Metasurfaces leveraging solar energy for icephobicity

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Department of Mechanical and Process Engineering
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Critical issues in surface icing

Automobiles

edie.net

Windows

blog.brack.xyz

Photovoltaics

www.cleanenergyauthority.com

www.boldmethod.com

nipgroup.com

Structure

- **Introduction, motivation, and state-of-the-art in icephobicity.** Economic figures and problems due to ice accumulation. Surface engineering of icephobic surfaces.

- **Metasurfaces for heat concentration with renewable energy.** Rational surface engineering: Fabrication and characterization.

- **Demonstrating a new icephobicity technology based on metasurfaces.** Ice formation prevention or removal.

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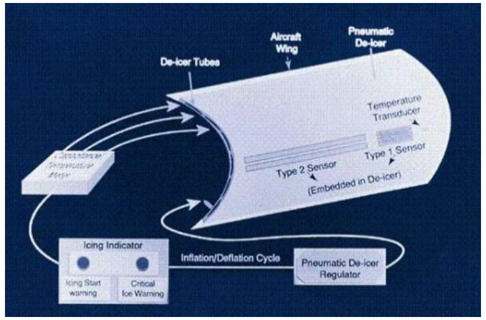
Economic impact of ice formation and accumulation on surfaces

- Aircraft deicing market: $1.30 billion (2020) [1]
- Global ice protection systems: $10.17 billion (2021) [1]

www.rt.com

- Vehicle windshield deicing: engine running for up to 30 min [2]



sbir.gsfc.nasa.gov

www.motorbeam.com

[1] MarketsandMarkets Research Private Ltd. (2015, 2017)
[2] Farag A & Huang L-J (2003)

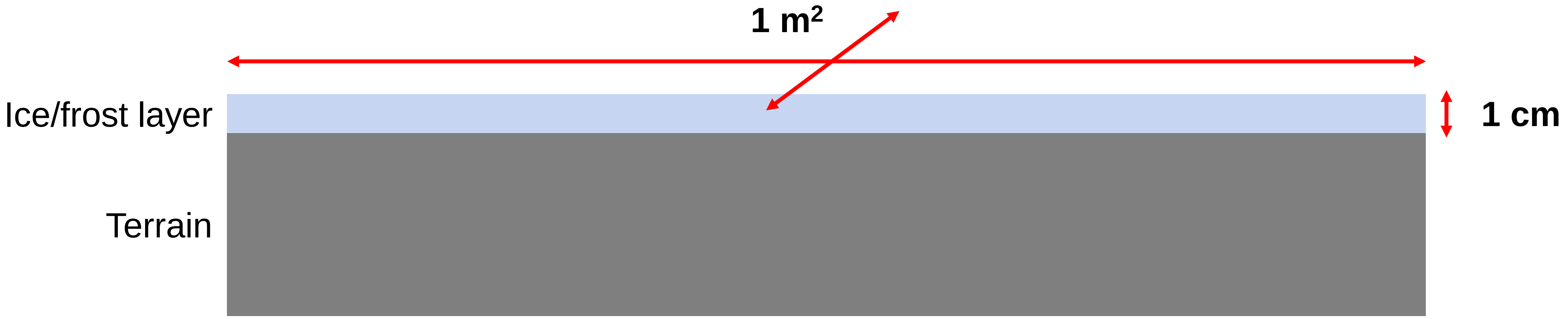
Economic impact of ice formation and accumulation on surfaces

- “Severe winter weather caused 15 percent of all insured auto, home and business catastrophe losses in the United States in 2014.”

- “It costs an airline about $6,000 to cancel a flight, according to masFlight. However, passengers also spend additional money as they accommodate their travel plans.”

www.accuweather.com

Energy required to melt ice



Mass = volume x density (0 ^oC) = 10^{-2} [m^3] x 916.7 [kg/m^3] = **9.2 kg of ice**

Energy = mass x enthalpy of fusion = 9.2 [kg] x 333.55 [kJ/kg] = **3070 kJ**

Energy required to melt ice

- Boeing 747 wing surface area: **524.9 m²**

- This leads to an energy consumption of **450 kWh** !

De-icing = energy-intensive task

Common de-icing methods

cif.org

- Sodium chloride
- Mechanical scraping
- De-icing fluids

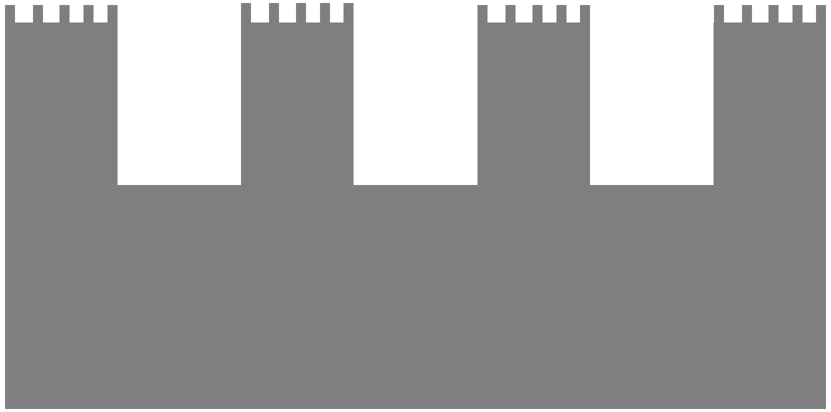
wikipedia.org

The city of Basel is using formates as thawing agents for de-icing.

Icephobicity: State-of-the-art

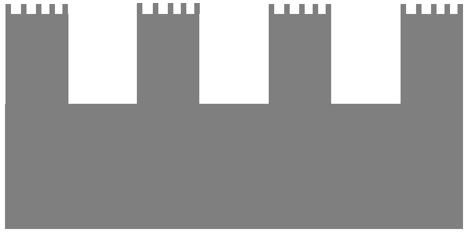
State-of-the-art passive icephobicity approaches

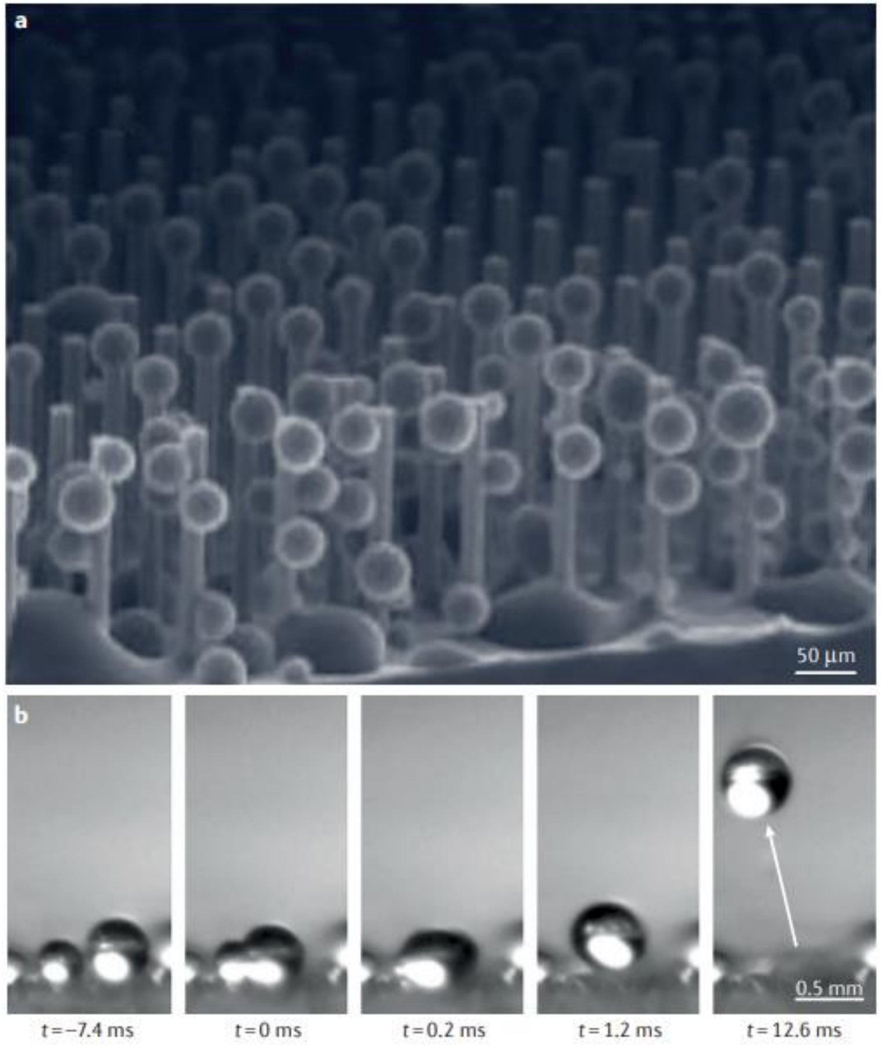
- **Hierarchical superhydrophobic surfaces**
- **Lubricant infused surfaces**



State-of-the-art passive icephobicity approaches

- **Hierarchical superhydrophobic surfaces** [1],[2]

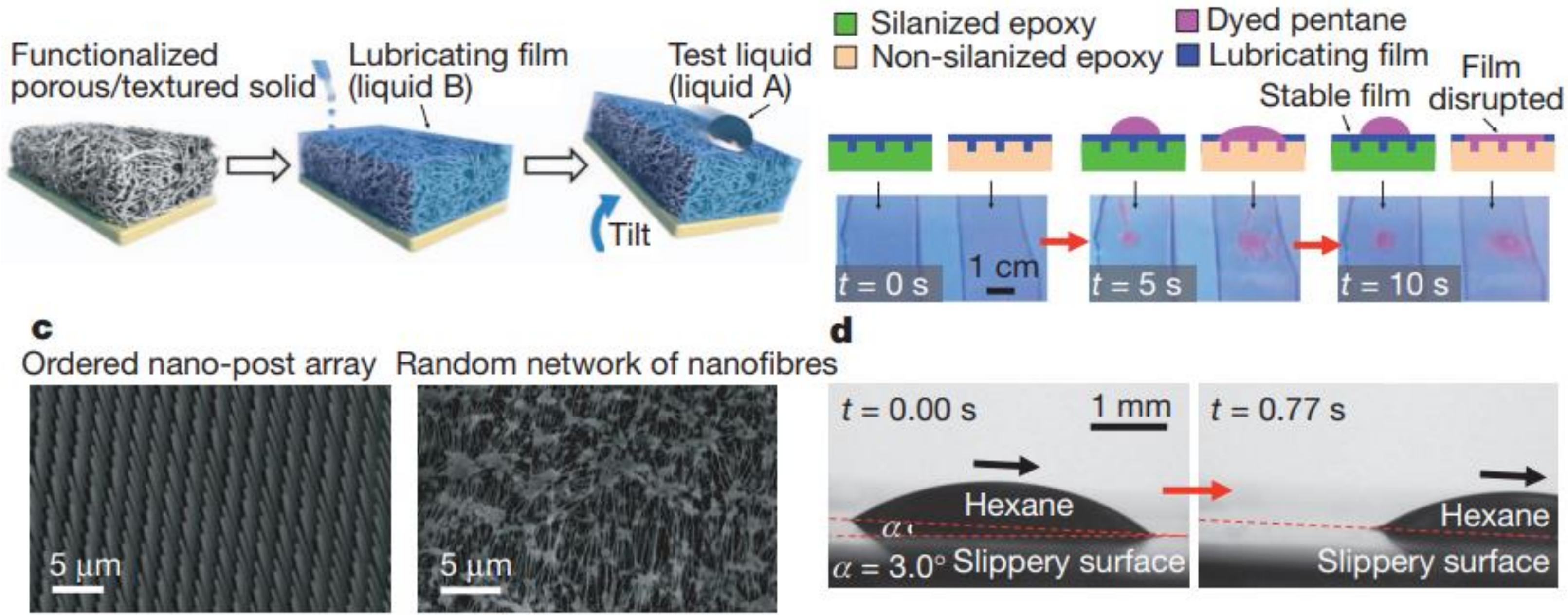




[1] Varanasi, K. K.; Hsu, M.; et. al. *Appl. Phys. Lett.* (2009)
[2] Boreyko, B. J.; Chen, C. *PRL* (2009)

State-of-the-art passive icephobicity approaches

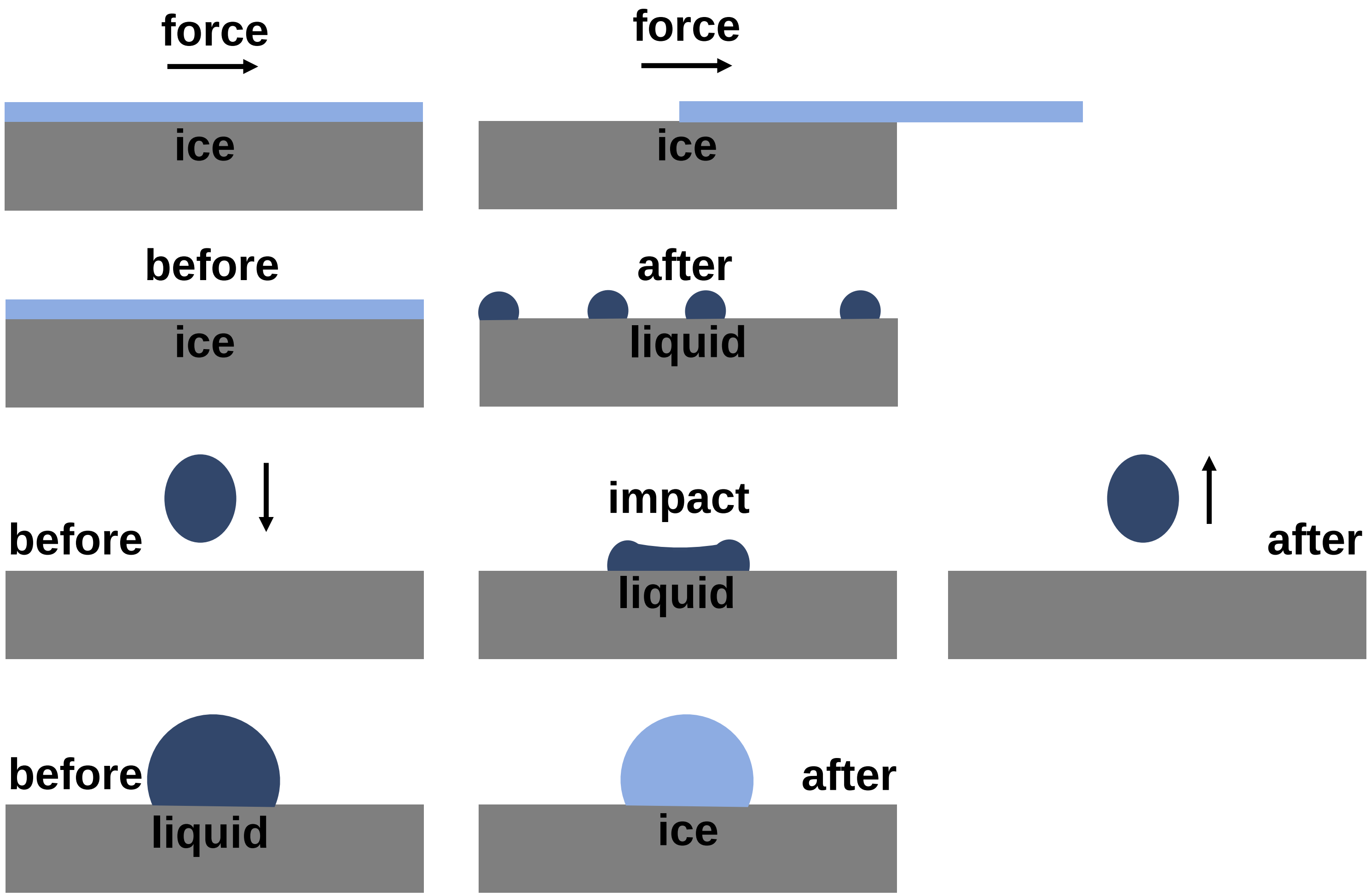
- **Lubricant infused surfaces** [3]



[3] Wong. T.; Kang H. S.; et. al. Nature (2011)

How do we define icephobicity?

