Superhydrophobicity to Supericephobicity: A technological Challenge

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Icing in aeronautics


www.staralliance.com/int/press/media_library/images/
Star/large-images/20050602_Swiss_Plane2_2489x2496_l.jpg

- a serious problem leading to:
  - excessive fuel usage due to increased drag
  - excessive energy consumption to combat icing
    - required power: order of kW/m2, 1-2% total engine power
  - aircraft crashes or engine damage
    - 12th Feb 2009: 49 people died in Buffalo.
    - 1st June 2009 : Air France Flight 447 from Rio de Janeiro to Paris, killing all 216 passengers and 12 crew members.


www.ucar.edu/news/features/wintertravel/images/wingice.jpg

Icing and condensation: daily-life problems

ICING

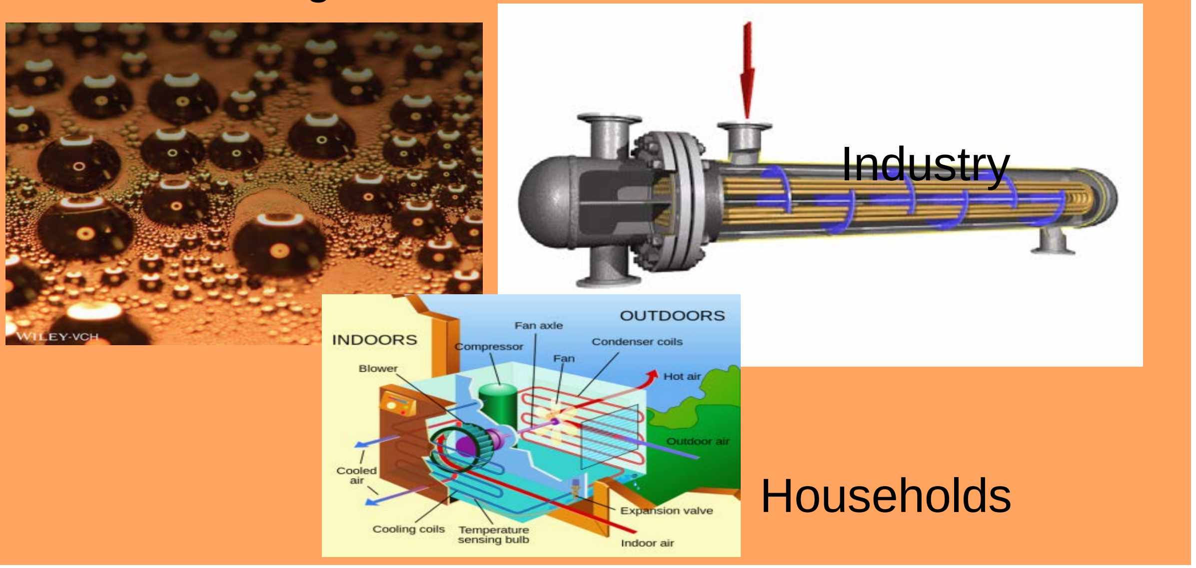
Aircraft Structures

- **SAFETY:** June 2009, Air France Flight 447 Rio de Janeiro - Paris, 228 people died.
- **COSTS**: 30 accidents/year in the US. Costs up to 2 million USD for engine damages


Wind Turbines

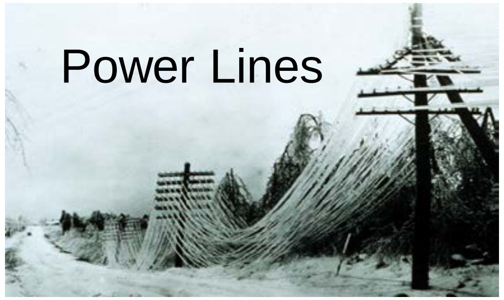
STEAM CONDENSATION

in heat exchangers



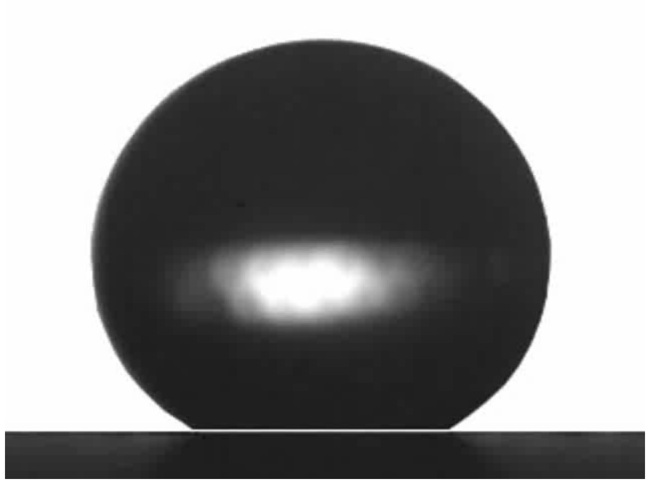
Industry

Households


Power Lines


Bridges

Influencing icing of surface:



Freezing of sessile water drop on surface

1. Ambient conditions:

- *Humidity*
- *Temperature*
- *Pressure*
- *Flow of gasses*

unraltered

2. Surface:

- *Texturing of surface (Micro, Nano or Micro/Nano engineered)*
- *Chemistry*

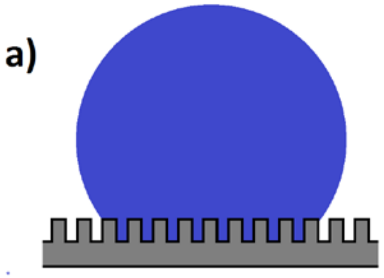
altered

Current study: The behavior of water with engineered surfaces at low temerature

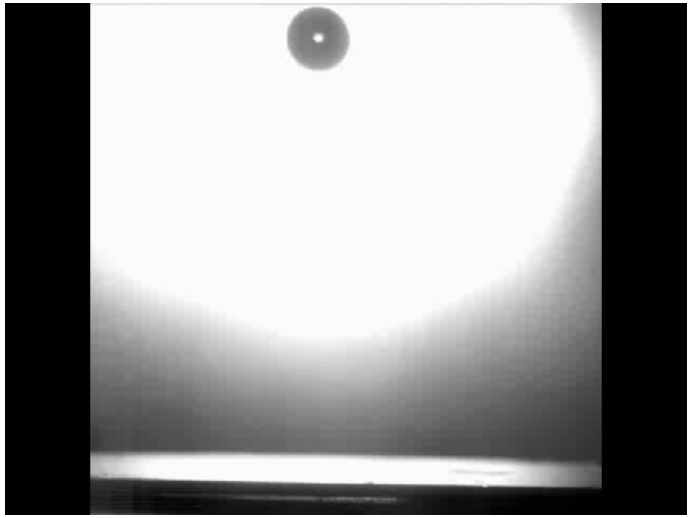
Superhydrophobicity:
to repel water; good strategy to avoid icing?

Bellanger et al. Chem.Rev.

