Functionalizing metallic surfaces using femtosecond laser surface processing

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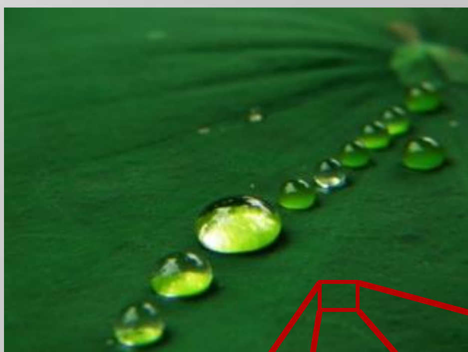
Biomimetic Surface Structures

CEFS
Center for Electro-Optics
& Functionalized Surfaces

Fabrication and application of biomimetic micro/nano surfaces via Femtosecond Laser Surface Processing (FLSP)

Natural Functionalized Surface



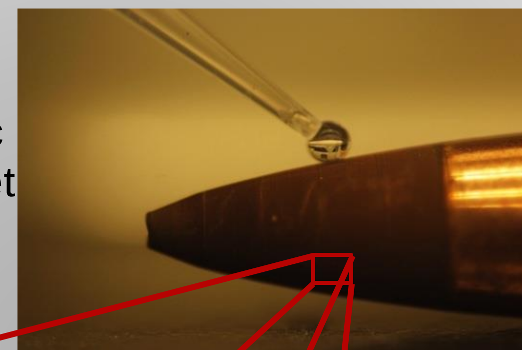
Superhydrophobic Lotus Leaf

K. Koch and W. Barthlott, Philos. Trans. Royal Soc. A, **367**, 1487–1509 (2009).

Natural Multiscale Surface Structure

FLSP Biomimetic Surface

Superhydrophobic Copper Alloy Bullet

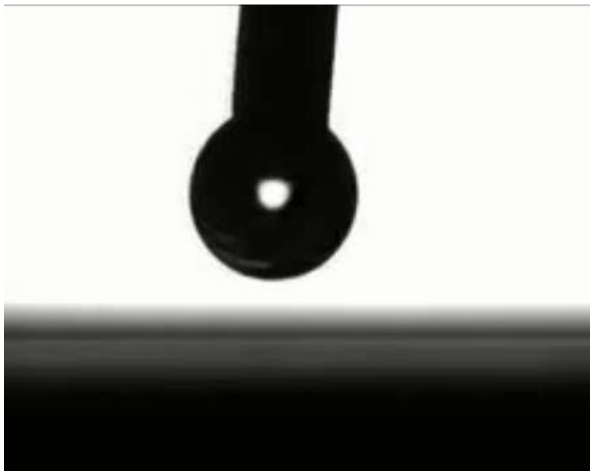


Fabricated Multiscale Surface Structure

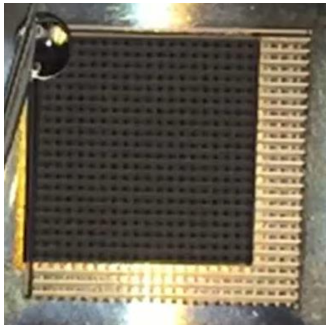
FLSP for Generating Extreme Wettability

The introduction of multiscale (micro- and nano-scale) surface features and controlled surface chemistry enables extreme control over the surface properties without using a coating

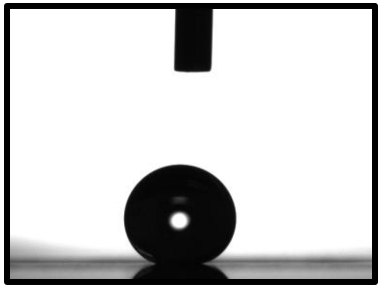
Superhydrophilic

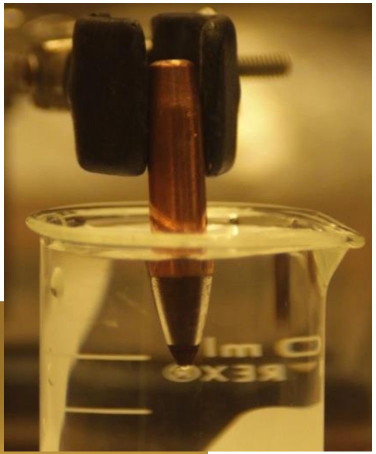


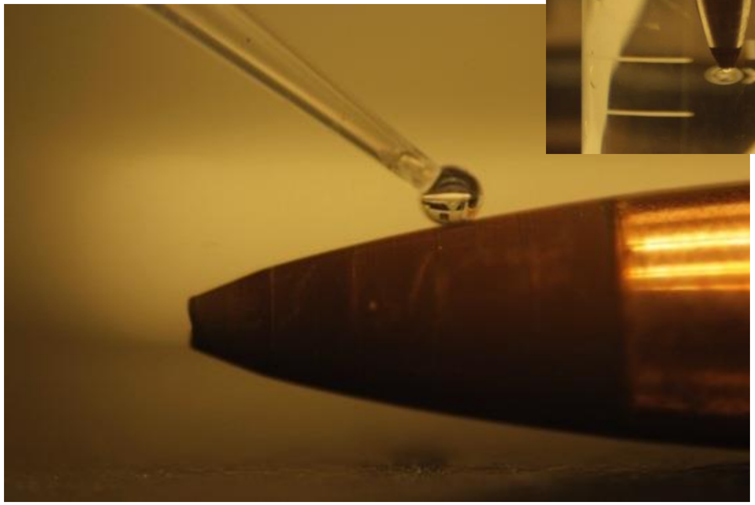
Alternating zones of wettability



Superhydrophobic

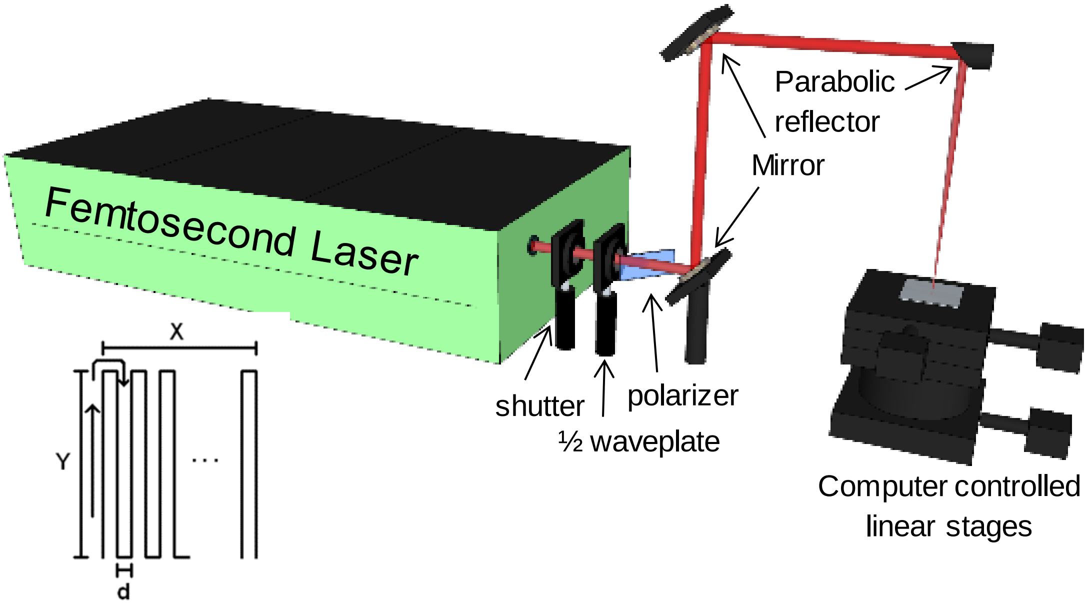






Femtosecond Laser Surface Processing (FLSP)