- Reduced ice adhesion
- Reduced defrosting time
- Reduced droplet contact time
- Nucleation delay



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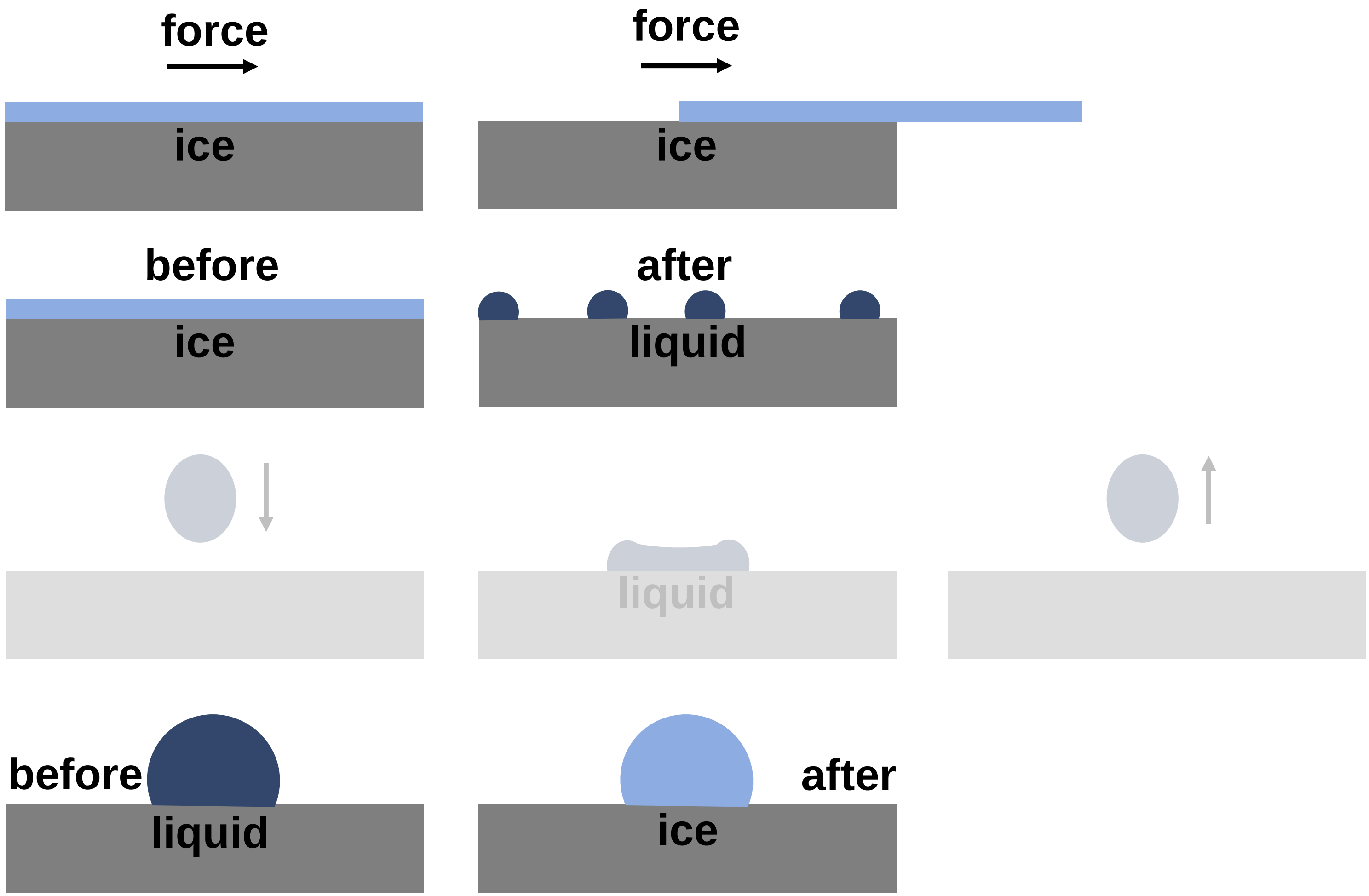

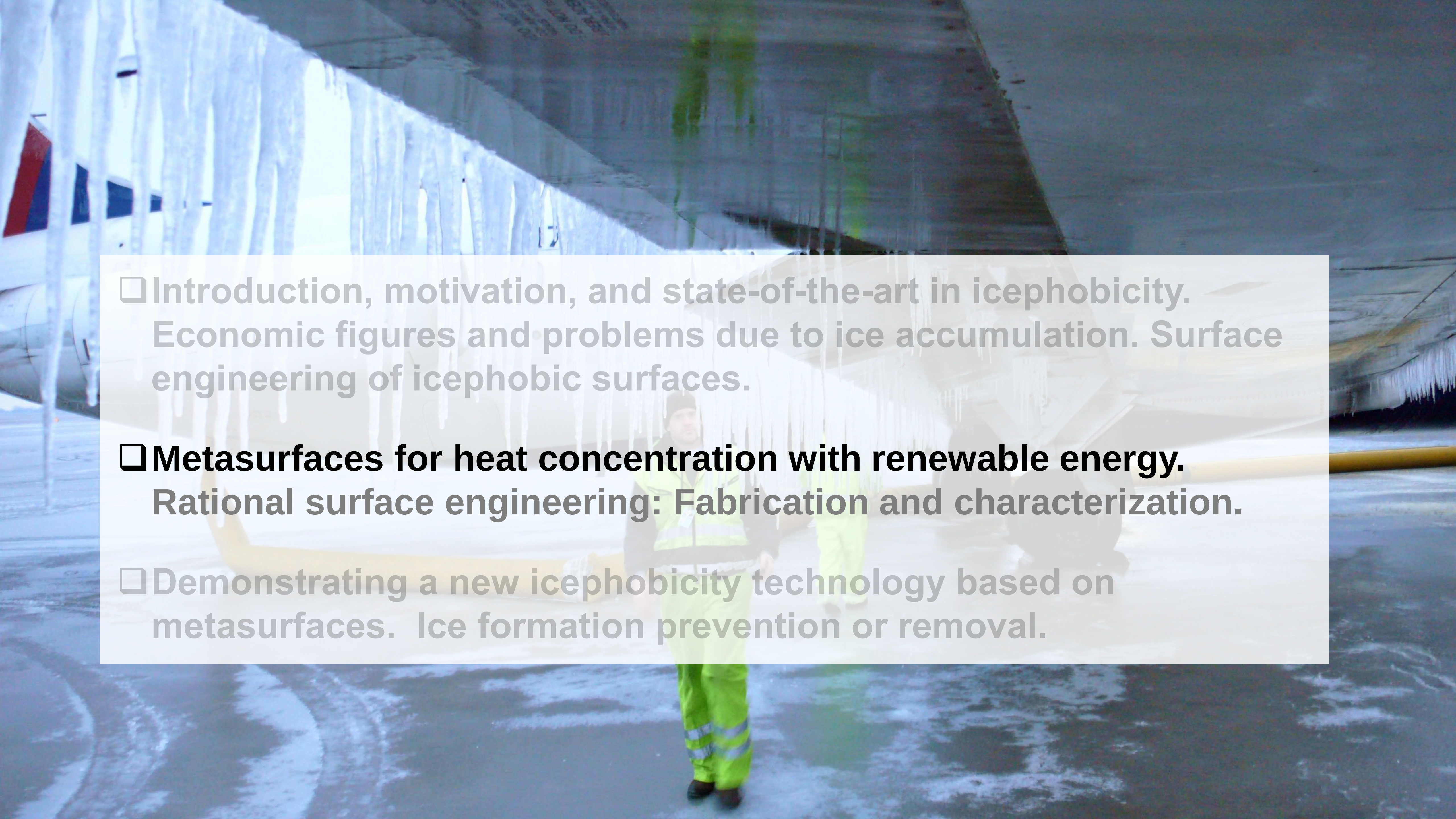

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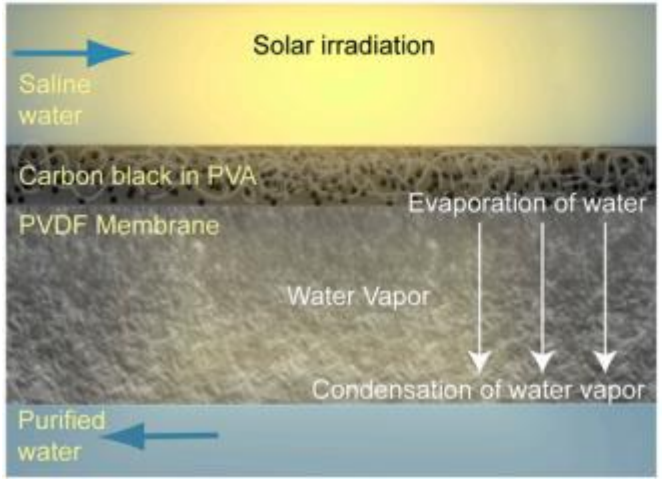
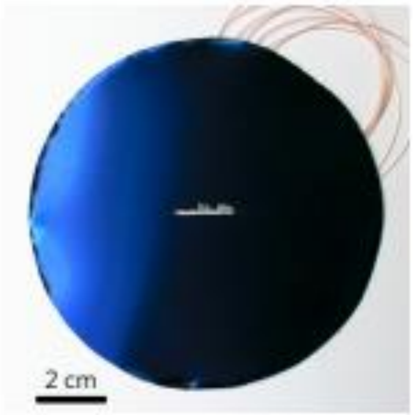
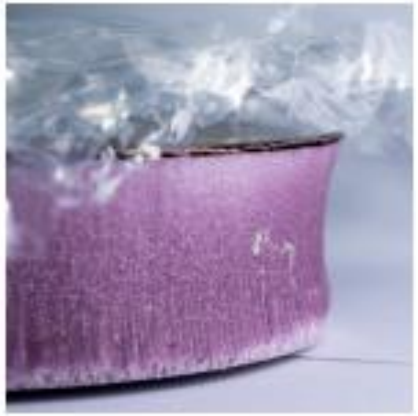
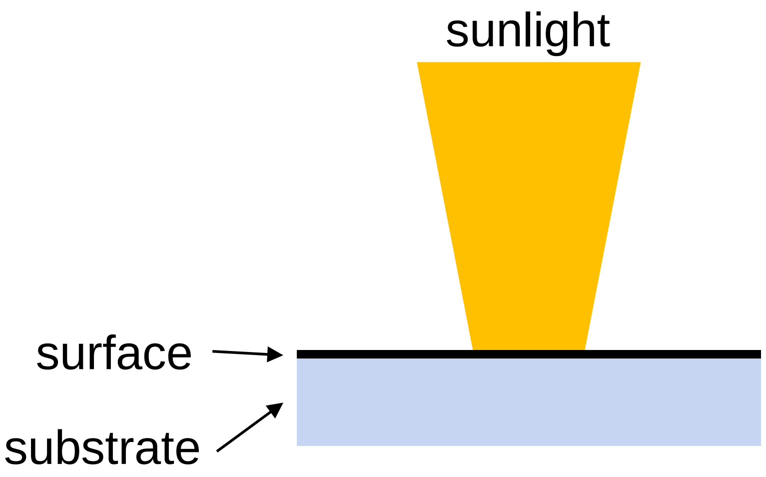
Inspiration

- Solar steam generation [1]
- Solar-enabled desalination [2]



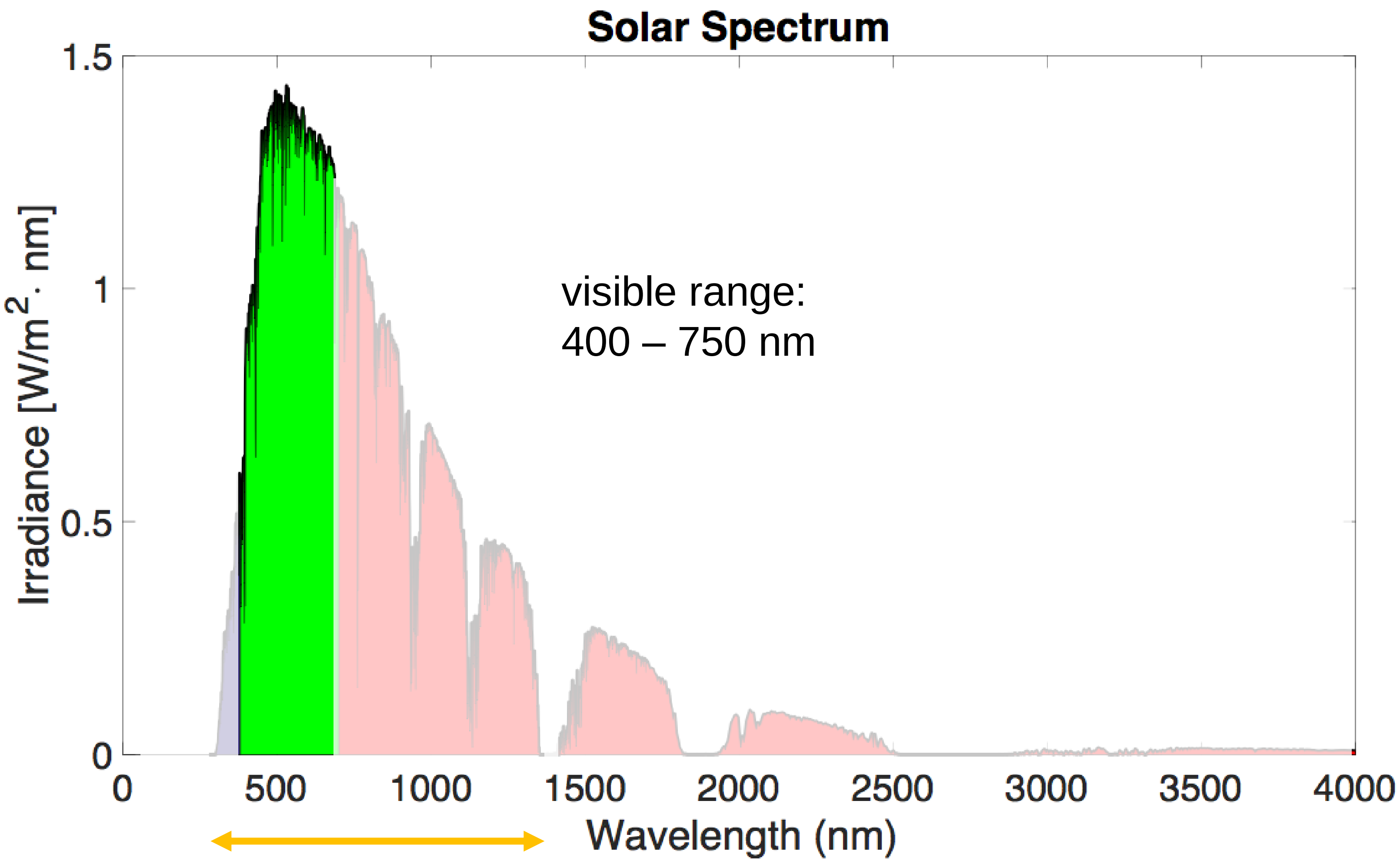






[1] Ni, G.; Li, G.; el. al. *Nature Energy* (2016)
[2] Dongare, D. P.; Alabastri, A.; et. al. *PNAS* (2017)

Metamaterials for solar energy absorption

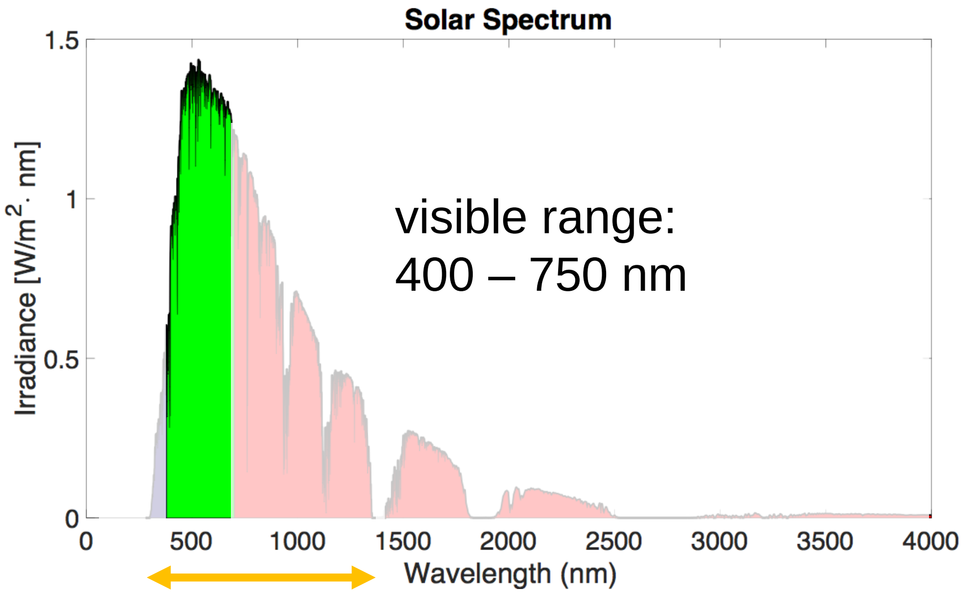


http://rredc.nrel.gov/solar/spectra/am1.5/

Metasurfaces for solar energy absorption

Facts:

- We need surfaces that absorb sunlight.
- Absorption also in the visible range => loss of transparency.
- The absorption spectrum has to be as broadband as possible.