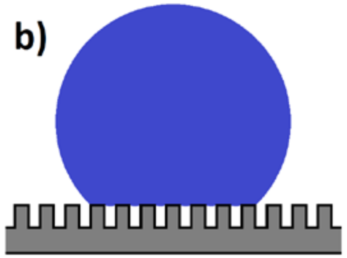
Superhydrophobicity: Basic Principle



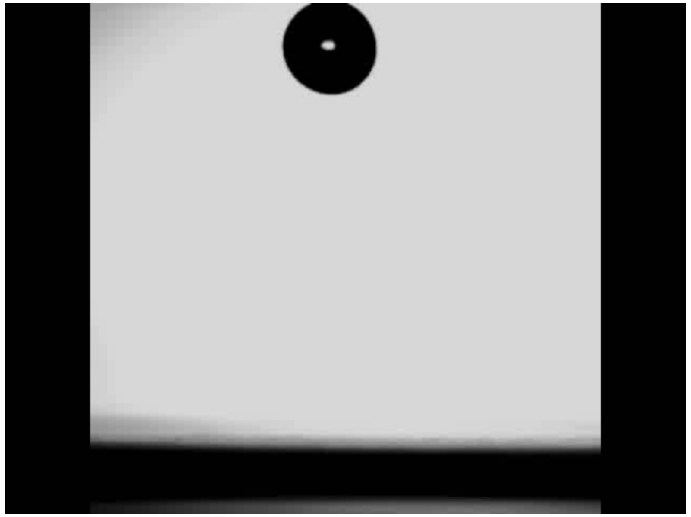
Wenzel state



Impalement through *roughness*



Cassie-Baxter state



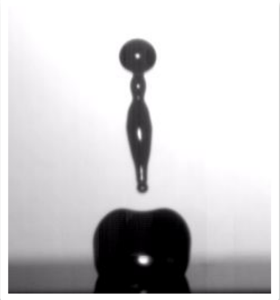
Non-impaled state

Advantages in Cassie-Baxter state:

- Low adhesion between water/surface
- Easy roll-off of water drop

Why superhydrophobicity breaks down?

- ***In dynamic condition:*** *with increasing* Impacting velocity



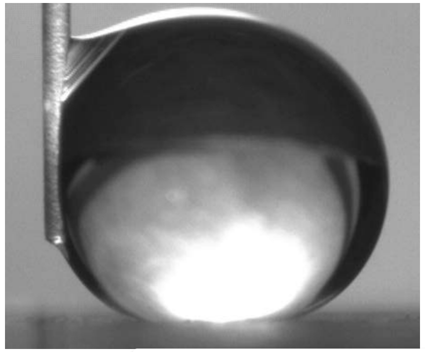
$$We = \frac{\rho V^2 d}{\gamma}$$

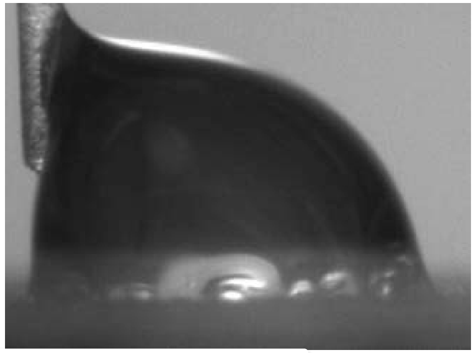
ρ density of water, V impact velocity,
d drop diameter, γ surface tension of water

