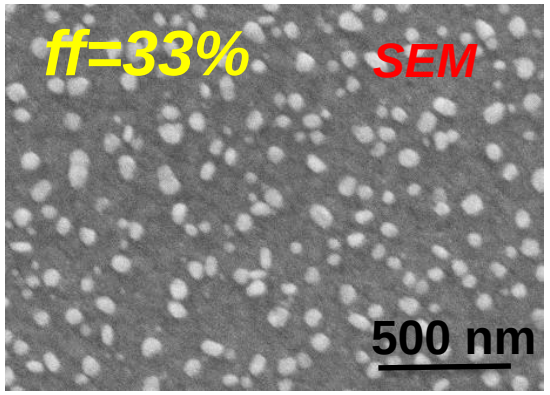


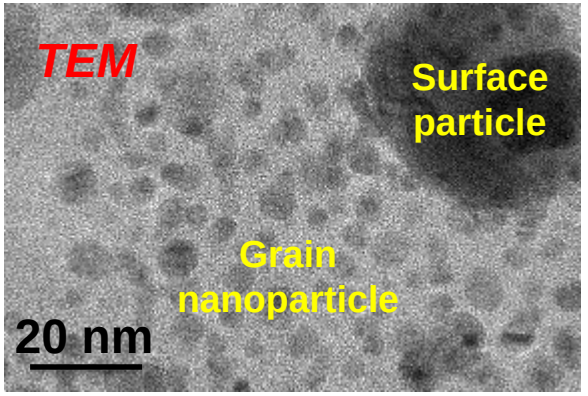
(b)



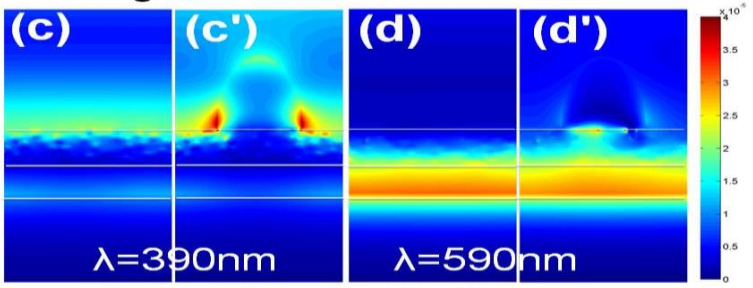
Enhanced light absorption

(1) Gap plasmon; (2) Destructive interference

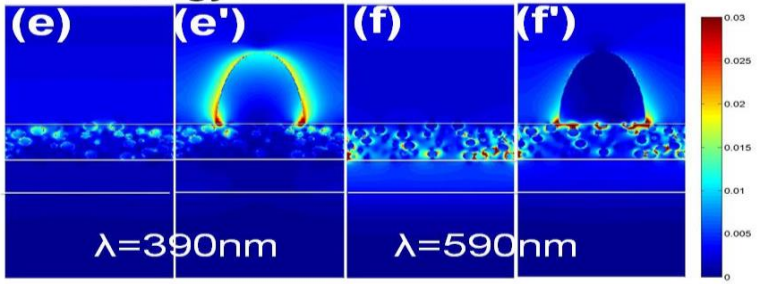




Magnetic field distributions



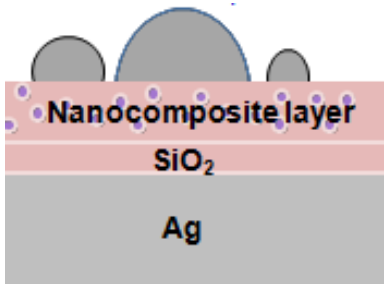
Energy flow distributions



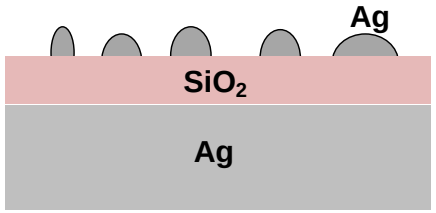
J.Y. Lu,…, T.J. Zhang, “Near-Perfect Ultrathin Nanocomposite Absorber with Self-Formed Topping Plasmonic Nanoparticles”, *Advanced Optical Materials*, vol.5, 1700222, 2017

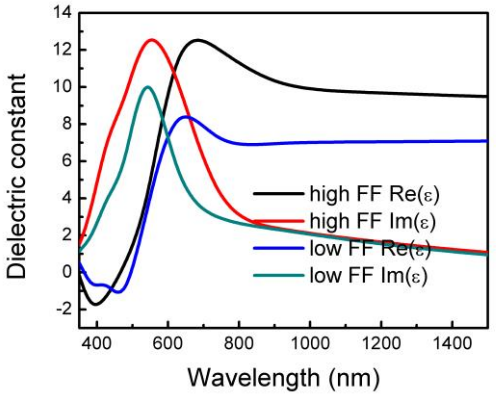
Light Absorption: Nanocomposite Absorbers

- **Additional Ag deposition on cermet absorption**

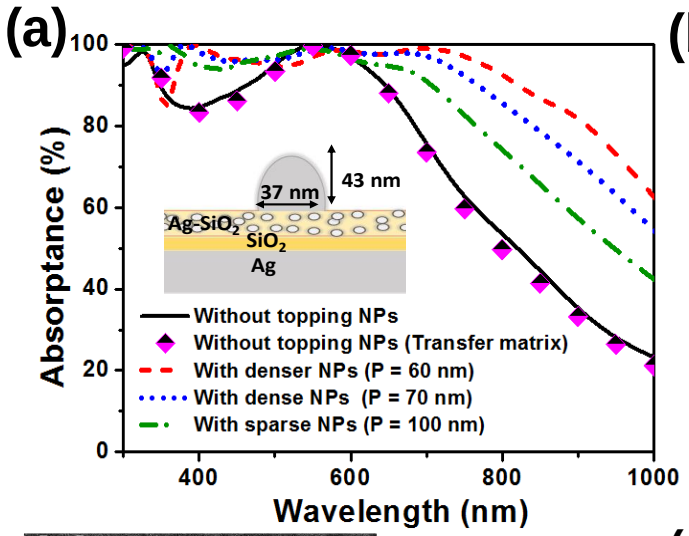


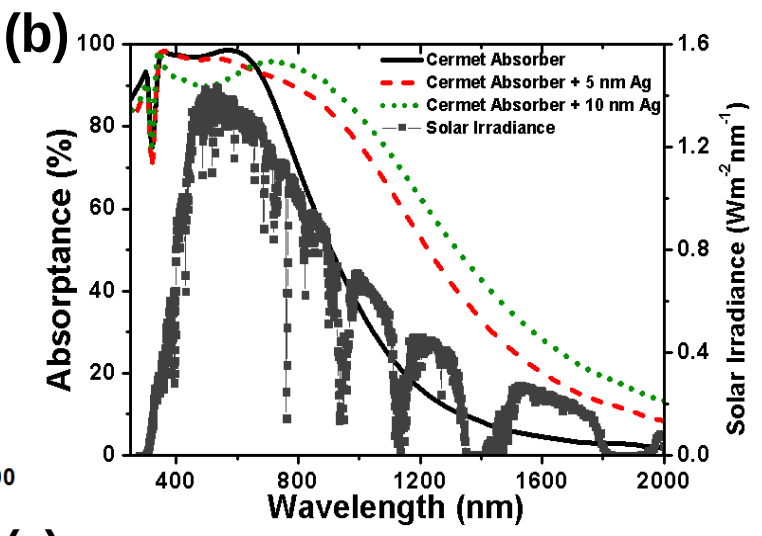
- **Ag deposition on SiO_2-coated Ag layer**