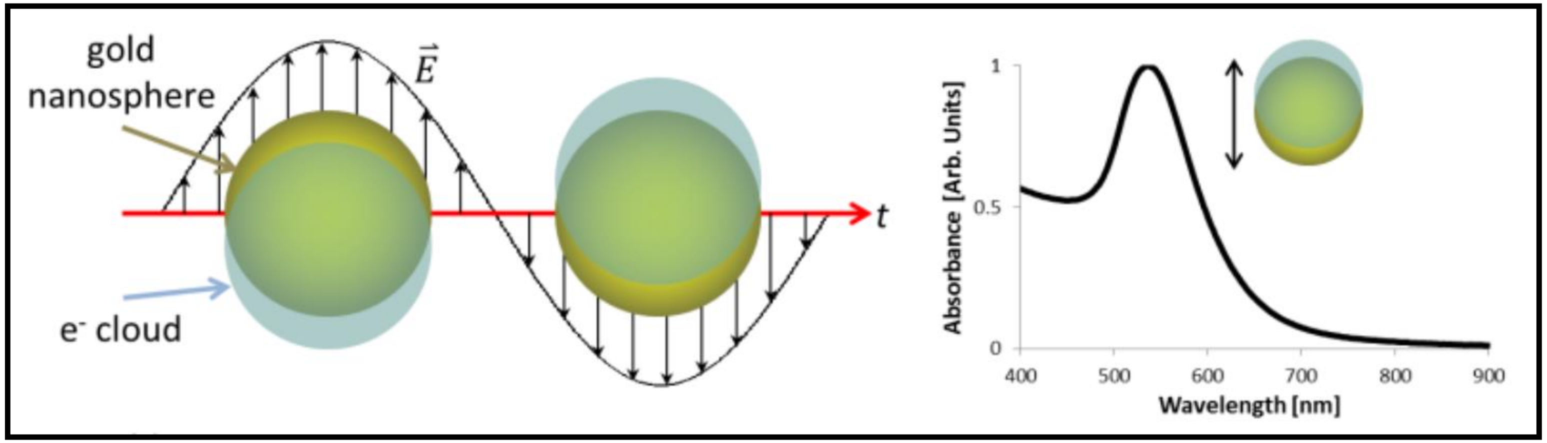
Metamaterials for solar energy absorption

Plasmonics: The most efficient way of creating sunlight absorbers that are ultra-thin at the same time.

Hint: Their properties cannot be found in natural materials.

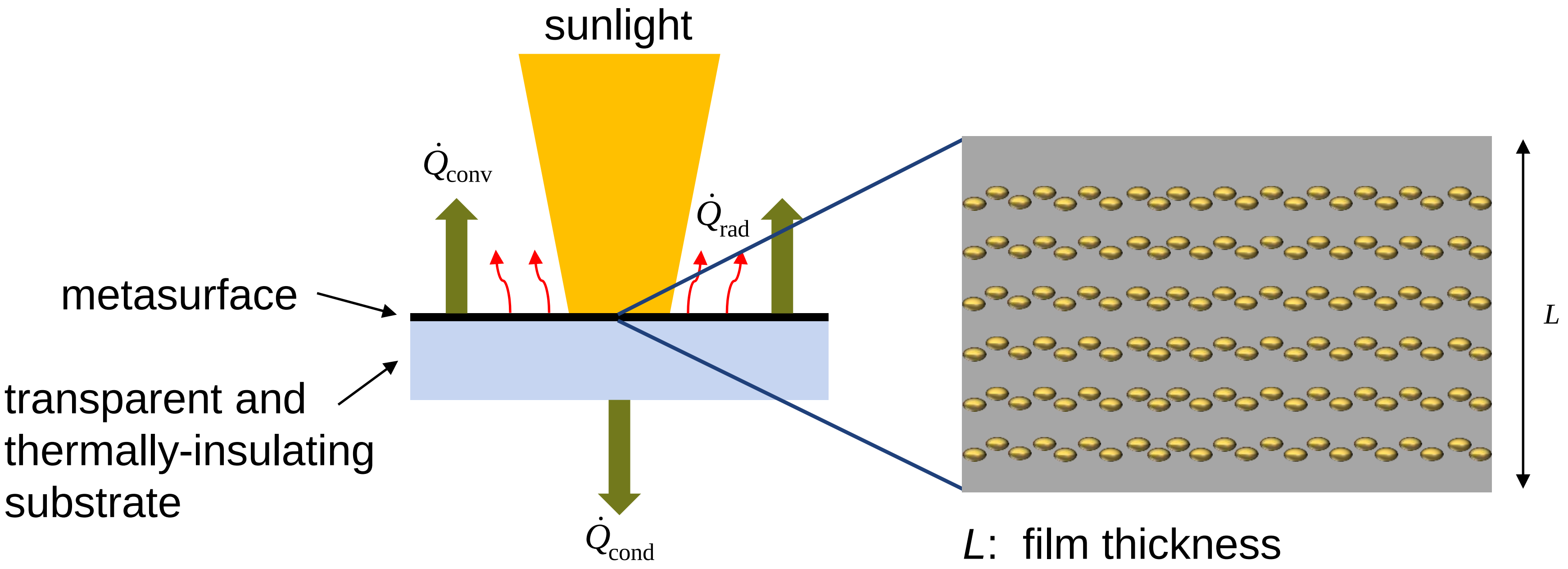
Material: **Gold** (Au) nanoparticles

Localized Surface Plasmon Resonance (LSPR)



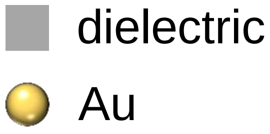
scholar.harvard.edu/ndurr/pages/multiphoton-luminescence-imaging

Design: Metamaterials for solar energy absorption



L: film thickness

v_{Au}: volumetric concentration of Au



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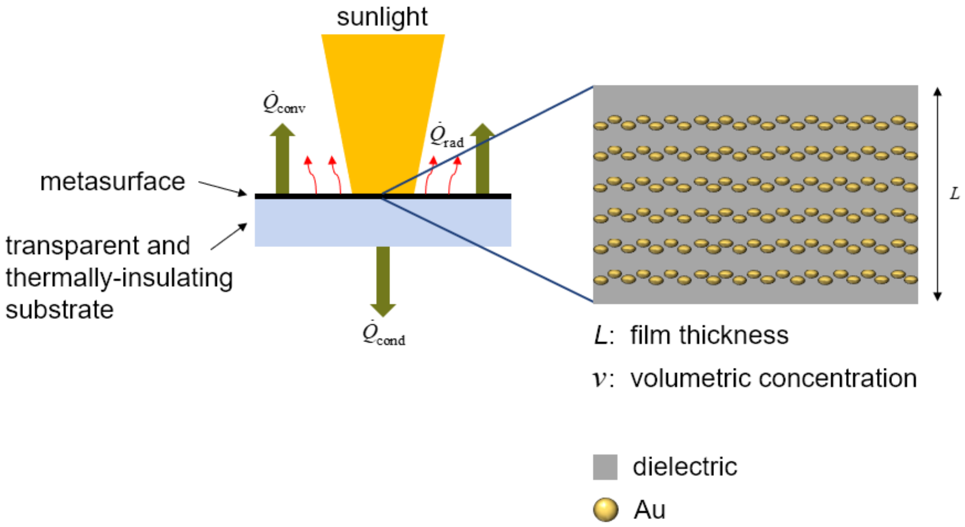
Design: Metamaterials for solar energy absorption

Bruggeman effective medium theory:

$$\varepsilon_{\mathrm{r,nc}} = \frac{1}{4}\left\{ \begin{array}{l} \left(3v_{\mathrm{Au}}-1\right)\varepsilon_{\mathrm{r,Au}} + \left(3v_{\mathrm{diel}}-1\right)\varepsilon_{\mathrm{r,diel}} \pm \\ \sqrt{\left[\left(3v_{\mathrm{Au}}-1\right)\varepsilon_{\mathrm{r,Au}} + \left(3v_{\mathrm{diel}}-1\right)\varepsilon_{\mathrm{r,diel}}\right]^2 + 8\varepsilon_{\mathrm{r,Au}}\varepsilon_{\mathrm{r,diel}}} \end{array} \right\}$$

$\varepsilon_{\mathrm{r,nc}}$: effective permittivity of the nanocomposite



Facts:

- ☑ We need surfaces that absorb sunlight.
- ☑ Absorption also in the visible range.
- ❑ The absorption has to be as broadband as possible.

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Design: Metamaterials for solar energy absorption

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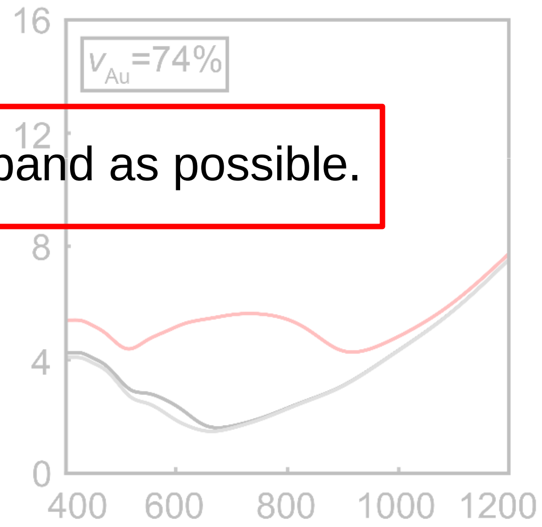
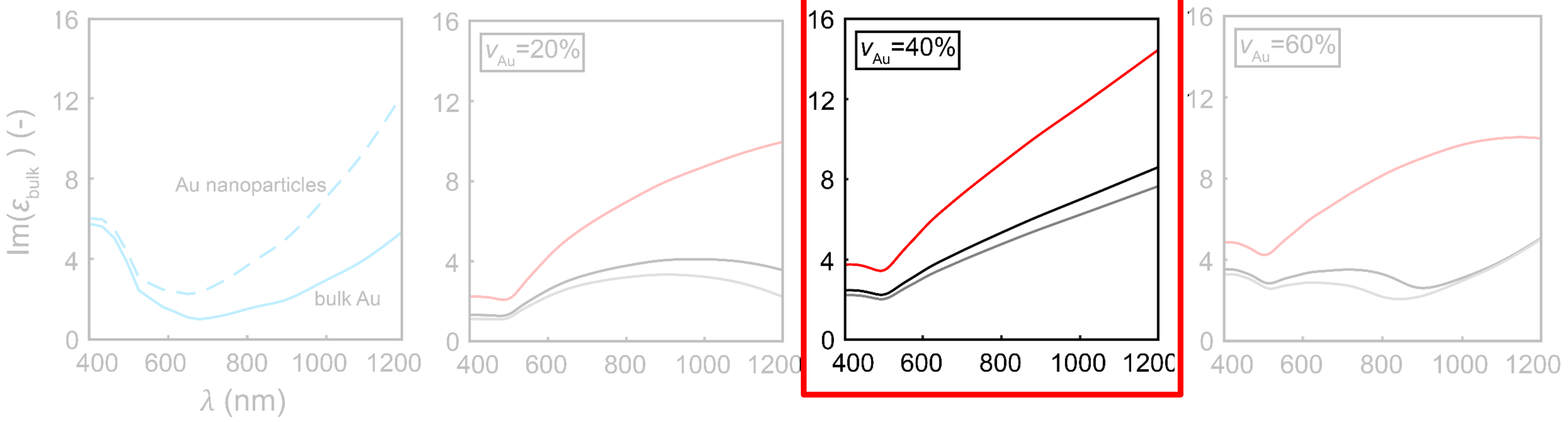
☑ The absorption has to be as broadband as possible.





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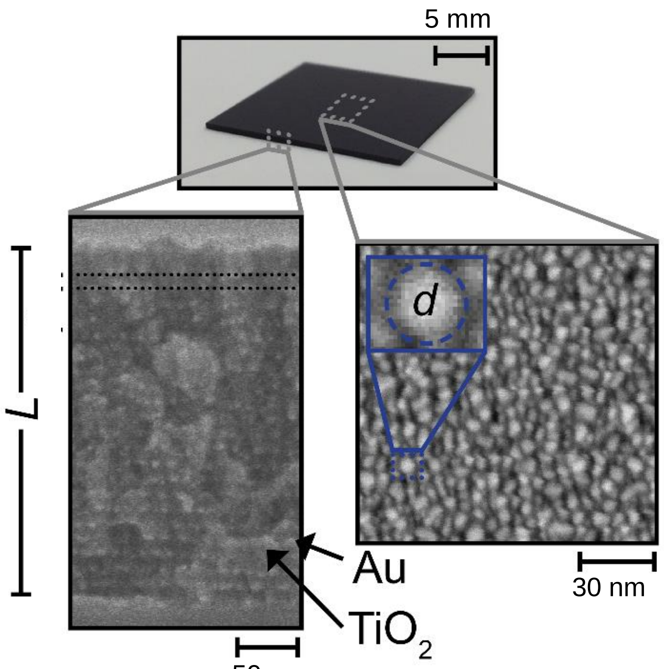
λ: wavelength of light

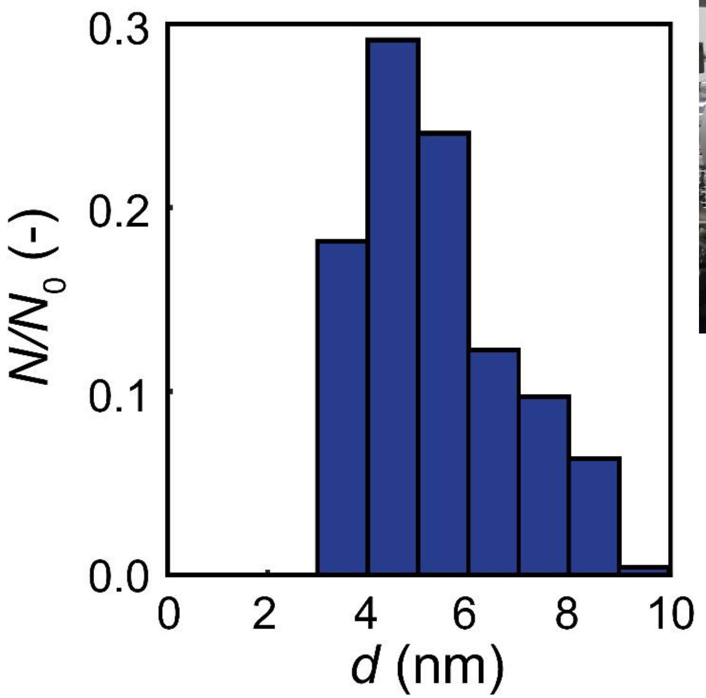
Metasurface engineering: Fabrication and characterization

Fabrication and optical characterization

Sputter deposition: Au and TiO_2.