Rebound

Impalement

- ***In static condition:*** *due to evaporation*



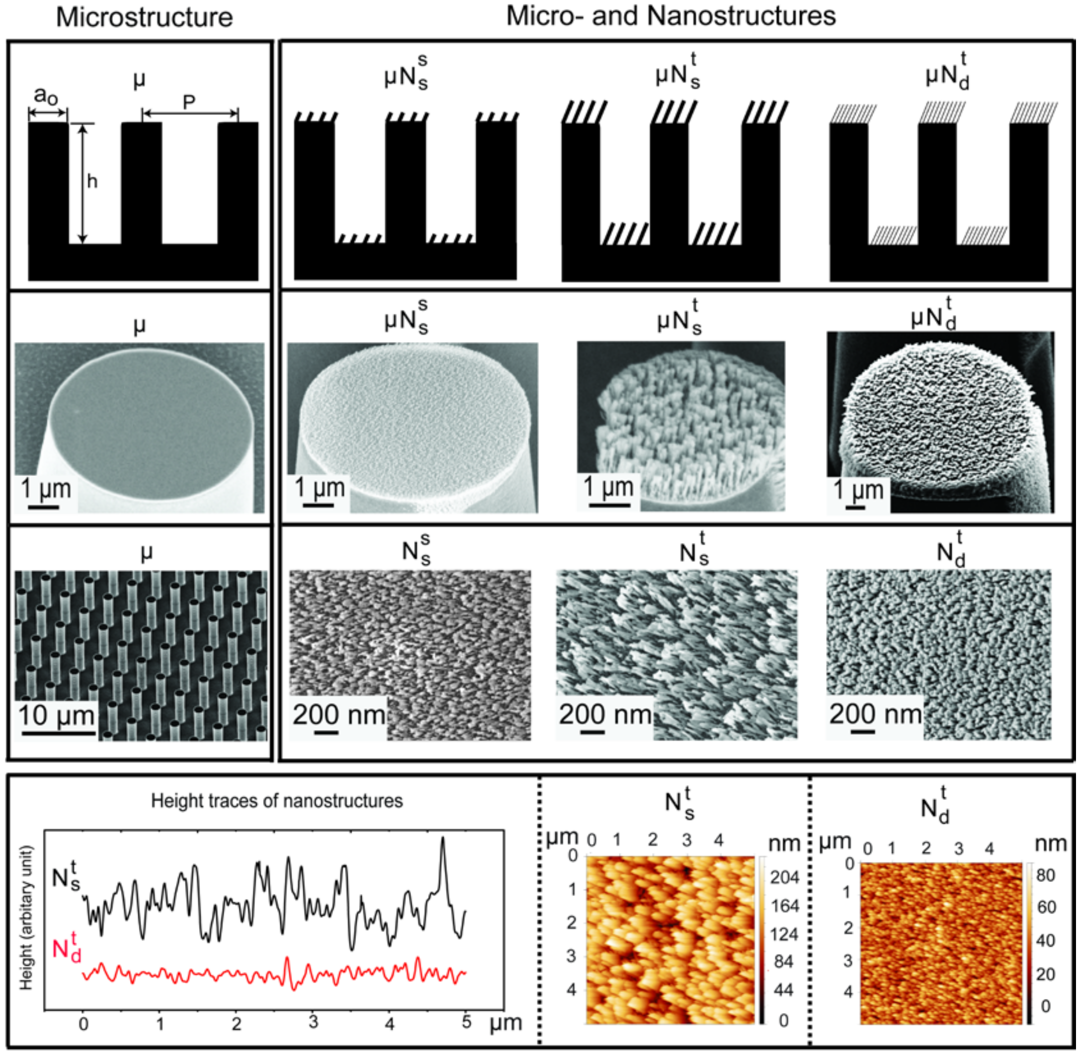


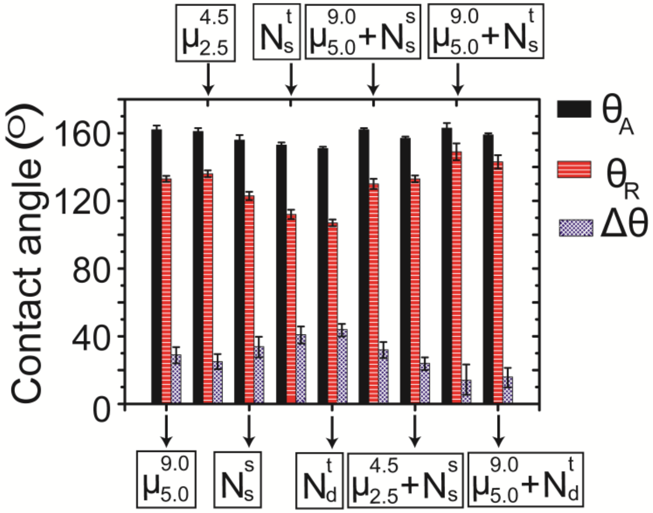
Loss of Superhydrophobicity

Due to evaporation in dry condition

Dynamic condition

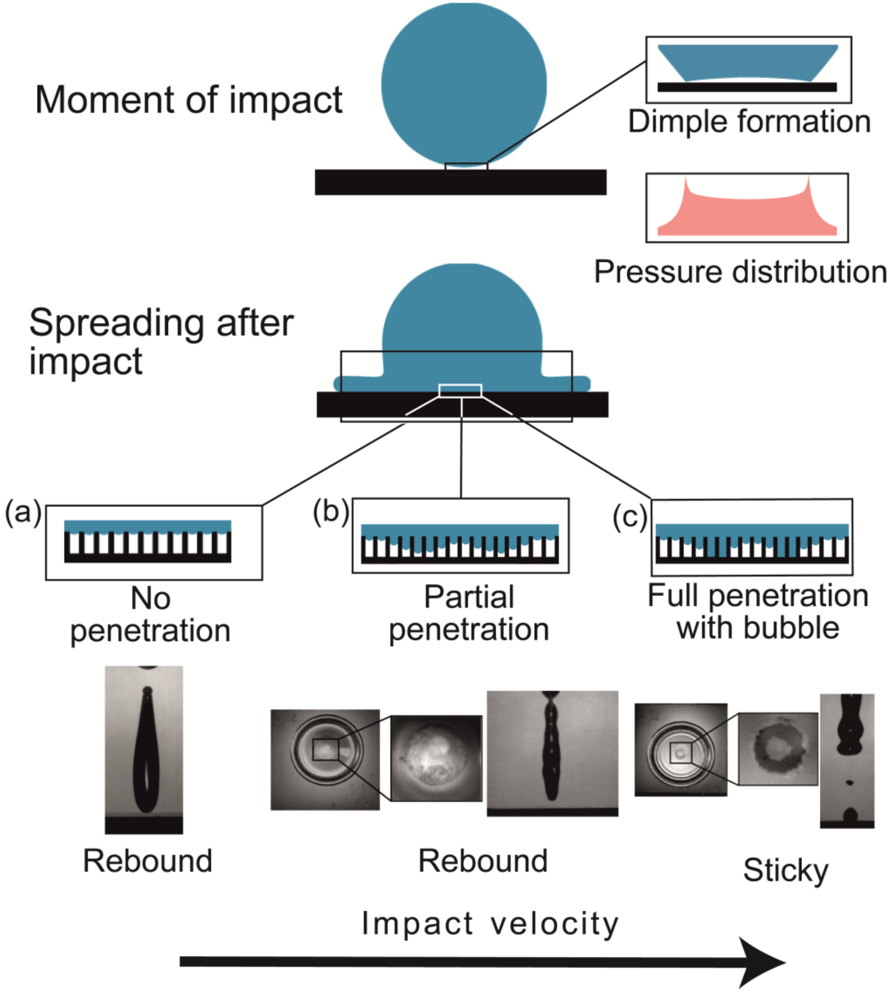
Micro/Nanoengineered surfaces



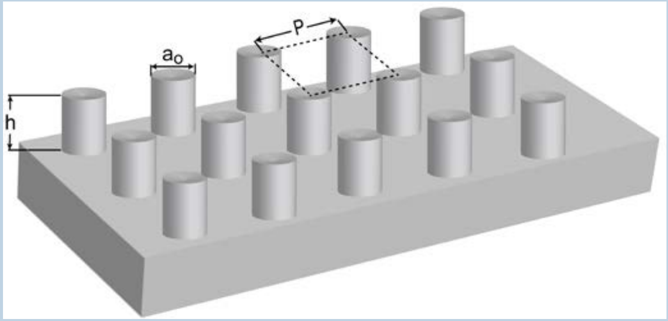


T.Maitra, M.K.Tiwari, C.Antonini, P. Schoch, S. Jung, P. Eberle and D.Poulikakos, ***Nano Letters*** **(2014)**

Dynamic Event: Drop impact

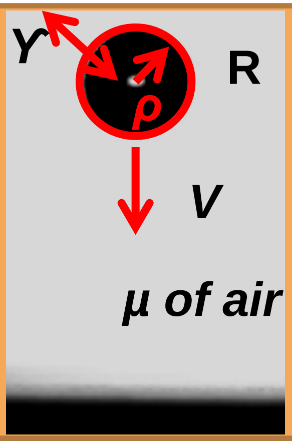


Inclusion of air between impacting drop and surface



$$P_C = \left(\frac{4\phi}{a_o(1-\phi)}\right)\gamma\cos\theta_A^*$$

Resisting Pressure: Capillary pressure

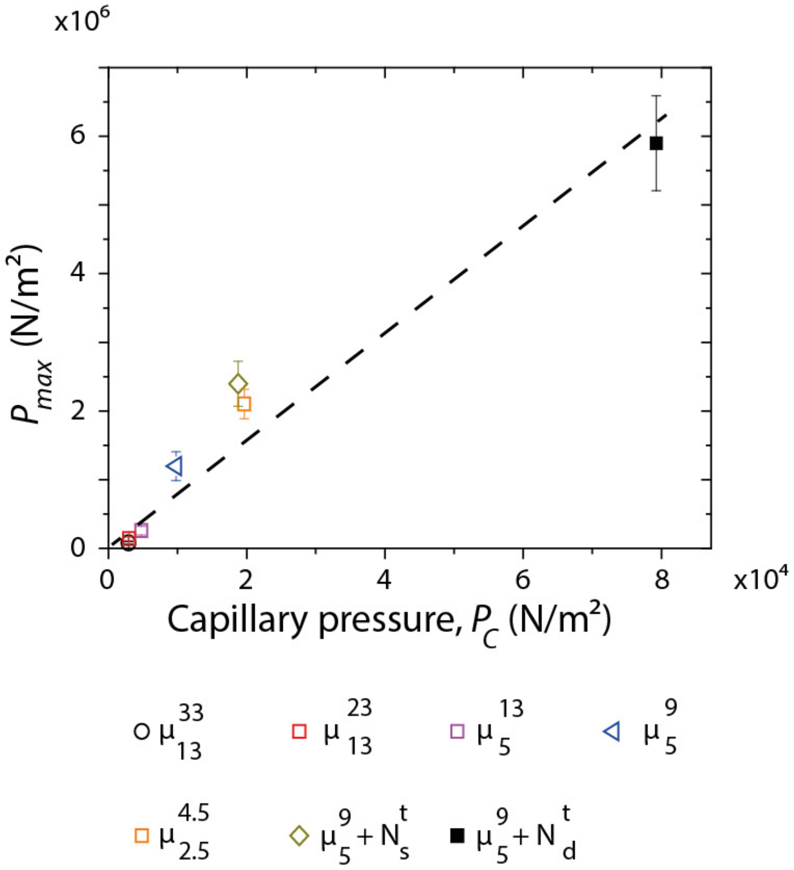


$$P_{\max} = 0.88\left(\frac{R^7V^{28}\rho_l^{16}}{\mu^4\gamma^3}\right)^{\frac{1}{9}}$$