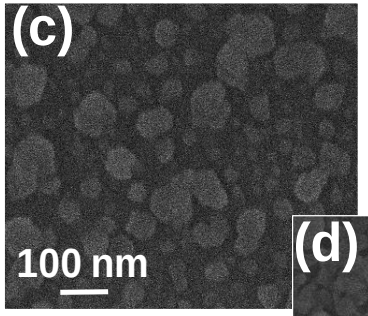


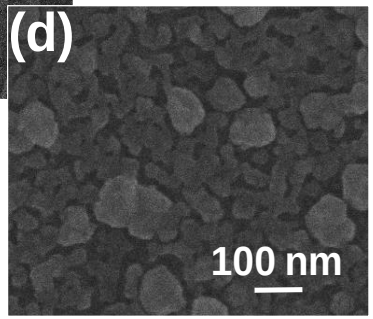


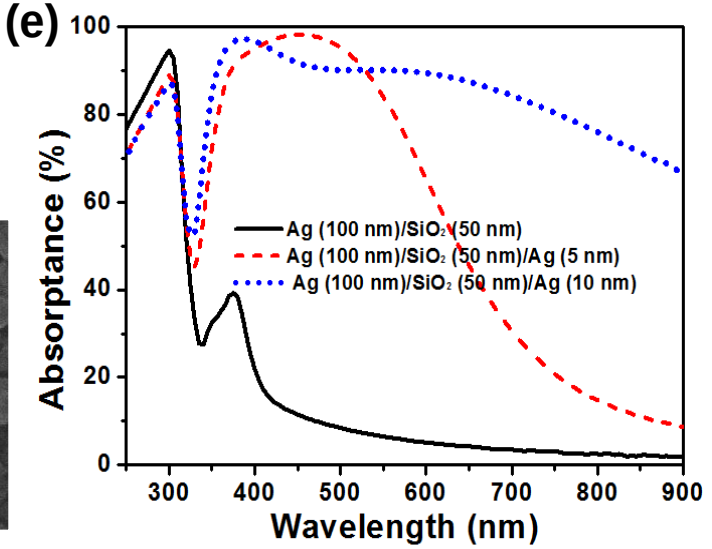
(Spectroscopic Ellipsometry)











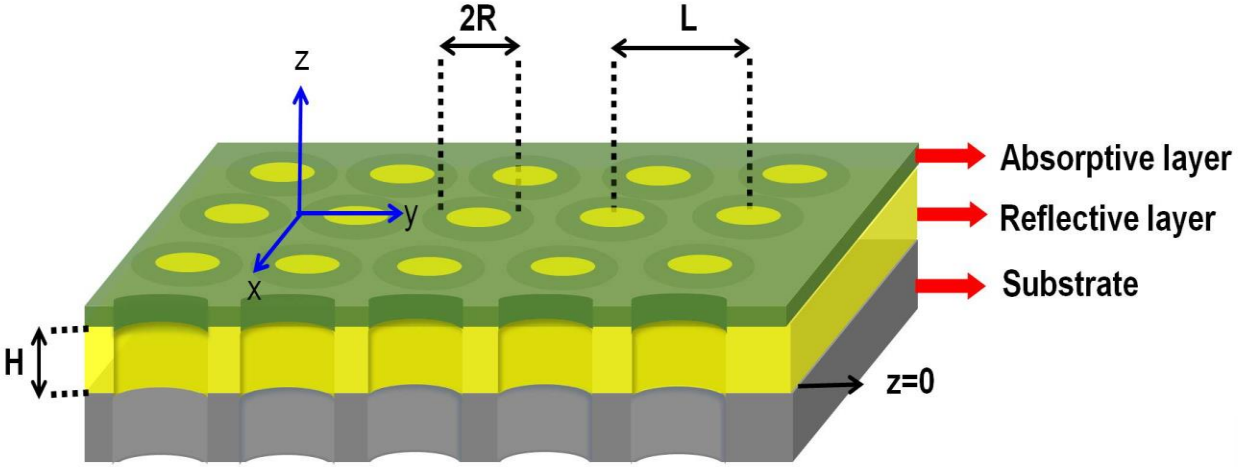
High FF~ 60%;
Low FF ~ 30%
10nm Silver
Nanoparticles

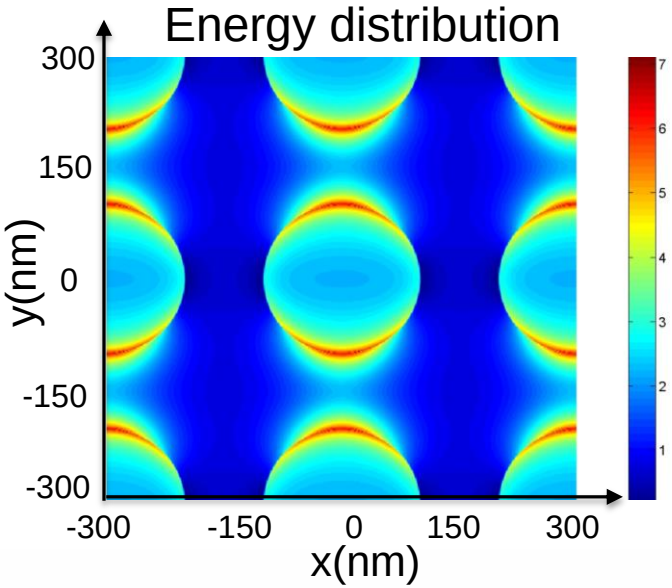
J.Y. Lu, …, T.J. Zhang, "Effective Dielectric Constants and Spectral Density Analysis of Plasmonic Nanocomposites", *Journal of Applied Physics – AIP*, vol.120, 163103, 2016.

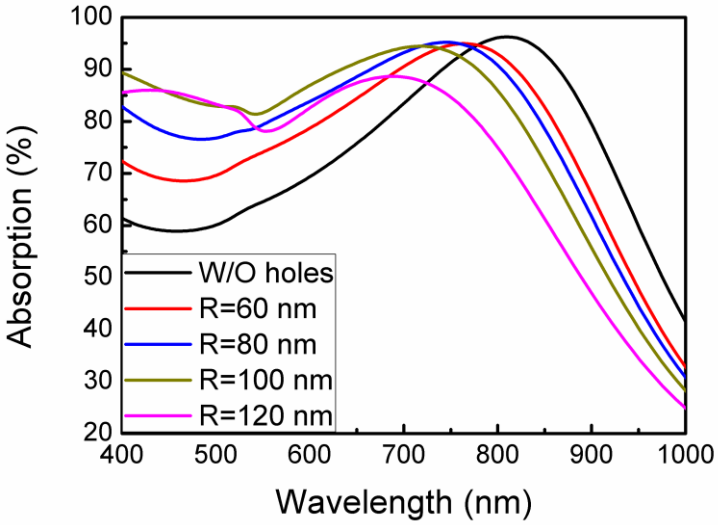
Light Absorption: Nanoporous Ultrathin Film

- To combine the strong interference in ultrathin Ge film absorber with localized surface plasmons around Au nanopores

Bilayer ultrathin film system (Ge 20nm onto Au 150nm)