$L_{max} < 300$ nm



d: nanoparticle diameter

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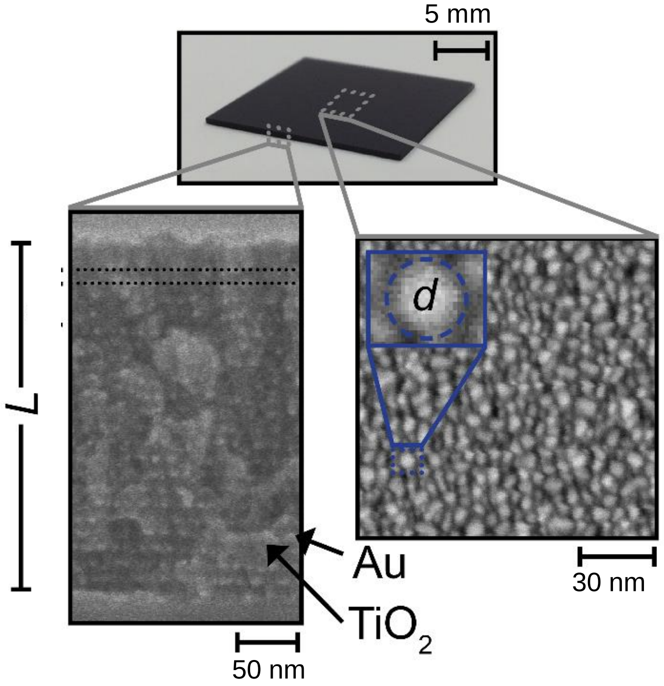
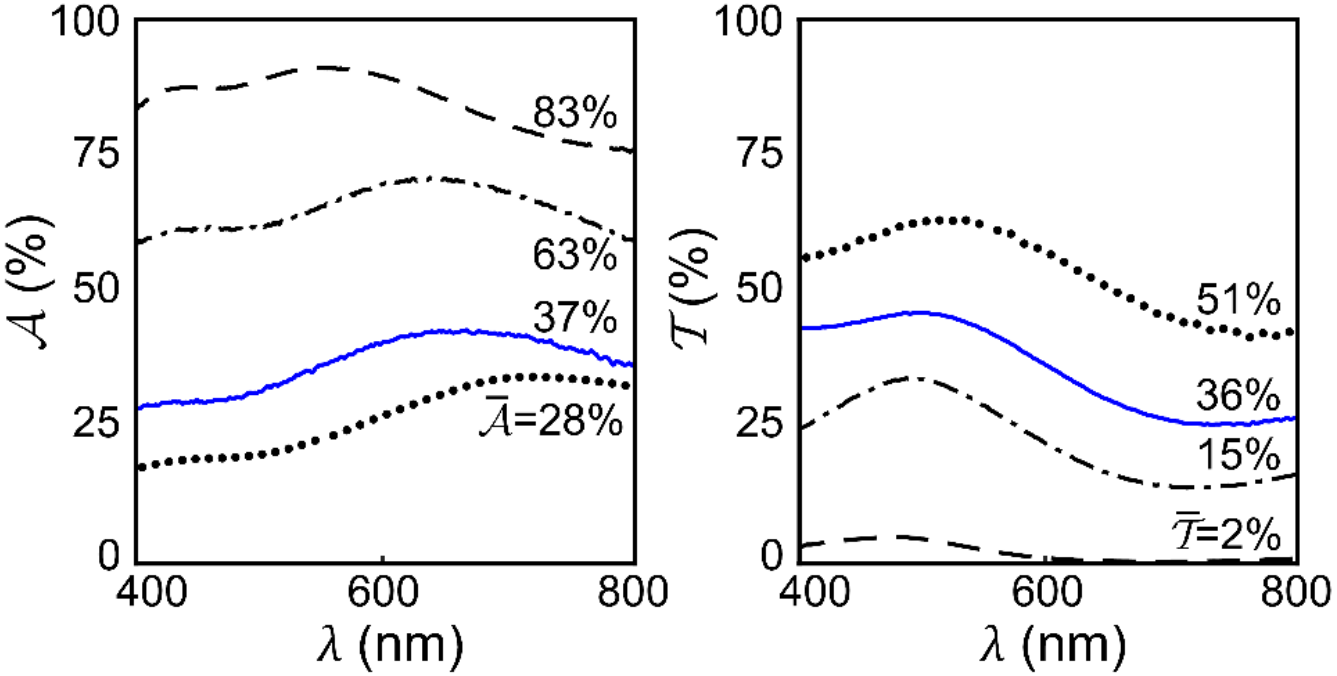
Fabrication and optical characterization

. . . 40 nm
___ 60 nm
_._ 100 nm
_ _ 270 nm

Sputter deposition: Au and TiO_2.





$L_{max} < 300$ nm

A: light absorption
T: light transmission

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Fabrication and optical characterization

. . . 40 nm
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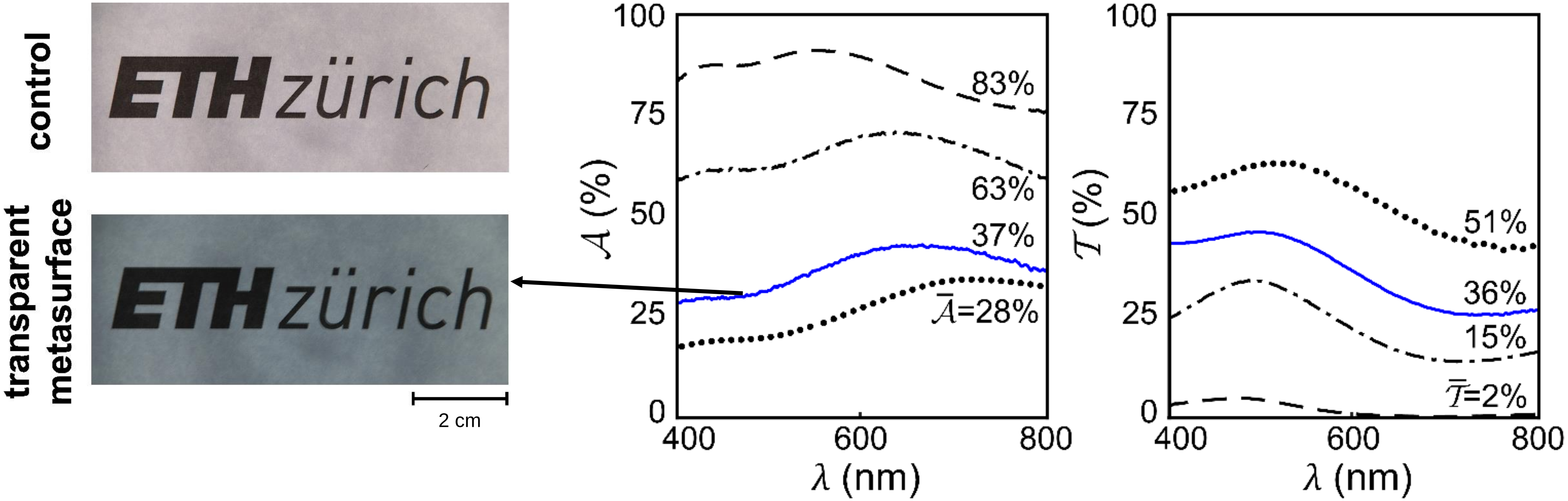
Sputter deposition: Au and TiO_2.



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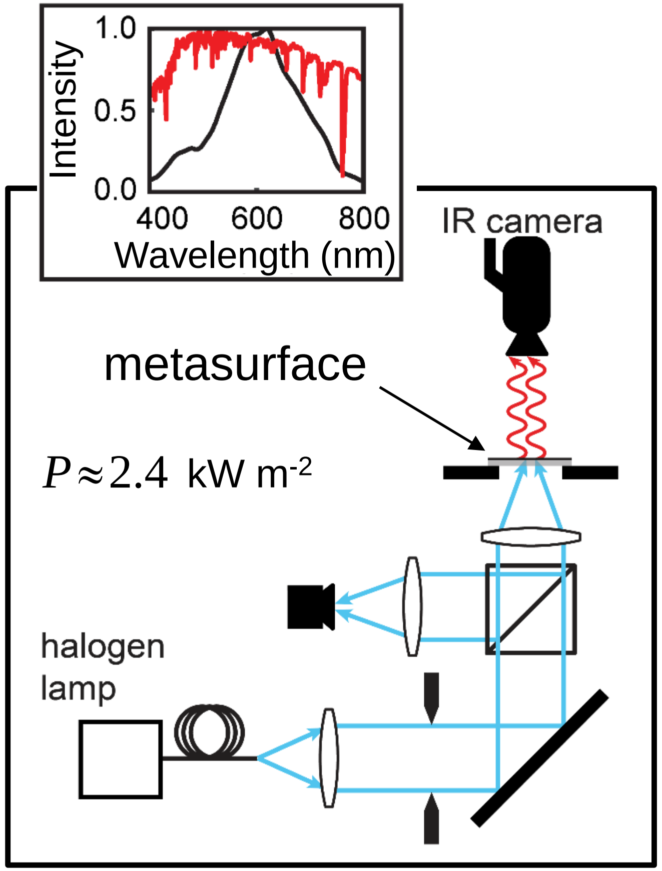
Light-induced heating and characterization with high-speed infrared imaging



P: power density

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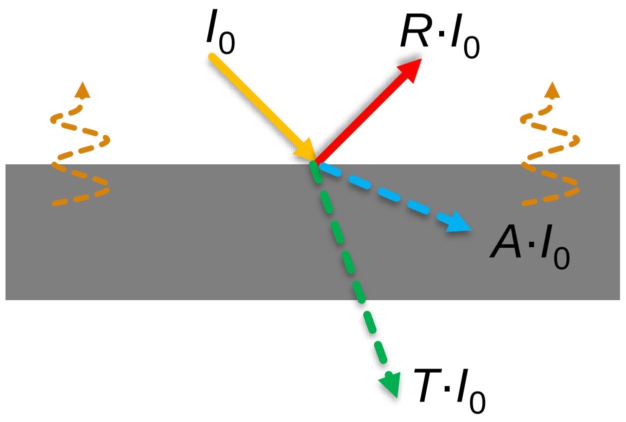
Infrared imaging: Basic principles

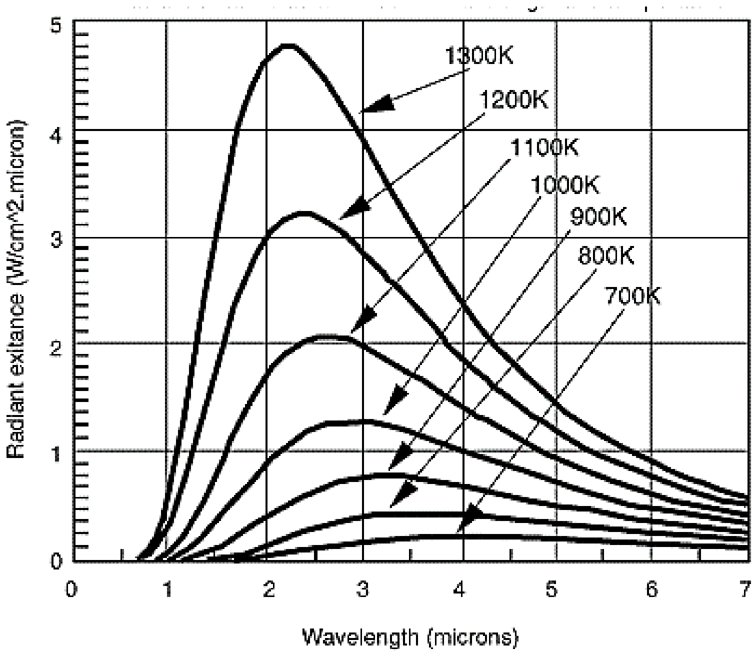
- **Total radiation**



$$A(\lambda)+R(\lambda)+T(\lambda) = 1$$

- For object temperatures <500 °C, thermal radiation lies completely in the infrared.

Infrared imaging: Basic principles



- **Thermal emissivity (ε)**

The effectiveness of emitting energy as thermal radiation.

$$\varepsilon(\lambda)=A(\lambda)$$

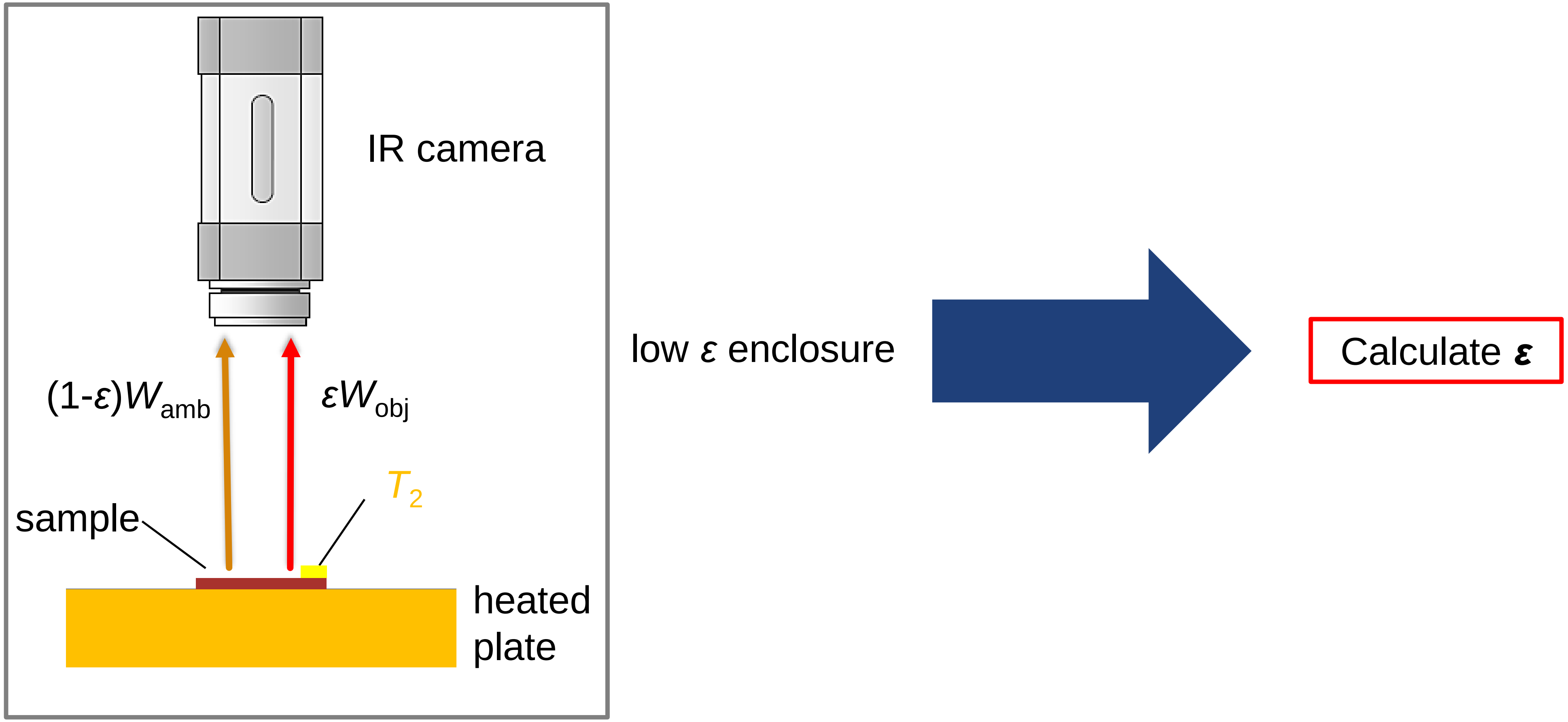
- The maximum emittance wavelength is inversely proportional to temperature.

