SAND2014-19935PE

The Effects of Pulse Shaping on Laser-Material Interaction Mechanisms

Ryan D. Murphy
Sandia National Laboratories
Albuquerque, NM USA

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Acknowledgements

Sandia Collaborators

Dr. David P. Adams

Dr. Robert V. Reeves

David J. Saiz

University of Michigan Collaborators

Prof. Steven M. Yalisove

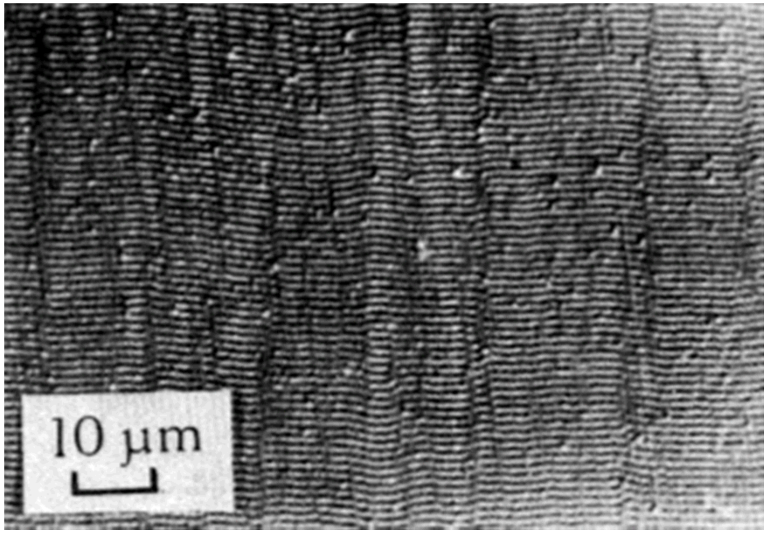
Dr. Ben Torralva

Michael J. Abere

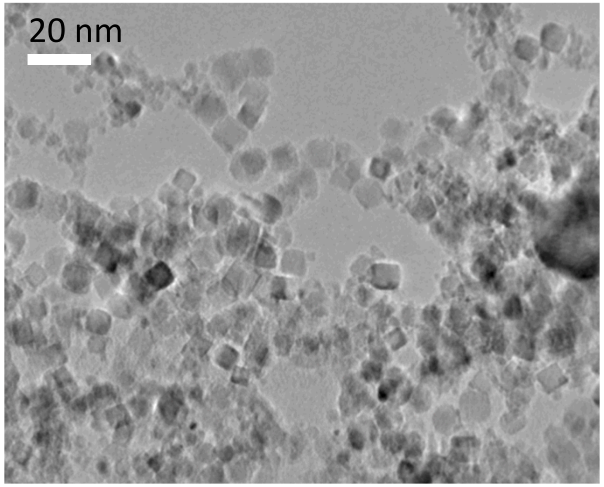
Keegan J. Schrider

Motivation

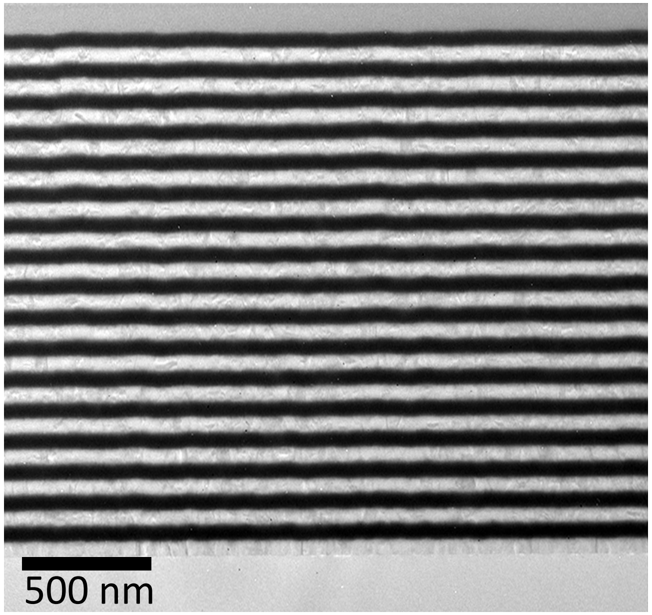
Machining



Nanoparticle Printing



Energetic Systems



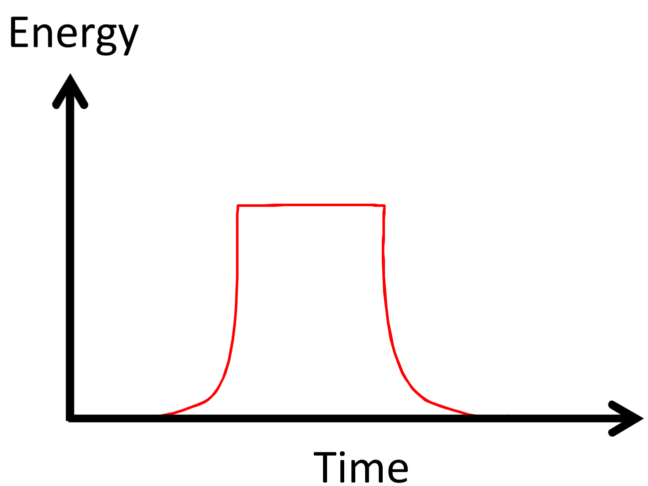
Laser Pulses Temporally Compressed

Pulse Shaping

- Laser light becomes more useful for changing materials when we compress light into *pulses*.
- Intensity of the laser pulse is directly related to pulse *energy* and *length.*
- Both Gaussian and "flat-top" spatial intensity distributions are utilized.

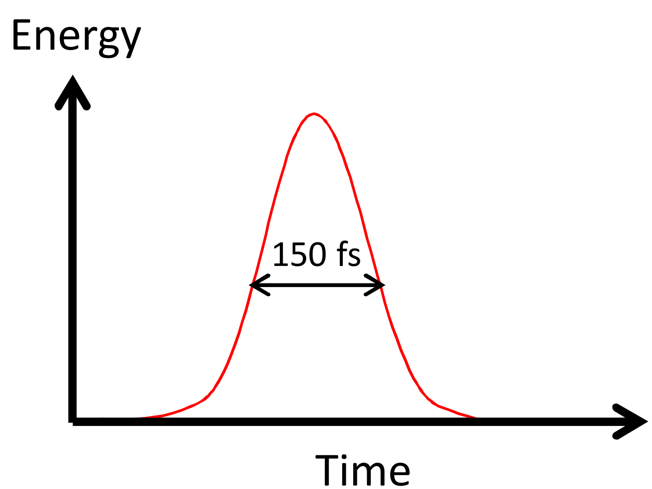
<u>Continuous Wave (CW) + Quasi-CW</u>

~ 10^3 W/cm^2



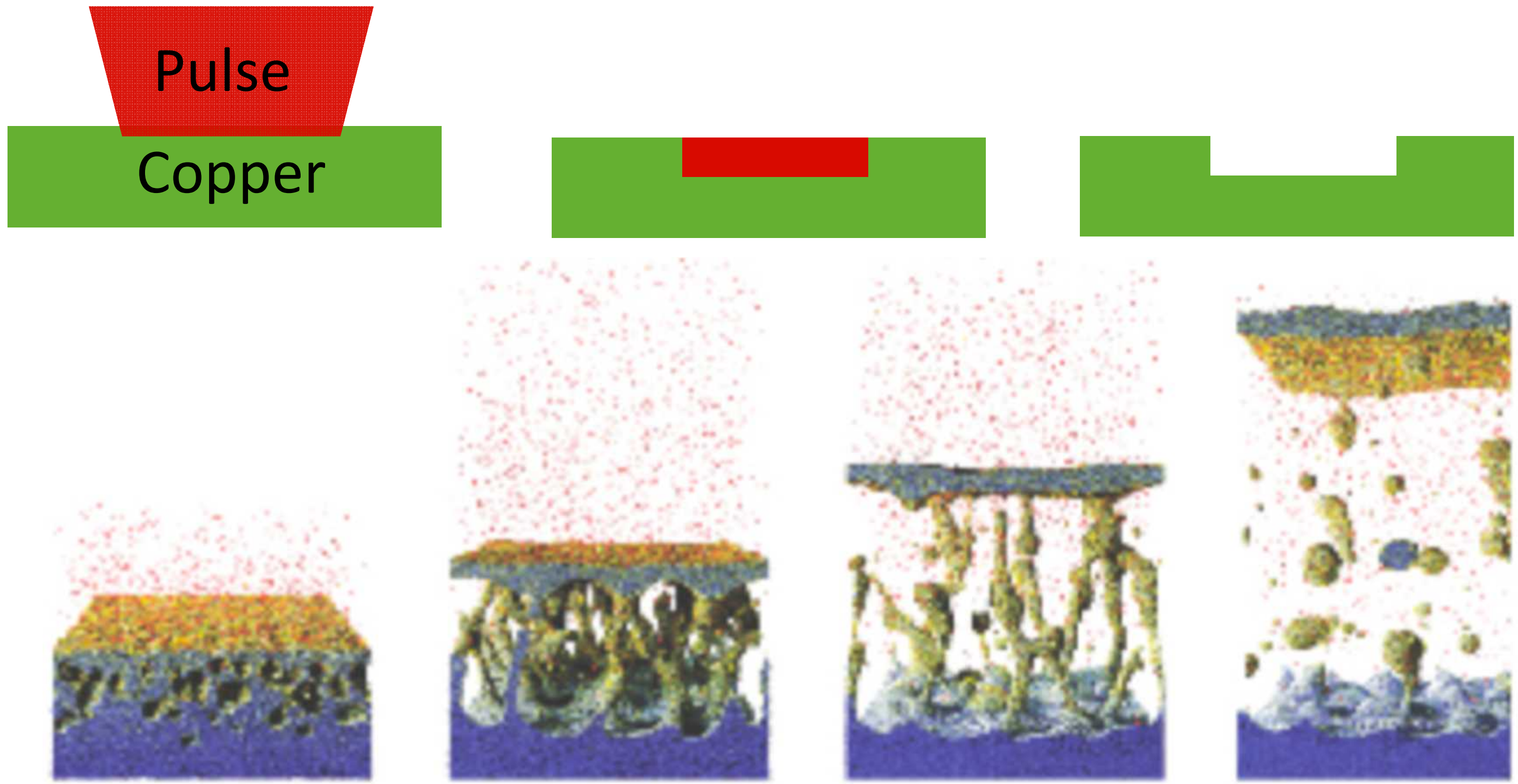
<u>Ultrafast (~ 150 fs)</u>

~ 10^{12} W/cm^2



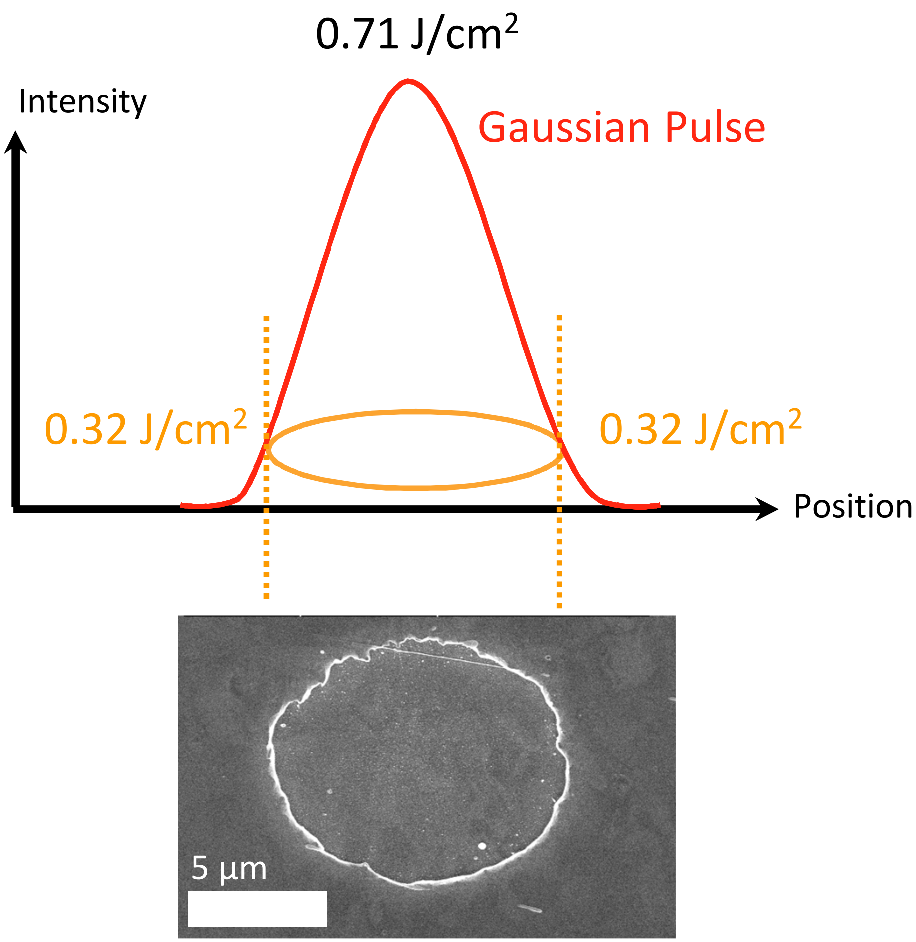
Ultrafast Laser Damage in Bulk Materials

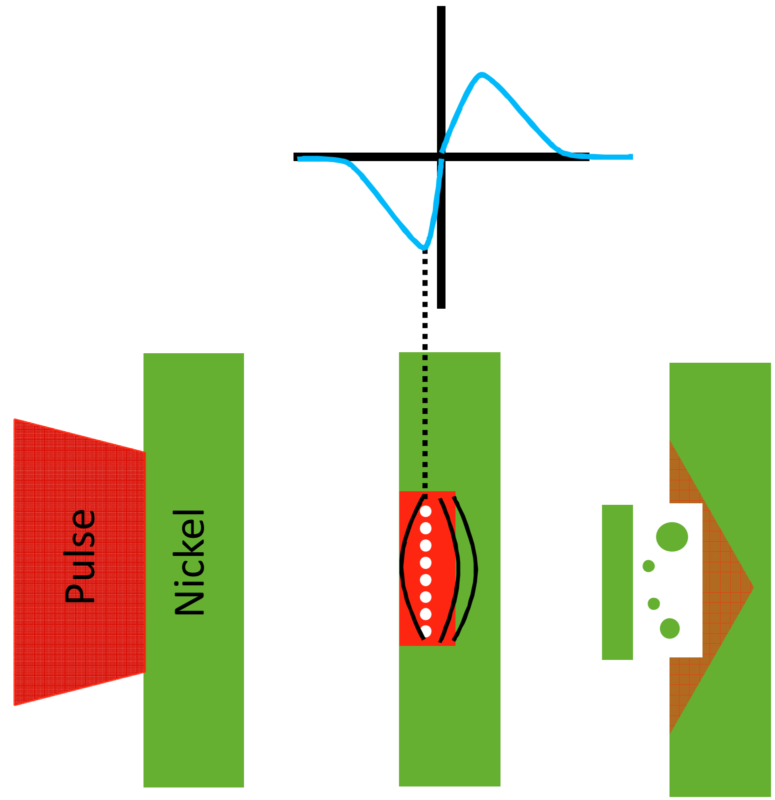
- First few nanometers of material melts in ~ 3 ps.
- Rapid expansion leads to homogeneous void nucleation within melt.
- Material “breaks” where voids nucleate.