CEFS Center for Electro-Optics & Functionalized Surfaces

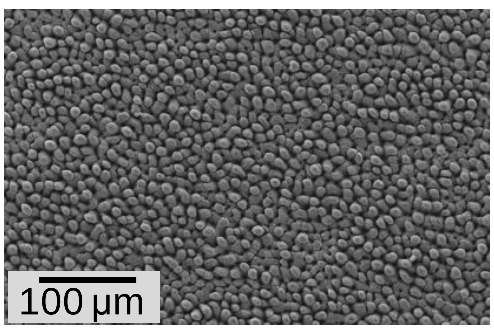


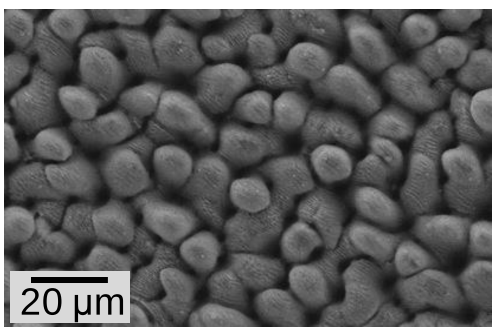
Typical programmed raster scan path

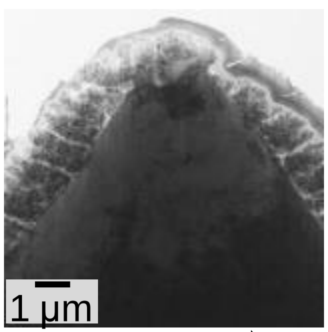
Specifications of main lasers associated with FLSP research

Laser	Astrella	DURIP laser
Pulse Energy	6 mJ	10 mJ
Center Wavelength	800 nm	1.1 µm – 15 µm; 800 nm + harmonics
Rep Rate	1 kHz	1 kHz
Pulse Duration	35 fs	35 fs

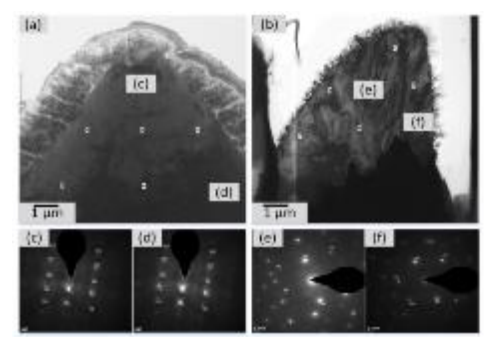
Other available high powered lasers: Extreme Light Core Facilities (100 mJ), Diocles (30 J) (note: low repetition rate > 10 Hz)







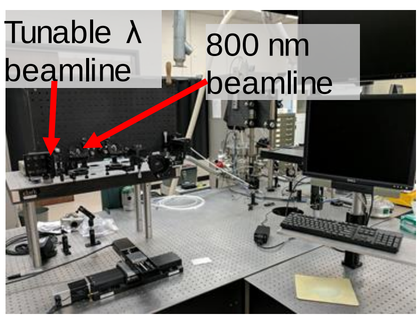
Typical Structure: Increasing Magnification



Internal crystalline structure

Developing World Class FLSP Research Facilities

DURIP 2016 funded femtosecond laser ($488,684): 10 mJ, 35 fs laser that is tunable from 1,100 – 15,000 nm plus the fundamental 800 nm wavelength and harmonics.

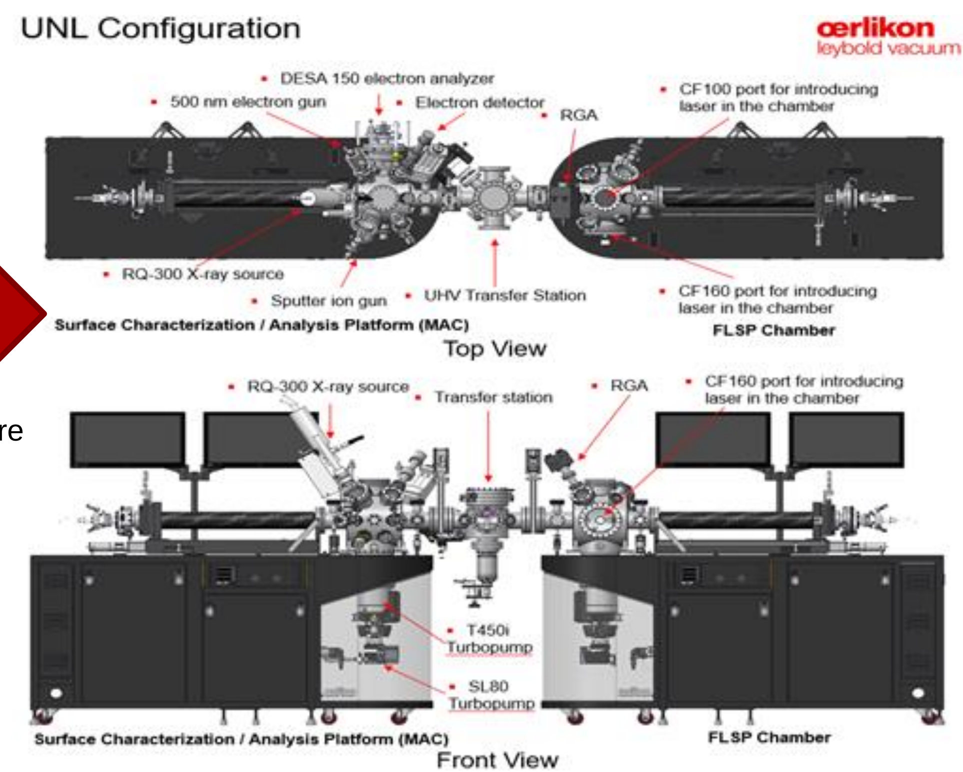


FLSP open air setup

FLSP environmental chamber

These systems are being combined

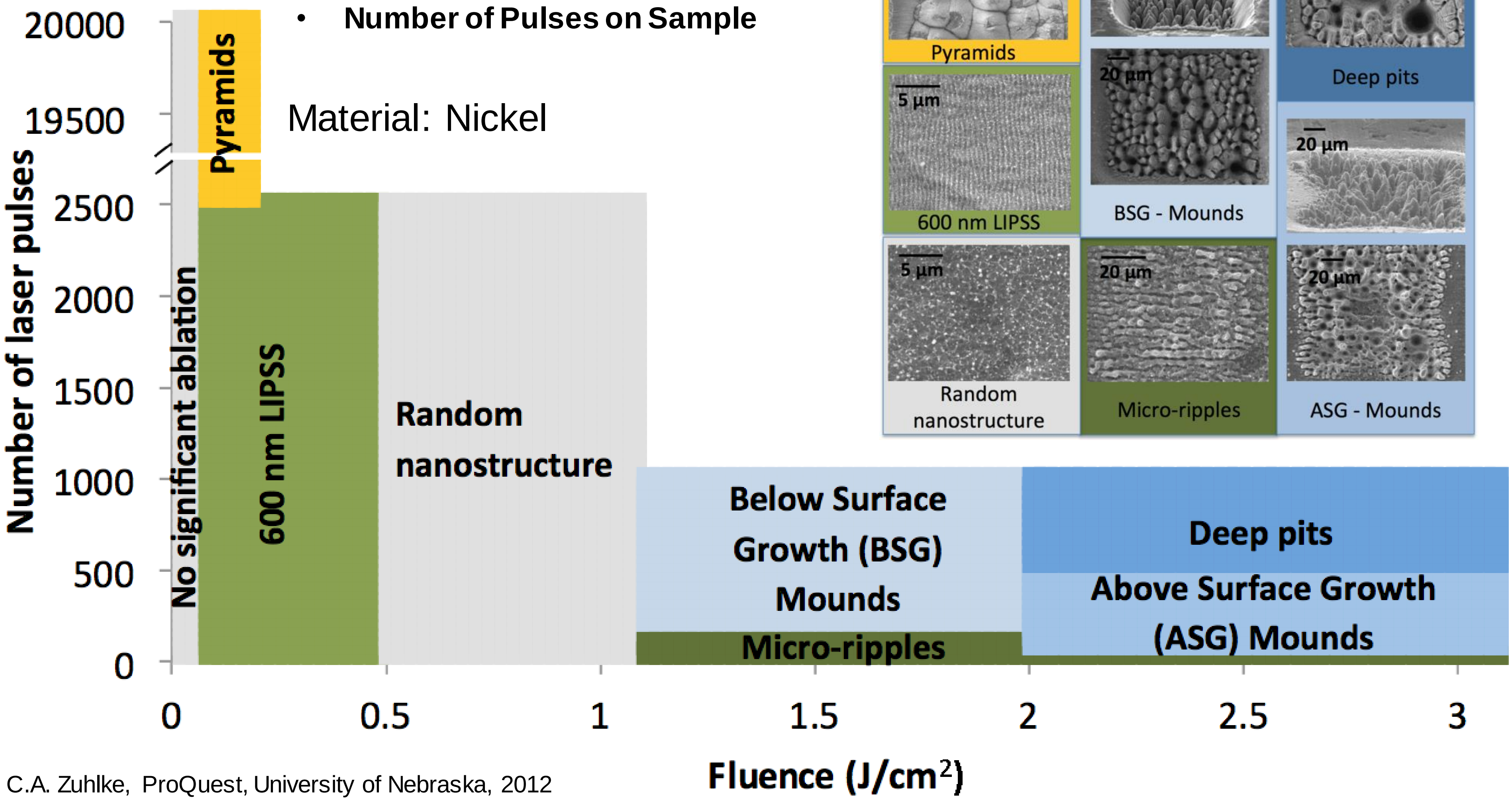
DURIP 2017 funded FLSP/material analysis chamber ($961,830): includes an UHV chamber for carrying out FLSP in controlled environments that is connected to a material analysis UHV chamber with SEM, AES, sputtering and XPS capabilities.