$$\lambda_{max}=2898/T$$

T: temperature [K]

Infrared imaging: Basic principles

- **Calibration**



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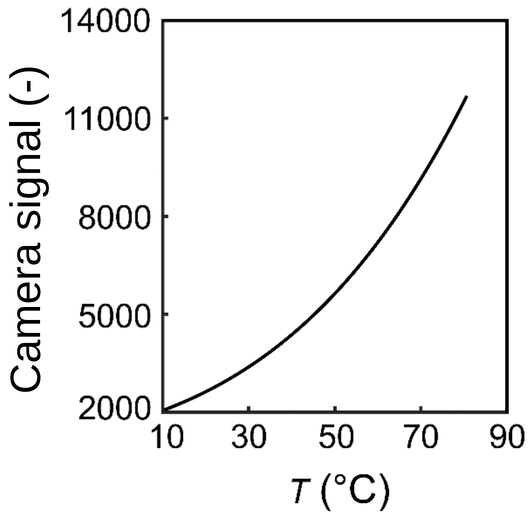
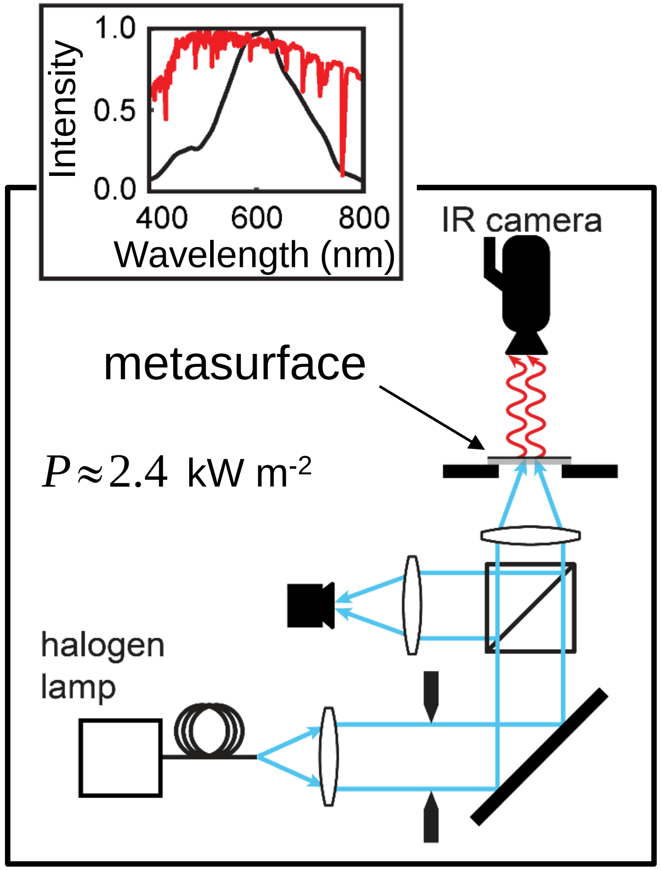


Calculate ε

Calculate **temperature**

Light-induced heating



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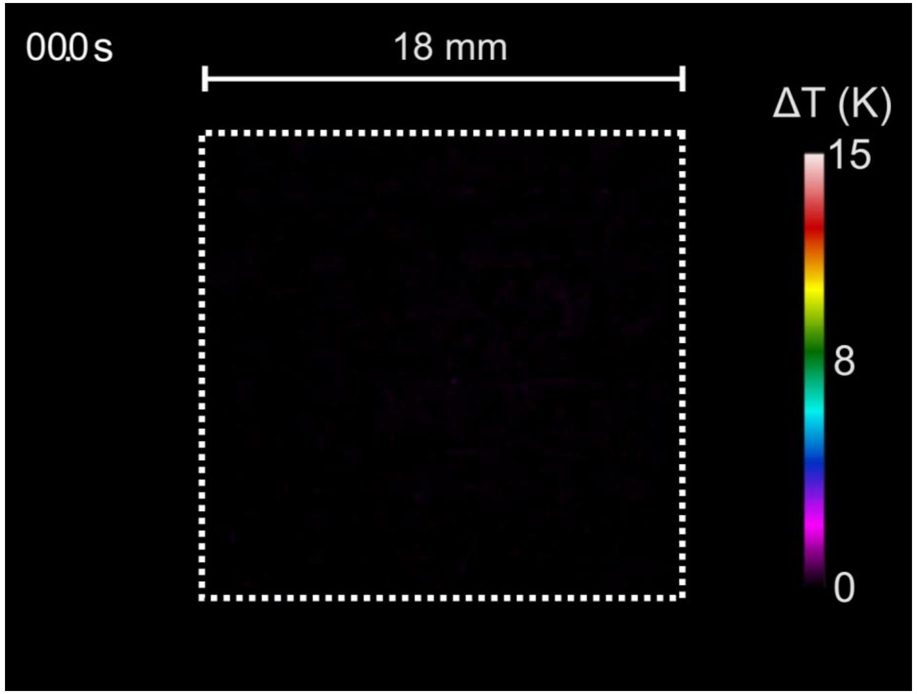

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Light-induced heating

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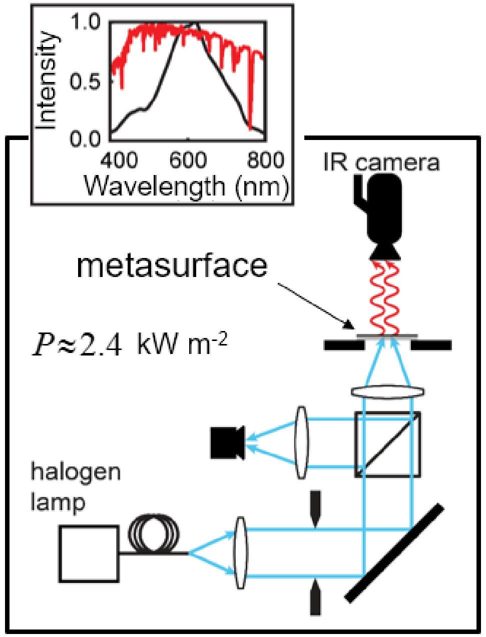

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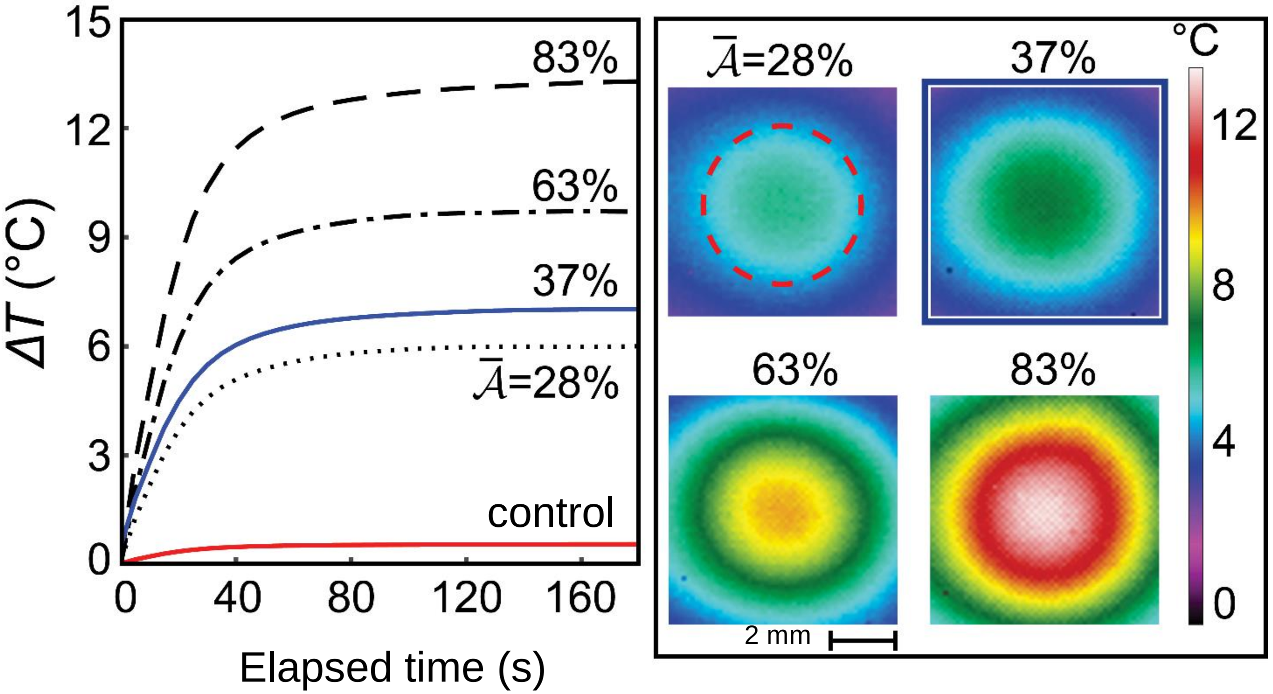

ΔT: temperature increase

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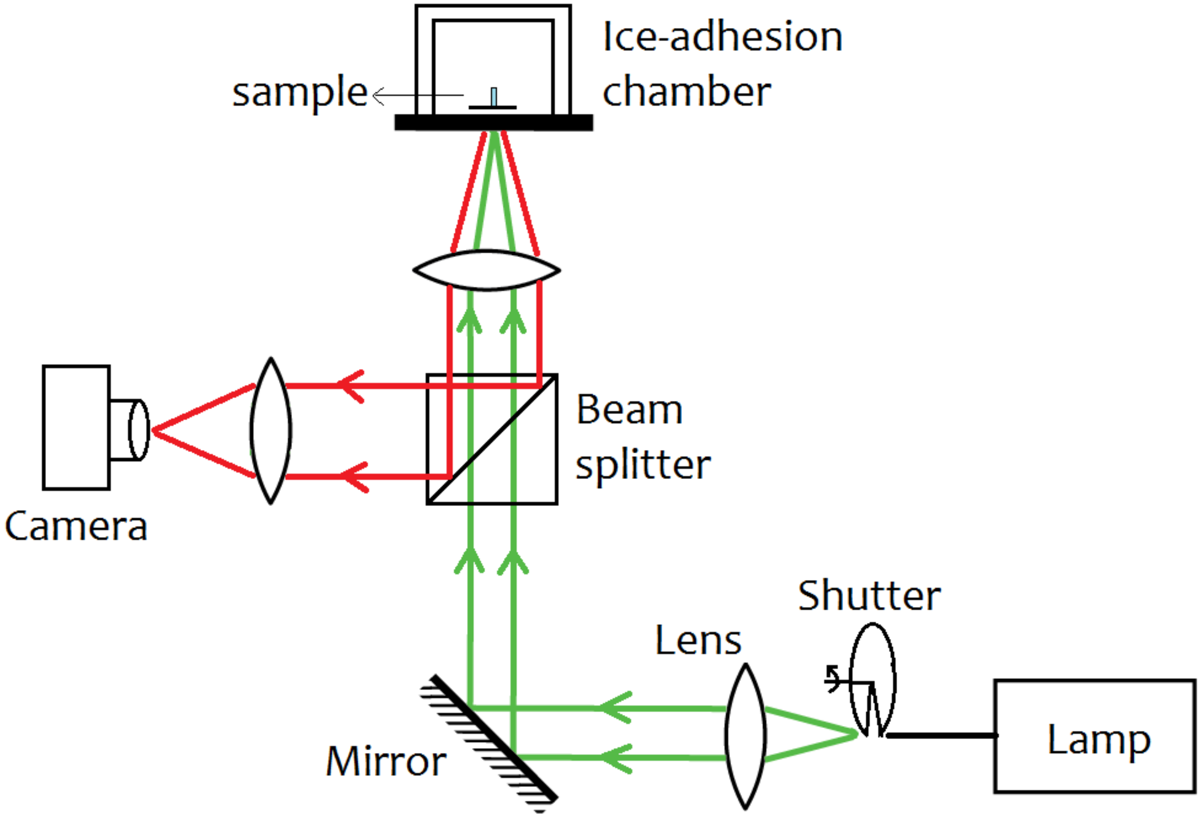
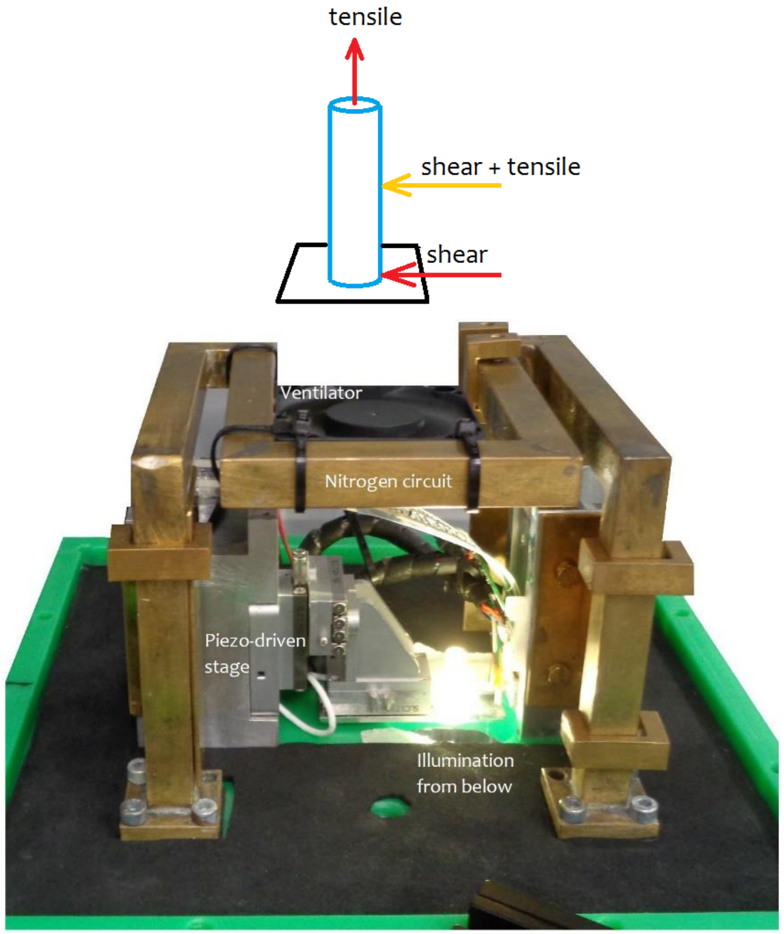
De-icing, anti-icing and defrosting