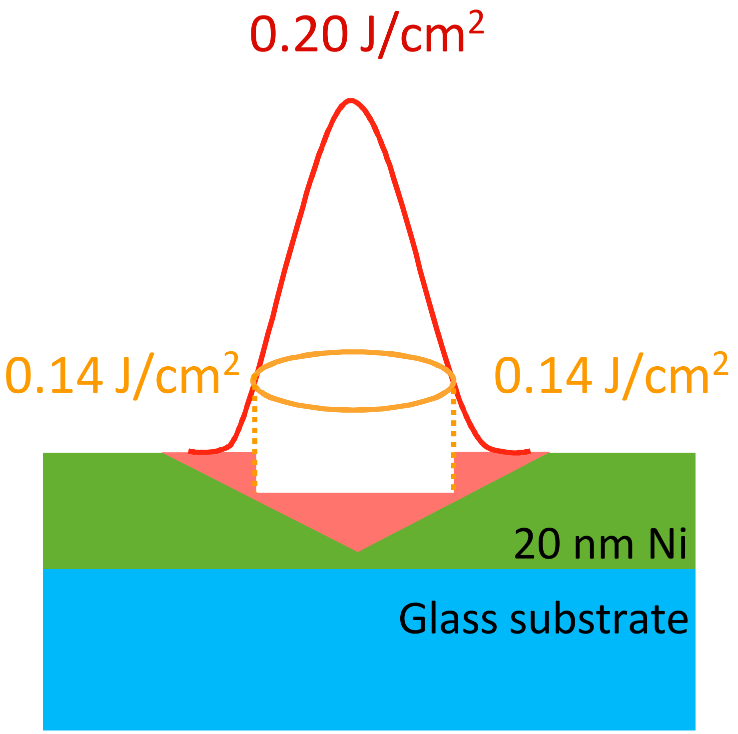
Gilmer (unpublished)

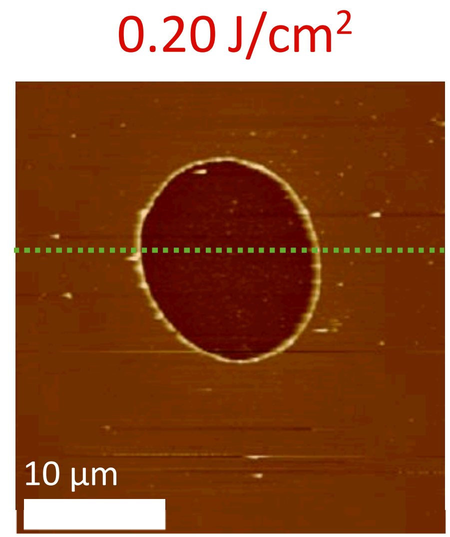
Deterministic Thresholds

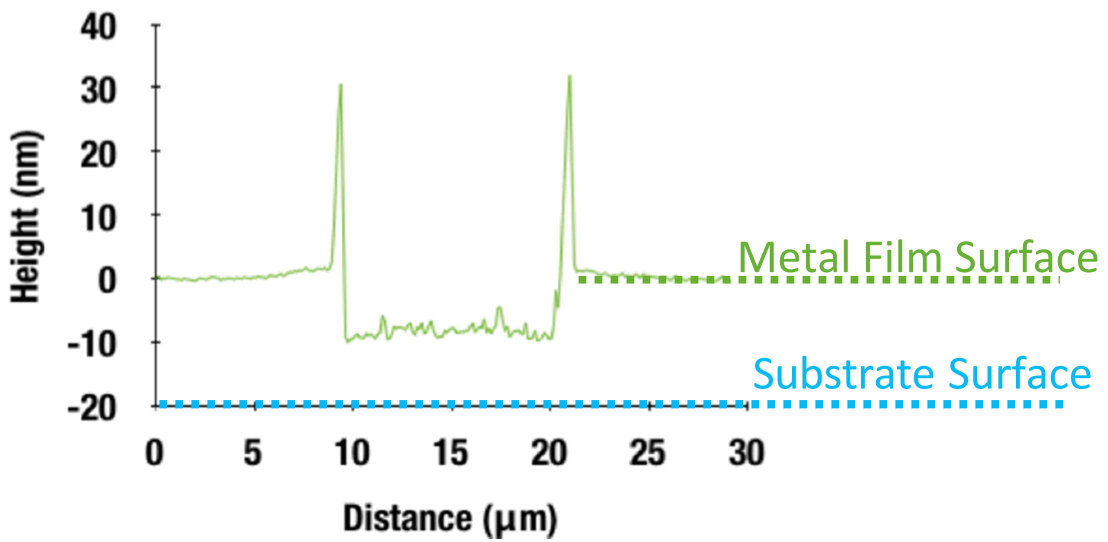




Low Fluence Removal Within Film

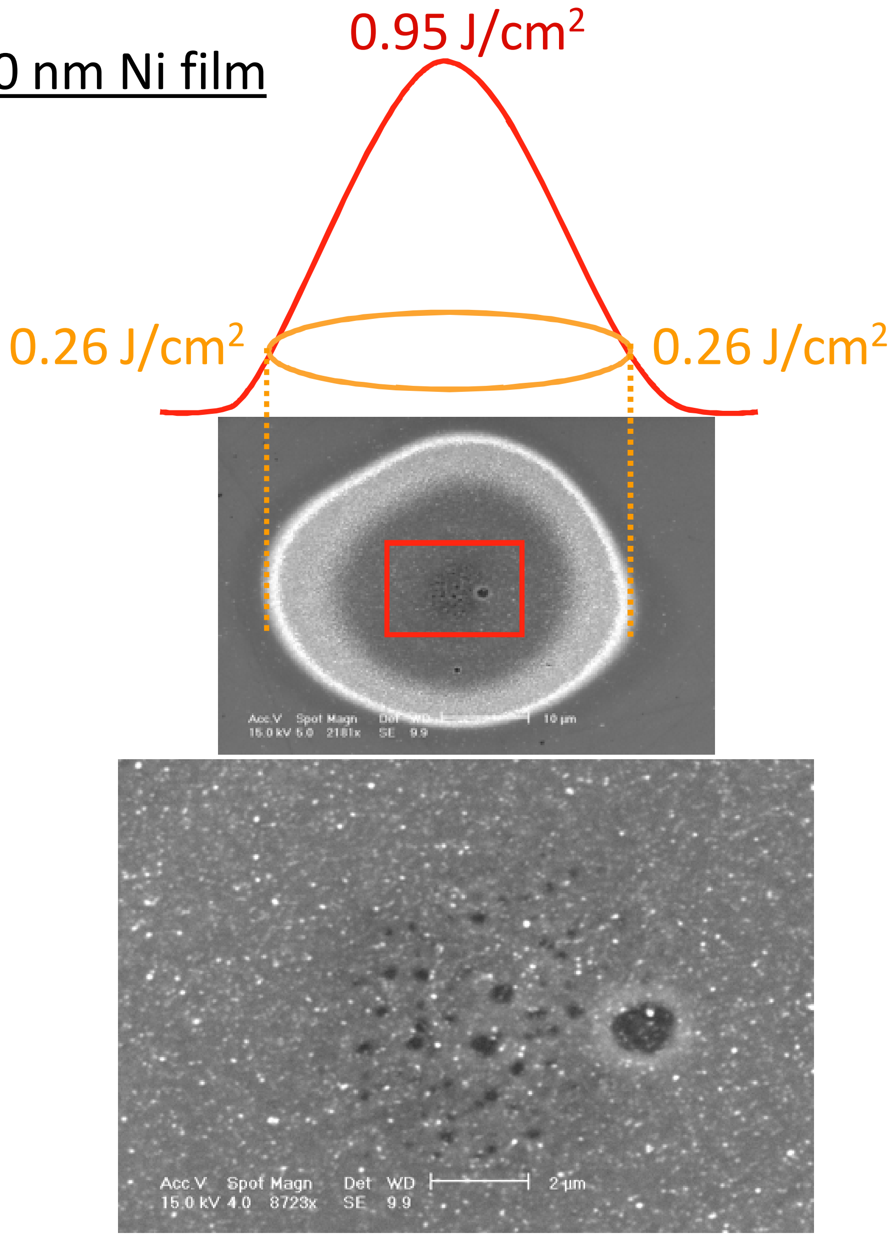


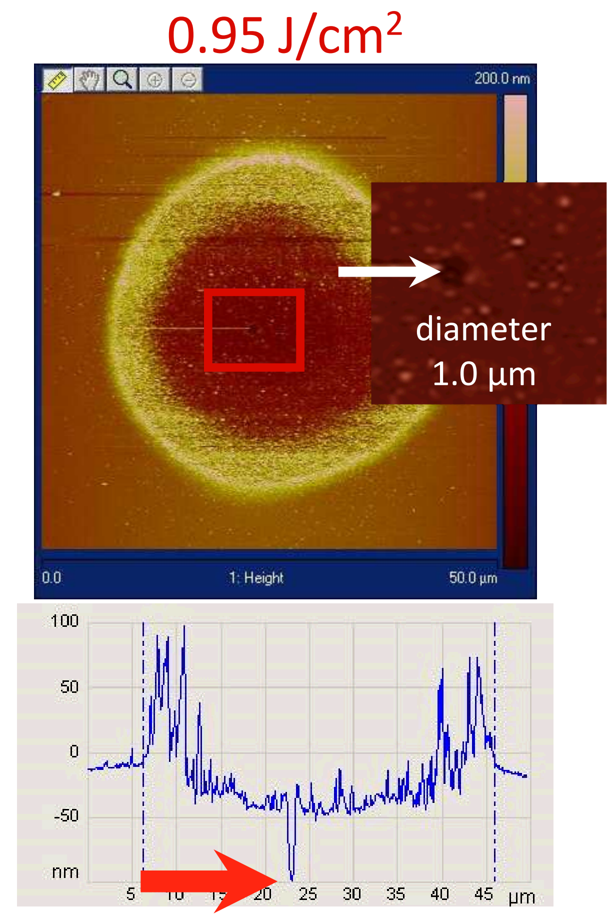




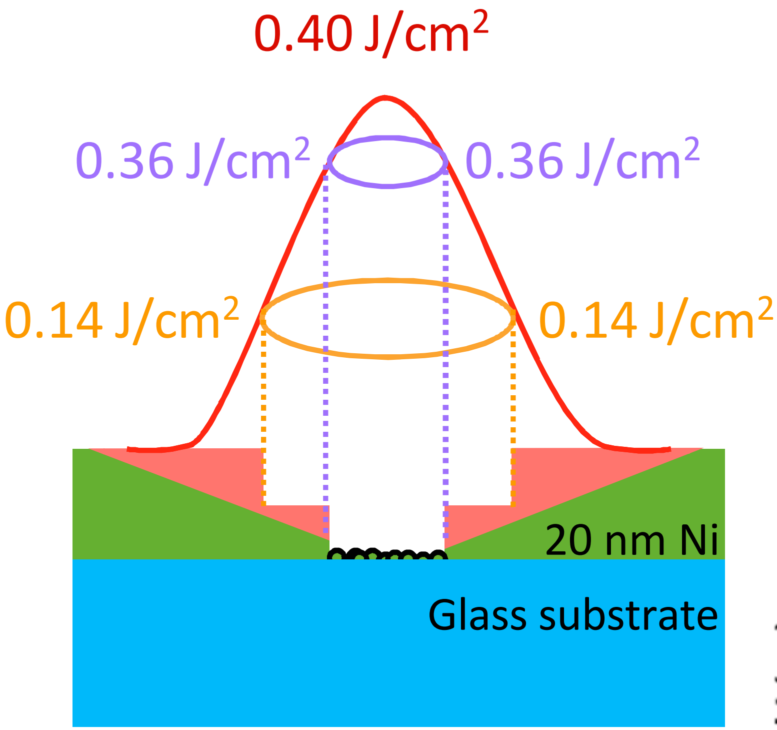
Interfaces Alter Material Removal Thresholds

