The Micro and Nano Fabrication Technologies of MEMS

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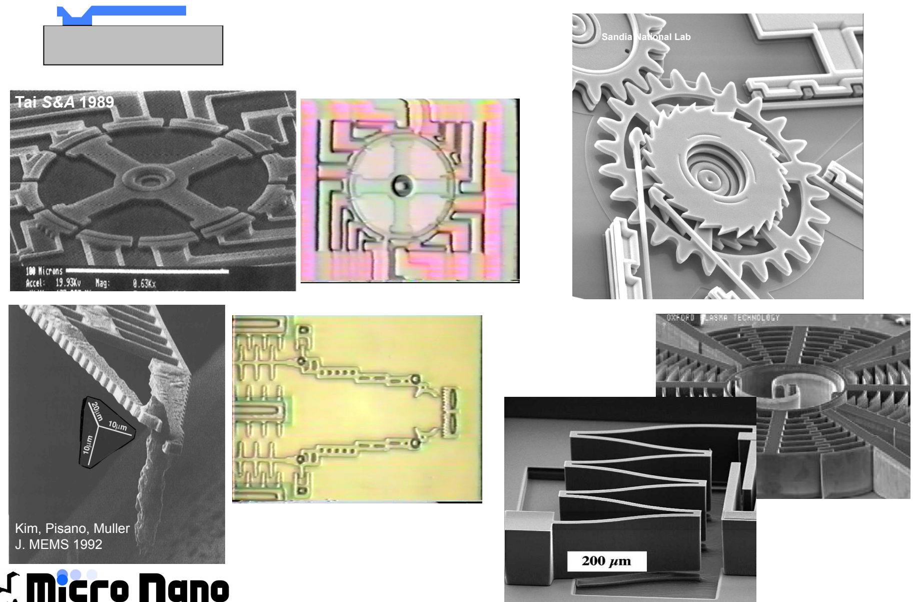
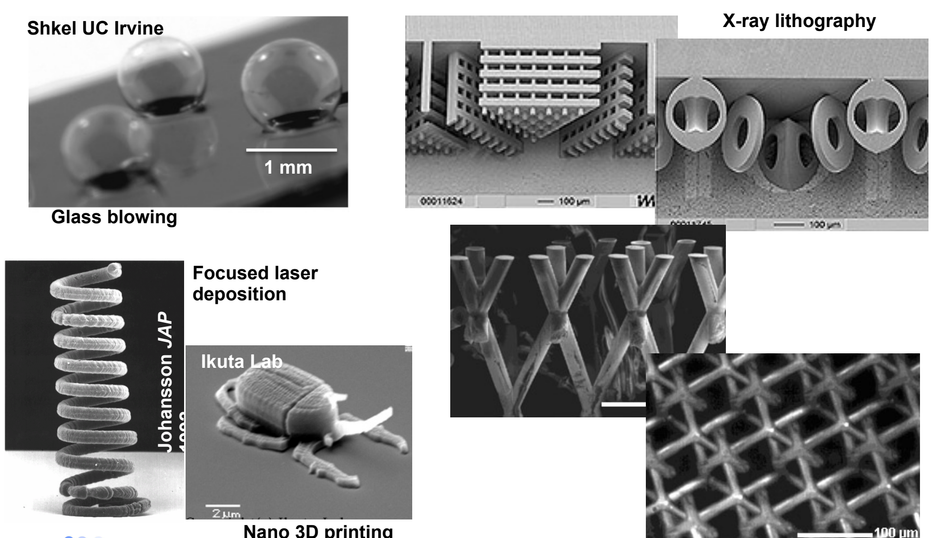
MEMS fabrication: research