- Ice adhesion measurements under visible light





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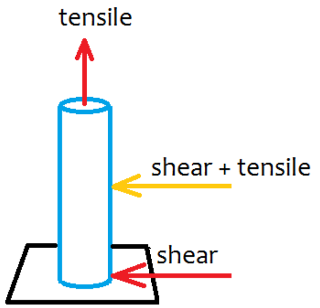
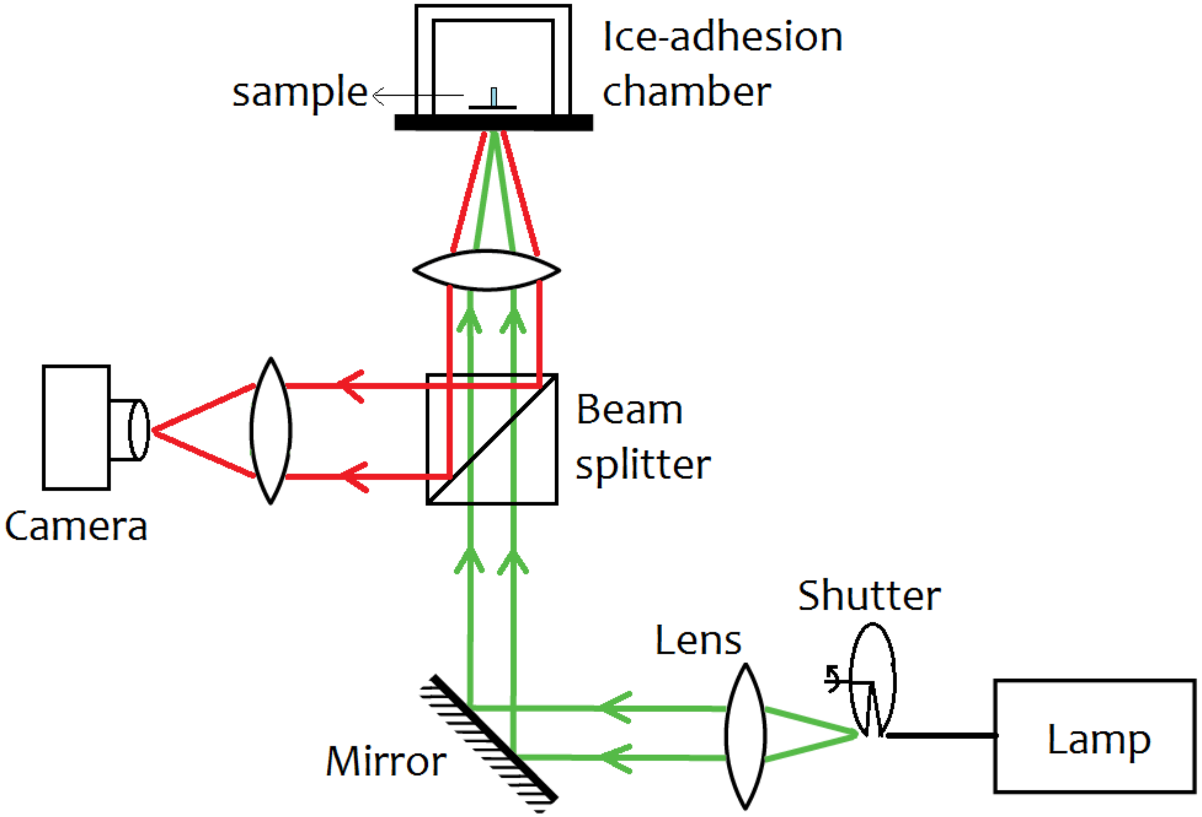
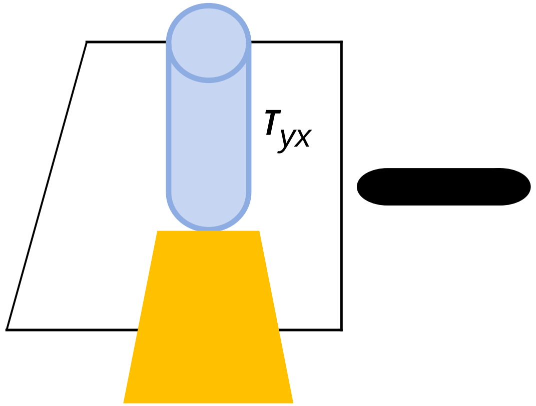
De-icing, anti-icing and defrosting



- **Ice adhesion measurements under visible light**





τ_{yx} : shear stress

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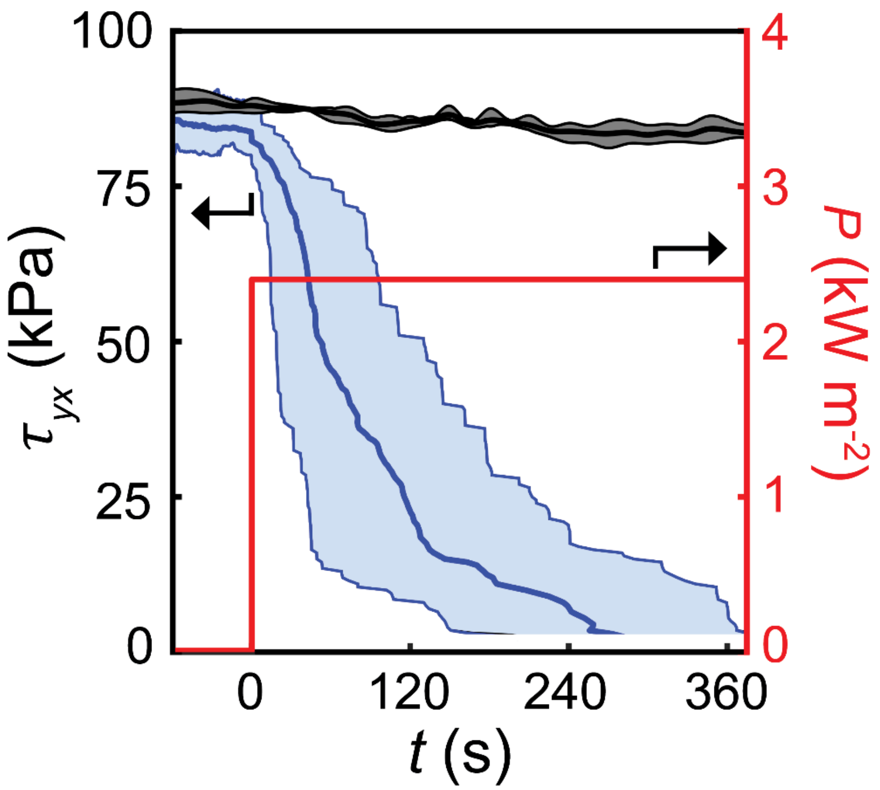
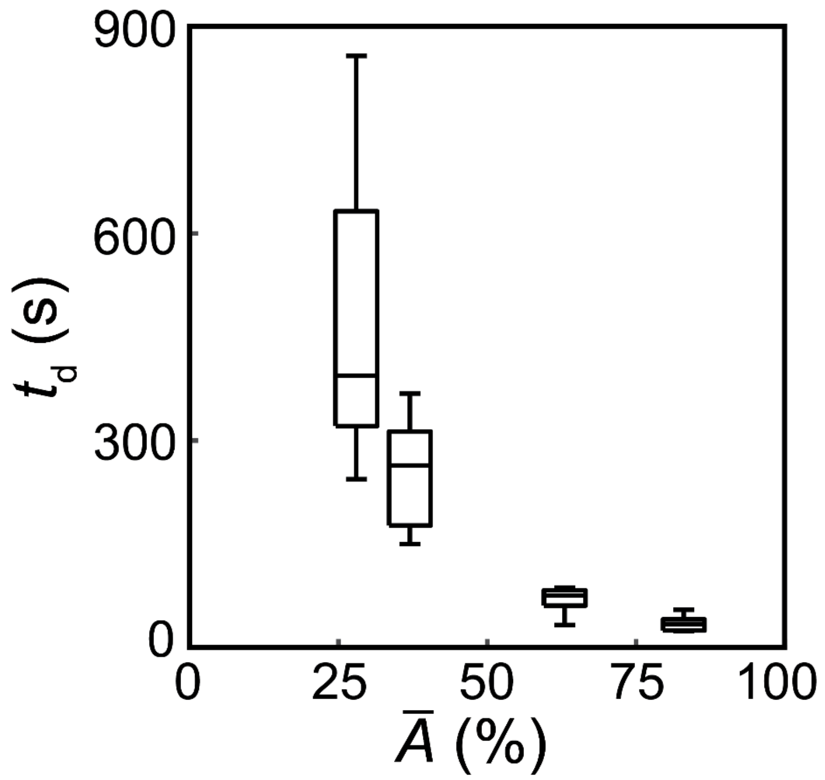
De-icing, anti-icing and defrosting

- Ice adhesion measurements under visible light





τ_{yx} : shear stress

t_d : de-icing time

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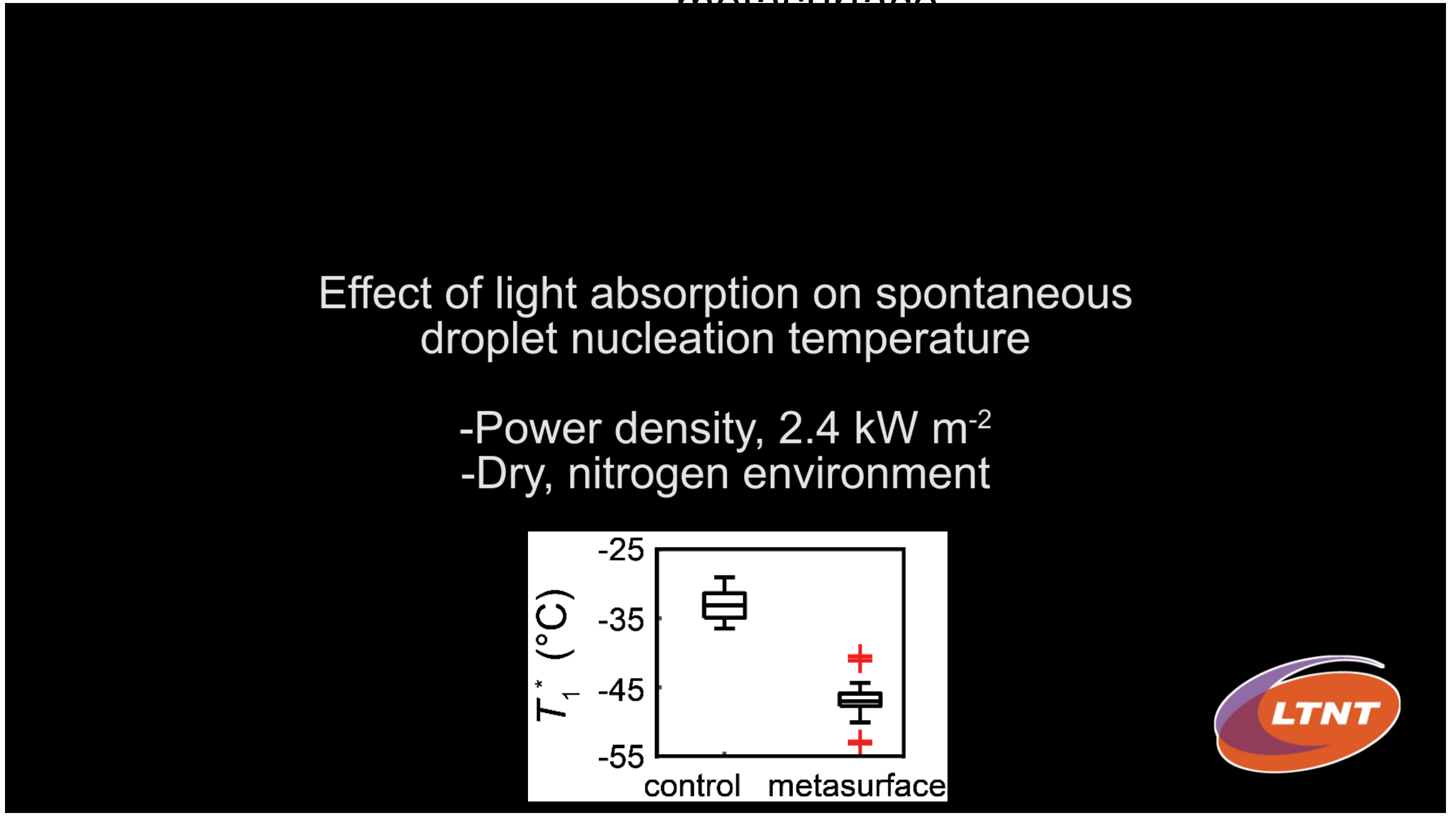
De-icing, anti-icing and defrosting

- **Light-induced anti-icing experiments with a single water droplet**



T_1: gas temperature

T_2: surface temperature

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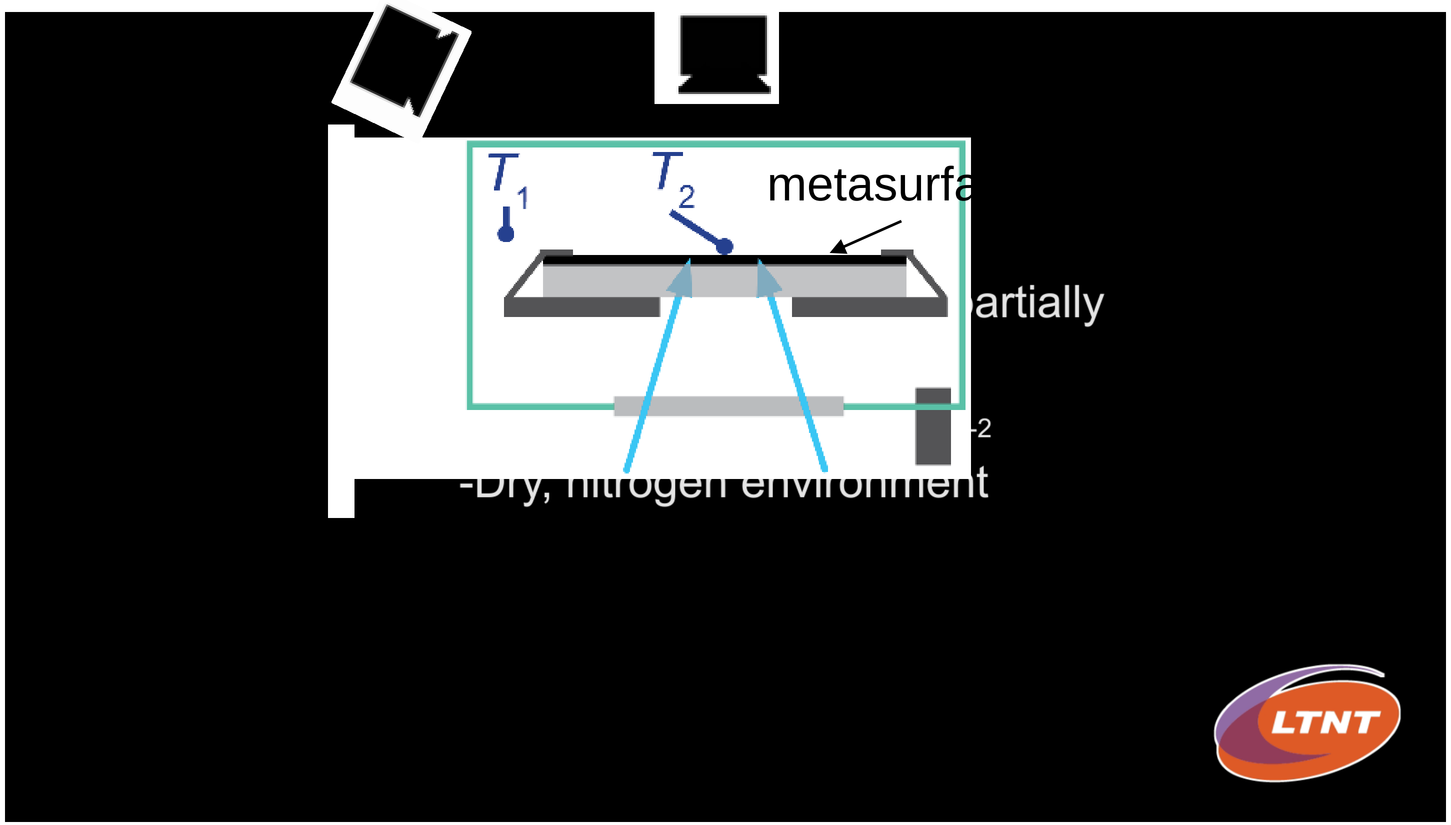
De-icing, anti-icing and defrosting