70 nm Ni film

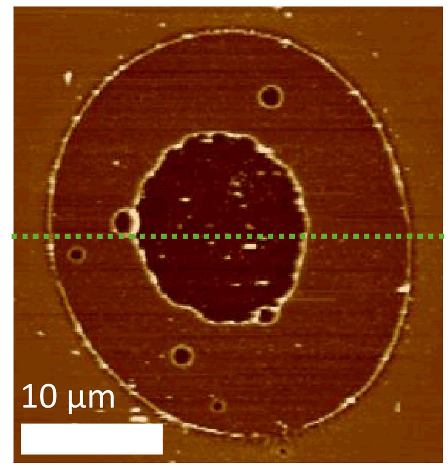


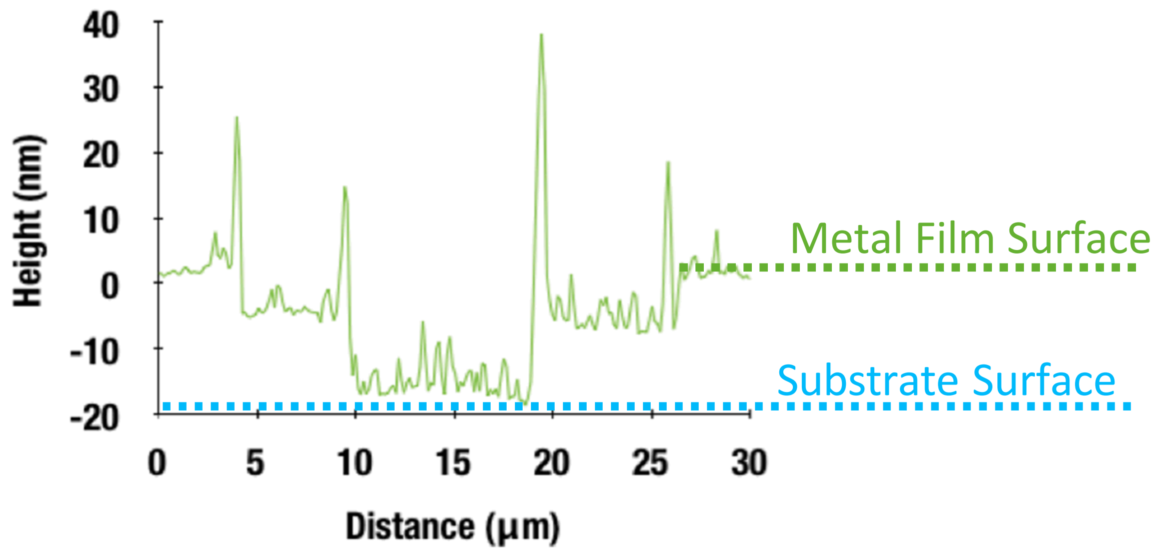


High Fluence Removal Within Film + at Interface



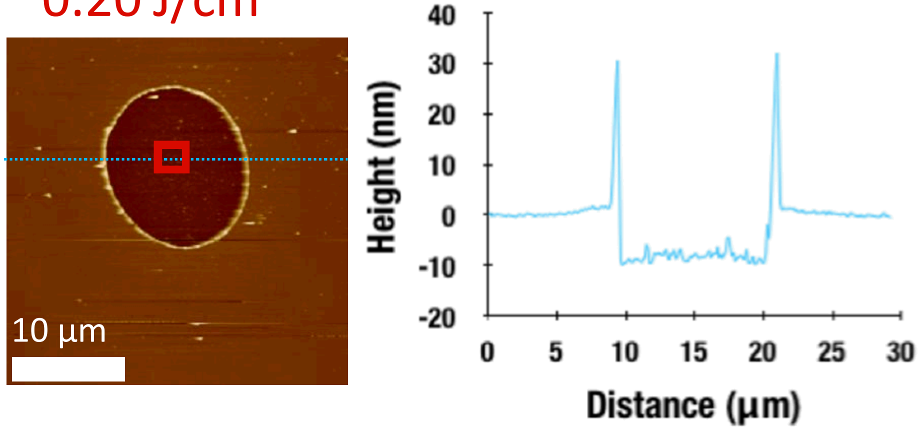
0.40 J/cm2



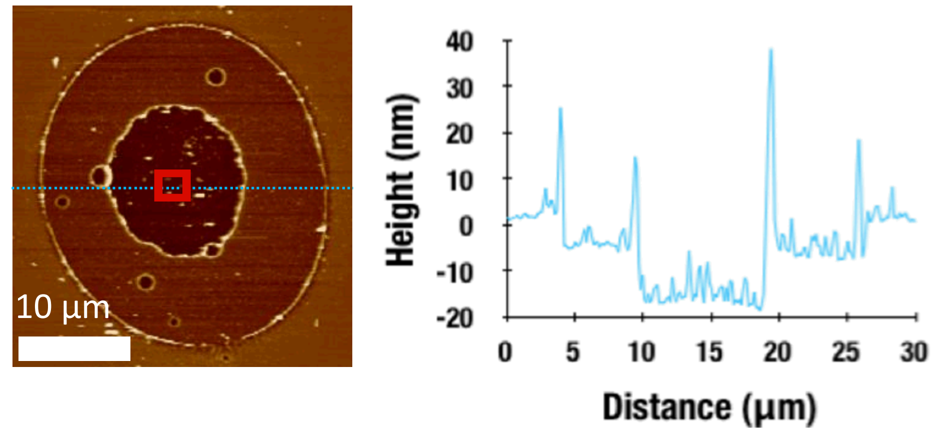


Void Nucleation Controls Surface Roughness

0.20 J/cm²

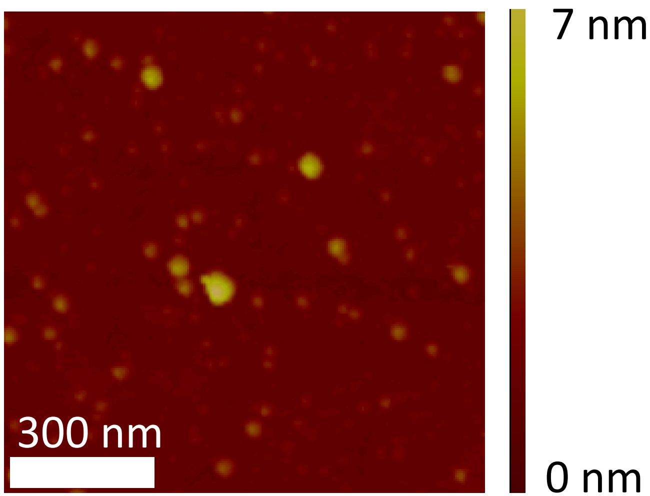


0.40 J/cm²



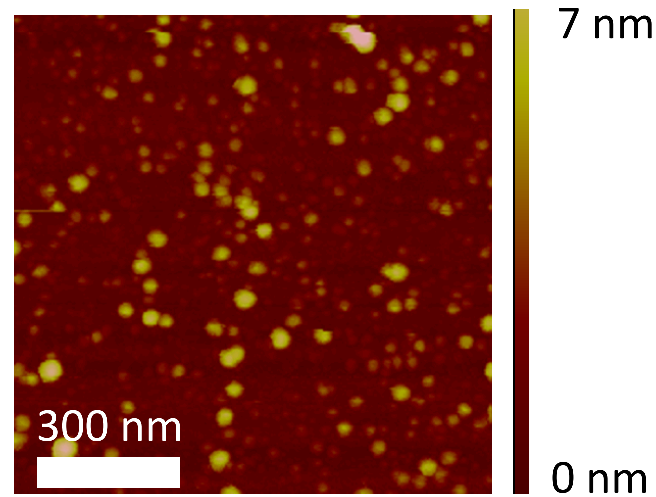
<u>Intra-film Separation</u>

RMS Roughness = 1.27 nm



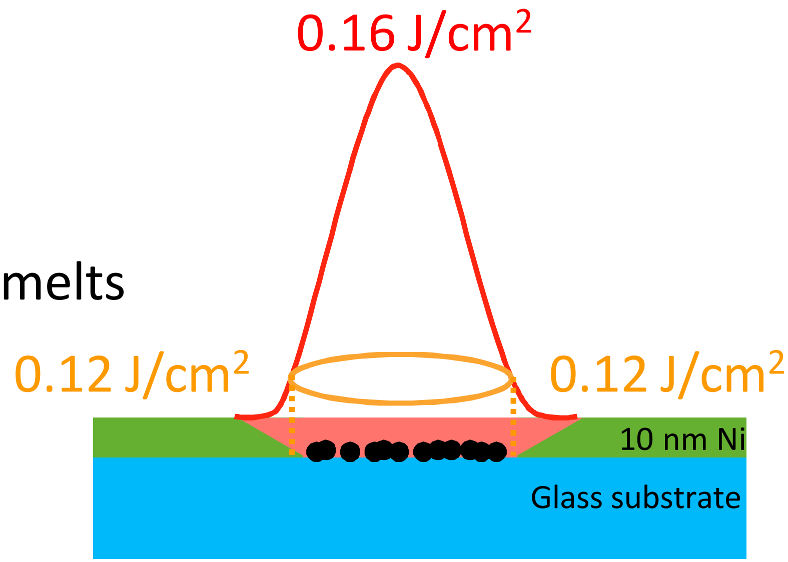
<u>Interface Separation</u>

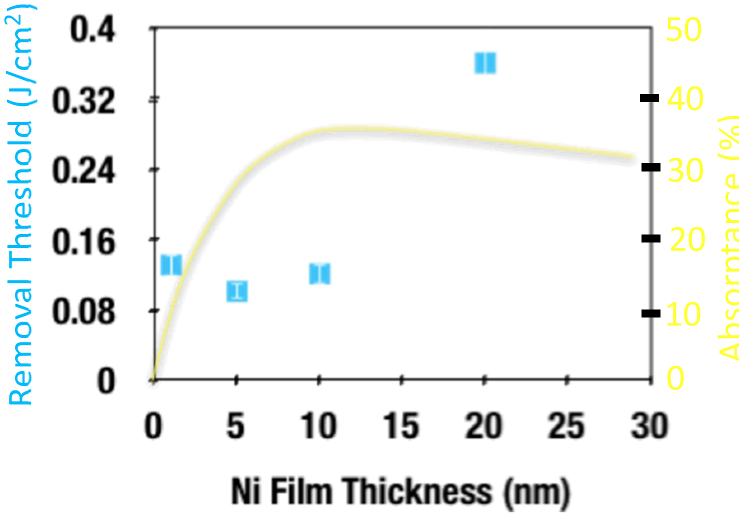
RMS Roughness = 3.06 nm



Heterogeneous Nucleation Dominates in Thinnest Films

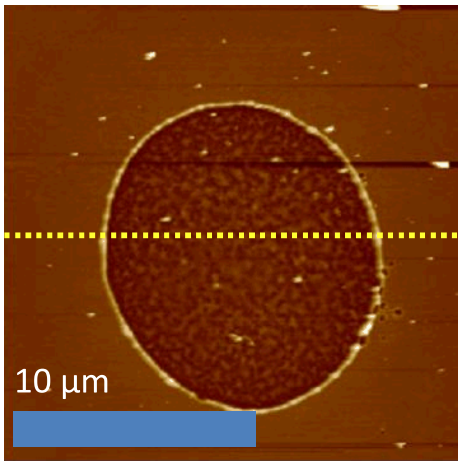
Entire film melts

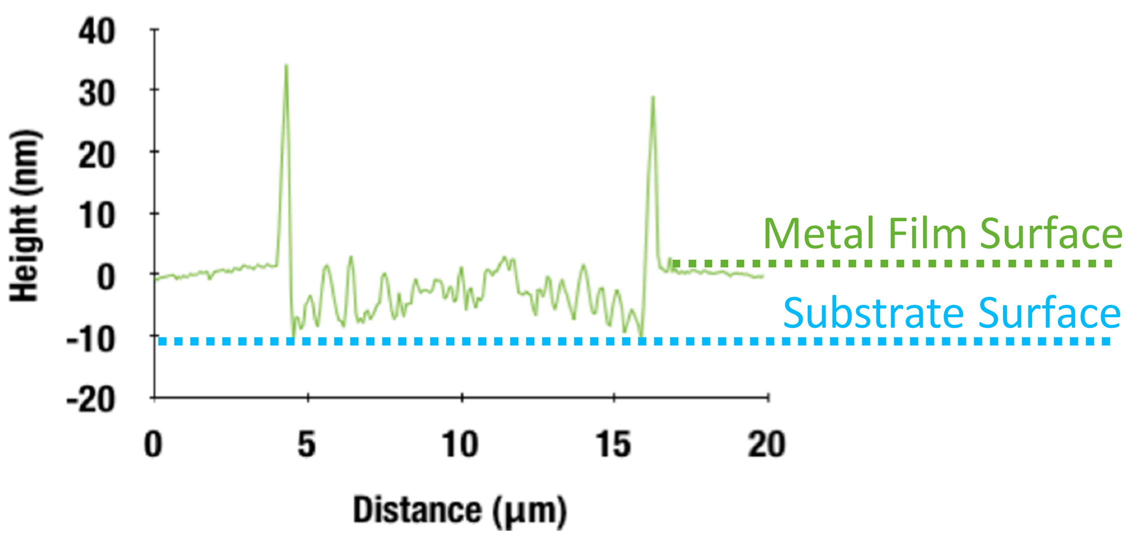




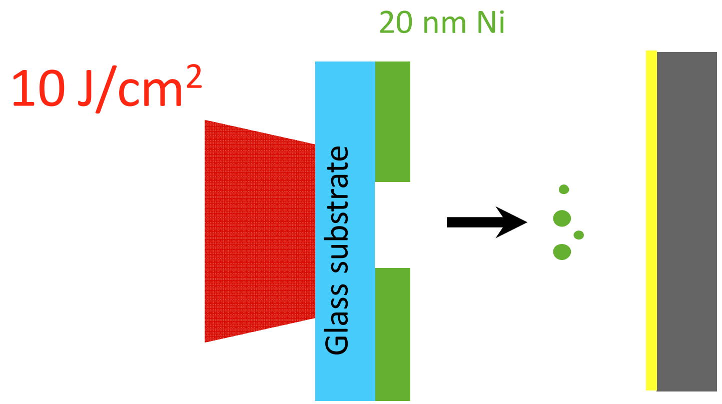