Range of Structures Produced by FLSP on Nickel

A diverse range of unique surface structures can be fabricated by varying two critical parameters:

- **Laser Fluence**
- **Number of Pulses on Sample**

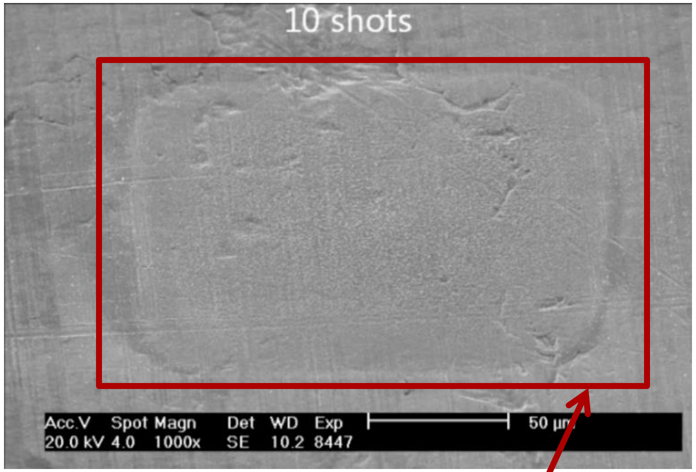


C.A. Zuhlke, ProQuest, University of Nebraska, 2012

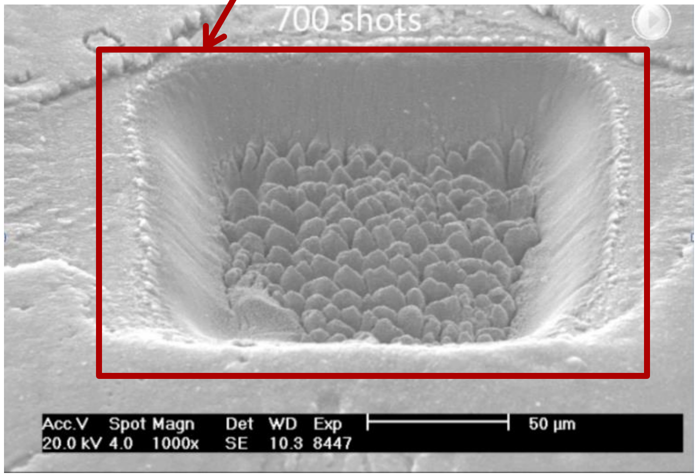
SEM Stop-Motion Imaging of the Dynamics of Self-Organized FLSP Structure Development

Analyze the shot by shot development of individual surface structures through a stop-motion technique utilizing a scanning electron microscope

1. Image the sample
2. Precisely realign the sample
3. Irradiate the sample with 1 (or several) pulses
4. Image the sample
5. Precisely realign the sample
6. Irradiate the sample with 1 (or several) pulses
7. …

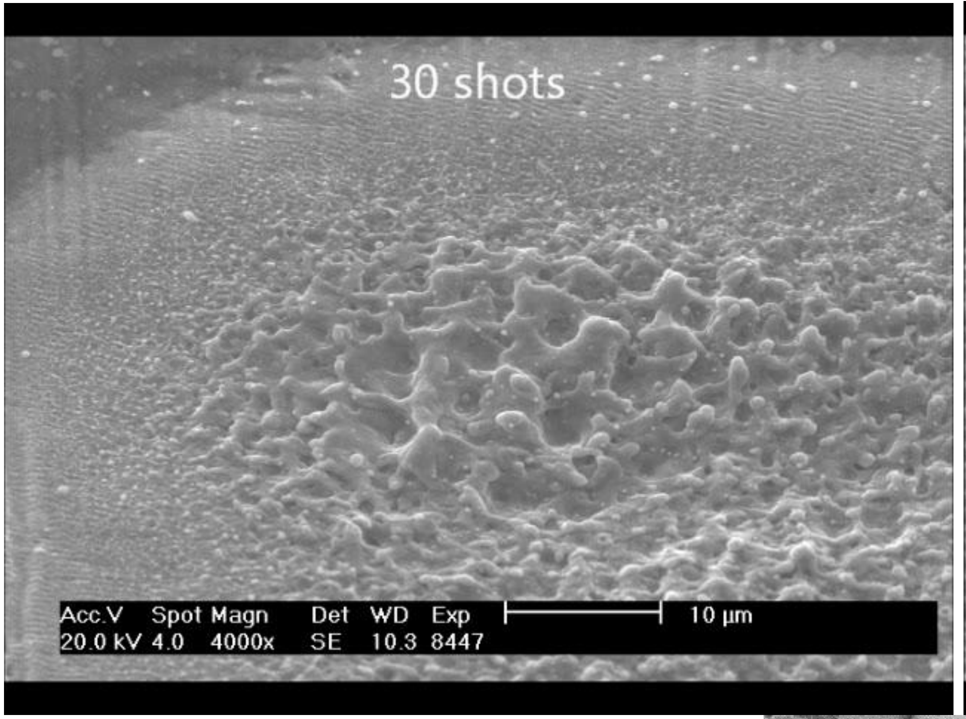


Outline of flat-top beam profile

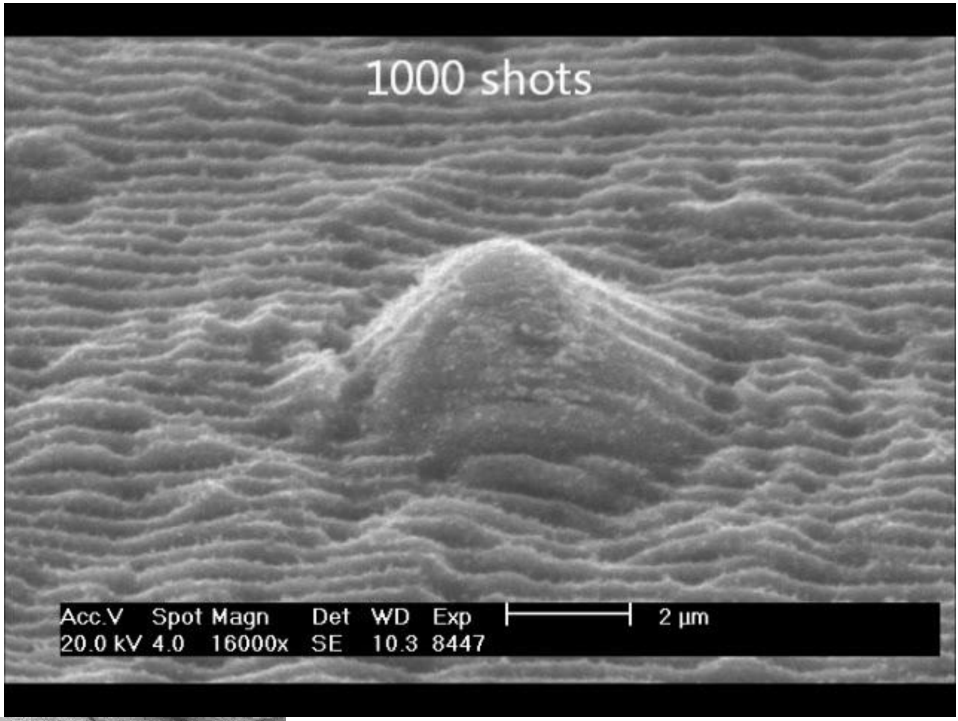


ASG-mound and NC-pyramid Development on Nickel

ASG-mounds:(3.08 J/cm²)