Surface-micromachined structures and devices



UCLA Micro Nano Manufacturing Laboratory

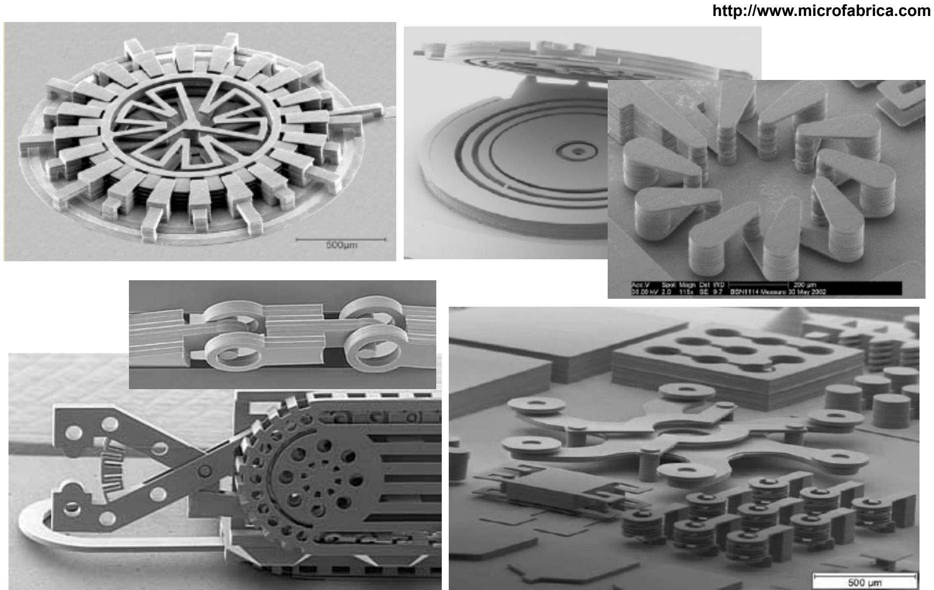
3D micro and nano structures



UCLA Micro Nano Manufacturing Laboratory

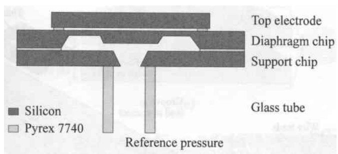
3D microstructures by EFAB (foundry)

http://www.microfabrica.com

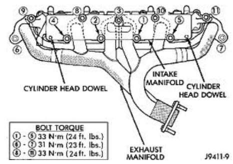


MEMS fabrication: commercial products

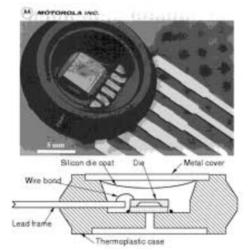
Pressure sensors



Principle of micro pressure sensor (late 1980s)

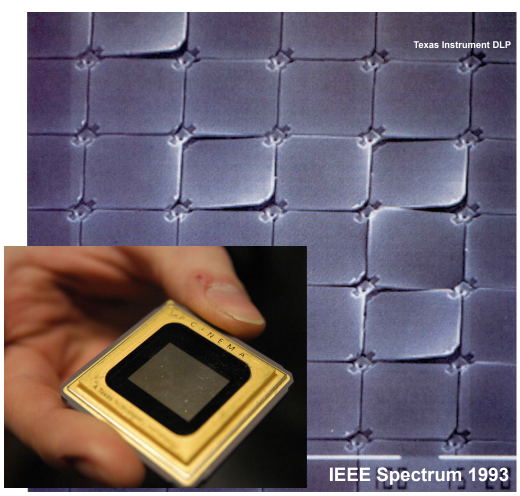


Pressure sensor for engine manifold

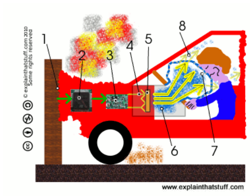


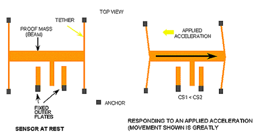
Tire pressure sensor

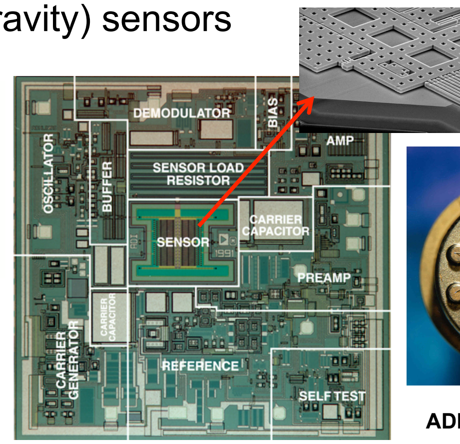
Mirror arrays

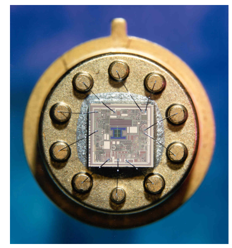


Acceleration (gravity) sensors









ADI ADXL-50

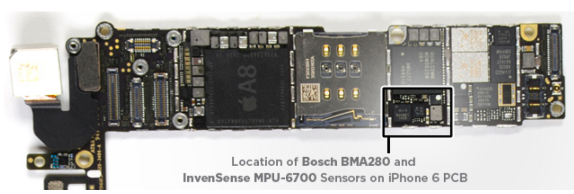
Beyond automotive applications:

Gaming

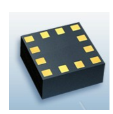
3D mouse

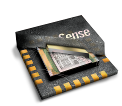
For smart phones

Microsensors: accelerometer, gyroscope, magnetometer, IMU, microphone, etc.