0.16 J/cm^2

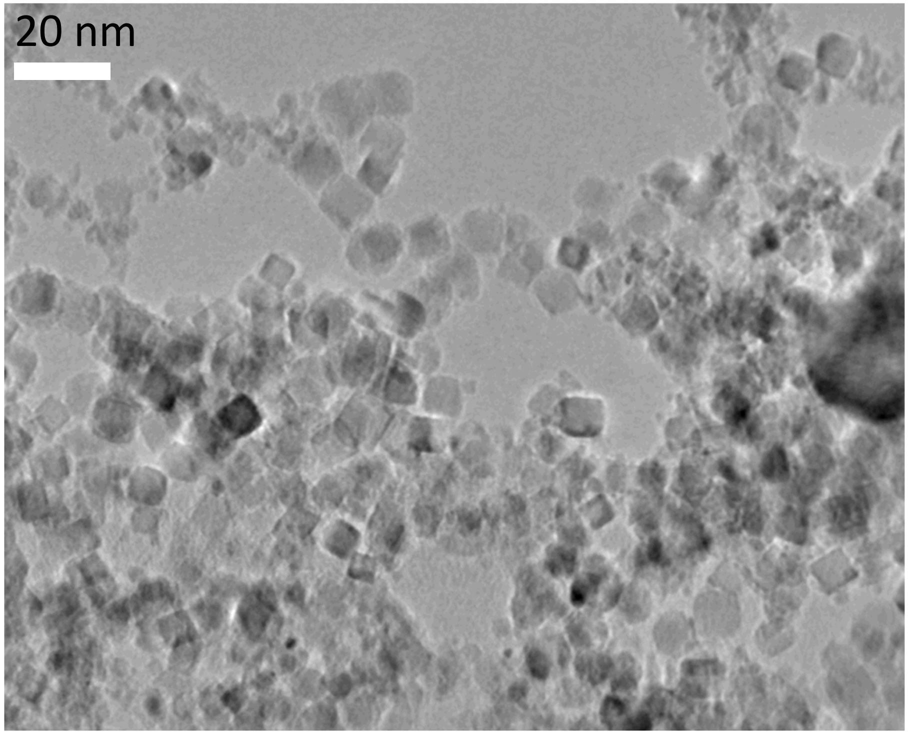
Heterogeneous Nucleation

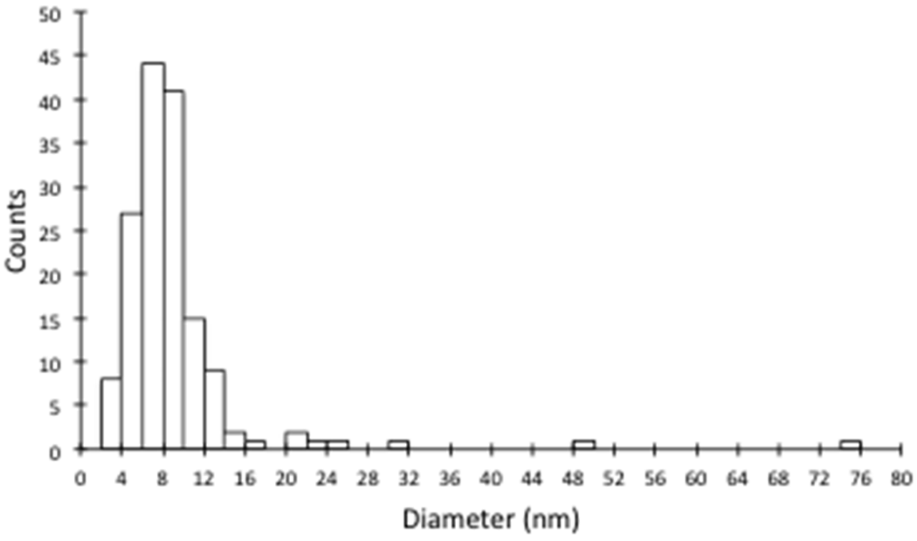




Ni Nanoparticle Printing



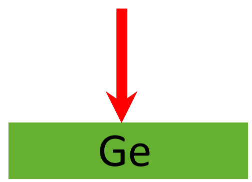




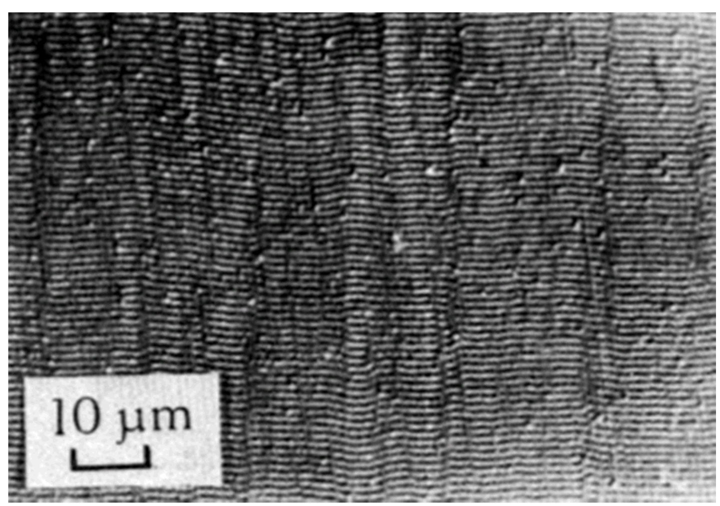
Surfaces Spatially Shape Laser Pulses

Typical Laser Induced Periodic Surface Structures (LIPSS)

- Randomly rough surfaces couple to laser light.
- Interference pattern is formed when scattered light interferes with incident laser light.



20 ns pulses
Incident λ = 1.06 μm
Λ ~ 1.06 μm
<u>30 pulses</u>

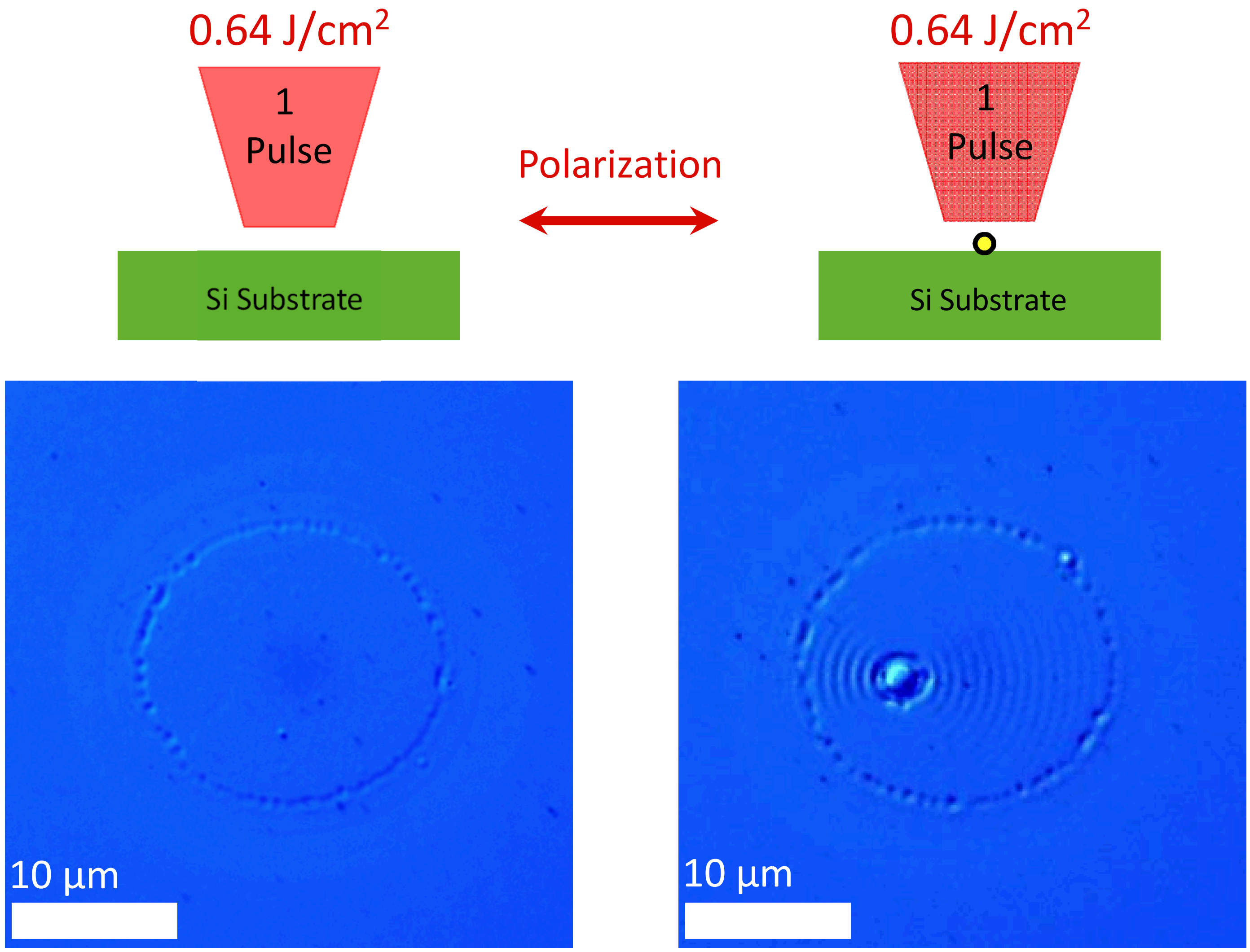


Polarization Direction

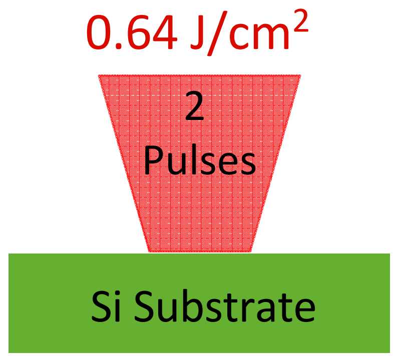
Young, et. al. Phys. Rev. B 27 (1983)

LIPSS After 1 Pulse

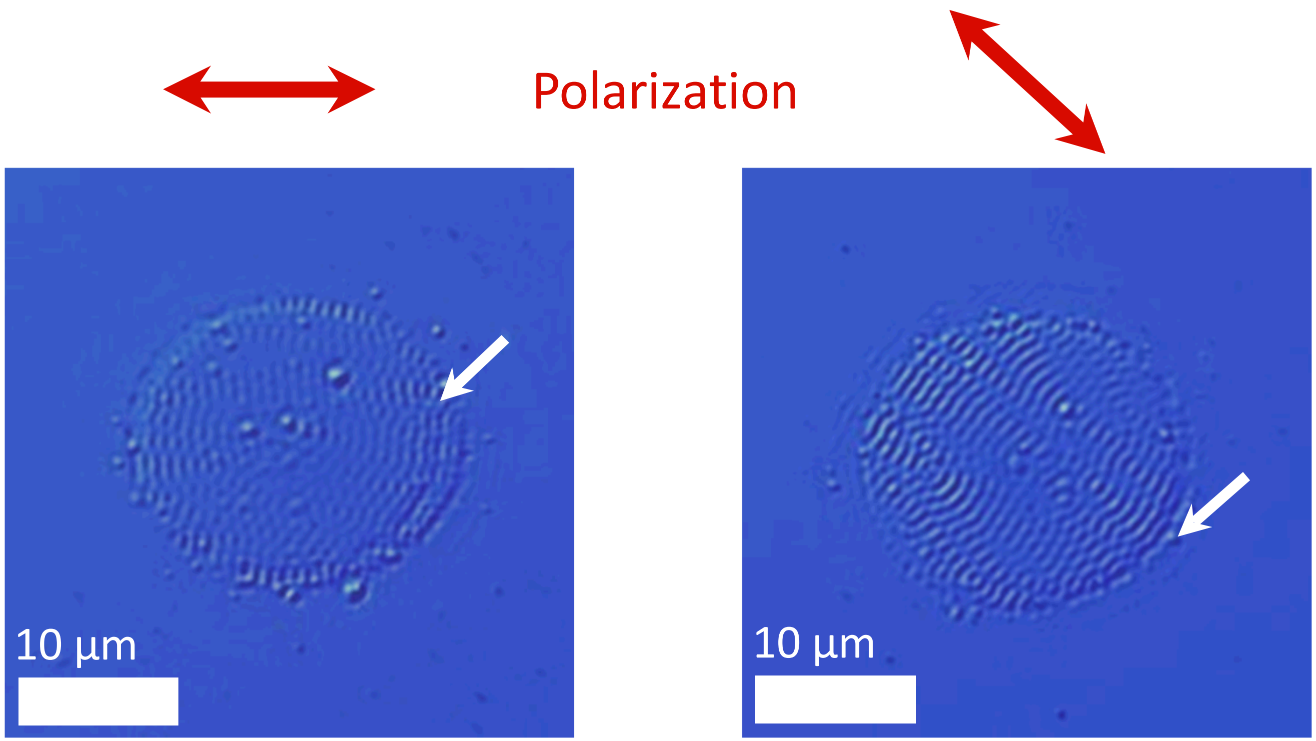
- LIPSS formation observed near surface defects.