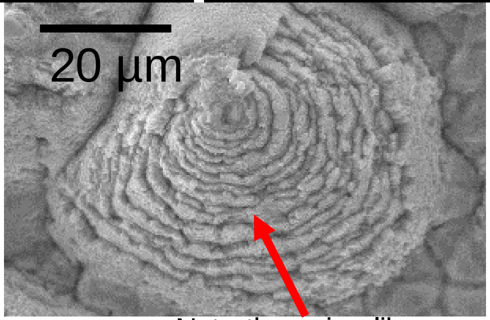


NC-pyramids:(0.12 J/cm²)



Video: clearly observable fluid flow/redeposition in structure development

Zuhlke, et. al. *Optics Express* (2013).



Note the onion-like layers of nanoparticles

Video: nanoparticles build up on the surface and preferential etching occurs simultaneously with incident pulses

Zuhlke C. A., et. al. (2013) *Applied Surface Science*, *21*(7), 8460–73.

Critical Strengths of FLSP

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These are all self-organized structures

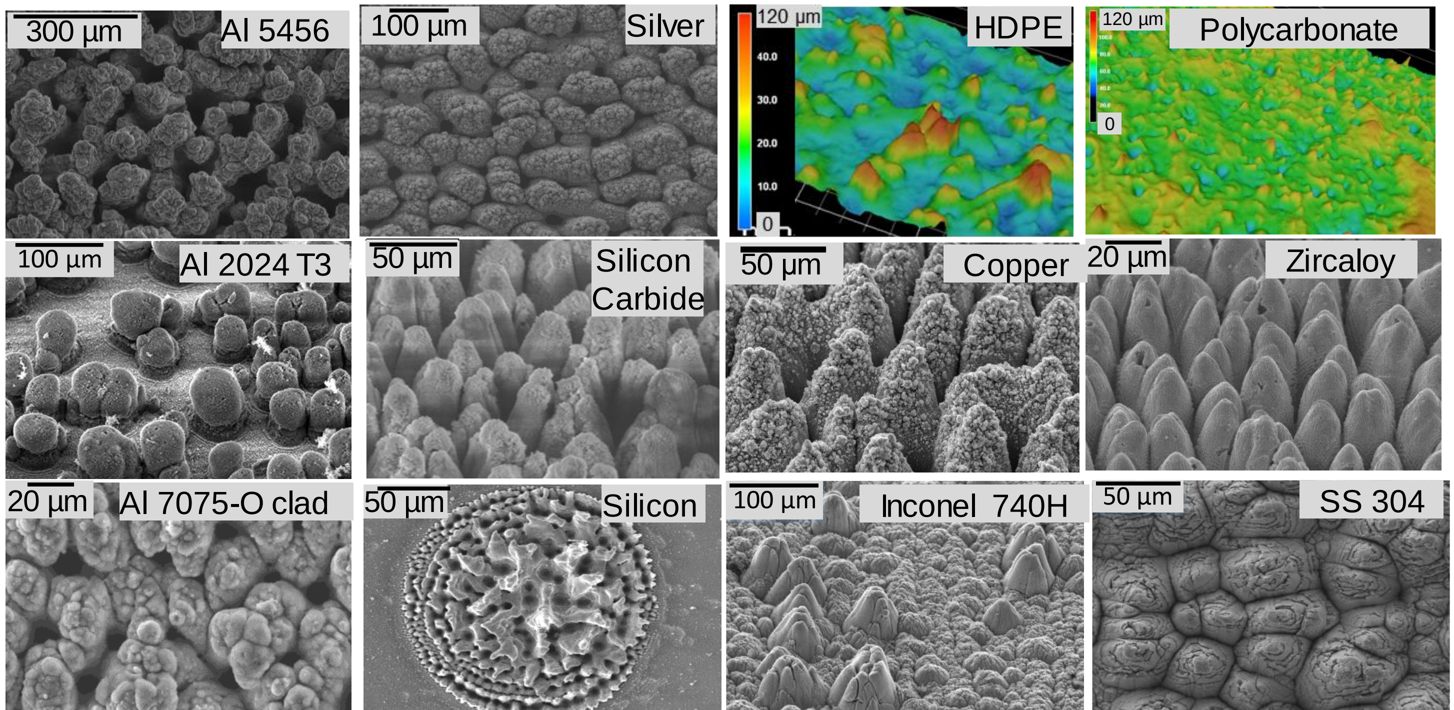
Multiscale Structures in a single step
Control over micro/nanoscale features via laser processing parameters

Structure Permanency
Functionalization through shaping of substrate – retain durability of substrate

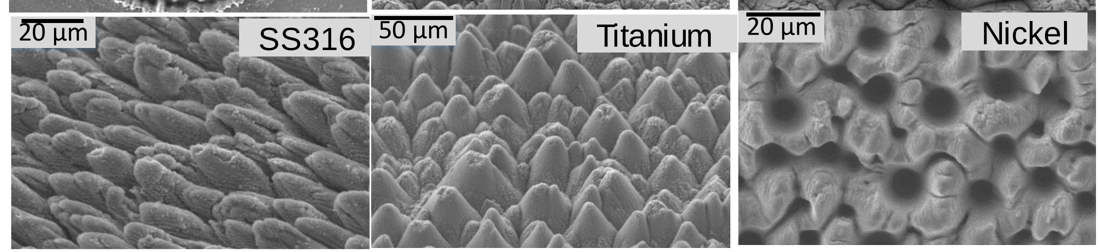
Contactless Fabrication
Open-air laser processing enables processing of arbitrary shaped 3D surfaces

Scalability
Large areas can be processed by scaling the laser power and repetition rate

Versatility
FLSP can be extended to a wide range of materials



Thus far CEFS has been successful in applying FLSP to every material attempted



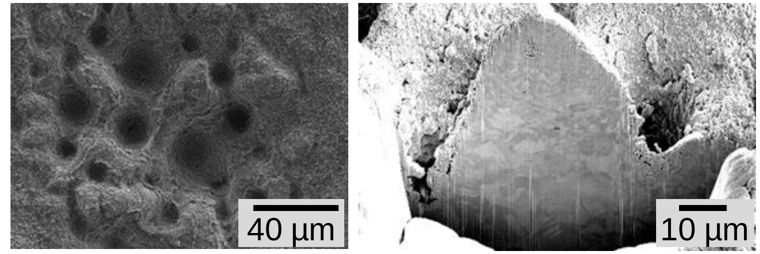
Material Characterization is Fundamental to Understanding FLSP Phenomena and Results Being Obtained in Specific Applications

FEI Helios NanoLab 660 (dual beam SEM/FIB mill)

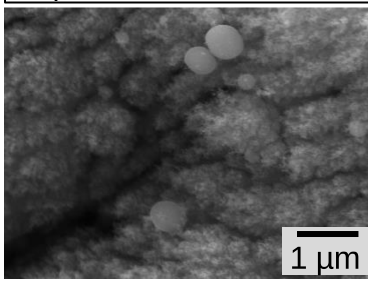
Microstructure analysis:

- Fundamental materials science/engineering
- Size, shape, phase of crystalline grains, material composition