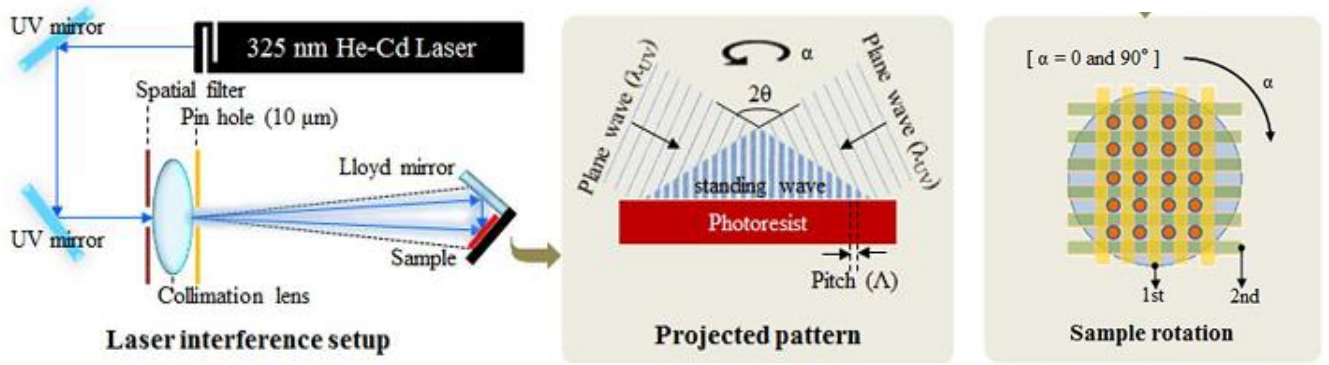


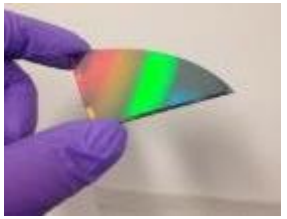
T.J. Zhang (Masdar Inst.) & N. X. Fang (MIT)

- FDTD simulation results
- Visible absorption enhancement
- Radius of holes<=100nm
- Good option for solar evaporation

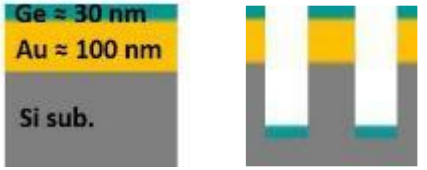
Light Absorption: Nanoporous Absorber Fab.

[Laser interference with Lloyd mirror]



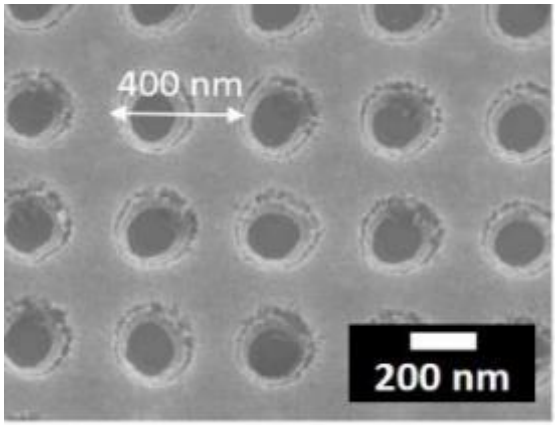


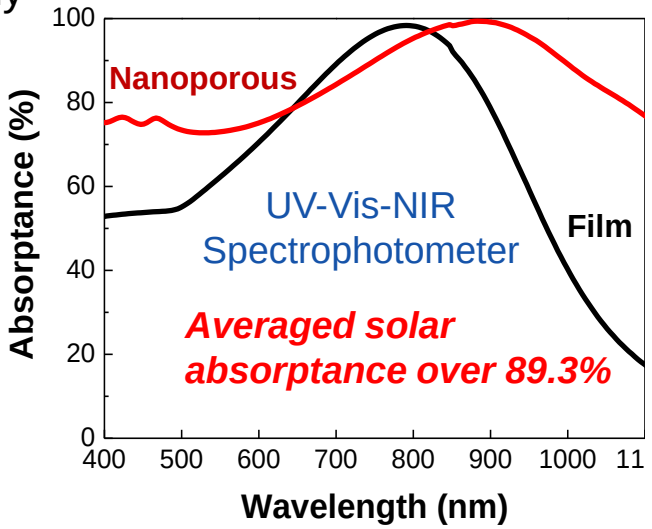
1 inch X 1 inch

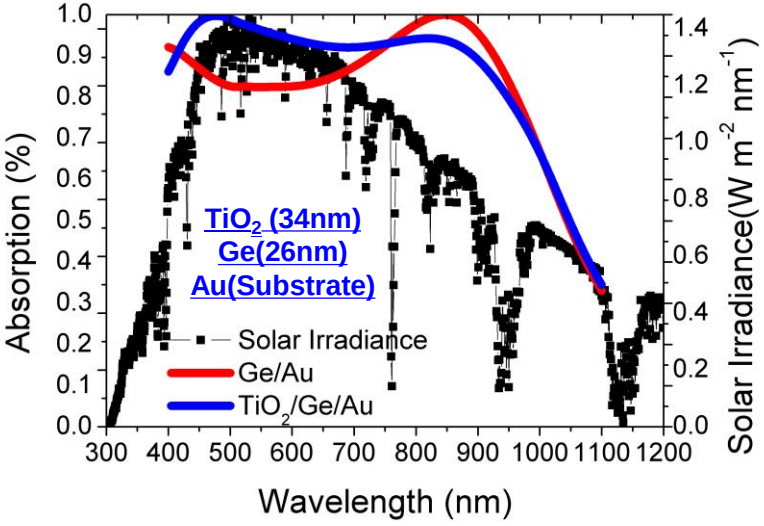


Film **Nanoporous**

(Laser interference lithography + E-beam evaporation)