LIPSS Formation After 2 Pulses



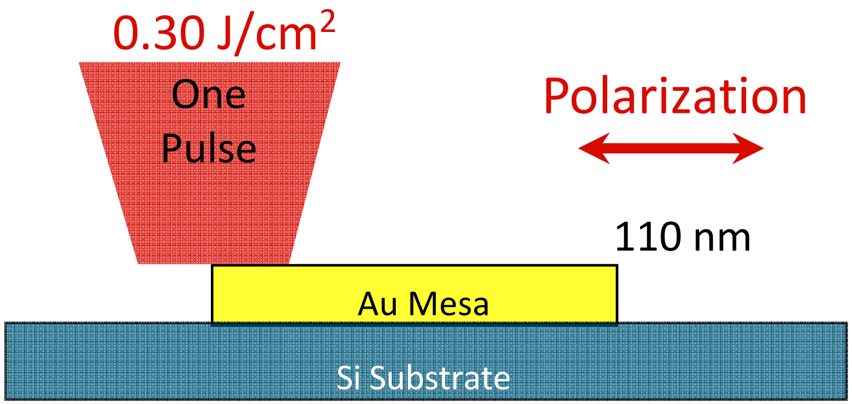
Average Period = 757 nm
Standard Deviation = 100 nm



LIPSS Formation Near Au Microstructures

Side View

Fundamental Wavelength = 775 nm

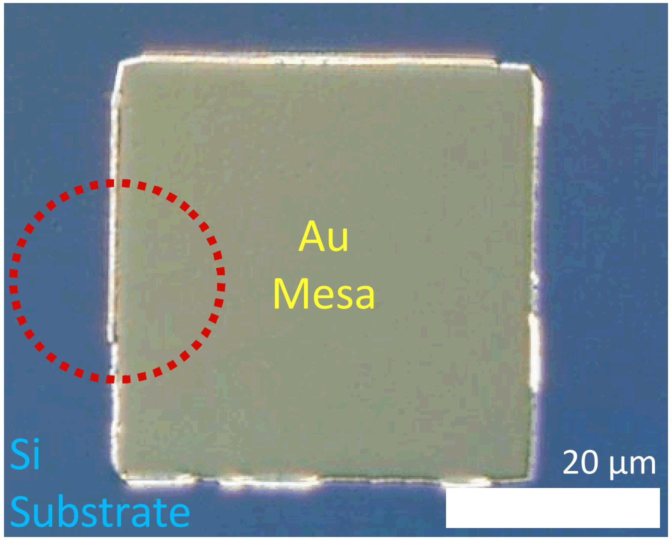


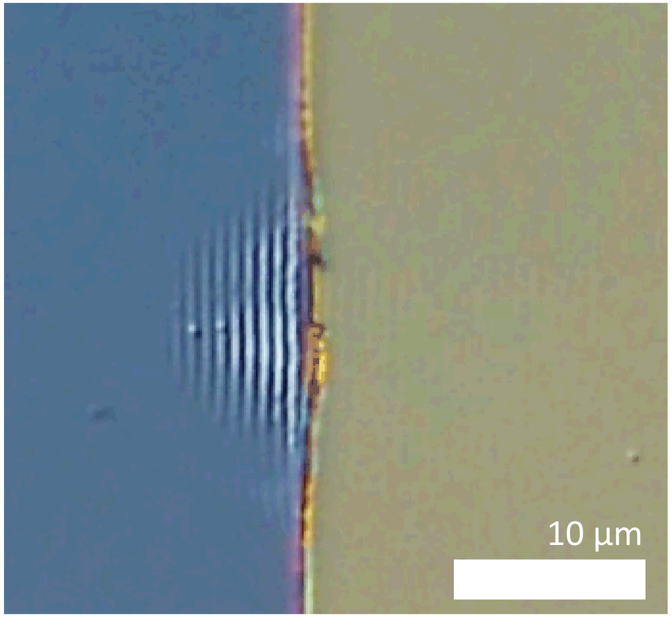
Au melt threshold ~ 0.55 J/cm²

Si melt threshold ~ 0.20 J/cm²

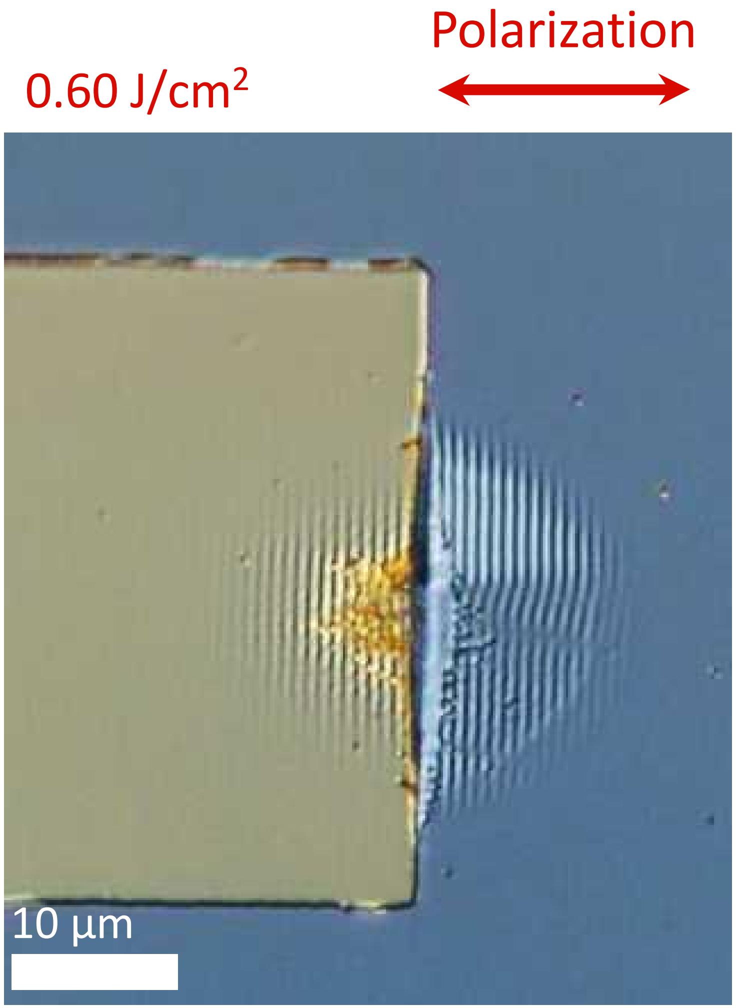
- Below crater threshold
- Above melt threshold

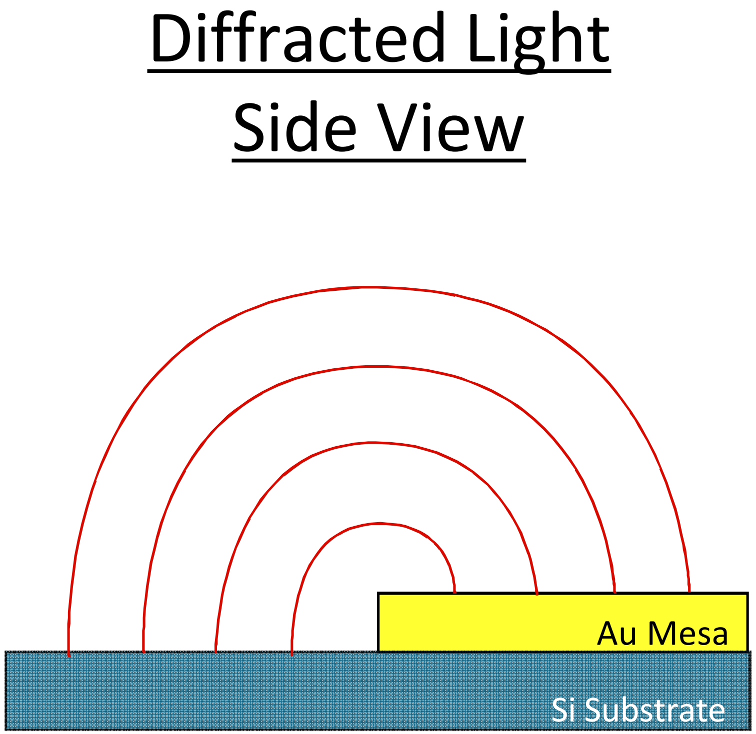
Top View



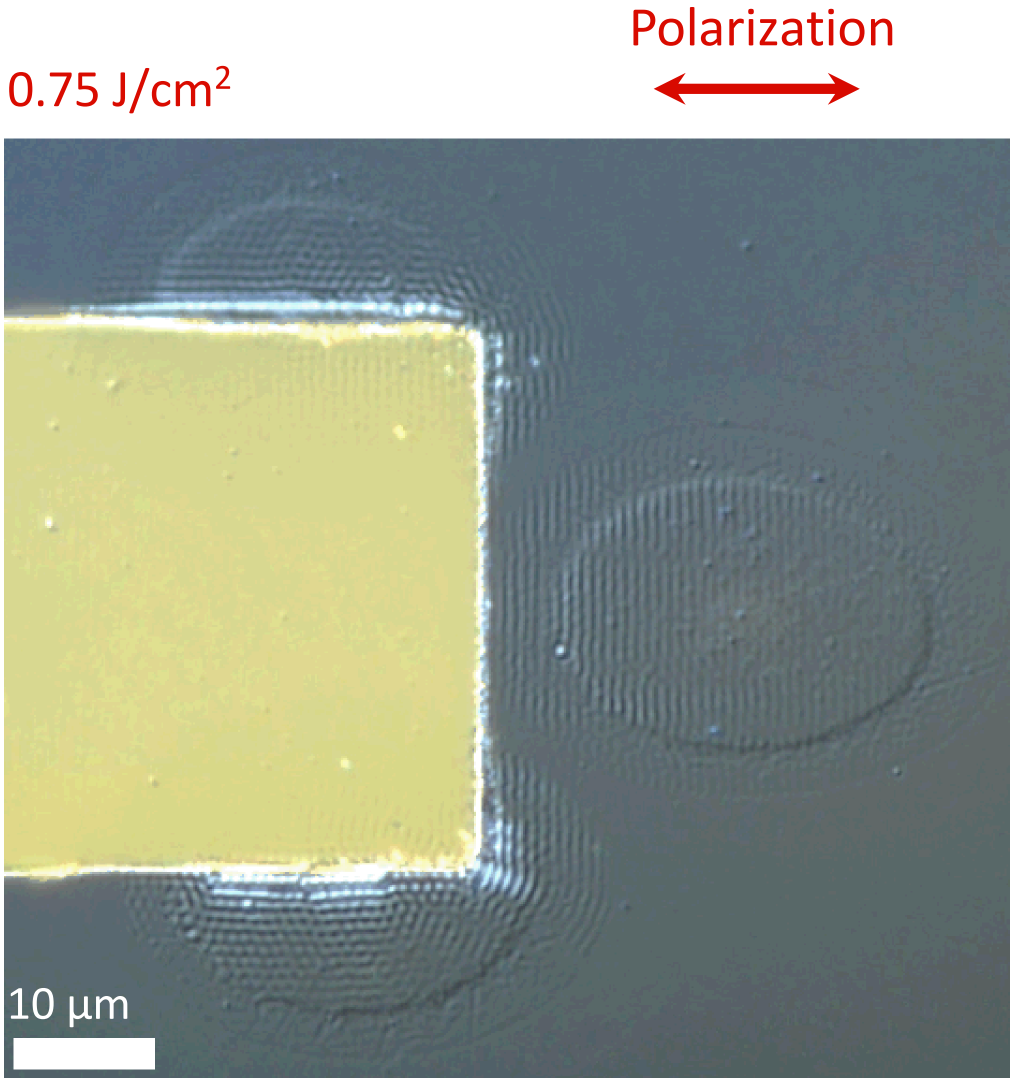


LIPSS Formation Near and On Top of Au Microstructures





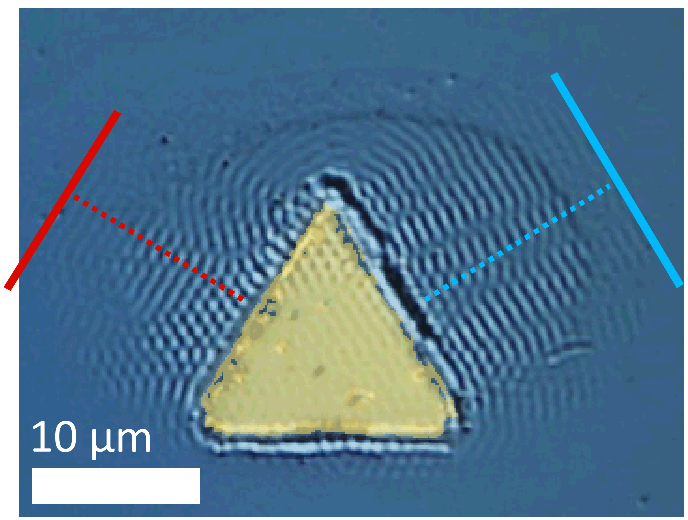
Mesa Edges Act As Sources for 1 pulse LIPSS Formation