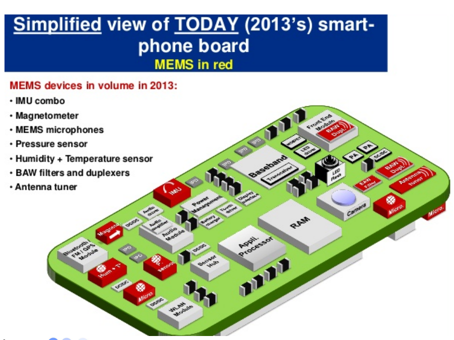


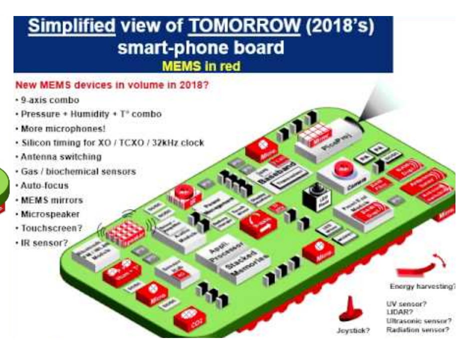
Bosch Sensortec BMA280 triaxial, low-g acceleration sensor





InvenSense MP67B 6-axis gyroscope and accelerometer





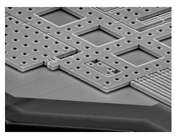
So far, predominantly electronic products

-- History

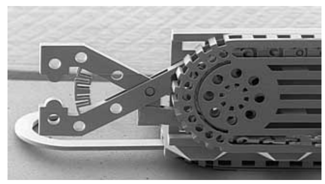
-- Compatibility with electronic circuits

-- Economy of volume

-- MEMS are relatively simple



vs.



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MEMS fabrication: next commercial products?

Next wave appears to be biomedical

-- Small, fast

-- Less sensitive to price

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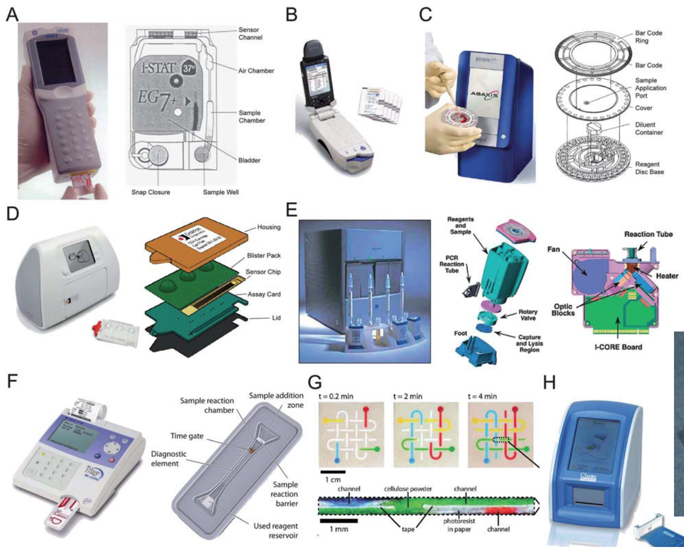
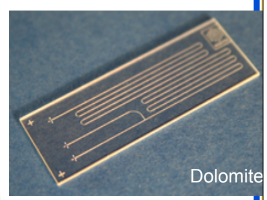
Microfluidics-based point-of-care systems

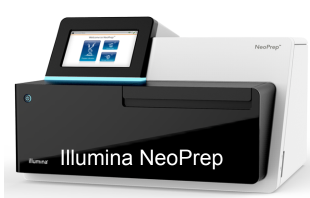




Chin *LabChip* 2012

Desktop bio analyzers

Agilent 2100
Bioanalyzer

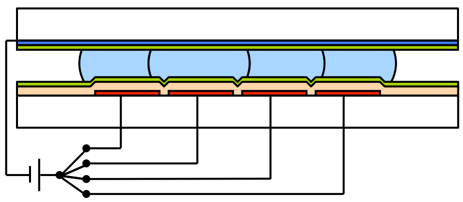


Electrowetting on dielectric (EWOD)

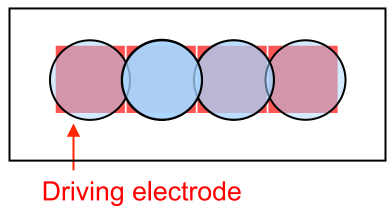
Droplet moved by electrowetting-on-dielectric (EWOD)

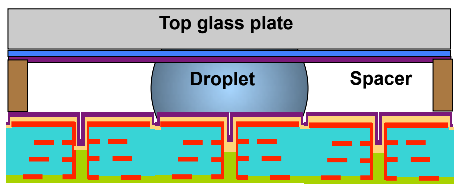
- Asymmetric wetting
- Patterned layer on one (or both) surface