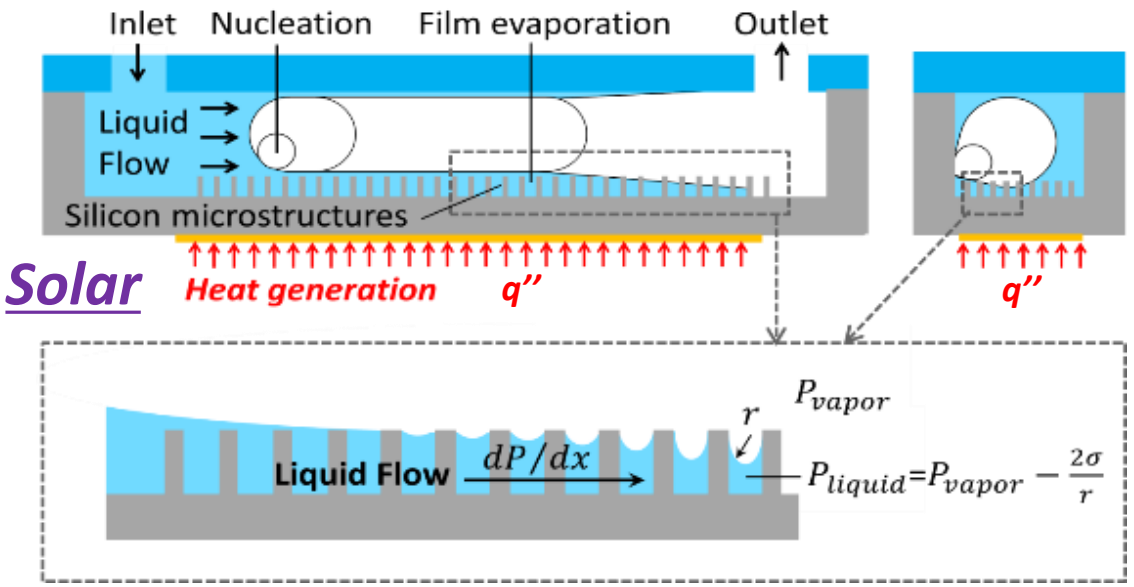


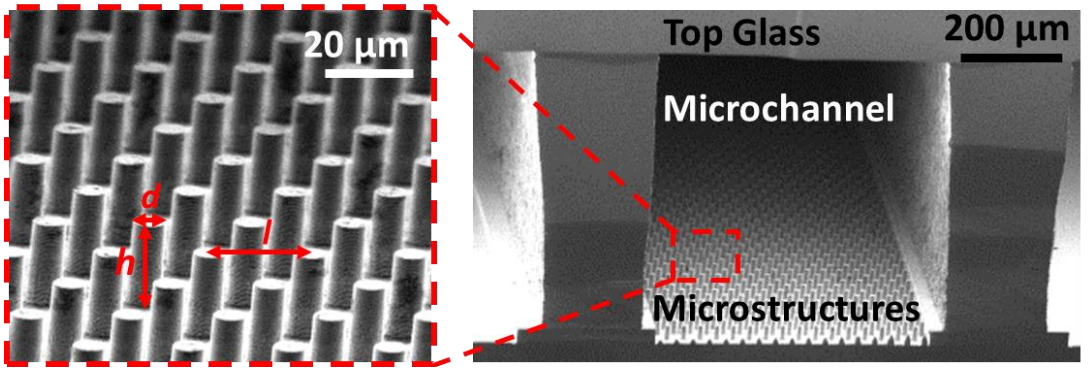


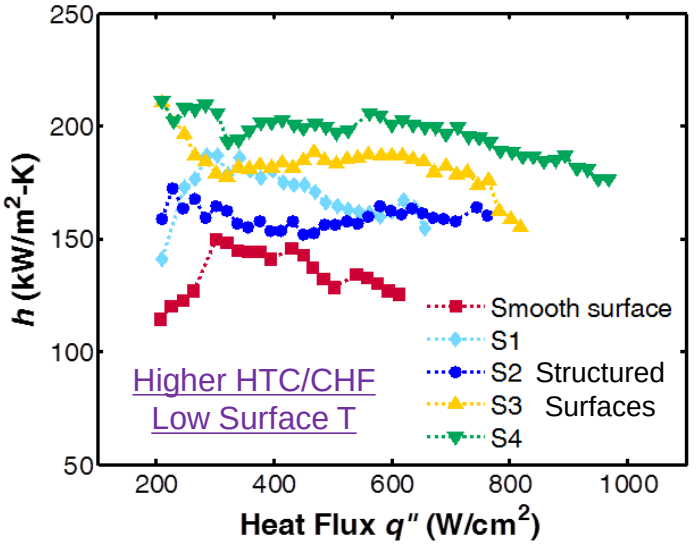


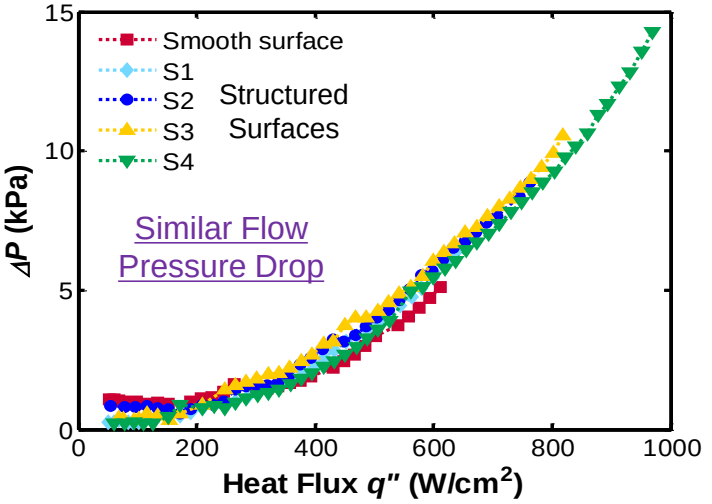
J.Y. Lu, …, N.X. Fang, T.J. Zhang, "Localized Surface Plasmon Enhanced Ultrathin Film Broad-Band Nanoporous Absorber", *Advanced Optical Materials*, vol.4, pp.1255-1264, 2016 **(AOM Top 5 most downloaded – July 2016 , MIT News)**

Vapor Generation: Microstructured Surfaces









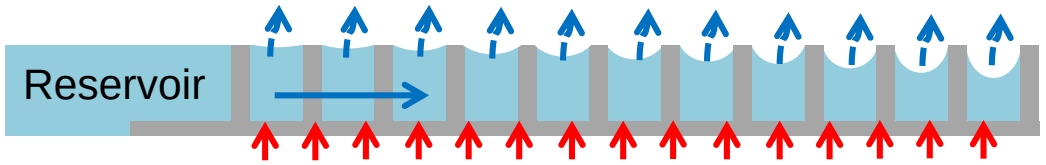
E.N. Wang (MIT) & T.J. Zhang (Masdar Inst.)

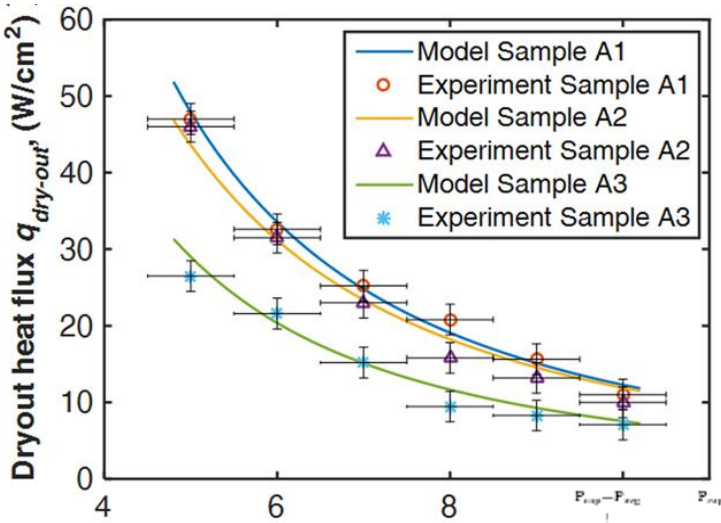
- Y.Y. Zhu, D.S. Antao, D.W. Bian, T.J. Zhang, E.N. Wang, "Surface Structure Enhanced Microchannel Flow Boiling", *Journal of Heat Transfer – ASME*, 138 (9), 091501, 2016.
- Y.Y. Zhu, D.S Antao, …, T.J. Zhang, E.N. Wang, "Suppressing high-frequency temperature oscillations in microchannels with surface structures", *Applied Physics Letters – AIP*, 110 (3), 033501, 2017.

Vapor Generation: Enhanced Liquid Propagation

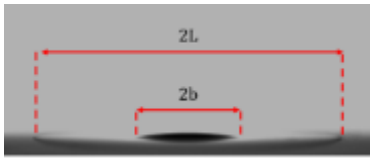
Development of a dry-out heat flux model for vapor generation

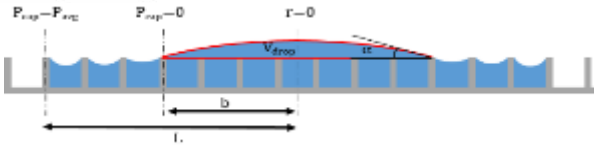
- Capture the meniscus along the wicking distance
- Capture the coupled fluid flow, pressure and interface

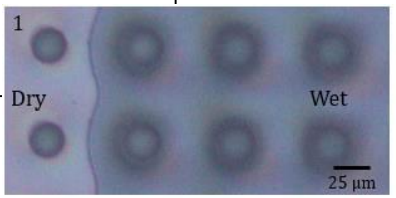


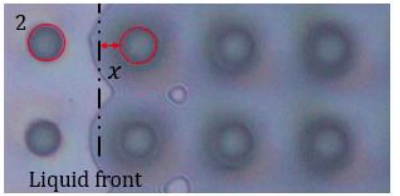


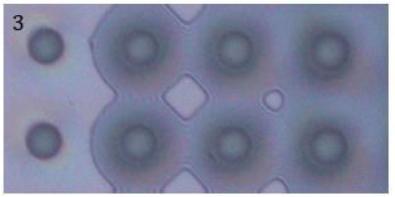
T.J. Zhang (Masdar Inst.) & E.N. Wang (MIT)