LIPSS Formation from Multiple Sources

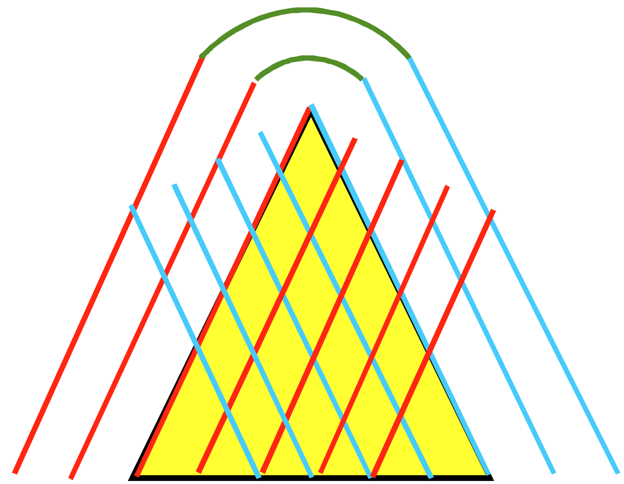
0.50 J/cm^2

Polarization



Diffracted Light

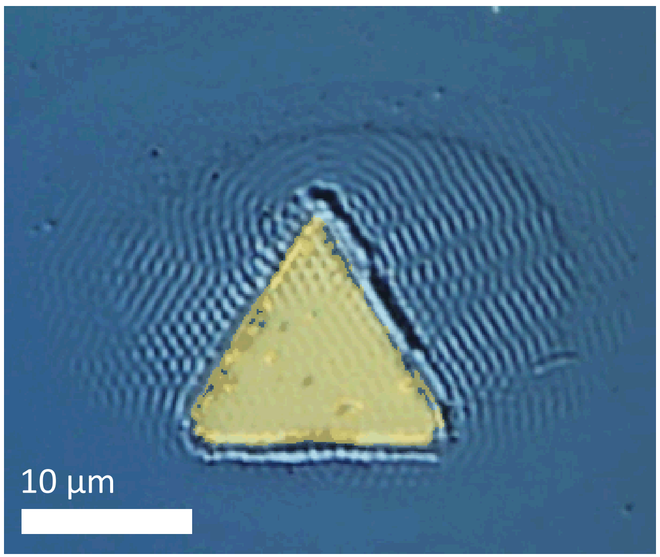
Top View



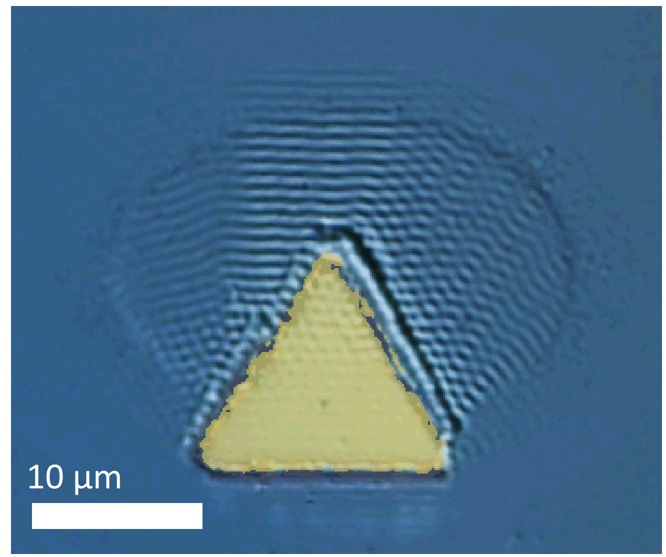
Dependence on Polarization

0.50 J/cm^2

Polarization

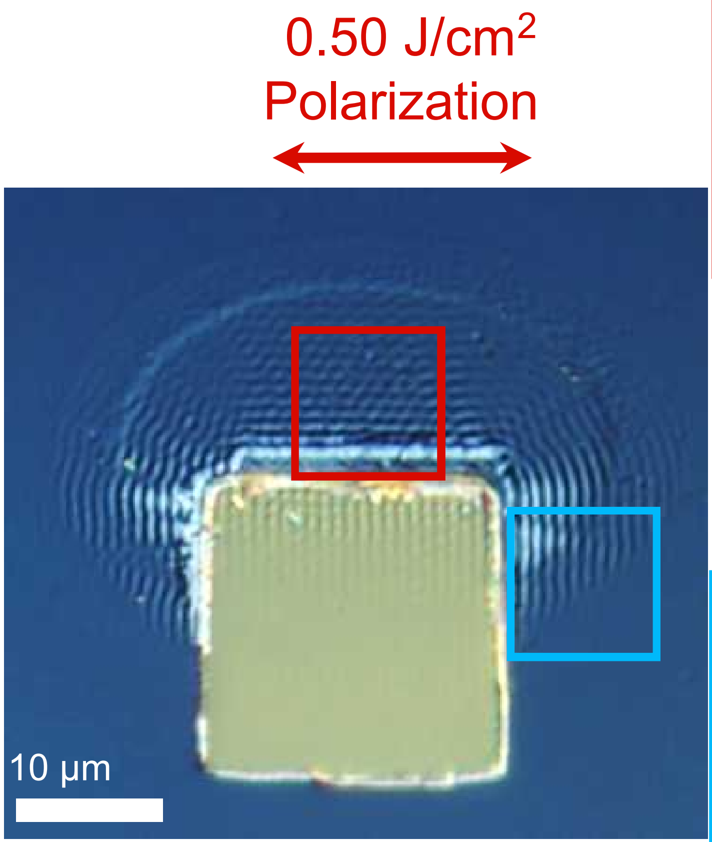


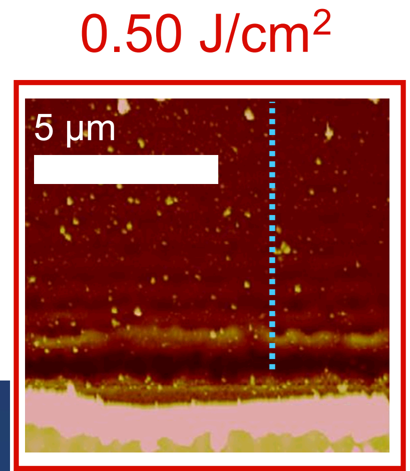
Polarization

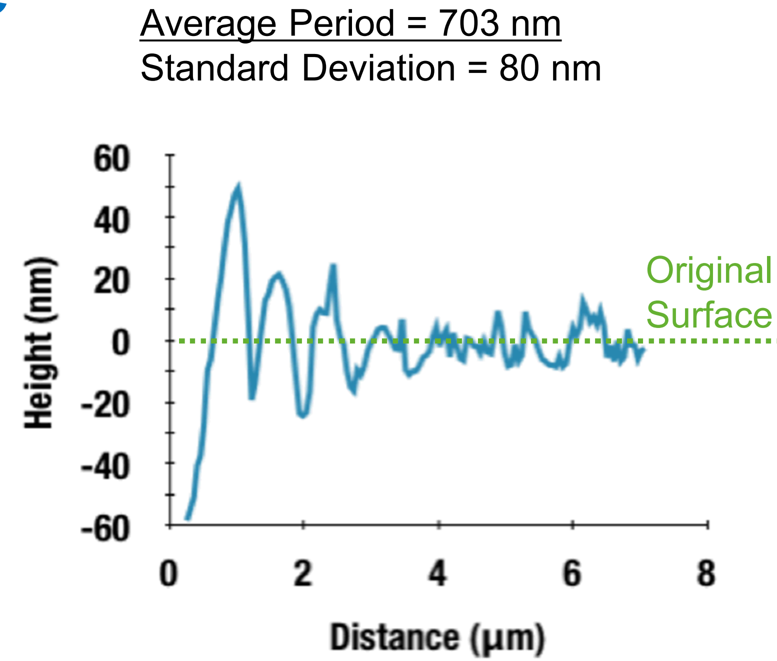


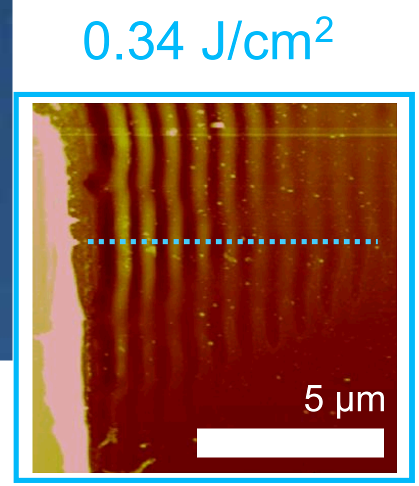
Two Mechanisms Playing a Role

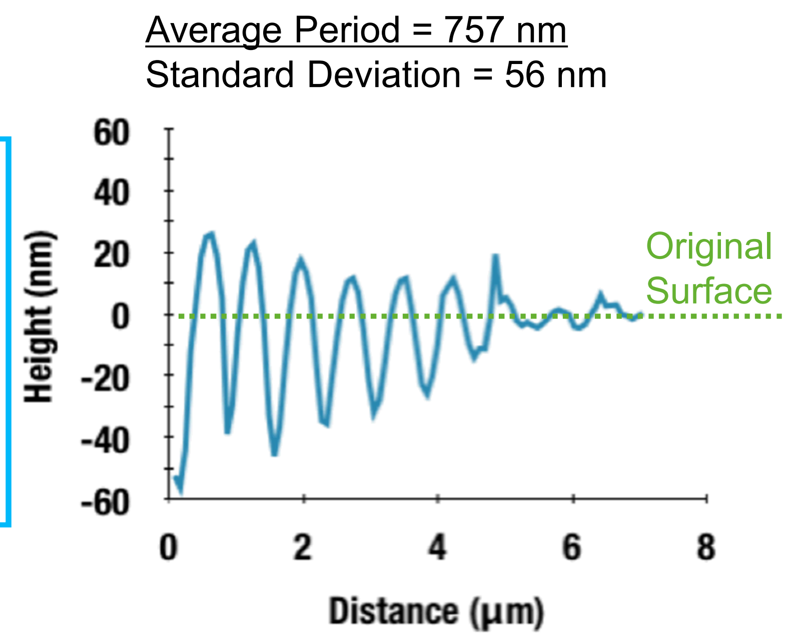
- Near-field diffraction
- Surface plasmon excitation









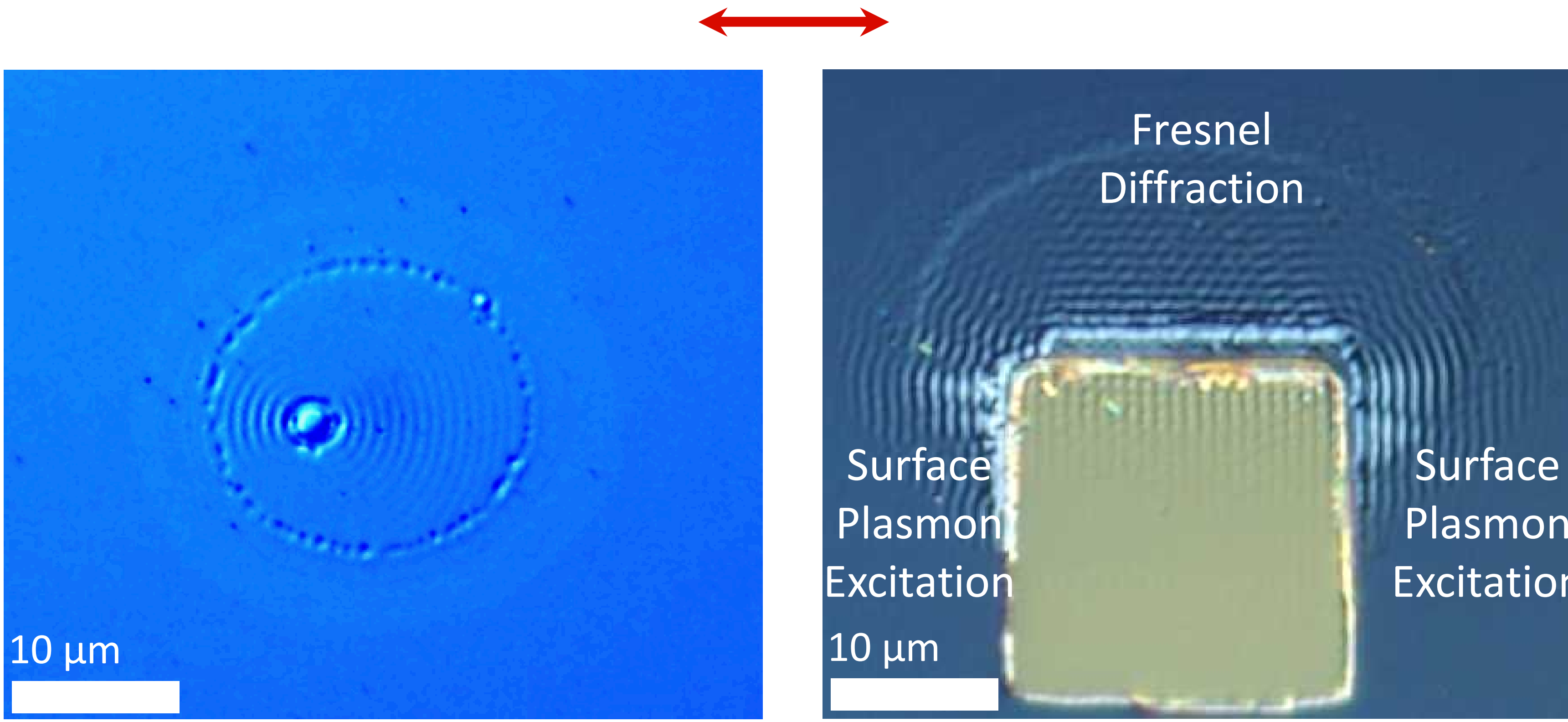


LIPSS Formation:
Sources + Material Removal

- The active LIPSS formation mechanism depends on the angle of the polarization vector with respect to surface features.

- LIPSS formation is due to material removal.