Cross section



Top view





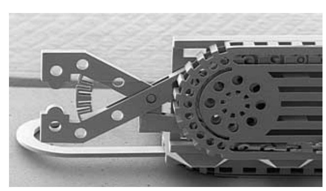
Biomedical product

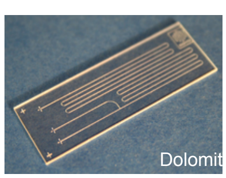
-- Simple fabrication

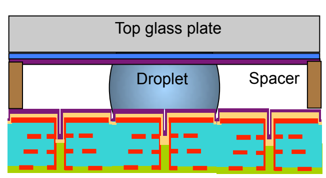
-- Bio compatibility

-- Reliability

vs.







MEMS fabrication: where are the real values?

-- Compatibility with electronic circuits

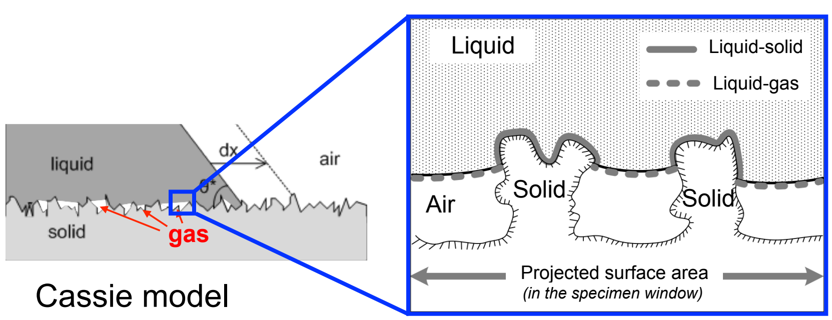
-- Economy of volume (electronics)

-- Small (bio)

-- When will we absolutely need the ability to make complex geometries?

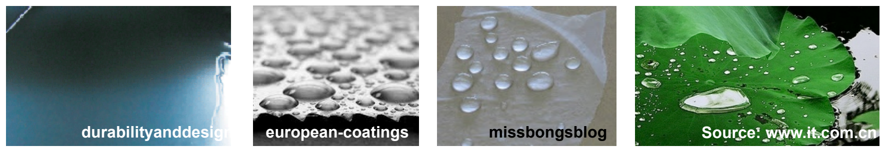
An example: superhydrophobic (SHPo) surface

Strongly repels water

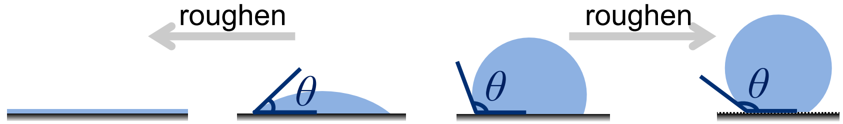


Water Wettability on Surfaces

Superhydrophilic | Hydrophilic | Hydrophobic | Superhydrophobic



roughen ← | roughen →



$\theta \sim 0°$
Wenzel state
e.g. rough glass

$\theta < 90°$
e.g. glass, PMMA

$\theta > 90°$
e.g. wax, Teflon®

$\theta > 150°$
Cassie state
e.g. lotus leaf

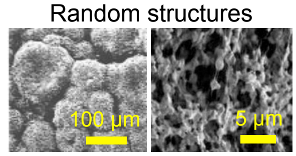
- General approach: combine hydrophobicity with roughness

Hydrophobic Material / Coating + Micro/Nano Structures = Super-hydrophobic

Polymers/SAM
- CFx, CHx
- Teflon®
- FDTS

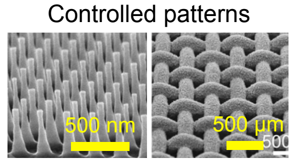
Ceramics
- rare-earth oxide

Random structures

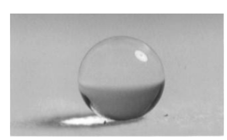


Onda, *Langmuir* (1996) | Erbil, *Science* 2003

Controlled patterns



Choi & Kim, *Nanotechnology* (2006) | Pan, *JACS* (2013)

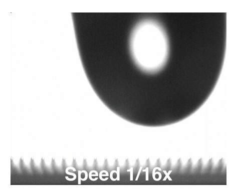


Onda, *Langmuir* (1996)

Commercial SHPo coating

Super*omni*phobic Surfaces

- Omni- = all
- Superoleophobic surfaces cannot repel extremely low energy liquids.
  - e.g., fluorinated solvents (CF_x)
- Challenge: extremely low energy liquids completely wets (θ ~0°) any existing material including the most hydrophobic coatings (CF_x).