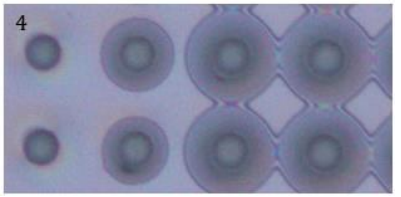


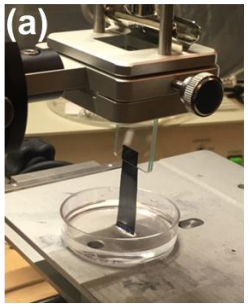


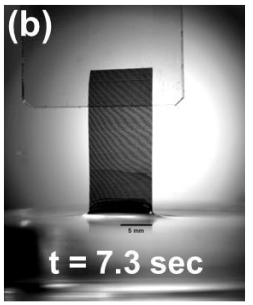


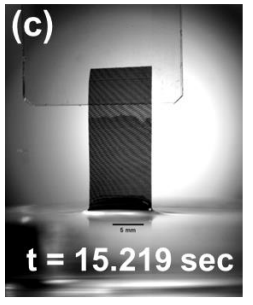


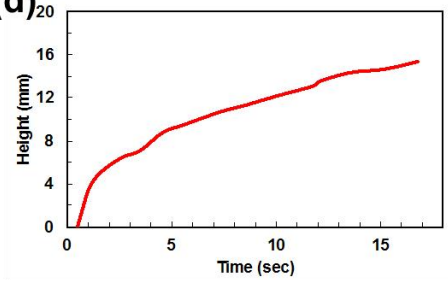


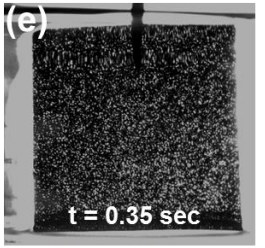








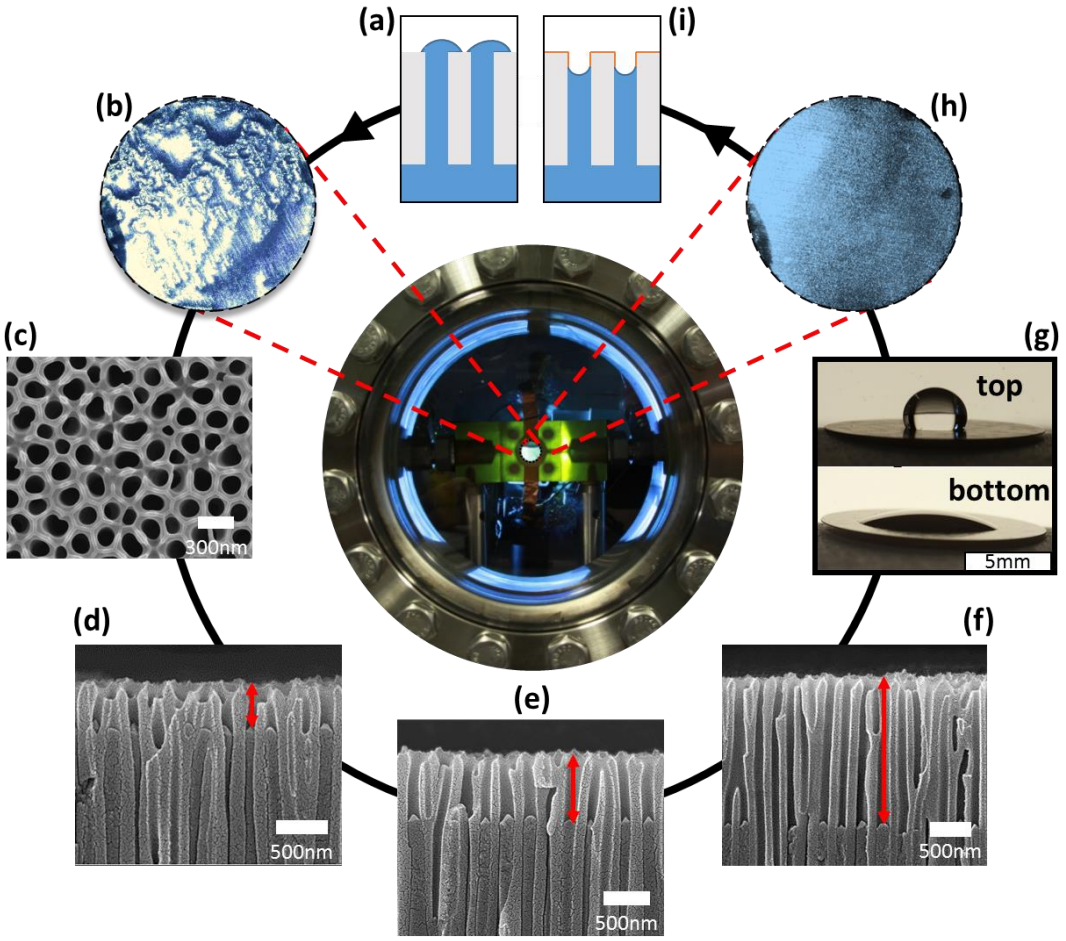


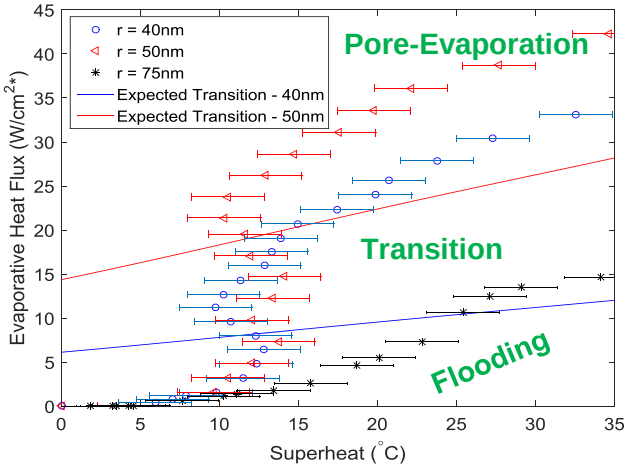


Ultra-fast liquid propagation

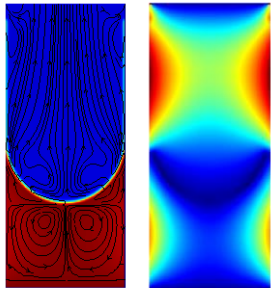
- M.H. Alhosani, T.J. Zhang, “Dynamics of Microscale Liquid Propagation in Micropillar Arrays,” *Langmuir – ACS*, vol.33, pp.6620-6629, 2017.
- Y.Y. Zhu, D.S. Antao, Z. Lu, S. Somasundaram, T.J. Zhang, E. N. Wang, "Prediction and Characterization of Dry-out Heat Flux in Micropillar Wick Structures," *Langmuir – ACS*, vol.32, pp.1920–1927, 2016.

Vapor Generation: Thin Liquid Film Evaporation





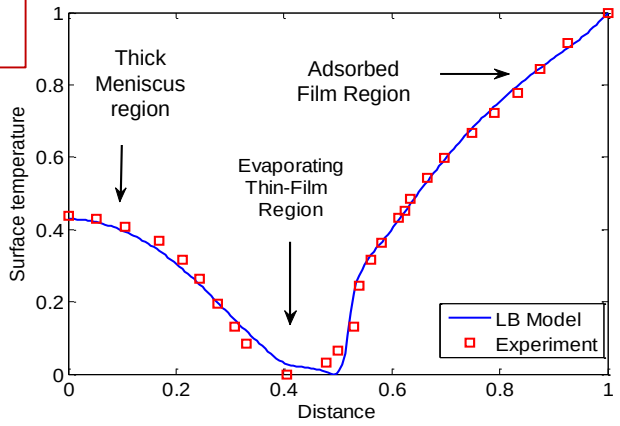
E.N. Wang (MIT) & T.J. Zhang (Masdar Institute)



Hydrophobic (137°)

Density (left)
Temperature (right)
(TFE Profile from Thermal LBM)