Polarization



Temporal and Spatial

Pulse Shaping

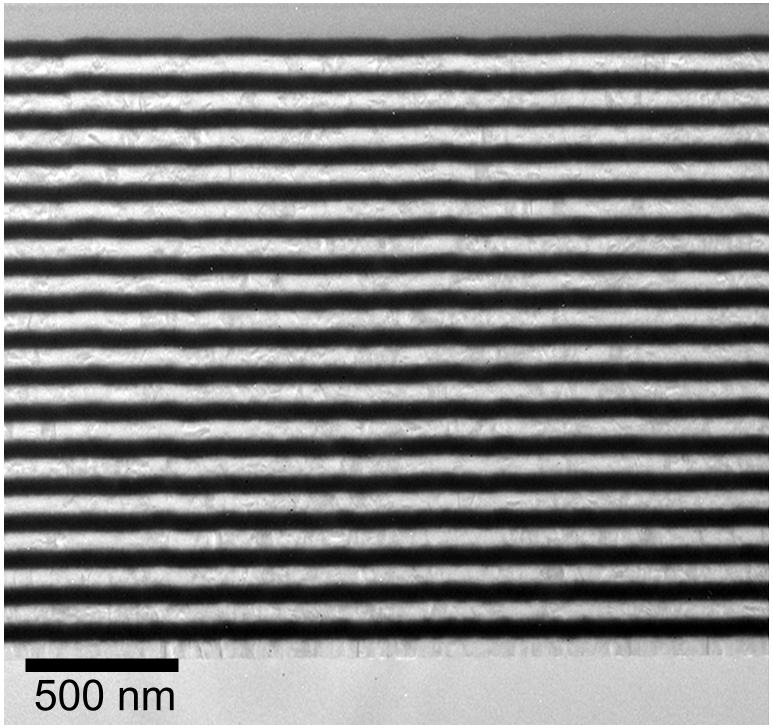
Reactive Multilayers

$Al + Pt \rightarrow AlPt$ (intermetallic phase) + 100 $kJ \cdot mol^{-1} \cdot atm^{-1}$

- Exothermic heat generation upon ignition.
- Self-propagating reaction.

- DC Magnetron sputtered layers
- 10 - 15 Å thickness variation
- 1 to 1 Al/Pt ratio
- Adiabatic reaction temperature = 2798 °C
- <u>Melting not required for ignition</u>

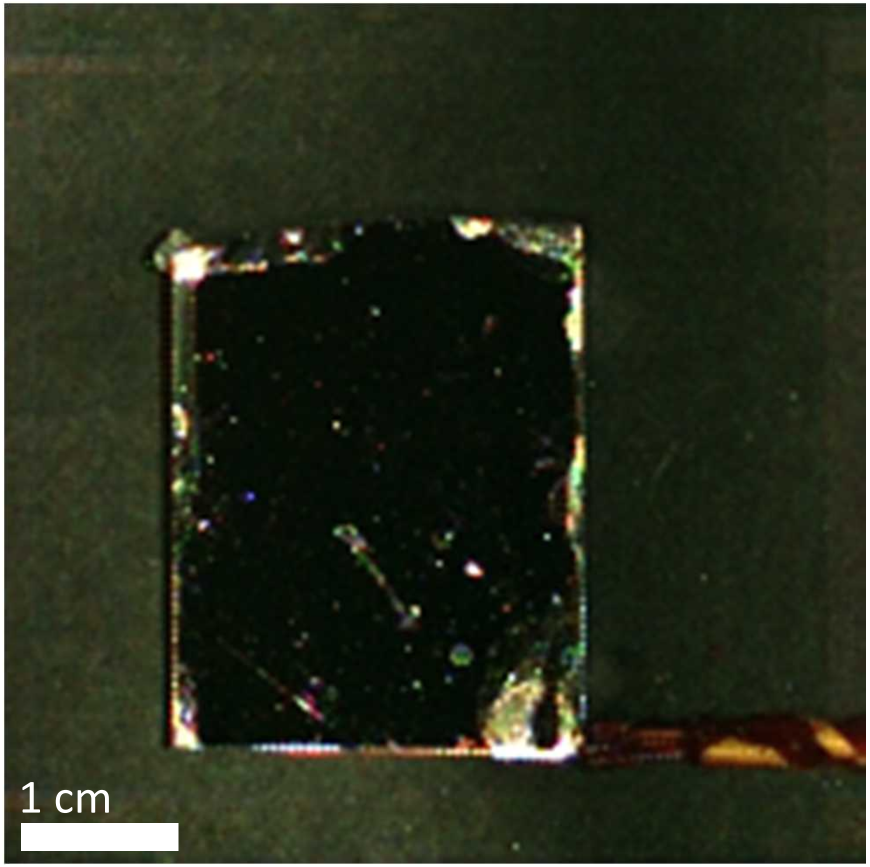
Al/Pt multilayer
TEM Cross-section

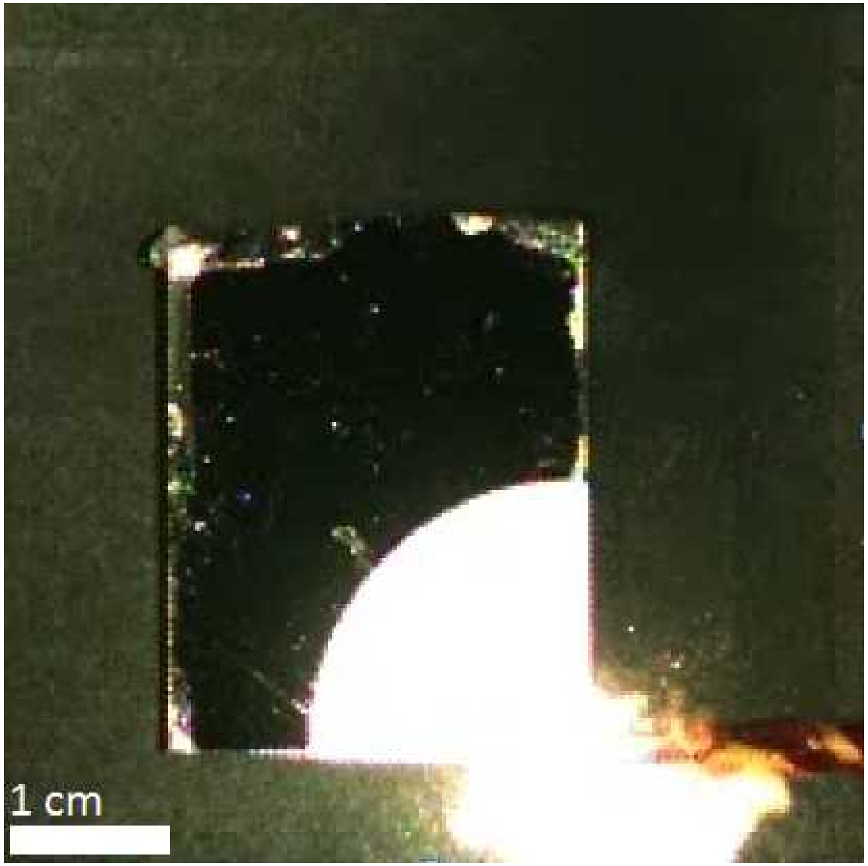


Ignition and Reaction Propagation

<u>Ignition by capacitive discharge</u>

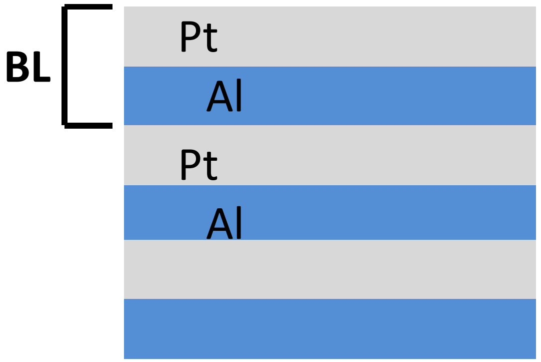
~ 600 microseconds after ignition

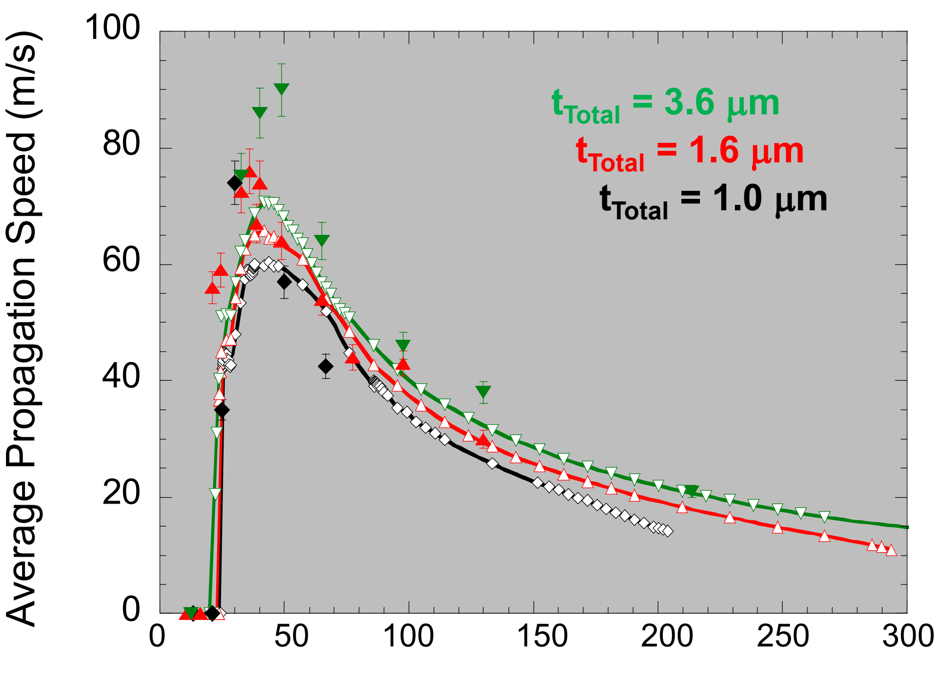




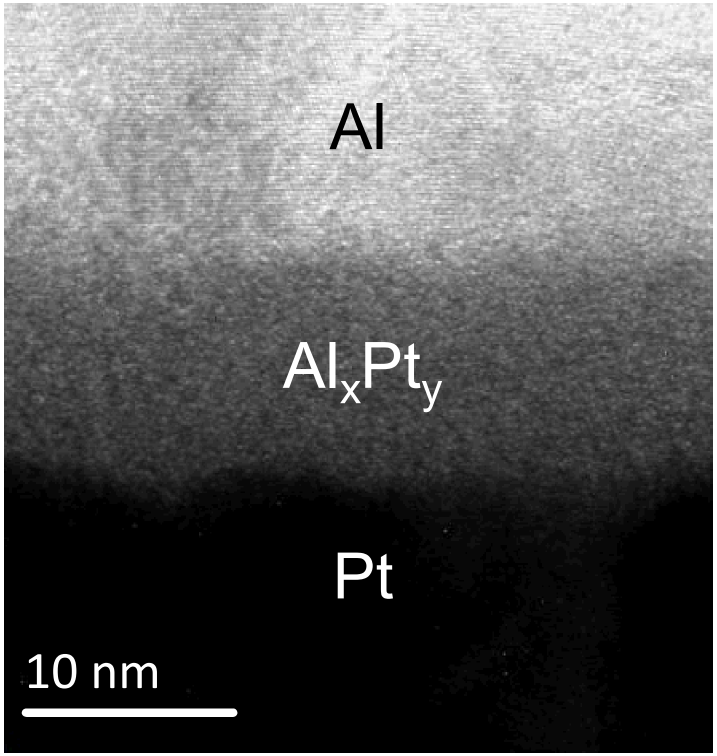
Bilayer Dependence

- Propagation speed increases with decreasing bilayer thickness.
- Shorter diffusion distances lead to shorter reaction times.
- Pre-mixing affects propagation speed of thinnest bilayers.