Assisting Pressure: Model Pressure

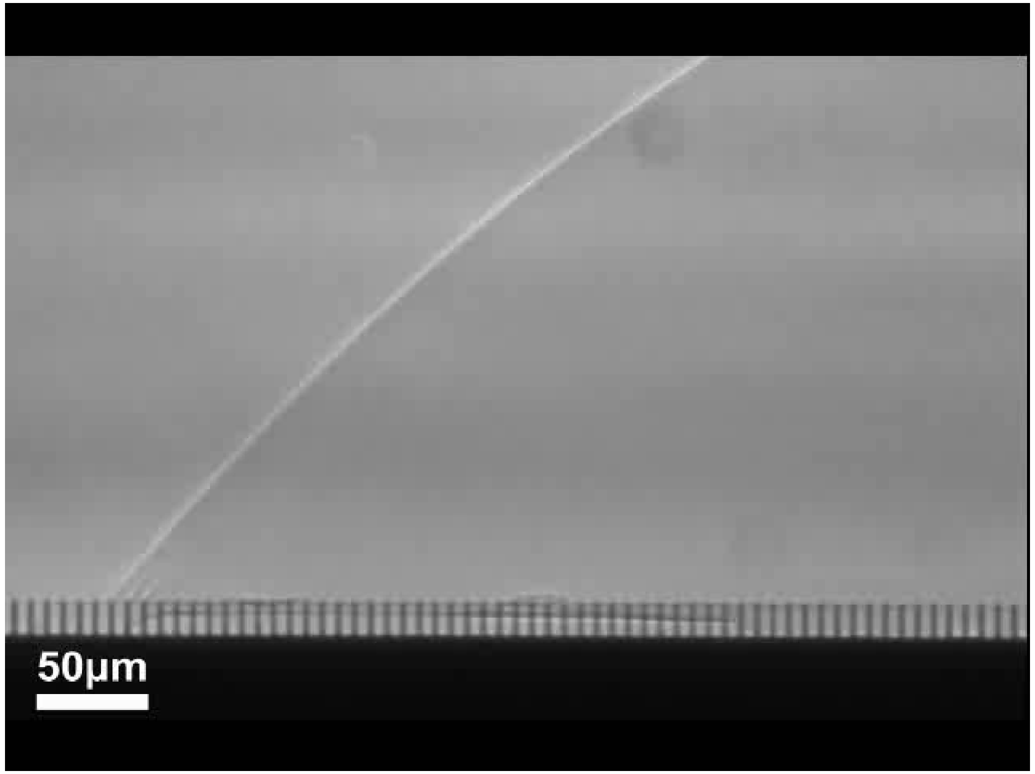
T.Maitra, M.K.Tiwari, C.Antonini, P. Schoch, S. Jung, P. Eberle and D.Poulikakos, ***Nano Letters*** **(2014)**

Capillary pressure (P_c) Vs. Model Pressure (P_{max}):



T.Maitra, M.K.Tiwari, C.Antonini, P. Schoch, S. Jung, P. Eberle and D.Poulikakos, ***Nano Letters*** **(2014)**

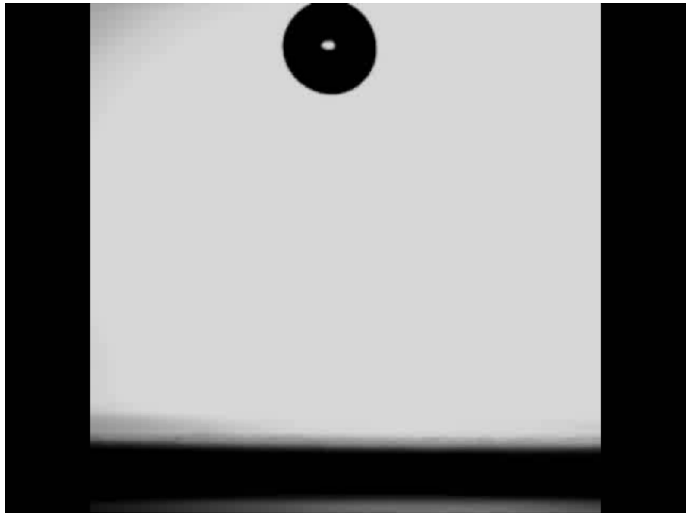
Entrappment of air during drop Impact on surface

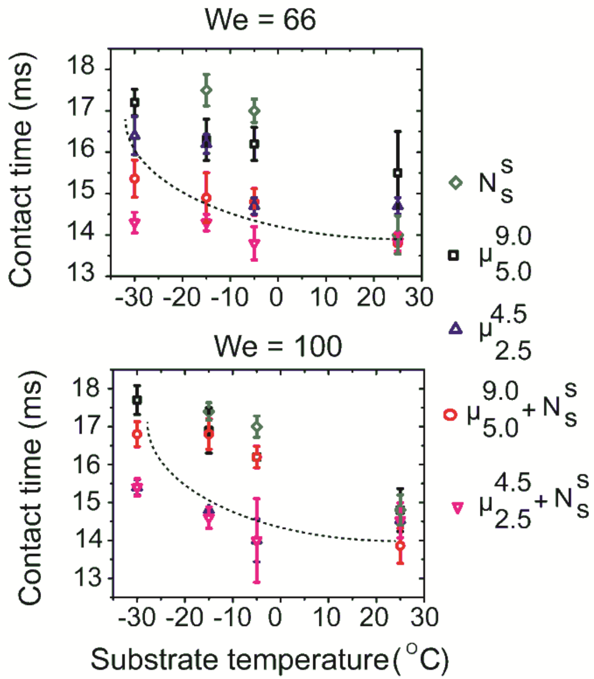


Visualization by **X-ray** after the drop impact

T.Maitra *et al.* ***Scientific Reports*** **(2014)**

Effect of drop impact at lower substrate temperature

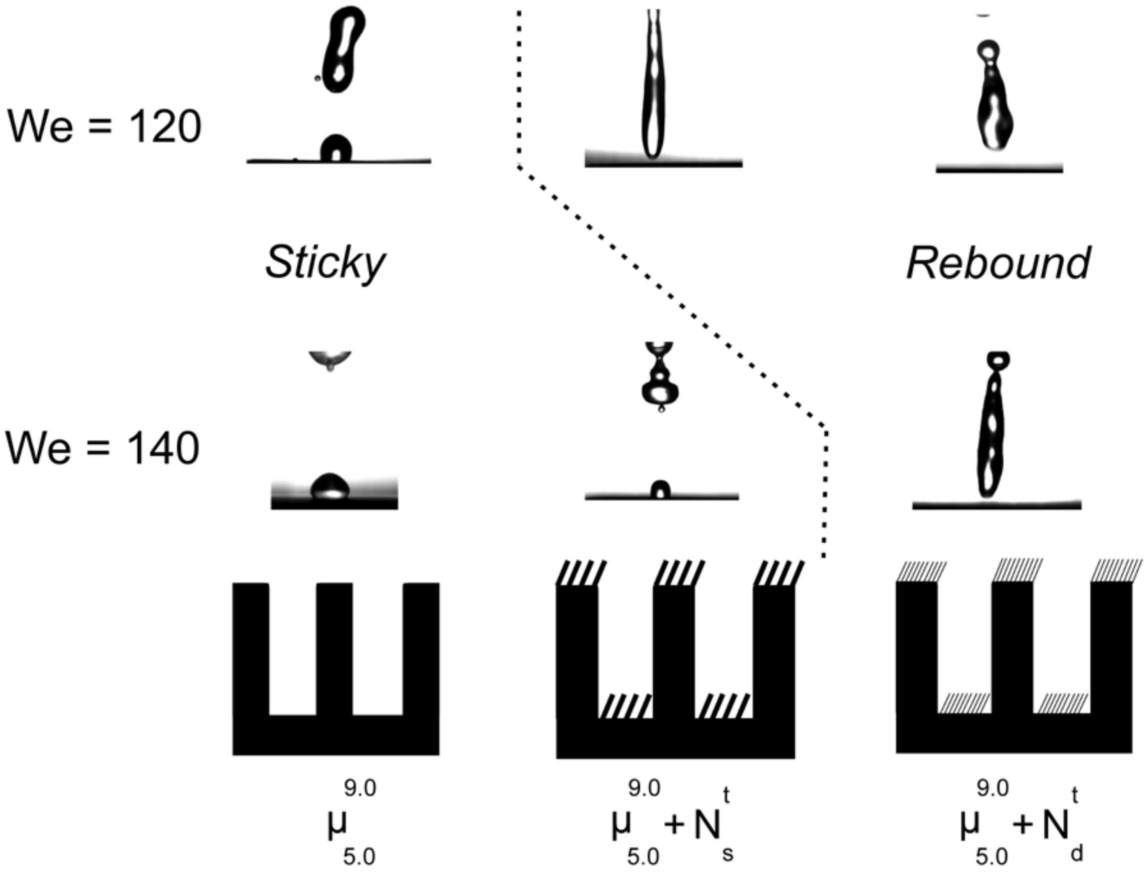




<u>Viscosity</u> of water rises up by **<u>5</u>** <u>times</u> compared to room temperature and surface tension and density varry by less than 10%

<u>T.Maitra</u>, M.K.Tiwari, C.Antonini, P. Schoch, S. Jung, P. Eberle and D.Poulikakos, ***Nano Letters*** **(2014)**

With controlled morphology (drop impalement stability)



Controlled morphology of nanostructures decides the *ultimate* water meniscus impalement stability

T.Maitra, M.K.Tiwari, C.Antonini, P. Schoch, S. Jung, P. Eberle and D.Poulikakos, ***Nano Letters*** **(2014)**

Static condition

In static study: Stable Superhydrophobicity

Why superhydrophobicity breaks down ?