Cross-sectional analysis

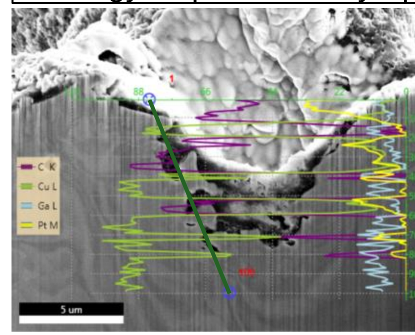


Extreme high resolution (XHR) imaging (SEM – sub-nanometer capabilities)



Dual-beam imaging (e- & Ga+)

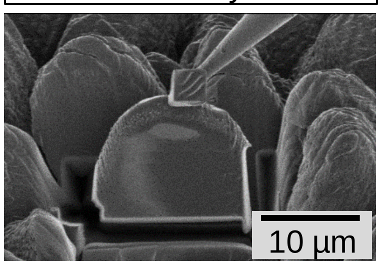
Energy-dispersive x-ray spectroscopy (EDS)



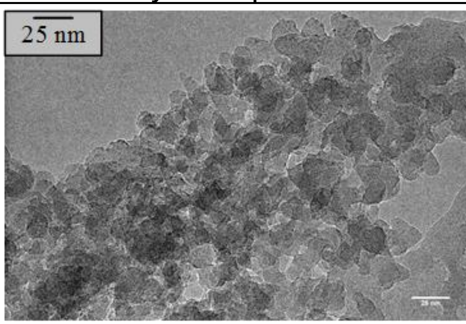
Octane Super EDS detector capable of detecting carbon

TEM analysis capabilities at UNL

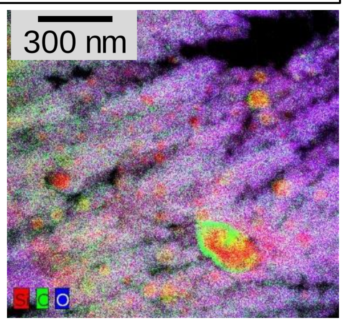
Structure lift-outs for TEM analysis



Crystal analysis – Selected area electron diffraction (SAED)



Sub-nanometer imaging



Spatial composition mapping

FLSP on Ti: Crystal Structure of ASG vs BSG Mounds

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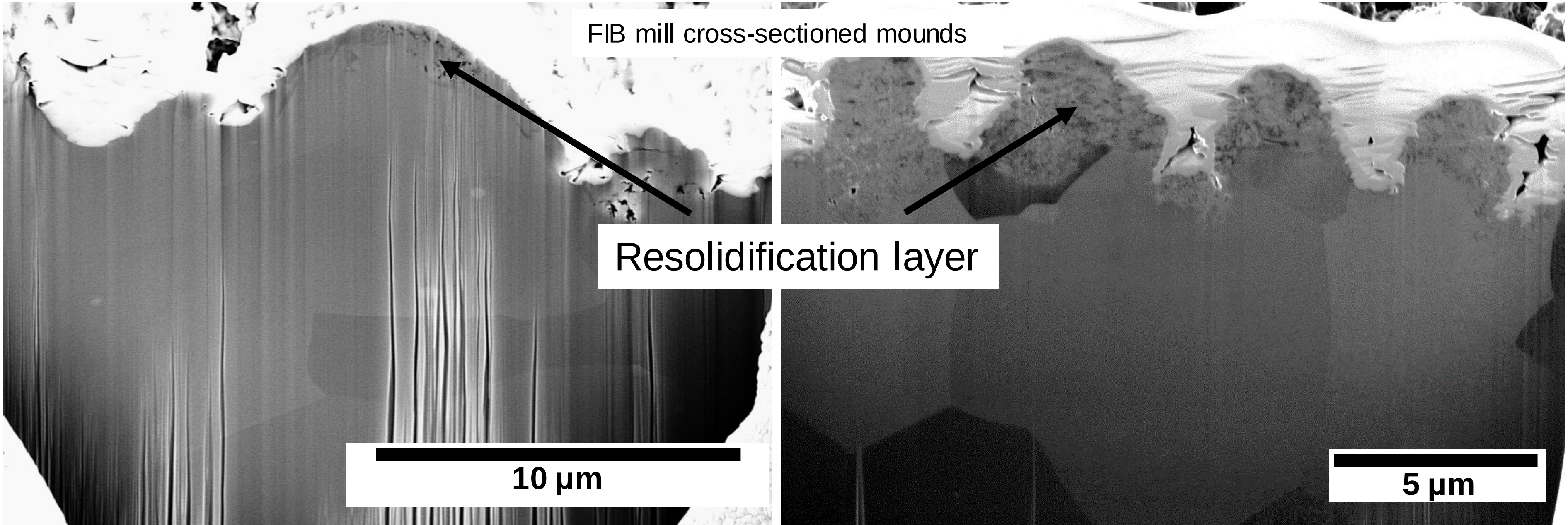
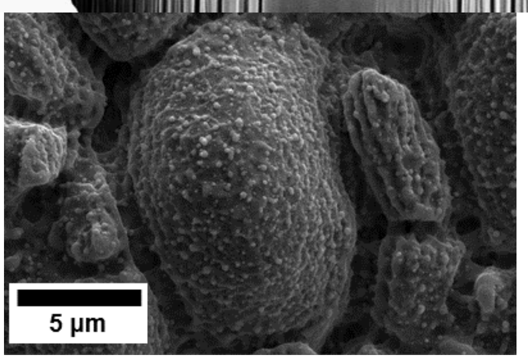
BSG-mounds   ASG-mounds

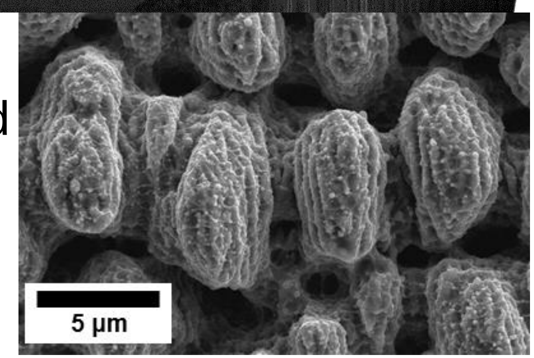




BSG-mound structure prior to FIB mill cross-sectioning

Microstructure analysis

- Rapidly resolidified layer composed of smaller Ti grains (e.g. 200 nm)
- Original Ti microstructure w/ large (average 10 µm) Ti grains



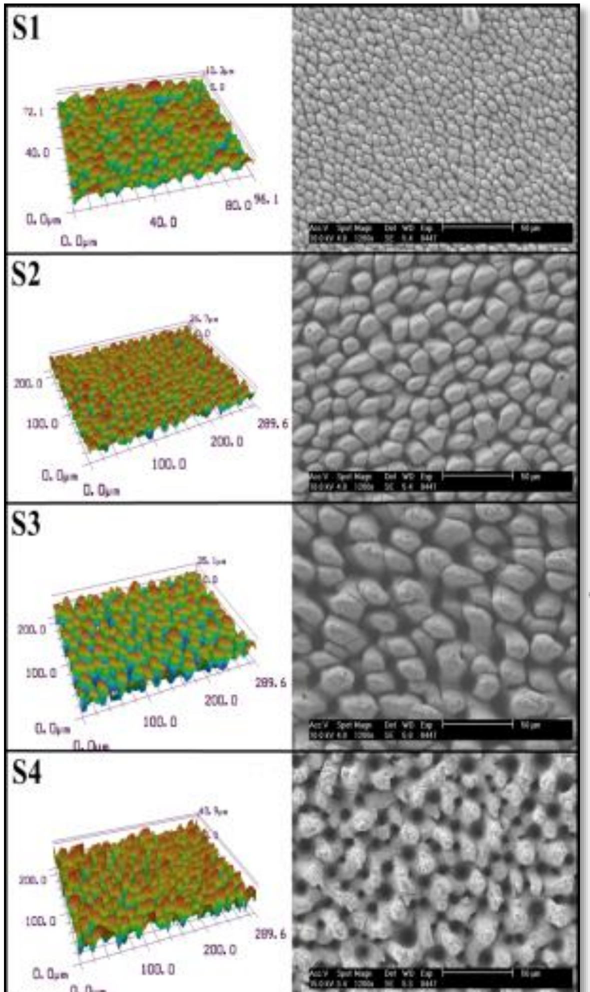
ASG-mound structure prior to FIB mill cross-sectioning