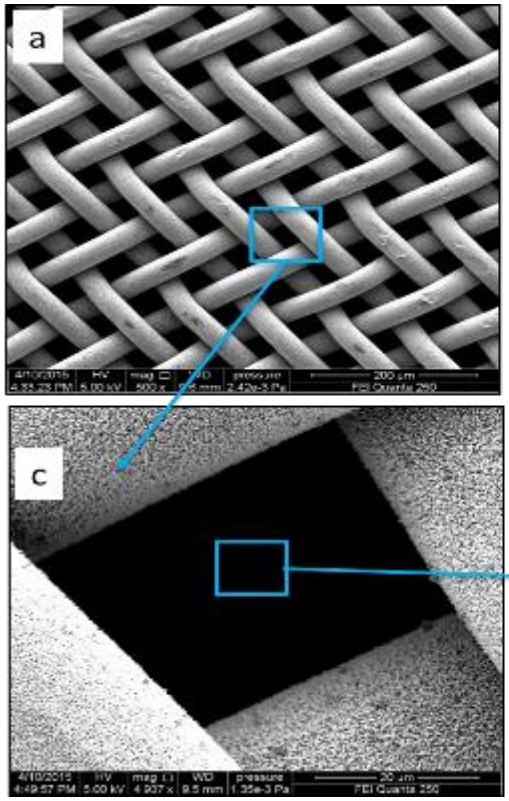
Hydrophilic (15°)

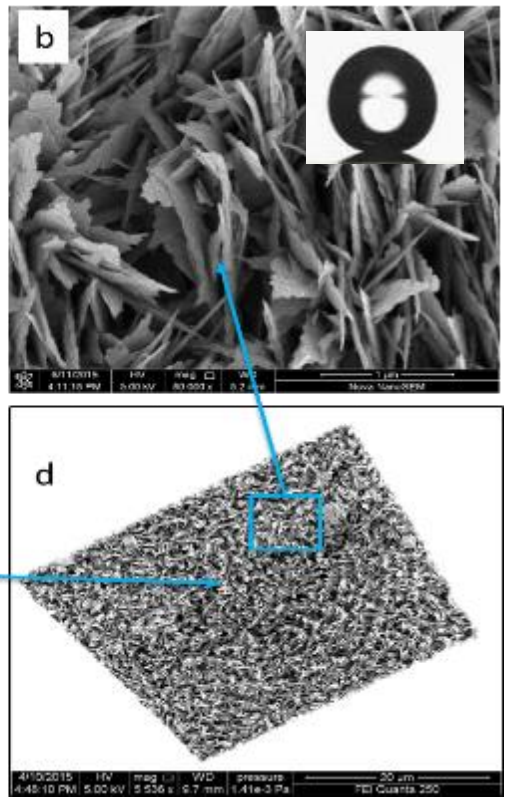


- K.L. Wilke, …, T.J. Zhang, E.N. Wang, "Parametric Study of Thin Film Evaporation from Nanoporous Membranes", *Applied Physics Letters – AIP*, vol.111, 2017.
- K.L. Wilke, …, T.J. Zhang, E.N. Wang, "Controlled Wetting in Nanoporous Membranes for Thin Film Evaporation", *Journal of Heat Transfer – ASME*, vol.138, 2016.
- W.L. Yang, H.X. Li, …, T.J. Zhang, "Prediction of Thin Liquid Film Evaporation Characteristics with a Thermal Lattice Boltzmann Method", *ITherm2016*, Las Vegas.

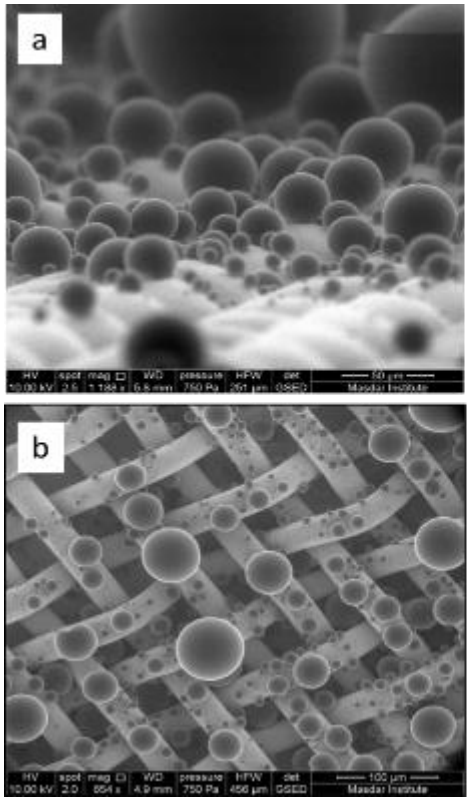
Condensation: Nanostruc. Microporous Surface

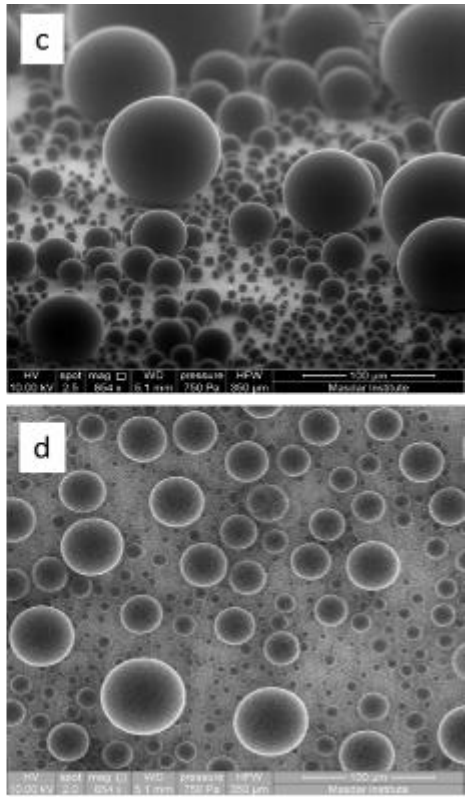
Superhydrophobic microporous surfaces for Jumping Droplet-enhanced Condensation





Nanostructured micro-mesh surface morphologies





Condensation on porous (left) & flat surfaces(right)