- In dry environment, evaporation occurs.
- Due to evaporation, droplet radius increases and so as *Laplace* pressure.

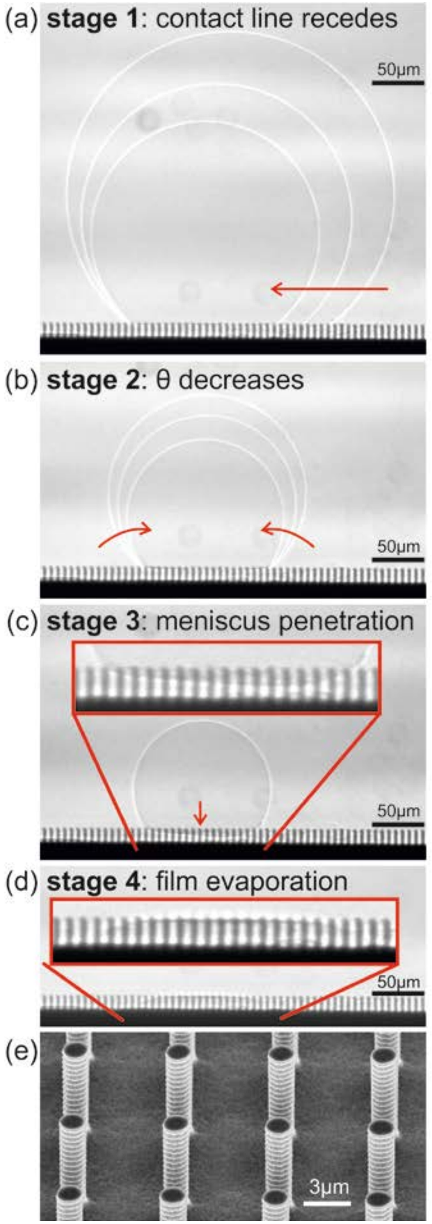
Considering the force balance,

$$\Delta p_L = 2\sigma_{\mathrm{lg}} / R$$ *Laplace Pressure*

$$P_C = \left(\frac{4\phi}{a_o (1-\phi)} \right) \gamma \cos \theta_A^*$$ *Capillary Pressure*

Visualization: *X-ray projection imaging*

Mechanism of break down of Superhydrophobicity



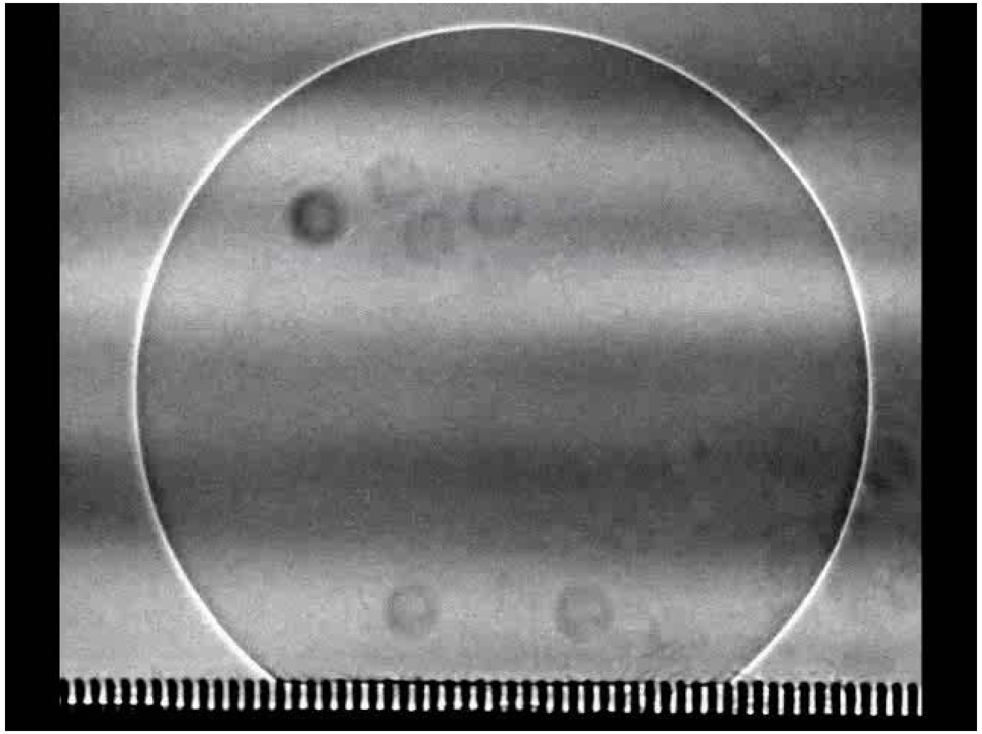
(a) **stage 1**: contact line recedes

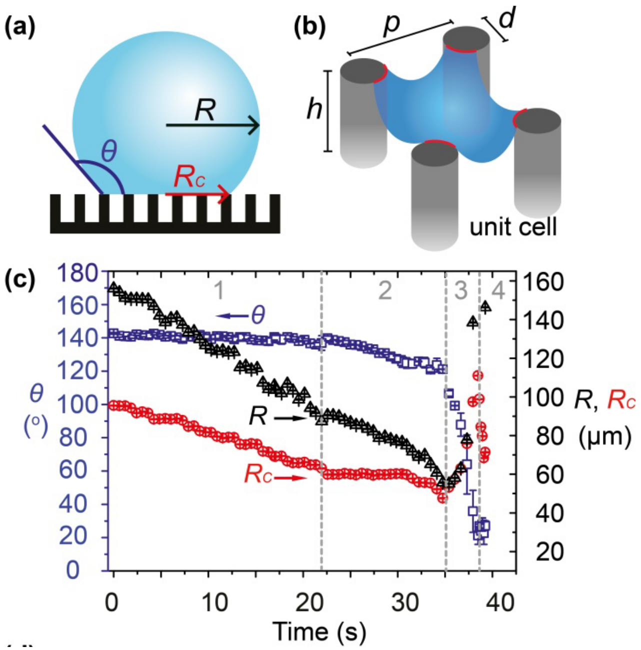
(b) **stage 2**: θ decreases

(c) **stage 3**: meniscus penetration

(d) **stage 4**: film evaporation

(e)





<u>T.Maitra</u> *et al.* ***Scientific Reports*** **(2014)**

Conclusions:

- Influence of Micro/Nano engineered surface on dynamic stability of water meniscus at low temprature.
- Mechanism of transition of Cassie to Wenzel (breaking down the Superhydrophobicity)

Practical Applicability:

- So far silicon-based surface; little applicability.
- Use of substrate greatly accepted in engineering application (?).
- Use scalable approach.