E. Peng, et. al., Appl. Phys. Lett. **108**, 31602 (2016).
E. Peng, et. al., Appl. Surf. Sci. **396**, 1170 (2017).

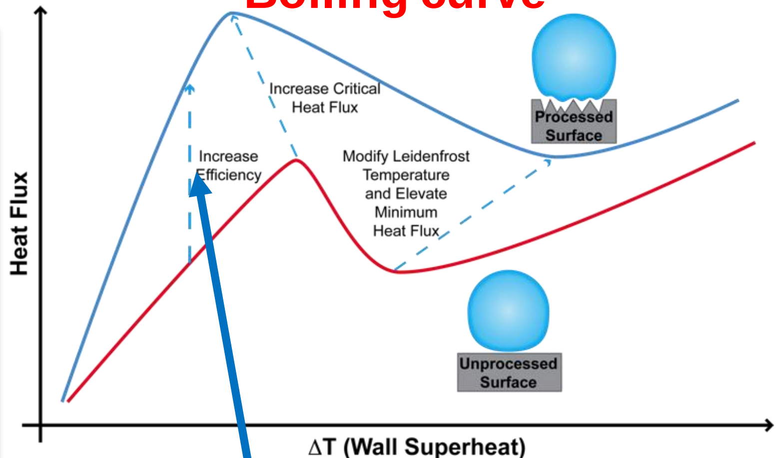
Enhanced Heat Transfer Using FLSP

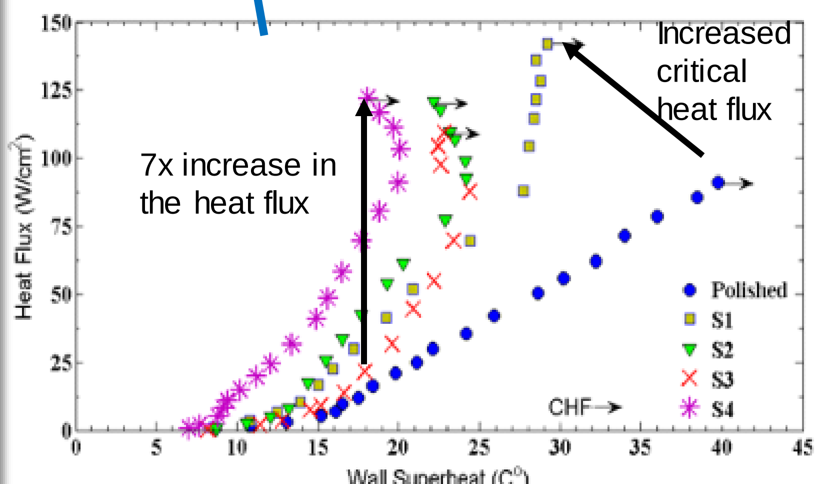
FLSP results in an enhancement of the critical heat flux and heat transfer coefficient

SS 304 FLSP surfaces



Boiling curve





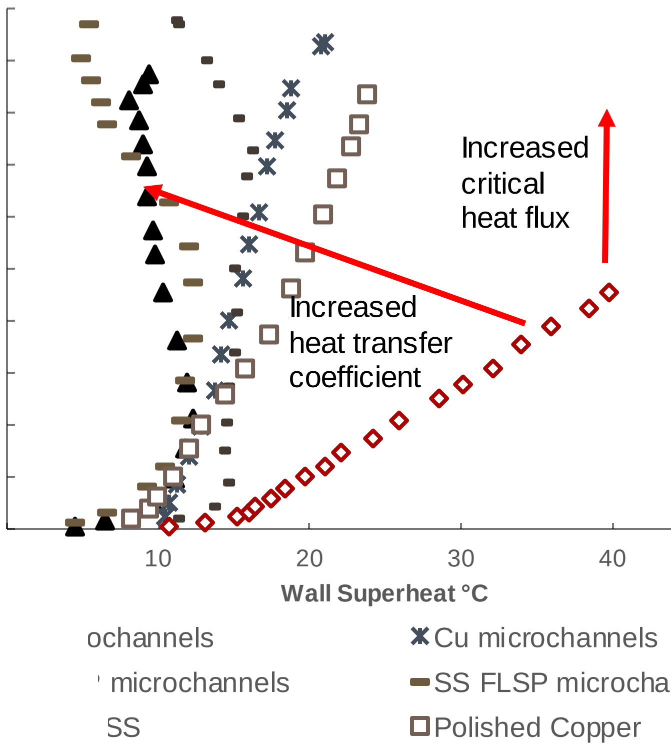
C.M. Kruse, et. al., Int. J. Heat Mass Transf. **82**, 109 (2015)
C. Kruse, et. al., Appl. Phys. Lett. 108, 51602 (2016)
C. Kruse, et. al., Langmuir **29**, 9798 (2013)

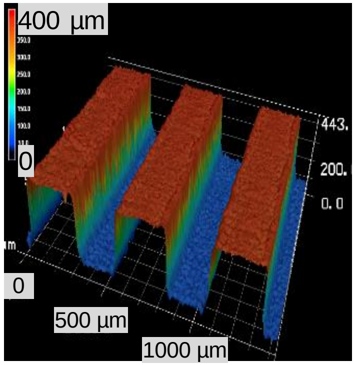
Video: enhanced nucleate boiling efficiency

Higher nucleation site density on FLSP enhanced surface

Unprocessed FLSP enhanced

Micro-Channel Pool Boiling Results





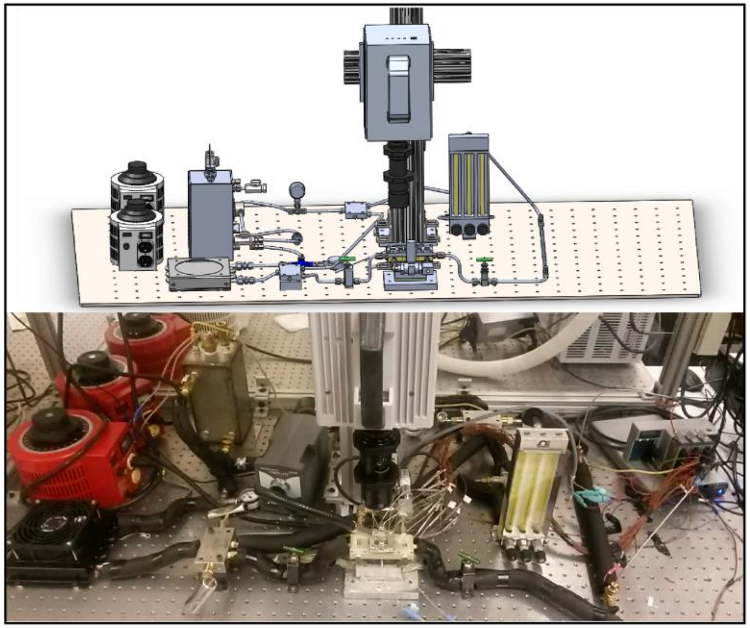
Cu FLSP functionalized microchannels

Pool boiling results for Cu and 304 SS surfaces comparing polished flat reference surfaces with surfaces with 400 µm deep and wide microchannels in the surface along with FLSP functionalized microchannel surfaces.