❑ Light-induced defrosting experiments



T_1: gas temperature

T_2: surface temperature

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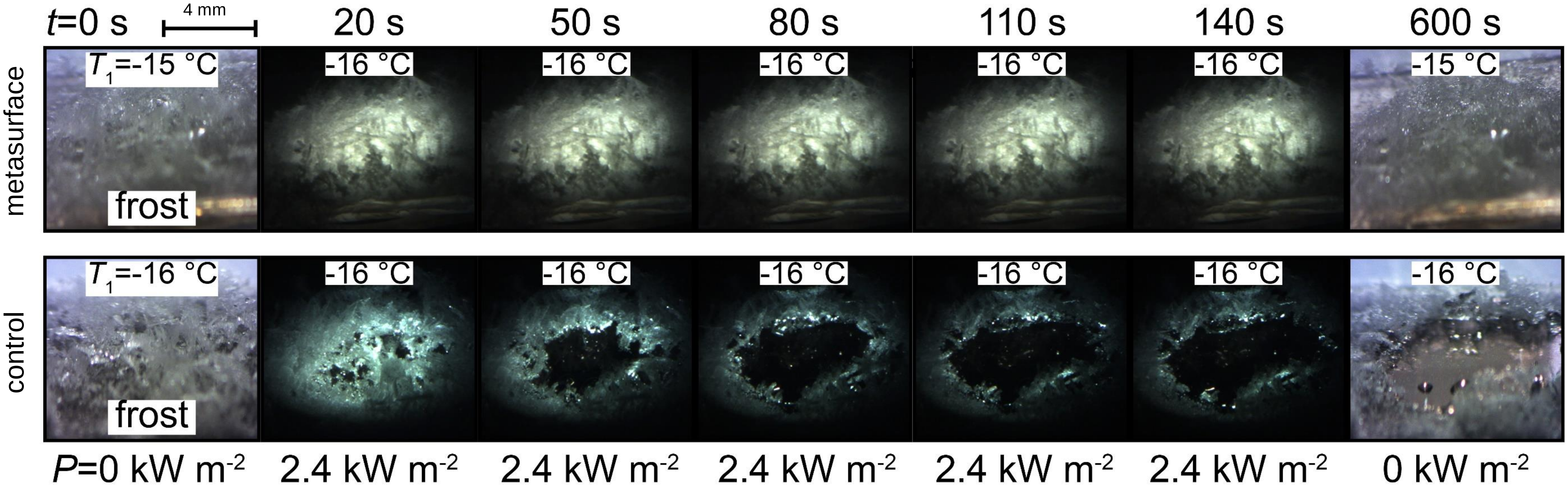
De-icing, anti-icing and **defrosting**

- **Light-induced defrosting experiments**



T_1: gas temperature

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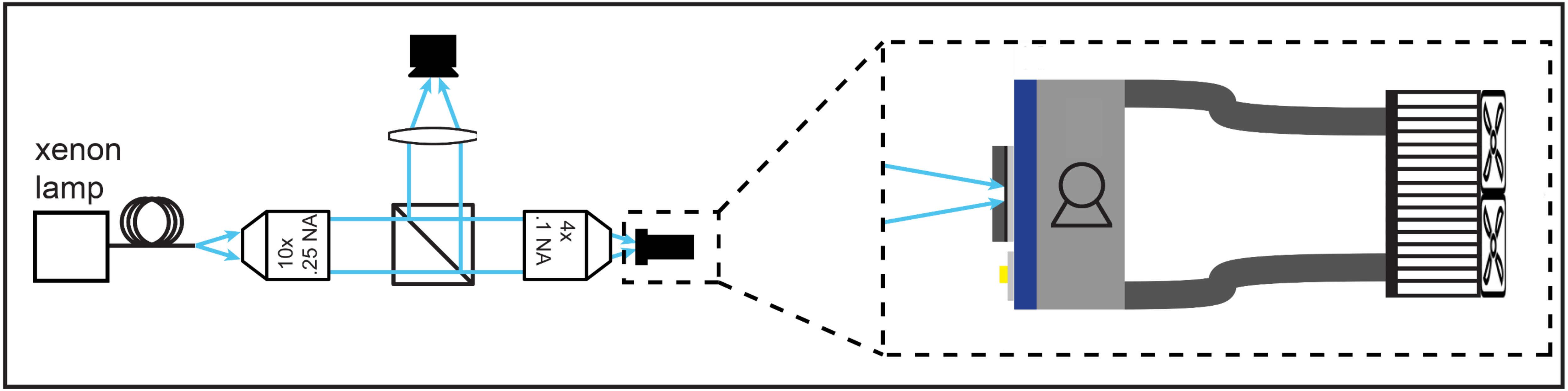
De-icing, anti-icing and defrosting

- Light-induced anti-icing under one sun



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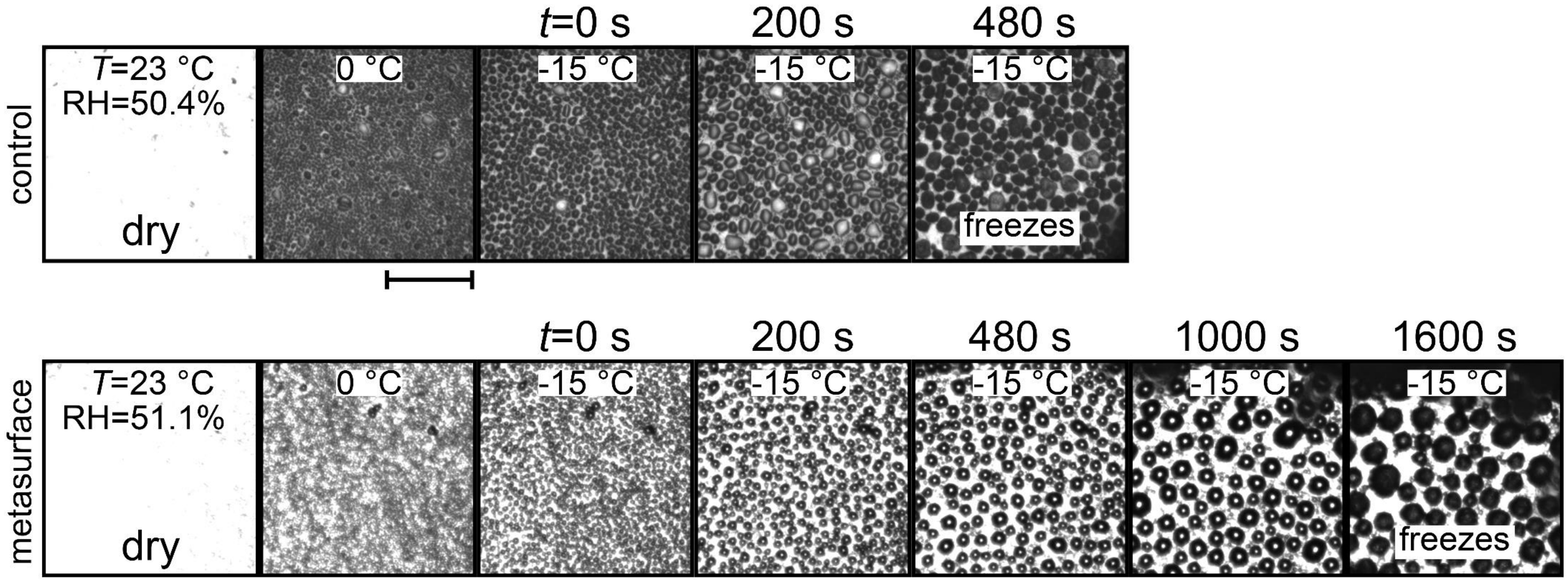
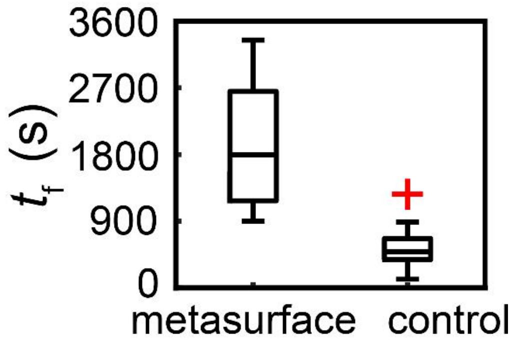
De-icing, **anti-icing** and defrosting

- **Light-induced anti-icing under one sun**





T: surface temperature
t_f: freezing time

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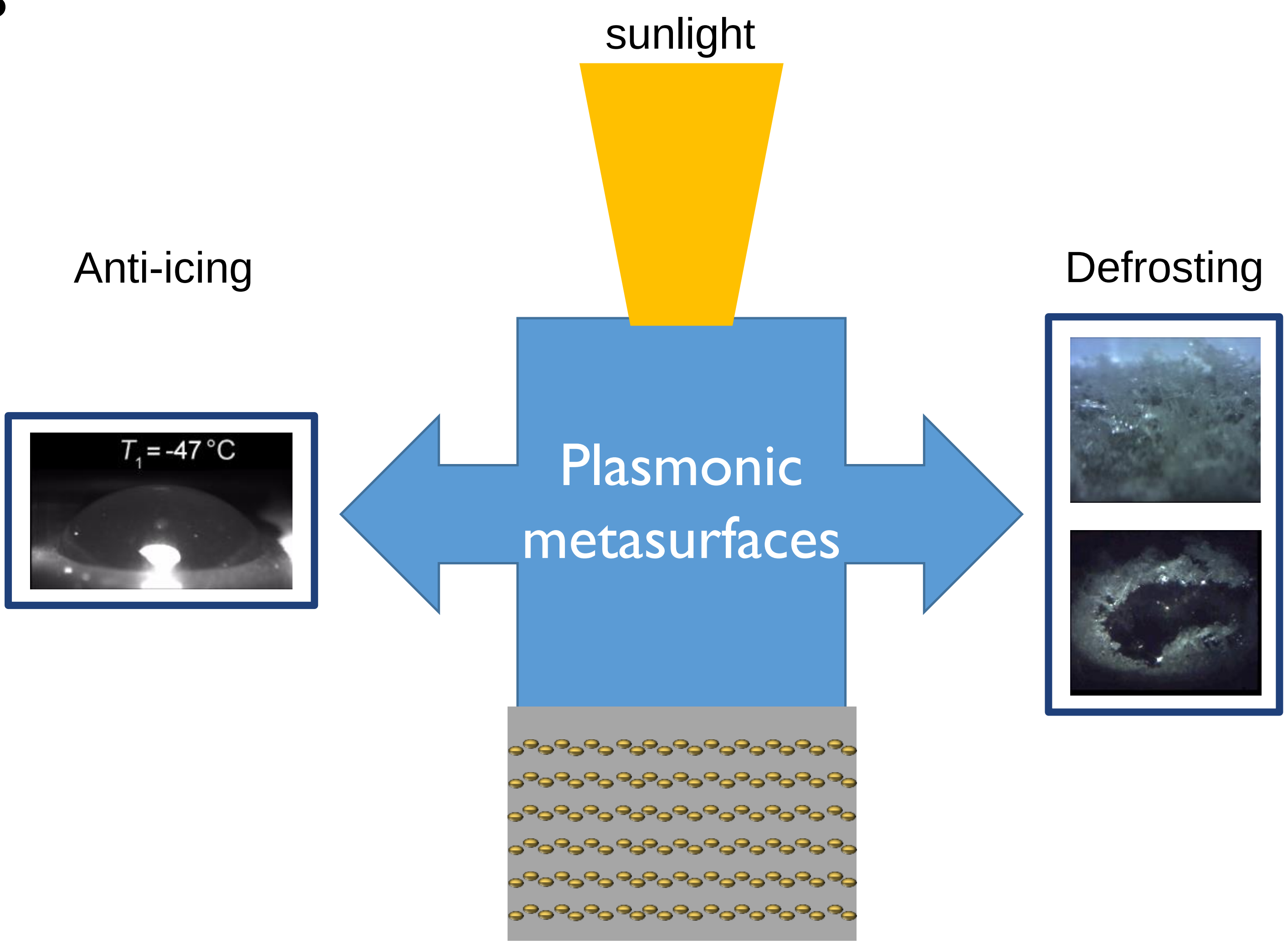
Conclusions and outlook

Conclusions



Conclusions

- ❑ Ultra-thin, easy-to-fabricate, metamaterial coatings provide broadband light absorption.
- ❑ Rationally tunable absorption: samples can be transparent or black.
- ❑ The exhibited temperature increase is enough to melt ice and prevent its formation.
- ❑ Trade-off between level of absorption and performance.

jansen.com

Applications:

- ✓ Windows and windshields
- ✓ Sun roofs

…and more applications where a degree of optical transparency is required

solarbuldingtech.com

The future

Facts:

- ✓ **Superhydrophobicity** enhances the anti-icing performance.
- ✓ Superhydrophobicity: requires **micro-/nano-texture** and suitable surface **chemistry**.
- ✓ Minimize thermal conductivity of the substrate, or resistance to heat transfer.

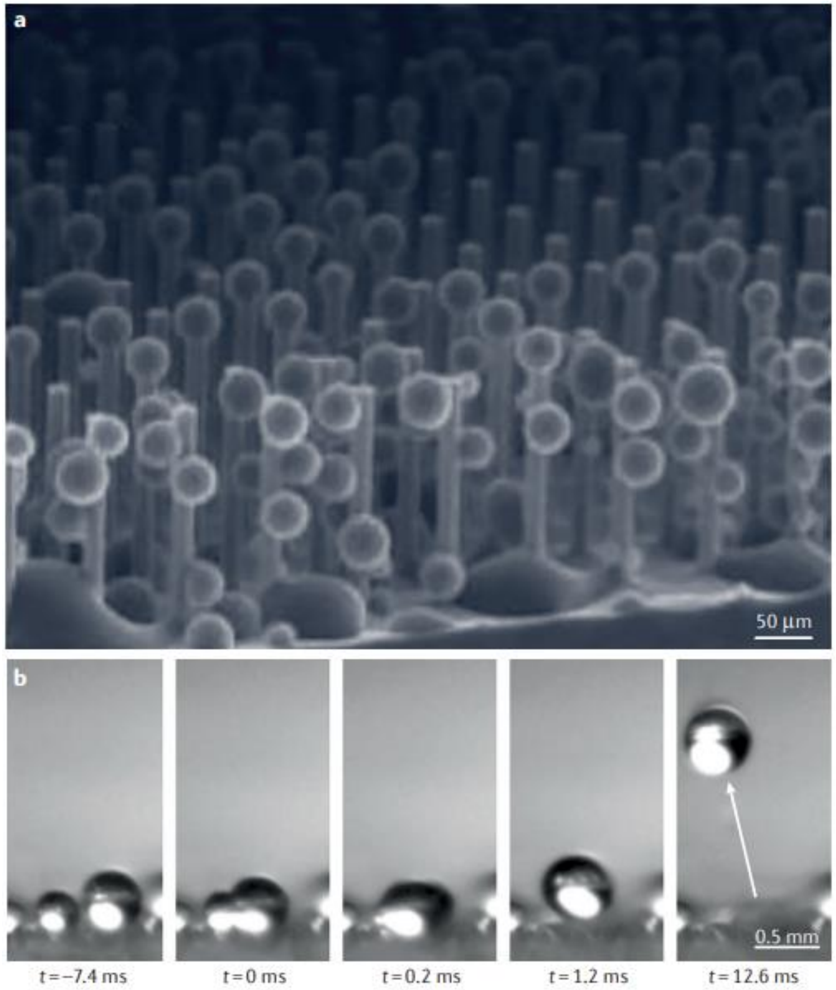
The future

Facts:

- ✓ **Superhydrophobicity** enhances the anti-icing performance.
- ✓ Superhydrophobicity: requires **micro-/nano-texture** and suitable surface **chemistry**.
- ✓ Minimize thermal conductivity of the substrate, or resistance to heat transfer.

The future

- ✓ **Superhydrophobicity** enhances the anti-icing performance. [1],[2]
- ✓ Superhydrophobicity: requires **micro/nano-texture** and suitable **chemistry**.