Superhydrophobic surface: a review

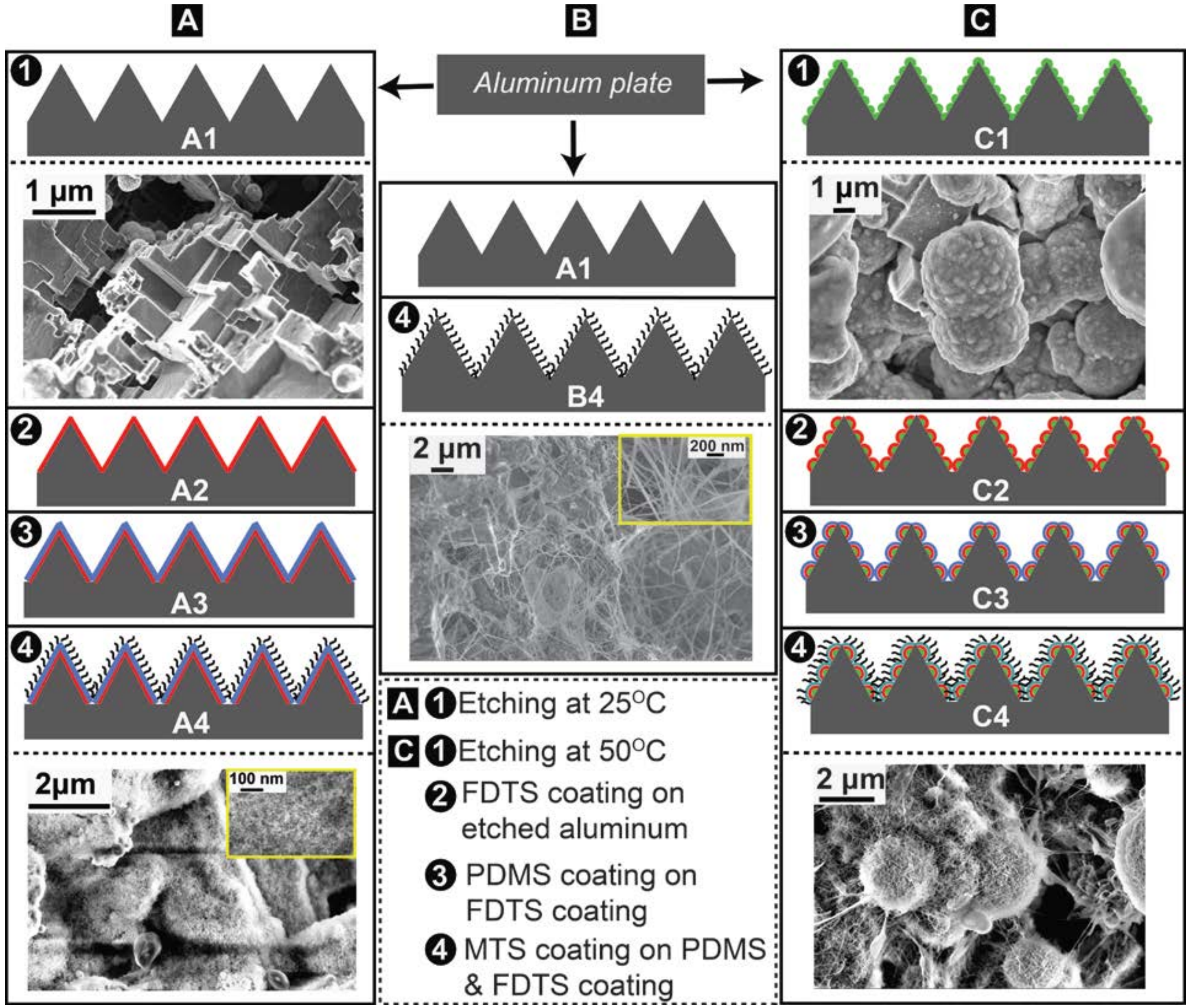
Rough morphology

Coating with **<u>low surface</u>** energy molecules

Possible substrate:

- Aluminum ("Chemical etching" to create rogh morphology)
- Multifunctionality to substrate (mechanical stability, drop meniscus stability and chemical stability)

Process schematic for fabrication of superhydrophobic surface:

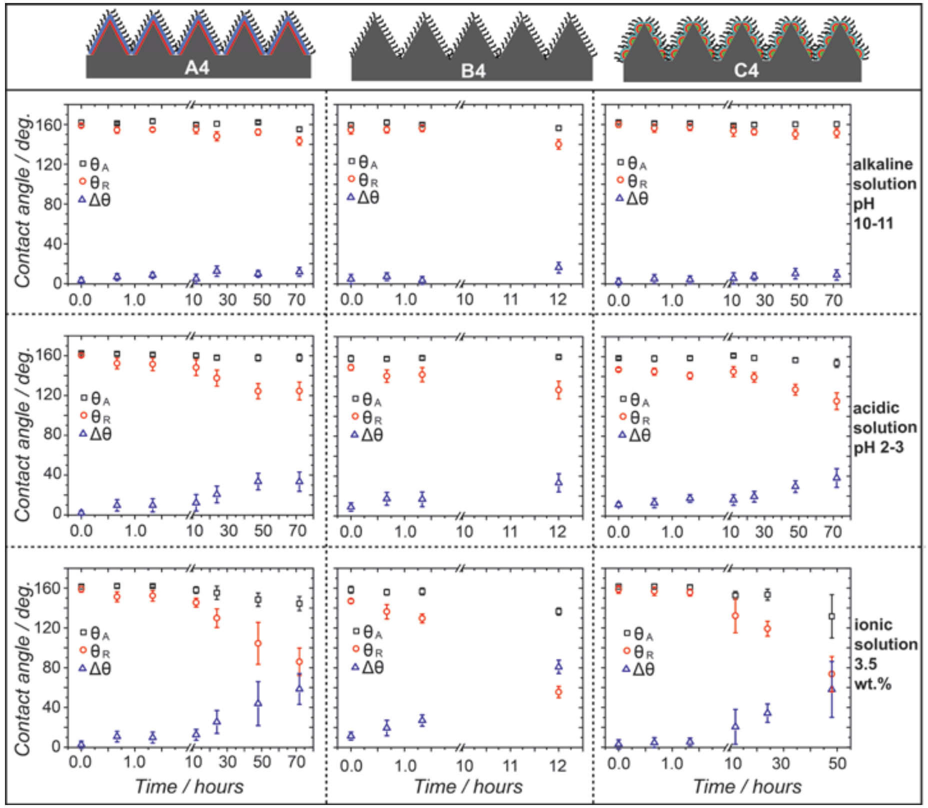


Multiple hydrophobic coatings to combat different *functionalities*

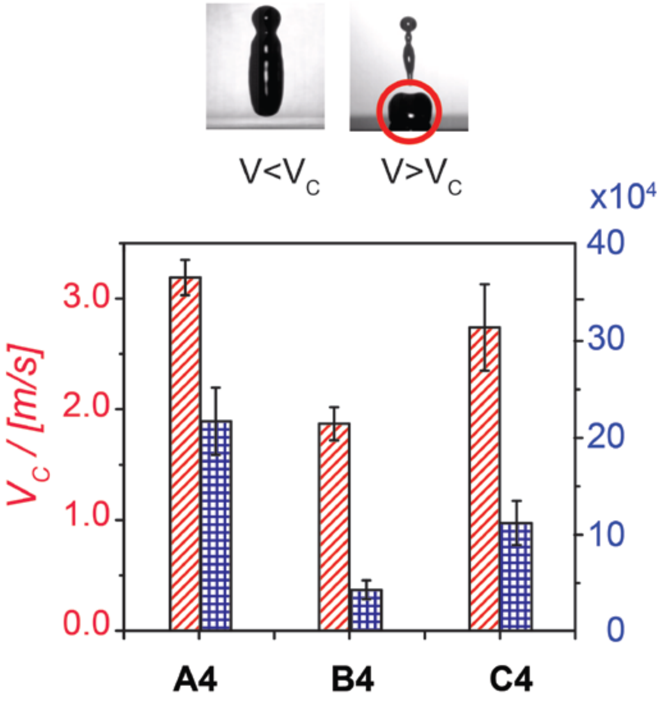
T.Maitra *et al.* Hierarchically nanotextured surfaces maintaining superhydrophobicity under severely adverse conditions, ***Submitted, 2014***

Multifunctionality of superhydrophobic surface:

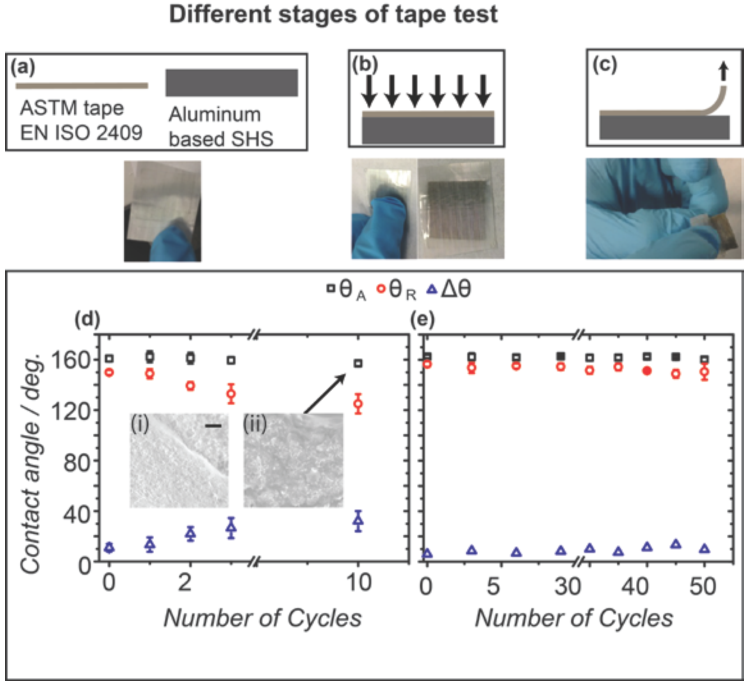
1. Chemical stability:



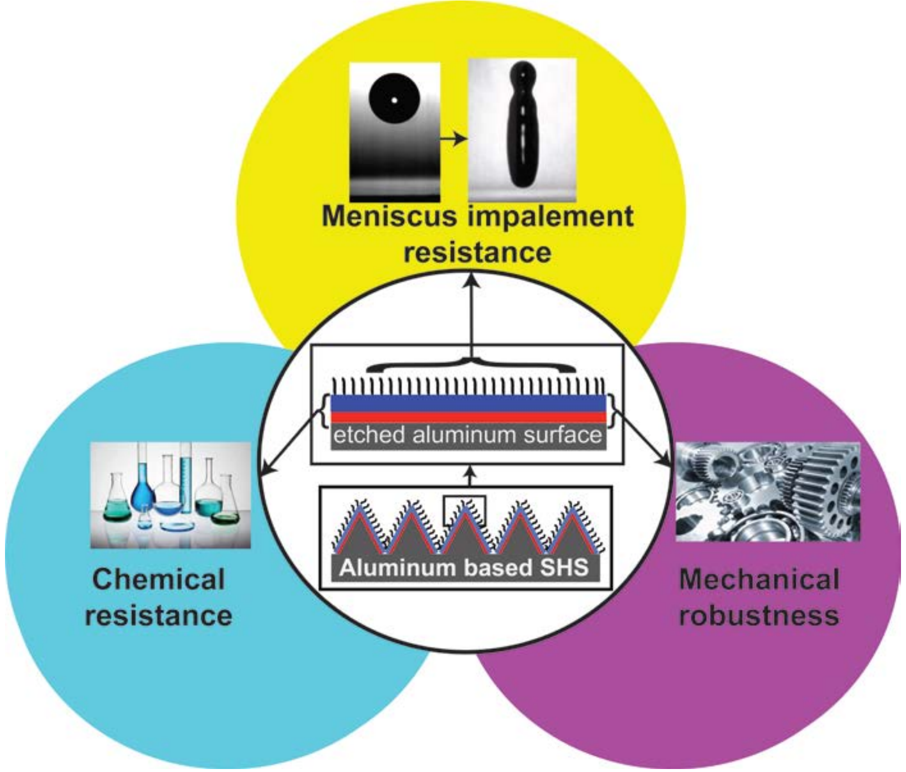
2. Water meniscus stablity:



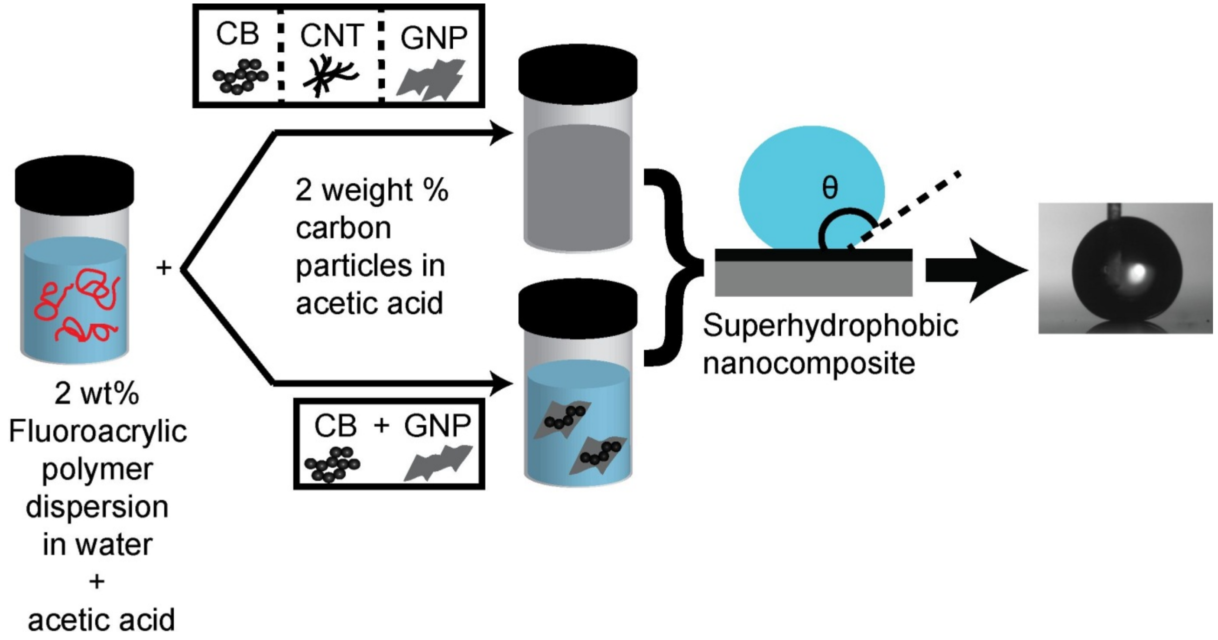
3. Mechanical robustness

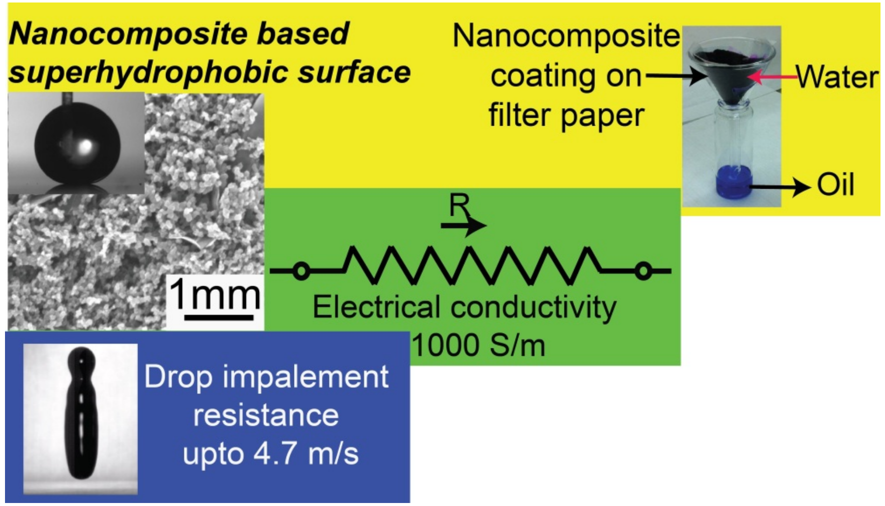


Multifunctionality of superhydrophobic surface:



Multifunctionality of superhydrophobic surface: another approach





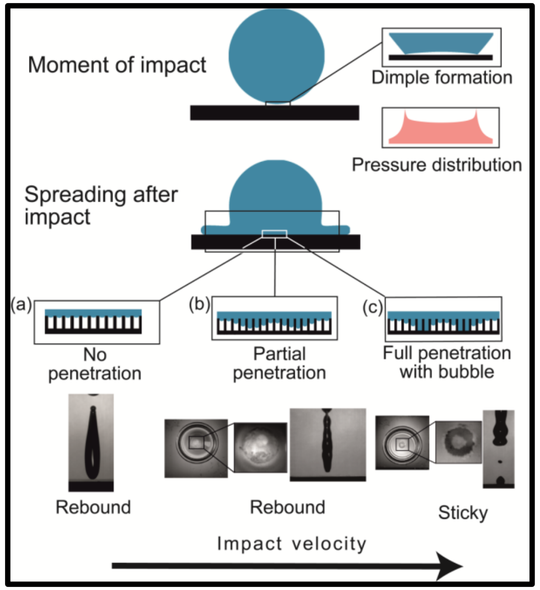
With *polymer/nanoparticle* Composite solution

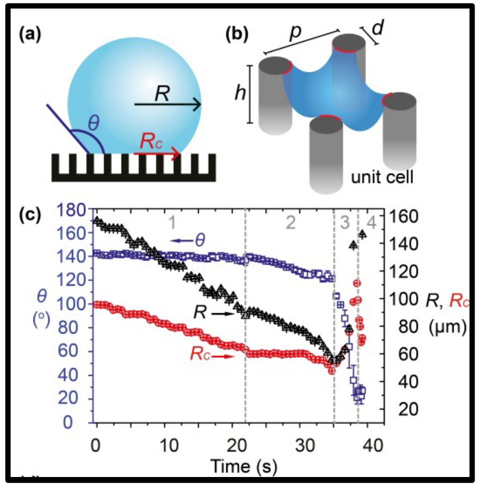
Multifunctional properties of the surface

Multifunctional Superhydrophobic Polymer/Carbon Nanocomposites: Graphene, Carbon Nanotubes or Carbon Black? ***Submitted, 2014***

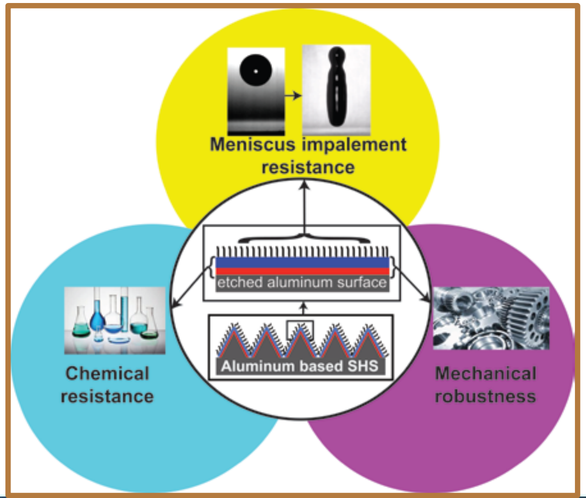
Conclusion

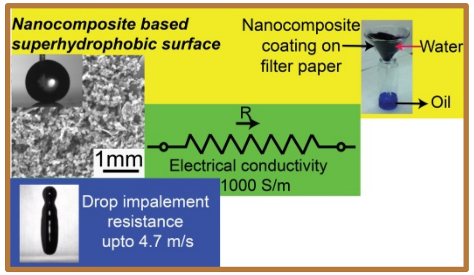
Fundamental studies on surface

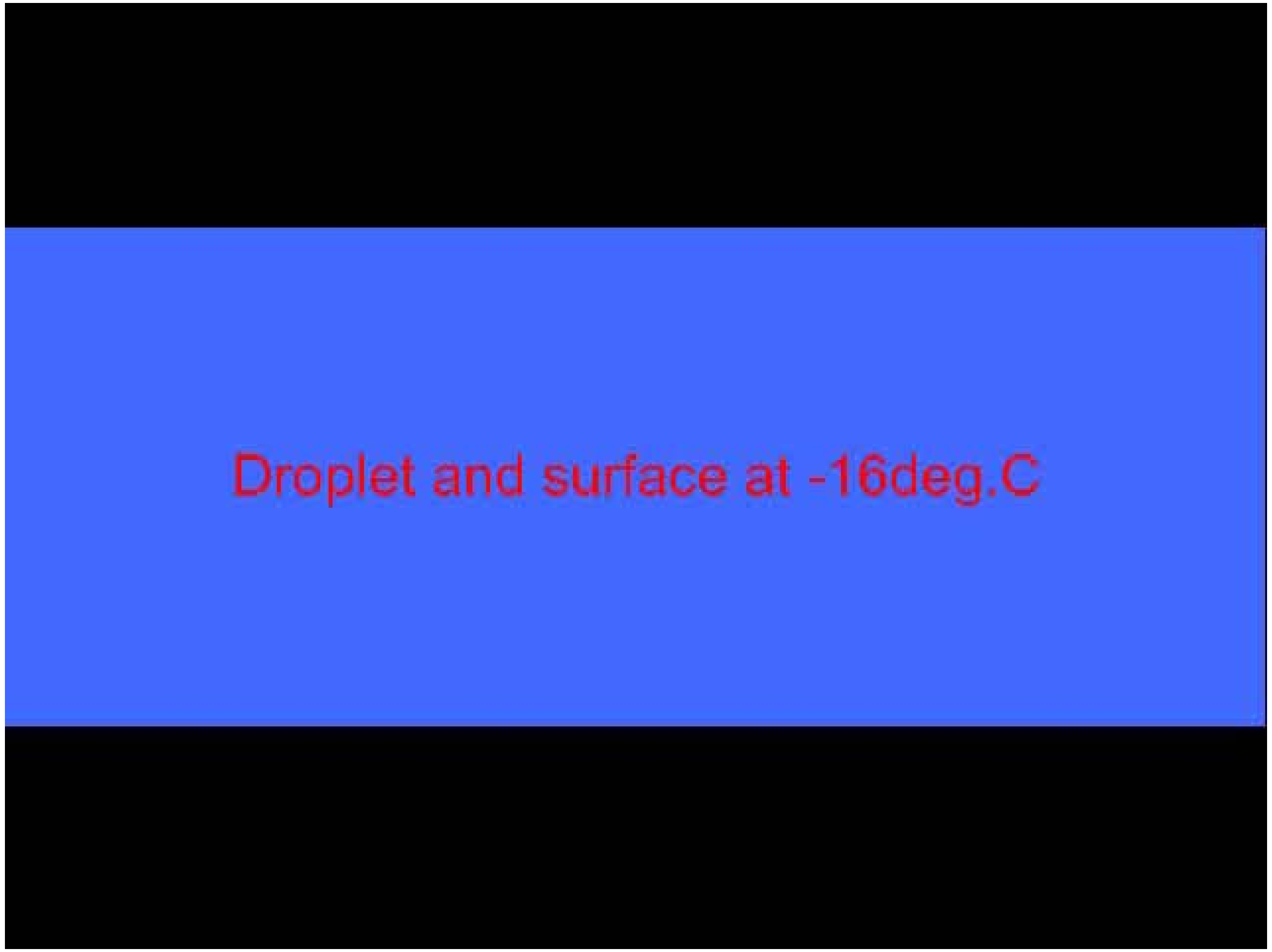




Upscalable process







Droplet and surface at -16deg.C