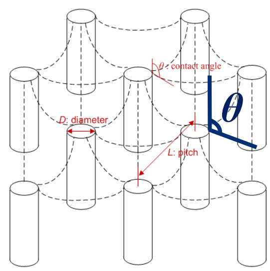
Video: FC-72 wets a superoleophobic surface instantly

Lowest known

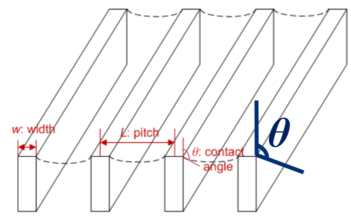
Liquids	γ @25°C (mN/m)
FC-72	10.0
HFE 7100	13.6
FC-40	16.0
Hexane	18.0
Methanol	22.0
Bromine	41.0
Water	72.0

Requirement #1: Liquid Suspension

- Suspension depends on meniscus angle formed at the edge of the micro/nanostructures.
  - E.g., common structures for artificial SHPo surfaces



Micro-posts

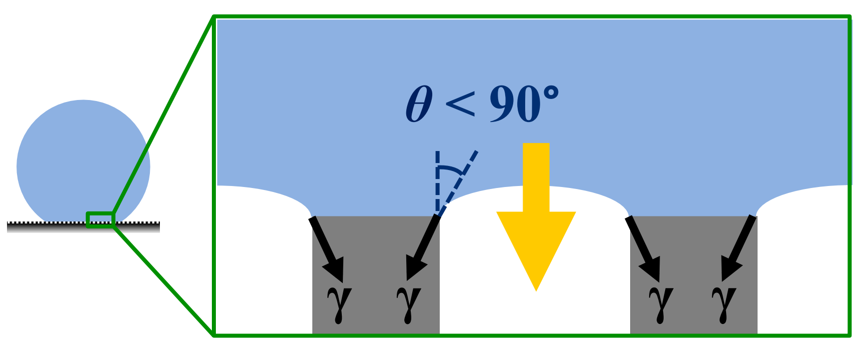


Micro-gratings

- Liquid suspension analysis is based on force balance.

Consider vertical microstructure.

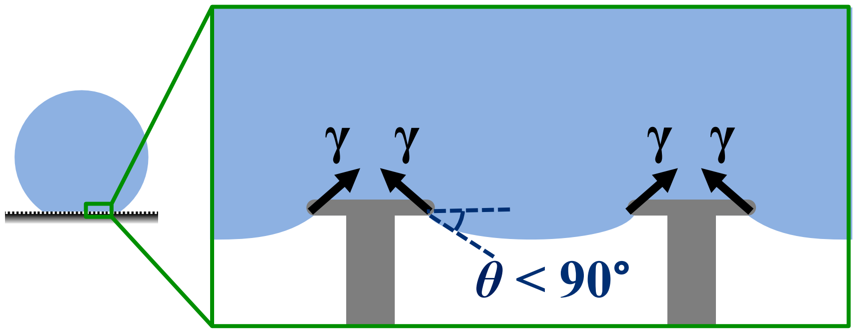
If the liquid wets the material, i.e., $\theta < 90°$
→ *Cannot suspend* → *Wetting*



Consider re-entrant microstructures.

If the liquid wets the material, i.e., $\theta < 90°$

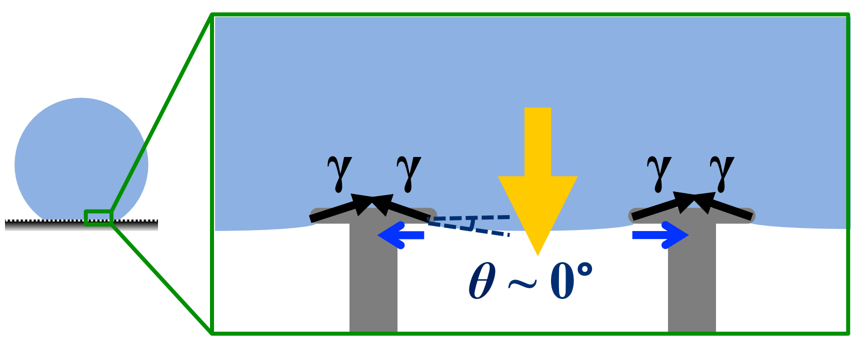
→ *If the wetting is moderate, suspension is possible*



Still consider re-entrant microstructure

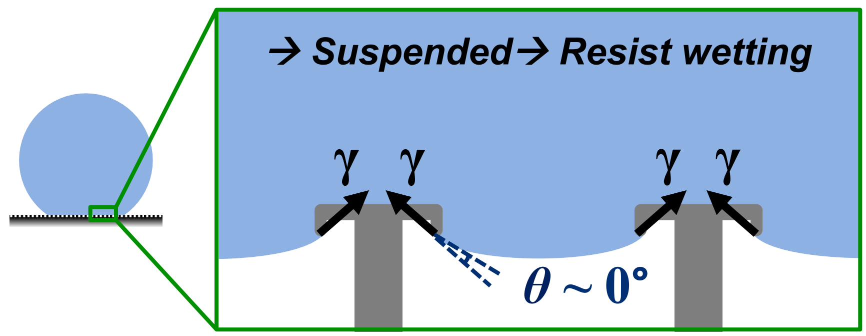
If the liquid wets the material strongly, $\theta \sim 0°$

→ *Cannot suspend* → *Wetting*



Consider doubly re-entrant microstructures.