<u>-LSP functionalized SS microchannel surface</u>

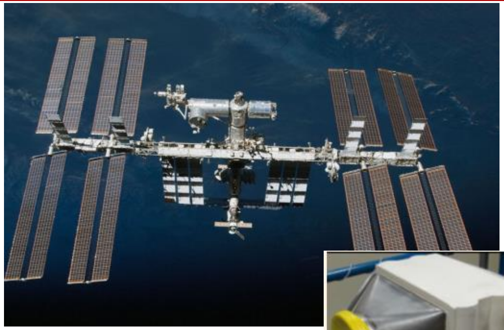
transfer coefficient: 355 kW/m^2K

:al heat flux: 195 W/cm^2

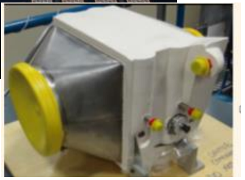


Experimental setup for measuring heat transfer performance of FLSP surfaces with two phase flow in microchannels

Antibacterial Work for NASA Johnson (Scott Hansen) on Next Generation Critical Heat Exchanger for ISS and Deep Space Missions

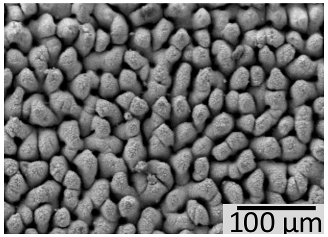


International Space Station (ISS)

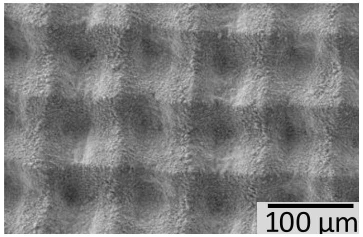


ISS CHX

Critical need: superhydrophilic or superhydrophobic, antibacterial surface that is permanent and does not contaminate the water supply.



al pulse FLSP mounds silver



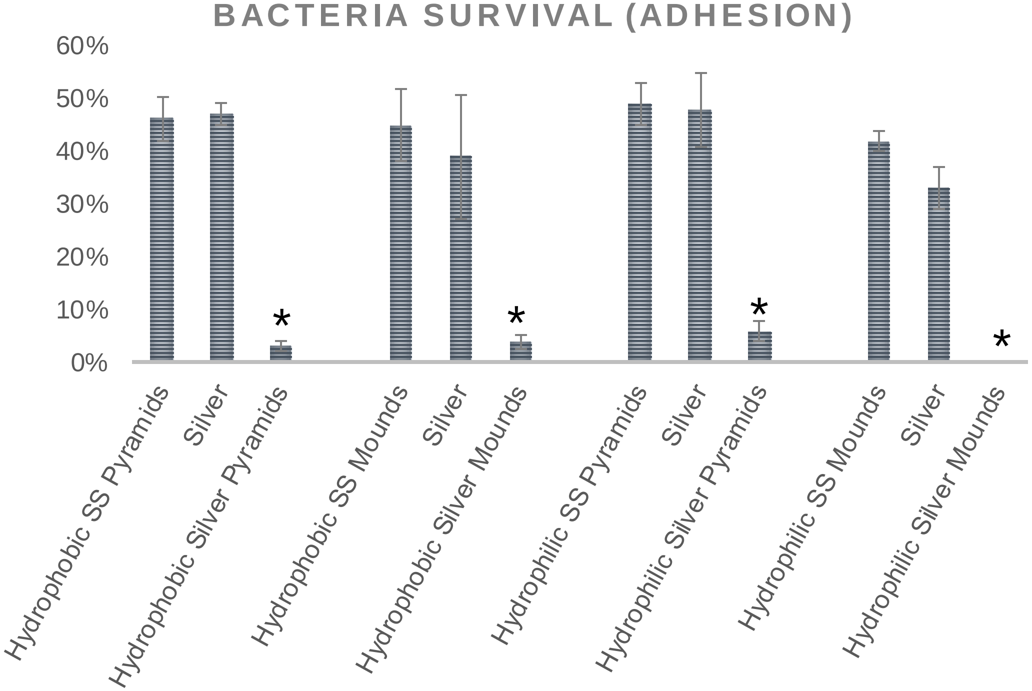
Direct write FLSP pyramids on silver

For the first time we are able to functionalize silver, which has important implications for anti-bacterial superwicking surfaces for ISS CHX's.

Laser processed CHX fins

Bacterial consortium used in this study:

- *Bacillus megaterium*
- *Staphylococcus epidermidis*
- *Sphingomonas paucimobilis*



* FLSP functionalized silver surfaces

Scott Hansen, et. al., ICES-2017-295, 16-20 July 2017

Anti-icing Properties of FLSP Functionalized Al 7075-O Clad Surfaces (Previously Funded by Boeing)

CEFS Center for Electro-Optics & Functionalized Surfaces

Supercooled droplet icing prevented through FLSP functionalization on Al 7075-O Clad surface

Unprocessed Al 7075-O Clad

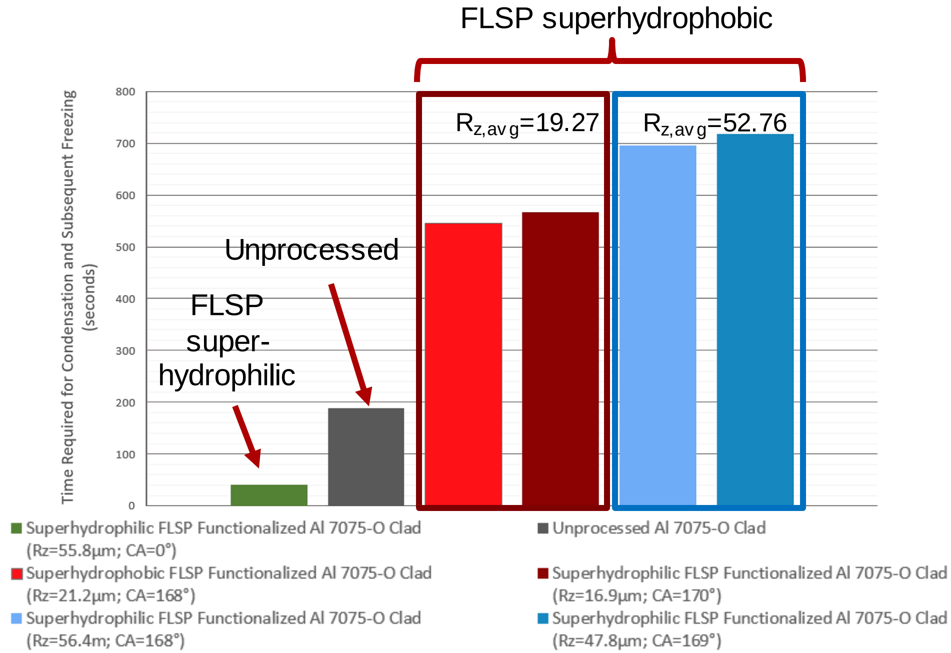
Video: supercooled droplets impact and stick (changing phase) to the unprocessed surface.

Superhydrophobic FLSP Al 7075-O Clad

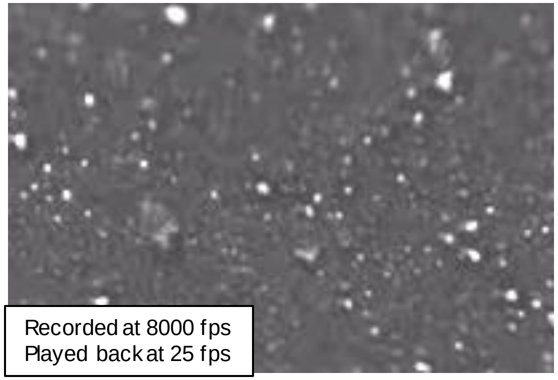
Contact Angle: 168.42 $\pm$ 1.13°

Video: falling supercooled droplets impact and bounces off the FLSP functionalized surface.

Condensation and delay in subsequent freezing on FLSP functionalized Al 7075-O Clad surfaces



Video: condensate droplet coalescence can cause self-propelled jumping from the FLSP functionalized surface.