- G.Q. Li, …, T.J. Zhang, “Microscopic Droplet Formation and Energy Transport Analysis of Condensation on Scalable Superhydrophobic Nanostructured Copper Oxide Surfaces”, *Langmuir – ACS*, vol.30, 2014.
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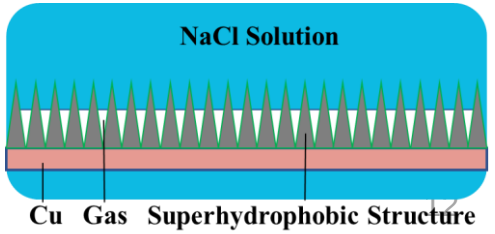
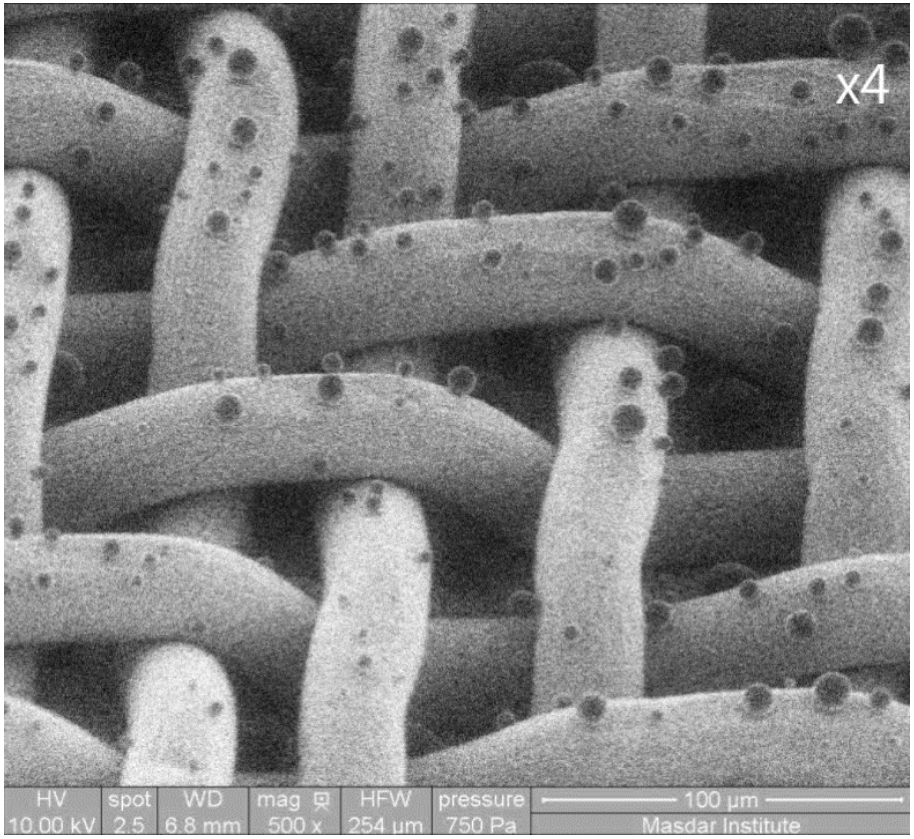
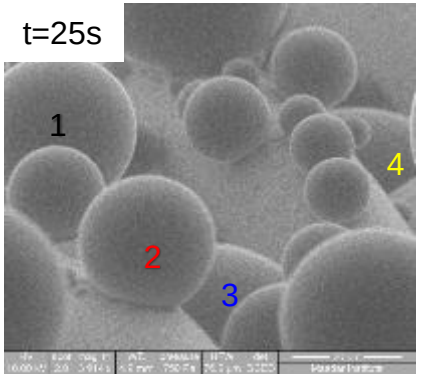
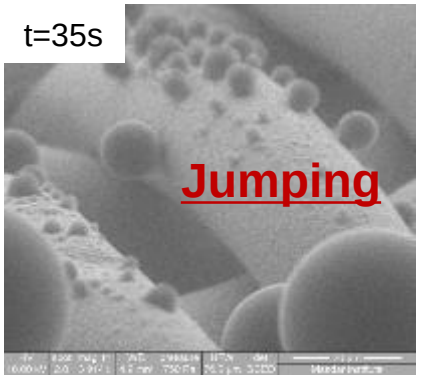
- A. Aili, Q. Ge, T.J. Zhang, "How Nanostructures Affect Water Droplet Nucleation on Superhydrophobic Surfaces", *Journal of Heat Transfer – ASME*, vol.139, 112401, 2017

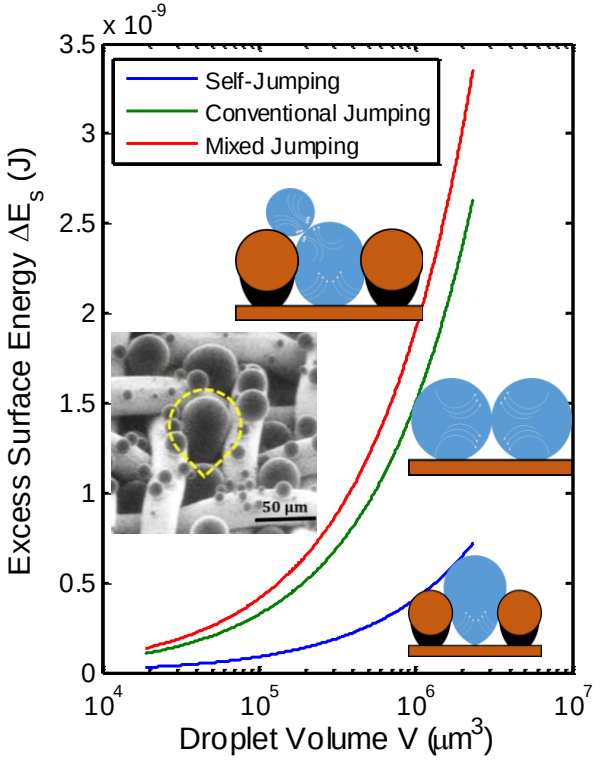


Condensation: Directional Droplet Jumping

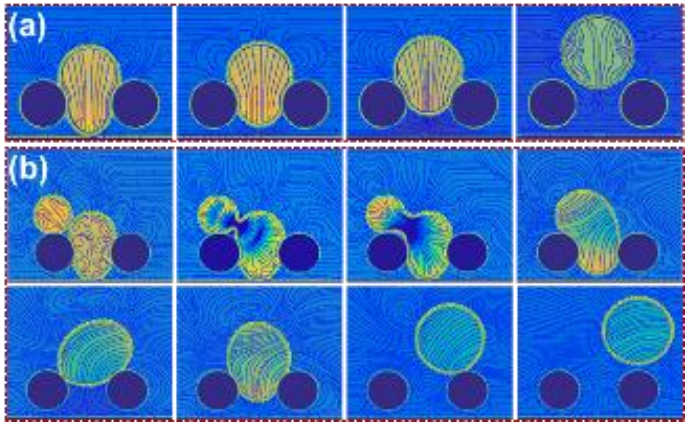








Faster growth of droplets on microporous surfaces:
1) Only in upward direction; 2) Larger solid contact area;
3) Lower temperature on base than on wire



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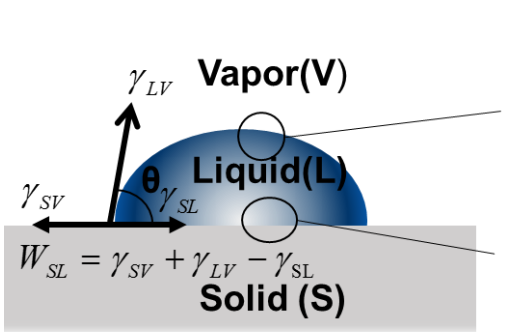
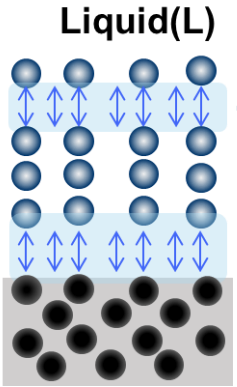
- H.X. Li, W. Yang, A. Aili, T.J. Zhang, "Insights into the Impact of Surface Hydrophobicity on Droplet Coalescence and Jumping Dynamics", *Langmuir – ACS*, vol.33, 8574-8581, 2017