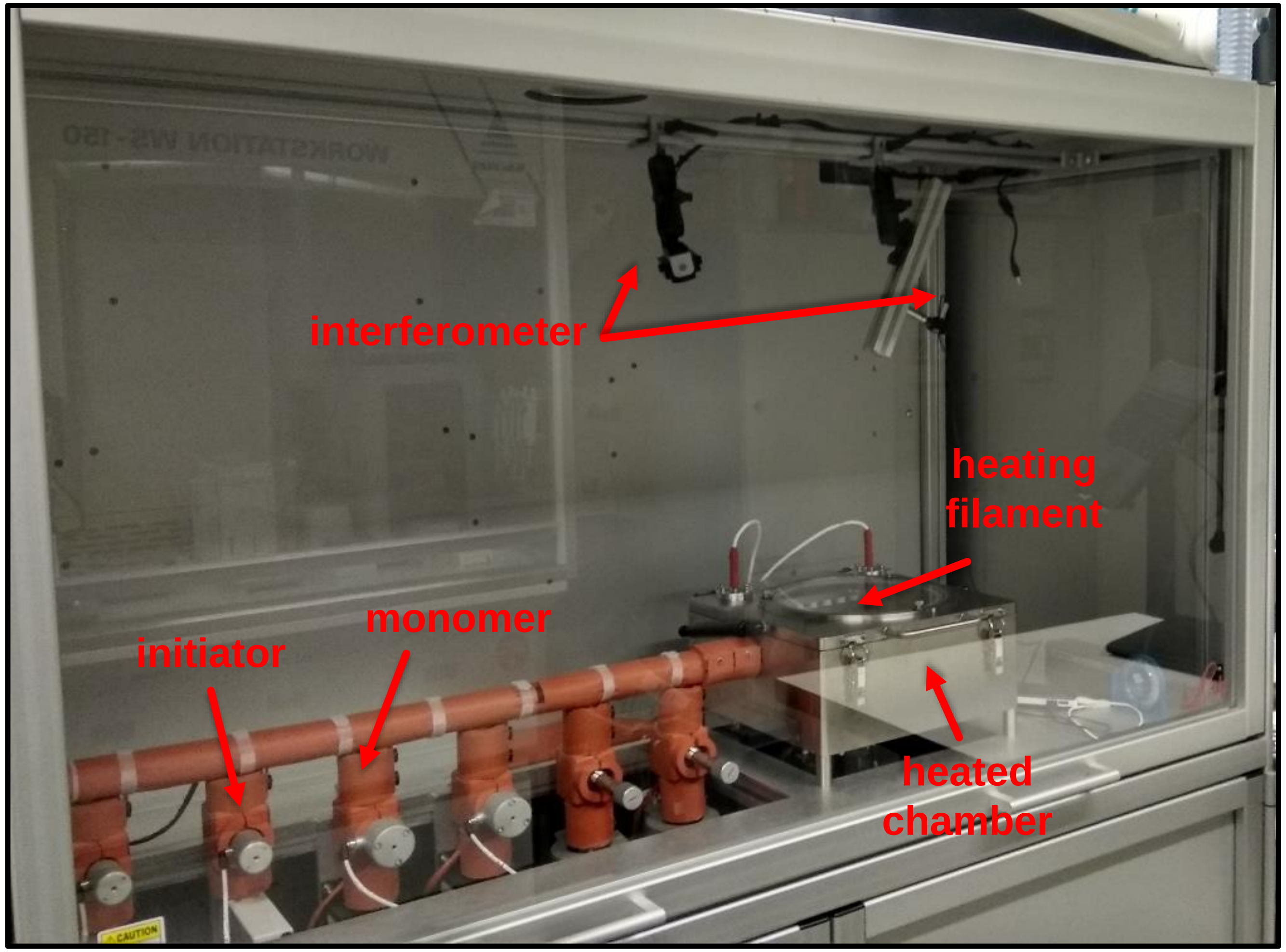
Micro/nano-texture: cleanroom or wet chemistry techniques

Chemistry: low surface energy coating: polymer

[1] Varanasi, K. K.; Hsu, M.; et. al. *Appl. Phys. Lett.* (2009)
[2] Boreyko, B. J.; Chen, C. *PRL* (2009)

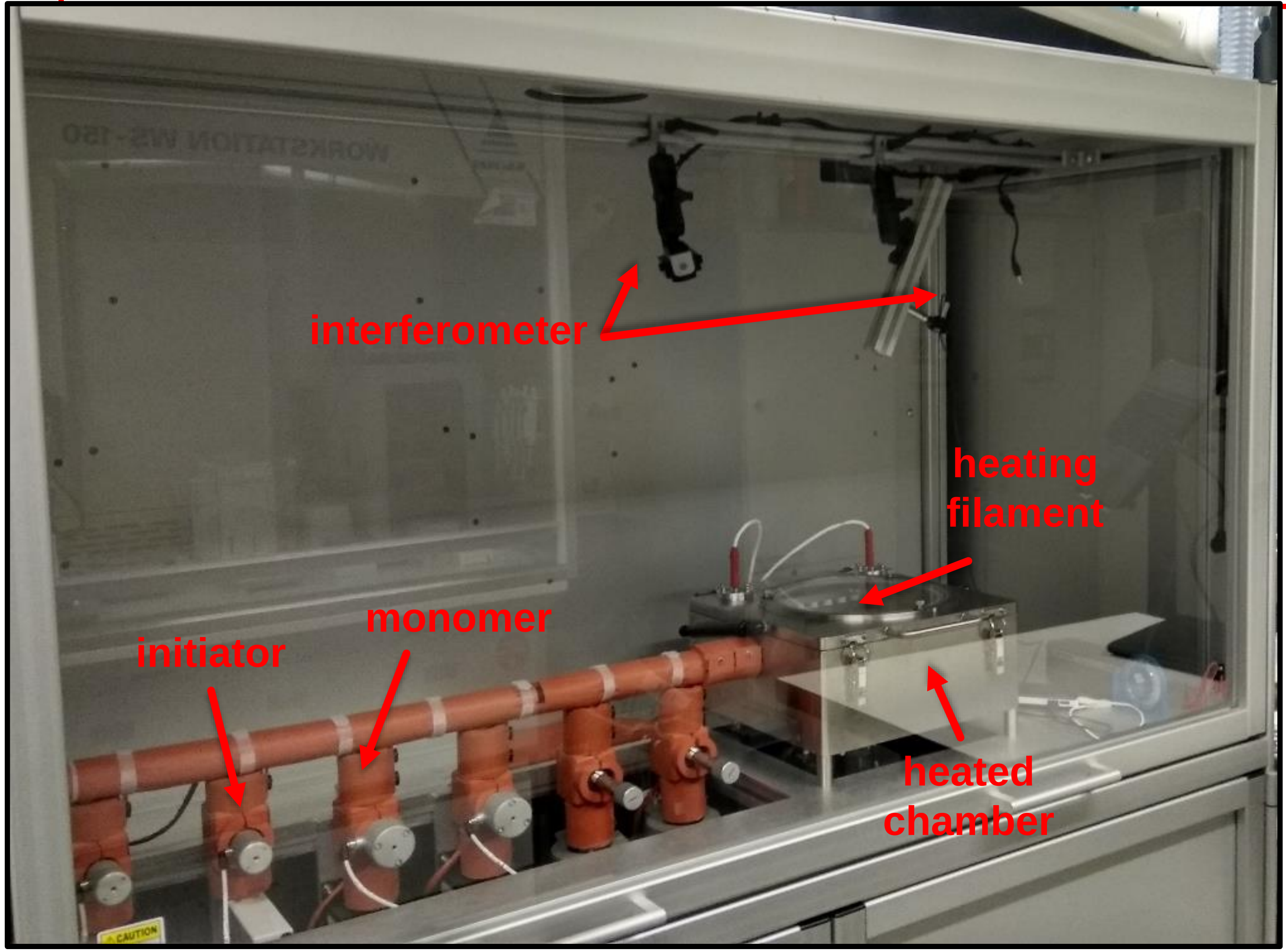
Initiated chemical vapor deposition (iCVD)

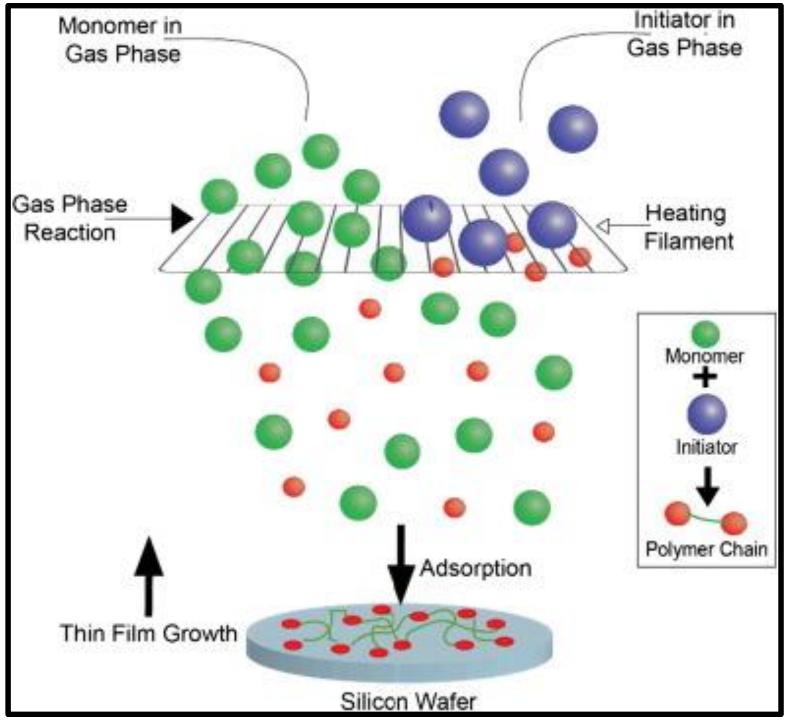
Chemistry: low surface energy coating: polymer



Initiated chemical vapor deposition (iCVD)

Chemistry: low surface energy coating: polymer

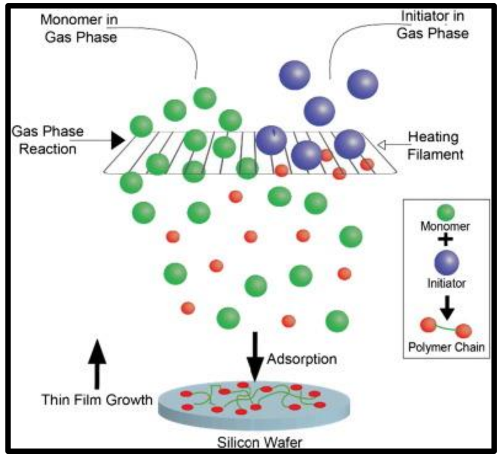




Initiator: *tert*-Butyl peroxide (**TBPO**)

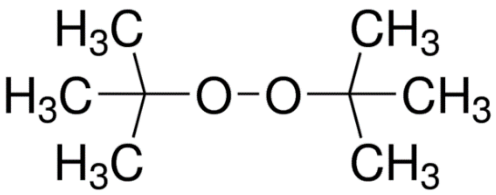
Monomer: 1H,1H,2H,2H-Perfluorodecyl acrylate (**PFDA**)

Initiated chemical vapor deposition (iCVD)

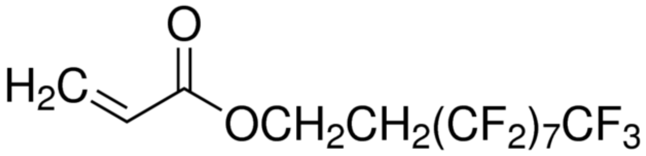


Chemistry: low surface energy coating: polymer

Initiator: *tert*-Butyl peroxide (**TBPO**)



- Used as initiator in free radical polymerization.

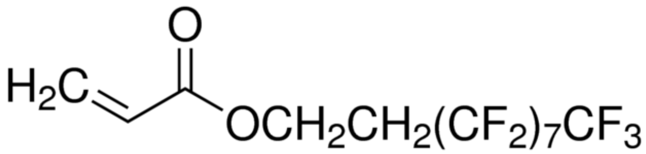


Monomer: 1H,1H,2H,2H-Perfluorodecyl acrylate (**PFDA**)

- Has one C=C bond that will be attacked by the free radical.
- Can lead to low surface energy hydrophobic polymer coatings.

$F_2C{=}CF_2$

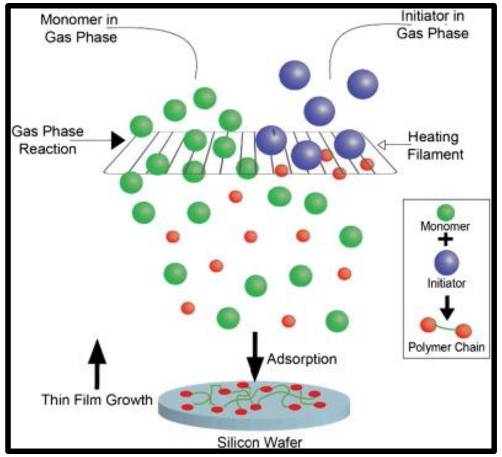
18 mN/m



9.3 mN/m

Initiated chemical vapor deposition (iCVD)

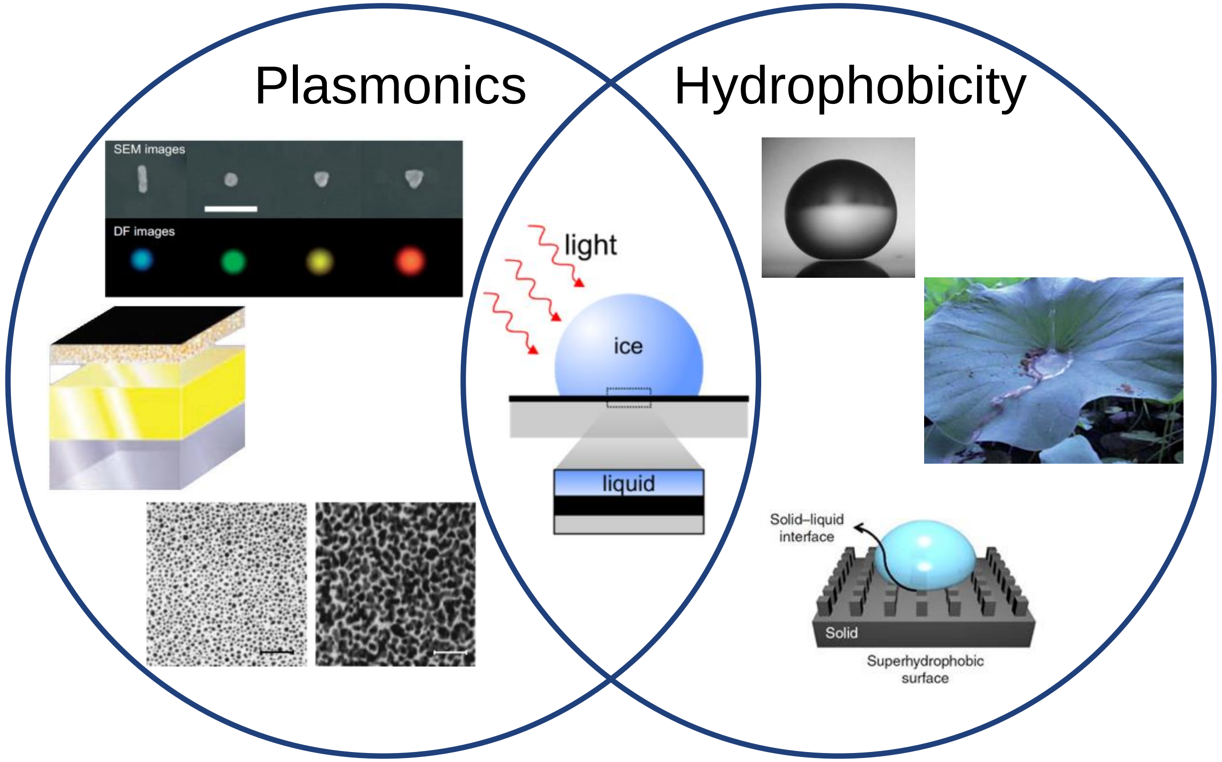
Chemistry: low surface energy coating: polymer



before deposition

after deposition

Hybrid icephobicity



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Thank you for your attention

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