If the liquid wets the material strongly, i.e., θ ~ 90°



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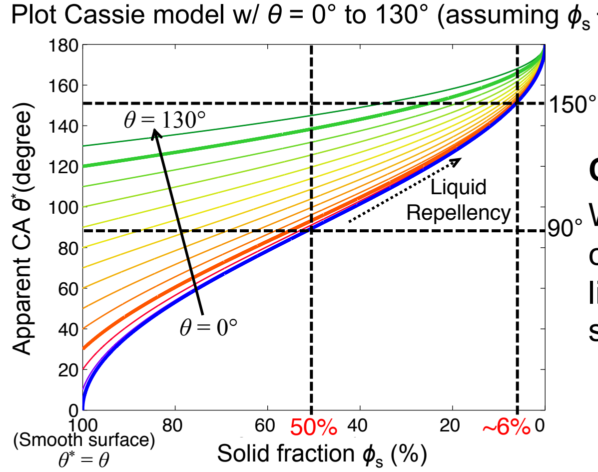
Requirement #2: Small Solid Fraction ϕ_s

How small ϕ_s should be?

Plot Cassie model w/ θ = 0° to 130° (assuming $\phi_s + \phi_g = 1$)



Conclusion: When ϕ_s < 6%, completely wetting liquids can be super-repelled.

Liu & Kim, *Science*, 2014

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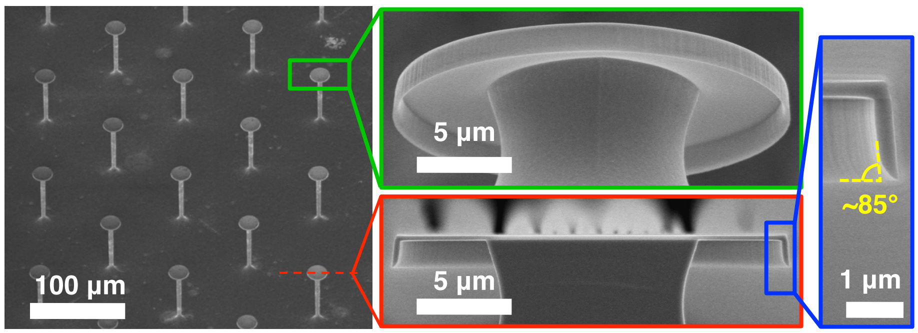
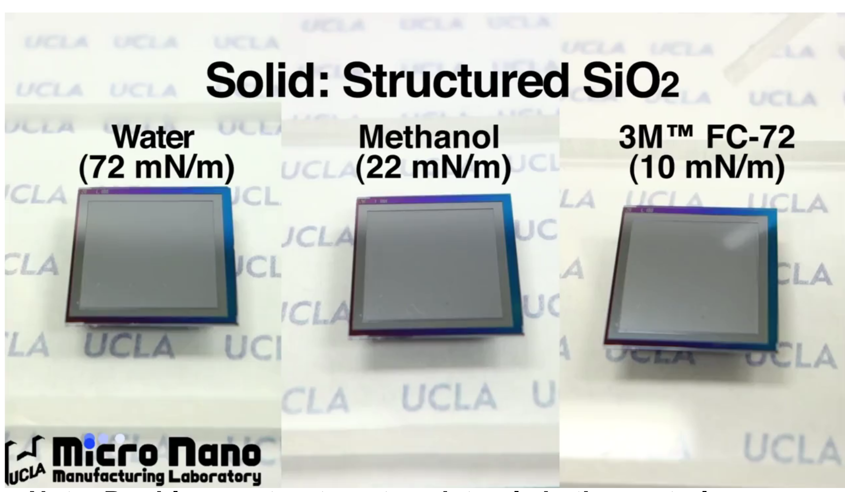
Super-repellency to "All" Liquids Confirmed

- Demonstrate with SiO_2 surface (θ < 10° for water)
- Doubly re-entrant structures for liquid suspension
- Micro-posts to have ~5% solid fraction



Super-repellency to "All" Liquids Confirmed
Liquids Rolling



Note: Doubly re-entrant posts exist only in the central square area.