Recorded at 8000 fps
Played back at 25 fps

Wide-Band Optical Absorption FLSP Surfaces

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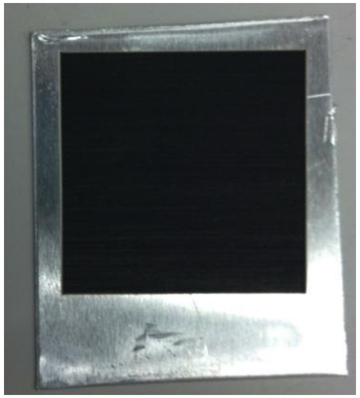
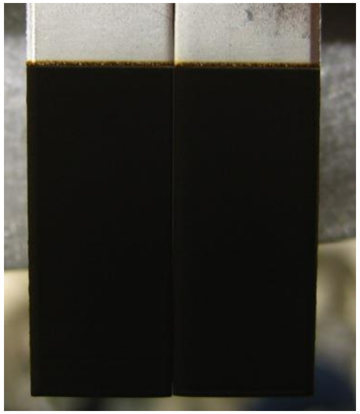
Copper

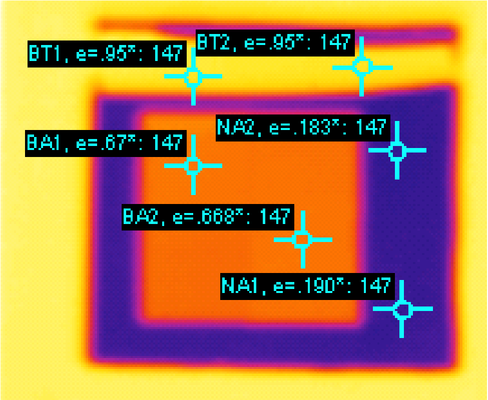
Aluminum



Stainless Steel



The emissivity of a metallic surface can be significantly enhanced through FSLP



Infrared image of processed (orange) and unprocessed (purple) surfaces on a computer processor

	Emissivity
Unprocessed	0.19
Processed	0.67

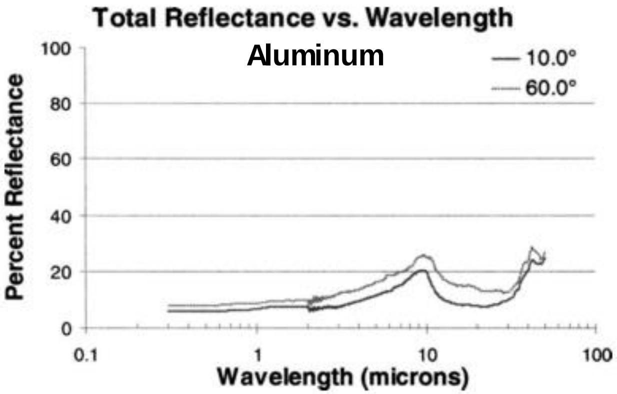
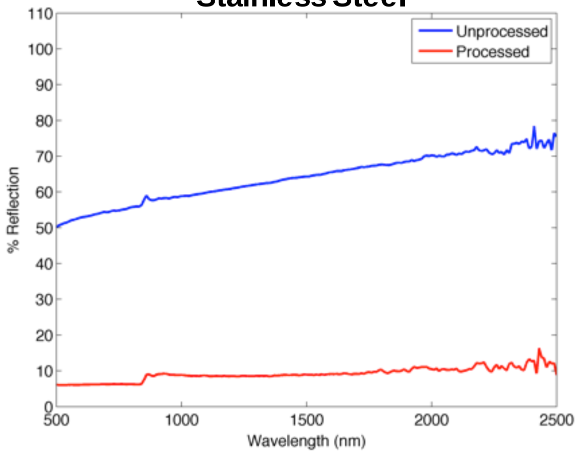


FIG. 6. Typical reflectence of Al sample ablated at fluence of 13.5 J/cm^2, in the wavelength range of 0.3–50 μm

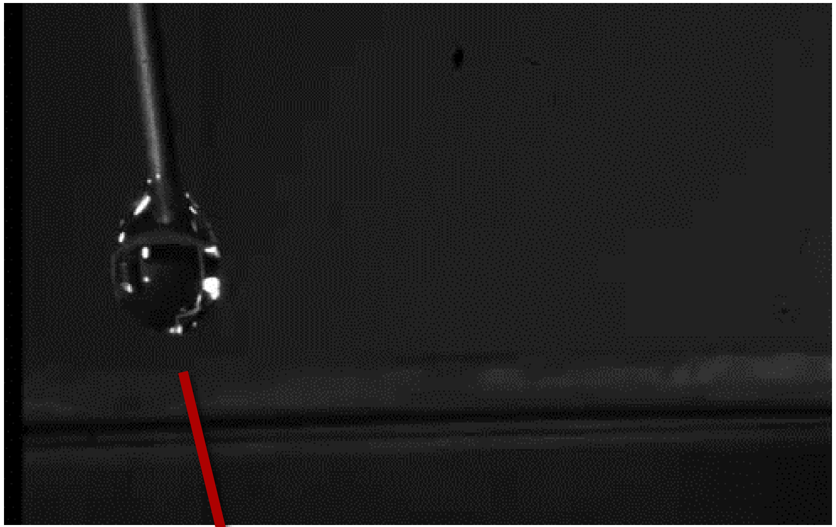
N. Singh, D. R. Alexander, et. al., J. Laser Appl. 18, 242 (2006).

Reflectance vs. Wavelength
Stainless Steel

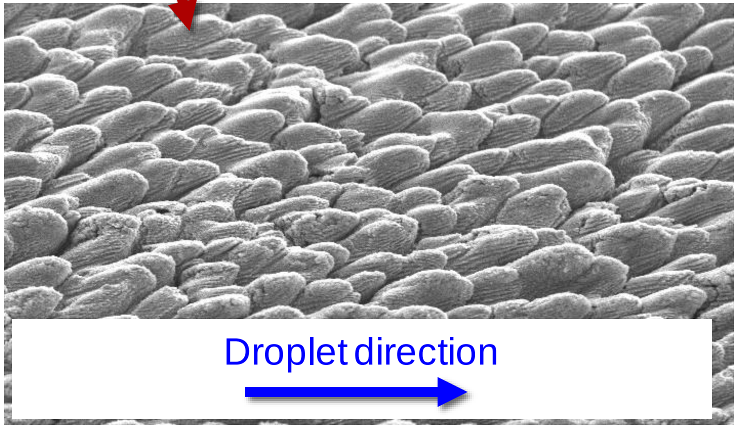


Droplet Motion Control and Microfluidics

Self-Propelled Leidenfrost Droplets

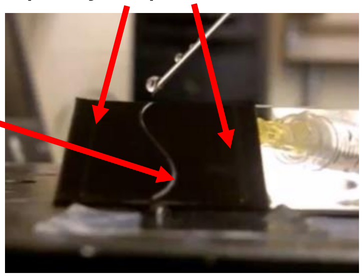


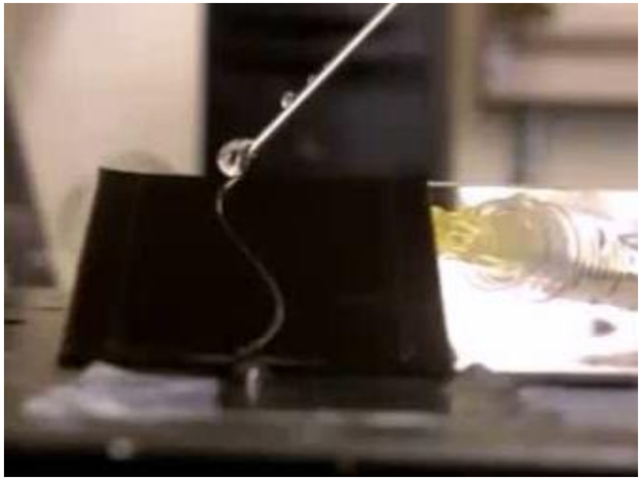
Video: Leidensfrost driven droplet motion on FLSP surface



C. Kruse, et. al., Microfluid. Nanofluidics **18**, 1417 (2015)

Alternating zones of wettability at room temp.





Video: Water droplet following superhydrophilic channel on superhydrophobic surface

Questions?

Center for Electro-Optics and Functionalized Surfaces (CEFS)

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Graduate students supported by ONR: Alfred Tsubaki, Corey Kruse, Henry Ems, Ethan Davis, David Allendorfer, Chongji Huang

Other CEFS graduate students: Ryan Bell, Anton Hassebrook, Nick Roth, Conner Thomas, Sarah Wallis, Edwin Peng, Yingxiao Song, Shacha Podlech (visiting scholar from Germany)

Other CEFS Undergraduate students: Cole Dempsey, Joseph Sheehan, Christopher Currey, Joshua Edgar, Angoua Konan, Owen Fike