Quantum Simulation of Surface Wettability

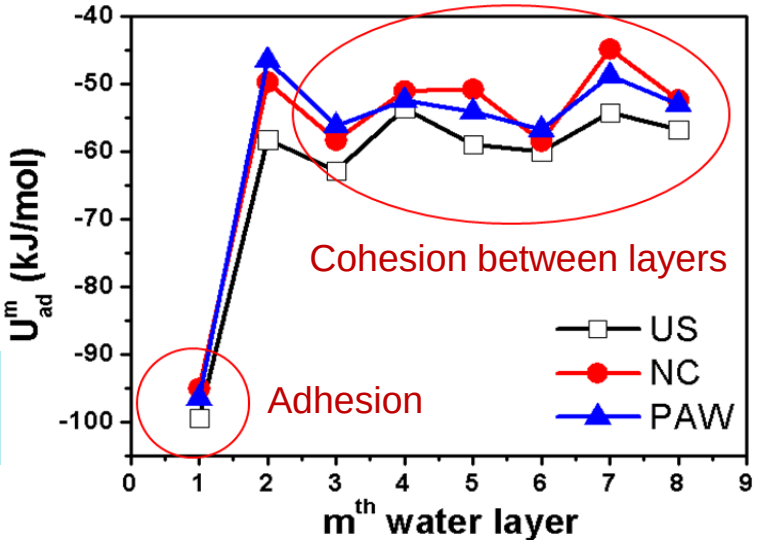


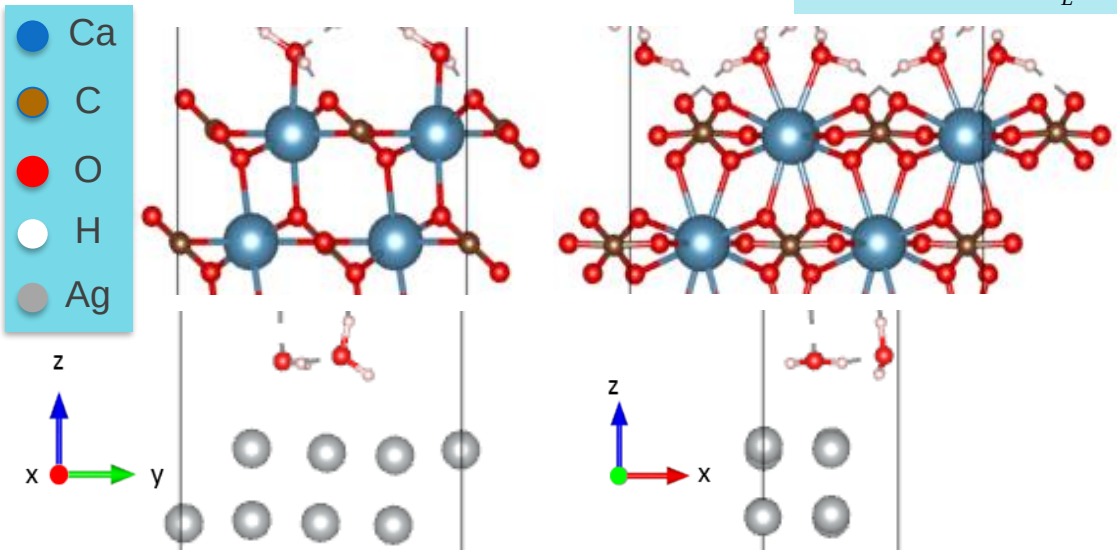


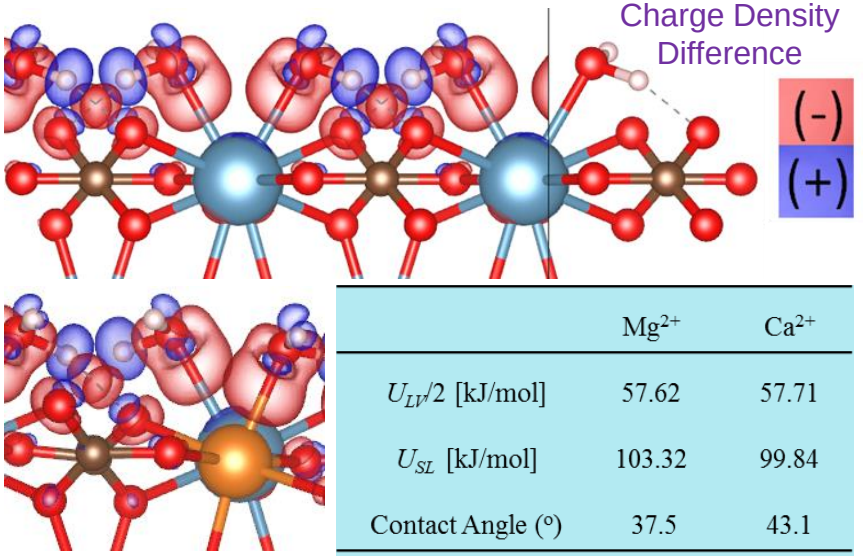
$$U_{ad}^{m=3\sim\infty} = -\frac{U_{LV}}{2}$$

$$U_{ad}^{m=1} = -U_{SL}$$

$$U_{ad}^{m} = \frac{U_{S+mL} - U_{S+(m-1)L} - U_{\mathrm{mL}}}{n_L}$$







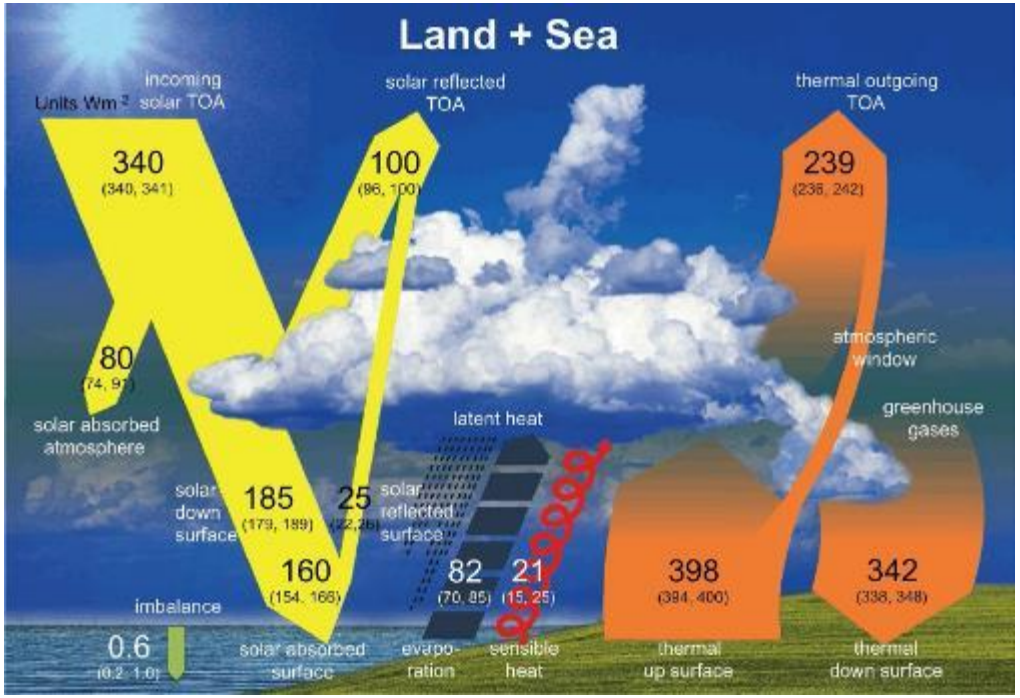
	Mg^{2+}	Ca^{2+}
$U_{LV}/2$ [kJ/mol]	57.62	57.71
U_{SL} [kJ/mol]	103.32	99.84
Contact Angle (°)	37.5	43.1

First-Principles Prediction of **Contact Angle**

$$\cos(\theta) = \frac{U_{SL} - U_{LV}/2}{U_{LV}/2}$$

J.Y. Lu, Q. Ge, H.X. Li, A. Raza, T.J. Zhang, "Direct Prediction of Calcite Surface Wettability with First-Principles Quantum Simulation", *The Journal of Physical Chemistry Letters – ACS*, vol.8, pp.5309-5316, 2017

Acknowledgments



Earth's Energy Budget

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High-Performance Compact Solar Thermal Power and Cooling Systems

Profs. TieJun Zhang, Amal Al Ghaferi, Weidong Xiao **(Masdar Institute of Science and Technology)**

Profs. Evelyn Wang, Gang Chen, Nicholas X. Fang **(Massachusetts Institute of Technology, MIT)**

Flagship Research Project, Funded by Cooperative Agreement between Masdar Institute UAE & MIT USA

Transient Characterization and Energy Harvesting of Shams-1 Concentrating Solar Power Plant

Prof. TieJun Zhang **(Masdar Institute of Science and Technology)**

University-Industry Research Collaboration Award, Funded by UAE Ministry of Higher Education & Scientific Research – National Research Foundation, in collaboration with the **Shams Power Company in Abu Dhabi**

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UNITED ARAB EMIRATES MINISTRY OF HIGHER EDUCATION & SCIENTIFIC RESEARCH

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