SHPo drag reduction

-- The most anticipated application of SHPo surface

-- Since early 2000s

-- Numerous publications

-- Some experimental success in lab tests

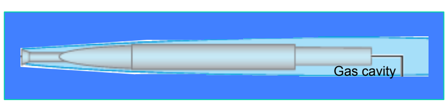
-- So far, no success in field conditions. Why?

<u>-- Should work while fully submerged under water</u>

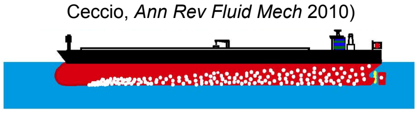
“Effective slip” by a lubricating layer

Possible scenarios

1. Inject gas over the surface



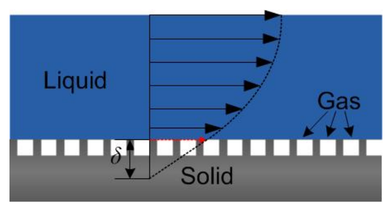
Ceccio, *Ann Rev Fluid Mech* 2010)



Center for Smart Control of Turbulence, Japan

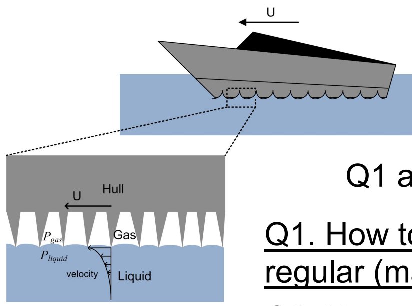
- How energy efficient?
- Robust against dynamic conditions?
- Worth the complication?
- etc.

2. Water-repellent surface



- How robust is the surface against becoming wet?
- How close is the surface to the ideal scenario?
- etc.

Will SHPo surfaces ever be practical for drag reduction?



Q1 and Q2 are fundamental.

<u>Q1. How to achieve slip large enough for regular (macro) fluidic systems?</u>

<u>Q2. How to maintain a stable gas layer under adverse (realistic) conditions?</u>

Q3. How to manufacture economical SHPo surfaces (mass production)?

Q4. How to overcome surface degradation (e.g. fouling)?

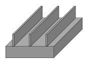
Question 1

How to achieve slip large enough for regular (macro) fluidic systems?

- To use a liquid slip for a drag reduction in a regular (macroscale) fluidic system (e.g. boundary layer ~ 1 mm), a giant slip length (> 100 μm) is desirable
- To design a SHPo surface of such a large slip, the correlation between surface parameters and slip length should be understood first
- Early experimental studies did not provide conclusive information about the effect of surface parameters on slip length
- How about in turbulent boundary layer flows?

Theory of slip length on patterned surface

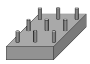
Analytical solution on grates (Philip *ZAMP* 1972; Lauga *JFM* 2003)



$$\frac{\delta}{L} = -\frac{1}{\pi}\log\left[\cos\left(\frac{\pi\phi}{2}\right)\right]$$

Slip length → δ; **Pitch** → L; **Gas fraction** → ϕ

Scaling law on posts at a high gas fraction (ϕ > 0.7) (Ybert *PoF* 2007)

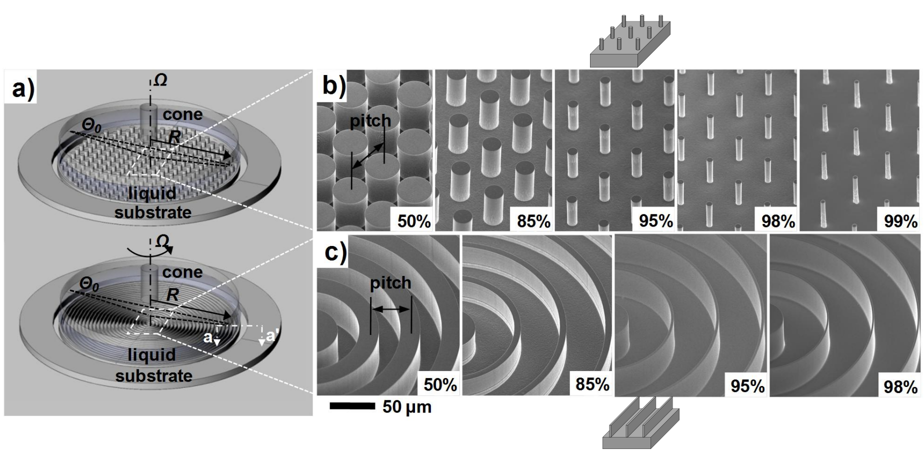


$$\frac{\delta}{L} = \frac{0.325}{\sqrt{(1-\phi)}} - 0.44$$

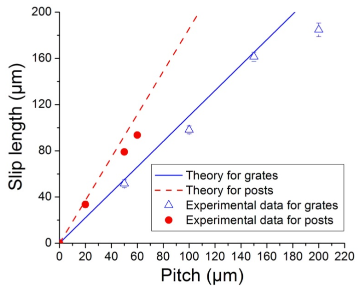
Coefficients (empirical): 0.325, 0.44

- According to the theories, pitch and gas fraction are two important surface parameters determining slip length

- Since previous experimental reports deviated from the theoretical predictions, we performed experiments to test the theories

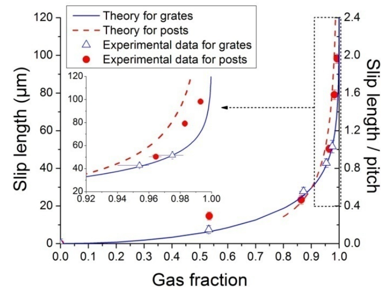


• Pitch effect (gas fraction = 98%)



δ increases linearly with a pitch

• Gas fraction effect (pitch = 50µm)

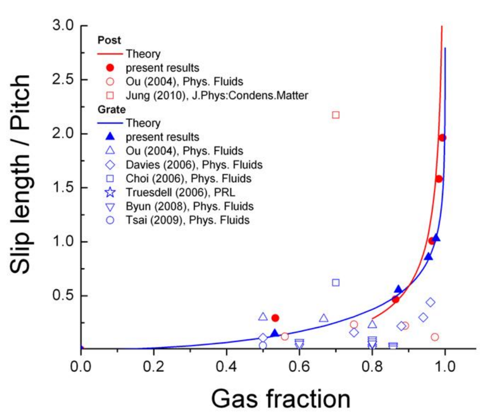


δ increases exponentially with a gas fraction

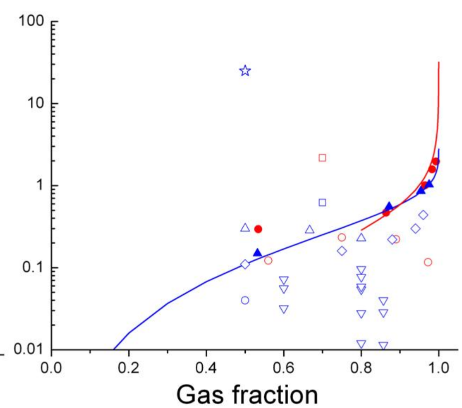
Note: Slip length could not be increased indefinitely. It is limited by the condition for the transition from a de-wetted to a wetted state (i.e., Cassie-to-Wenzel transition)

Comparison of published data

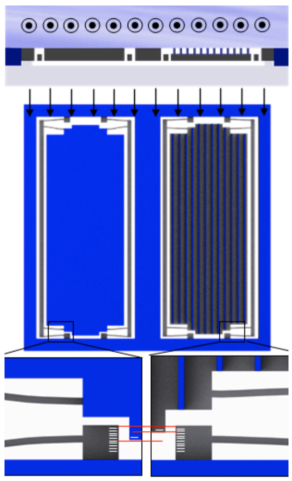
Linear-scale

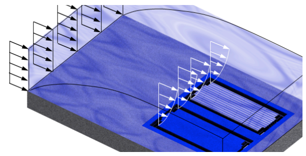


Log-scale



Drag reduction in turbulent boundary layer flows





A SHPo surface is dragged
less than a smooth counterpart
in a turbulent flow

Hyungmin Park, Guangyi Sun
and Chang-Jin "CJ" Kim (UCLA)

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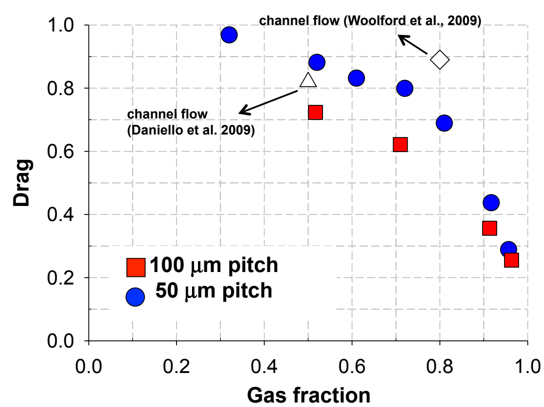
Park, Sun, Kim, *JFM* 2014

Results



Drag on SHPo surface to as low as 25% of that on the smooth surface obtained, i.e., 75% reduction!

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Summary

Fabrication technologies of MEMS has a irreplaceable value to experimentally study some topics that are otherwise impossible.