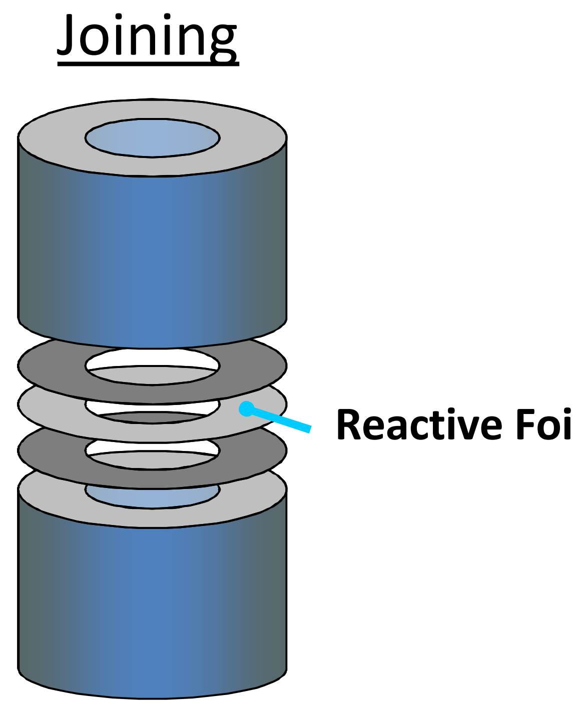


M. Hobbs, D.P. Adams, et al. 8th World Congress Comp. Mech. (2008).

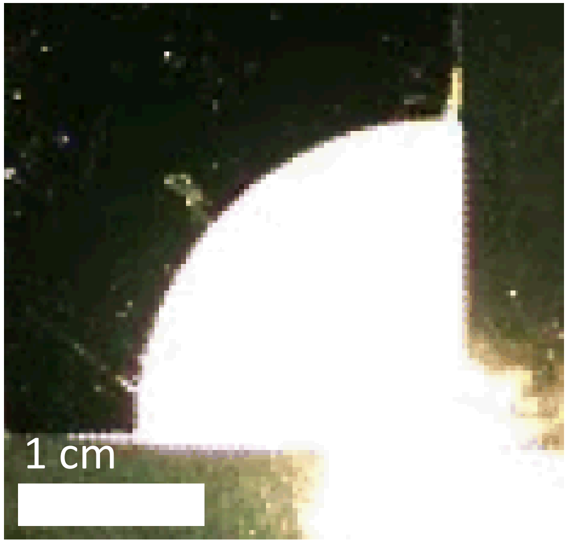


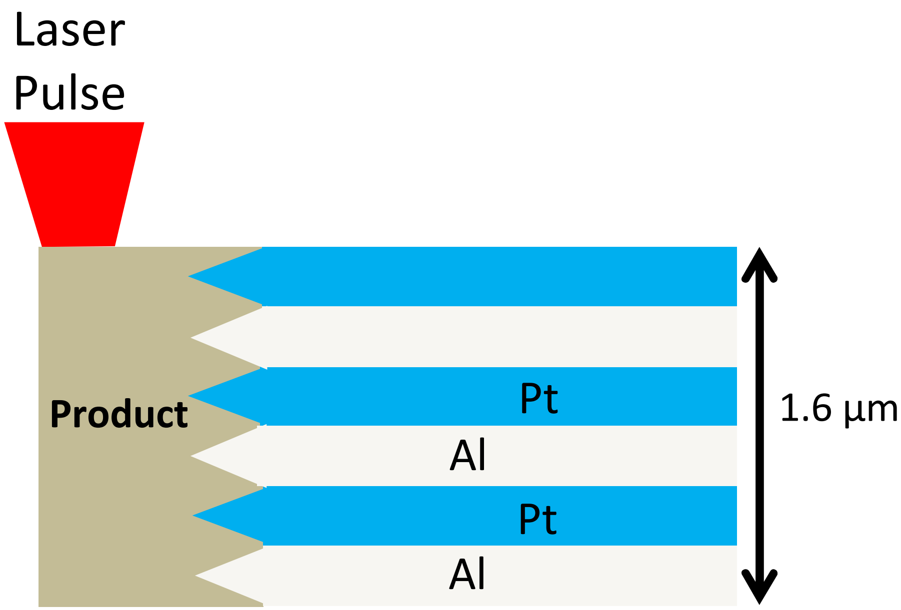
Laser Ignition

- Laser irradiation leads to more control over energy delivered to foil.
- Laser irradiation allows for remote ignition.
- Study effects of rate of heat input on ignition.
- Vary pulse length from femtosecond to millisecond to study effects of heating rate on ignition.



~ 600 microseconds after ignition



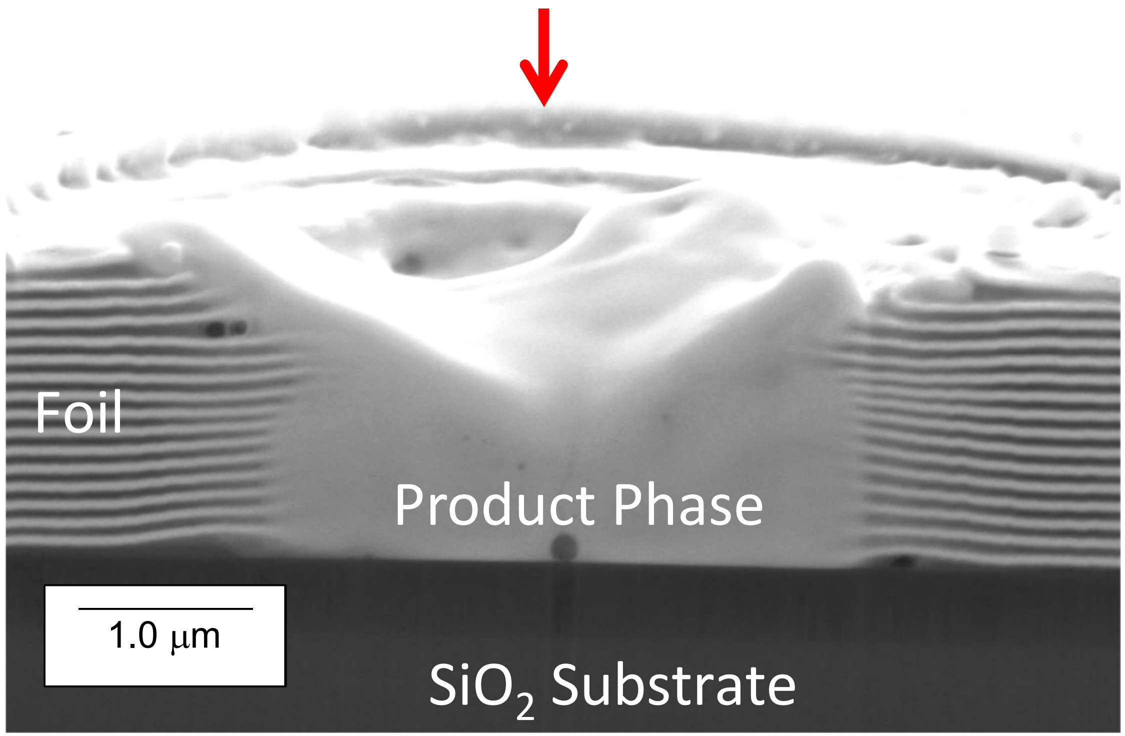


Laser Irradiation

- Laser irradiation can modify foils without ignition.
- Pulse length dependent.

Al/Pt Irradiated at 80% ignition threshold

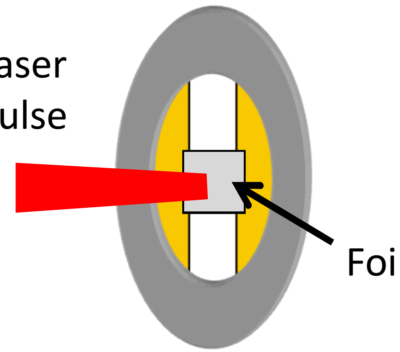
150 fs pulse



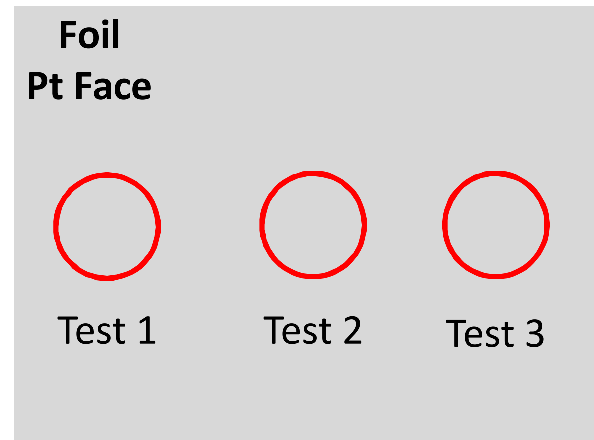
Picard, Yoosuf N. Ph.D. thesis University of Michigan, 2006.

Determining Laser Ignition Threshold

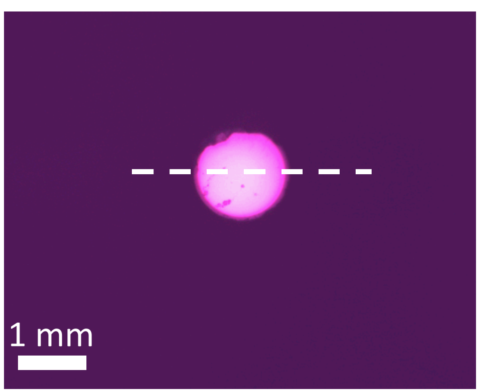
- Foil not on substrate
- Single Pulse Irradiation
- “Flat-top” Beam Profile
- Irradiate Pt side



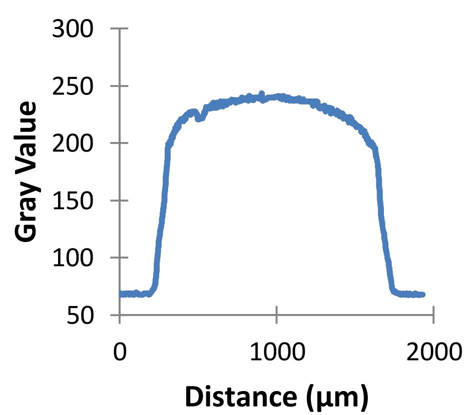
- Laser energy is increased until foil ignites.
- Non-irradiated region of sample is used for each test.

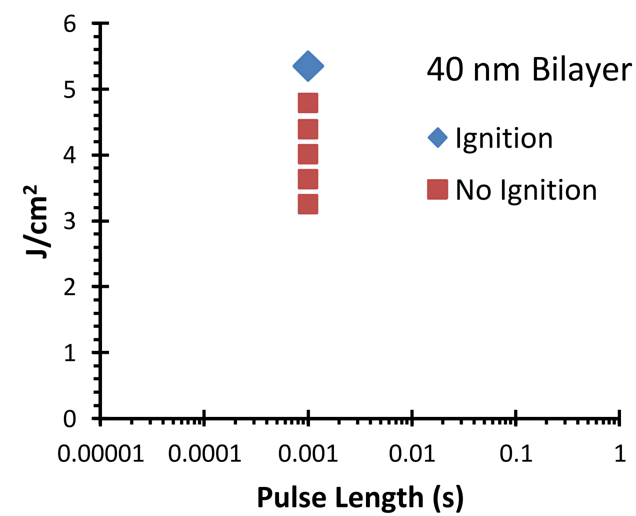


Focused Beam

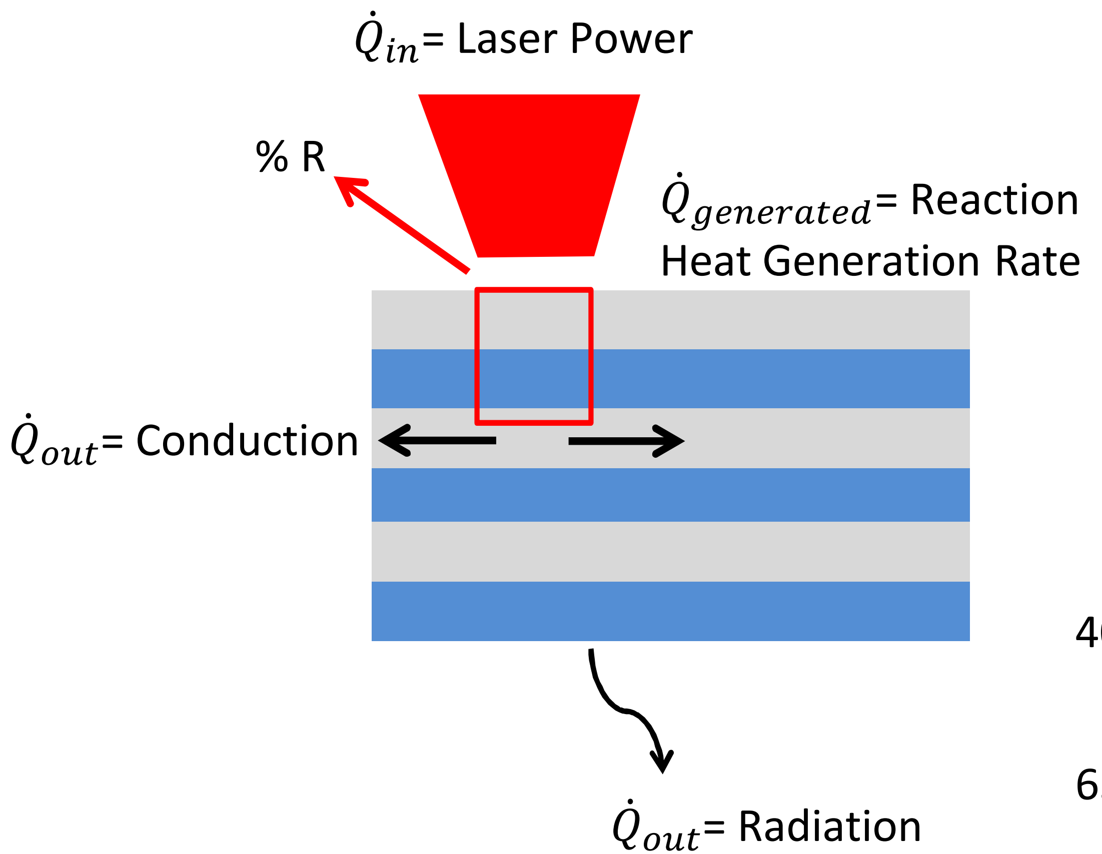


“Flat-top”



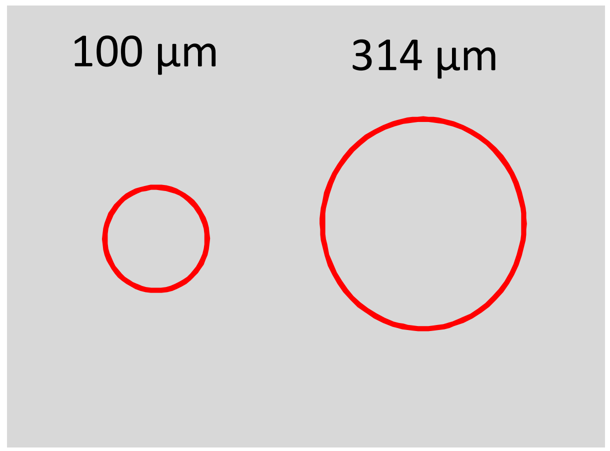


Heat Flow and Interaction Volume



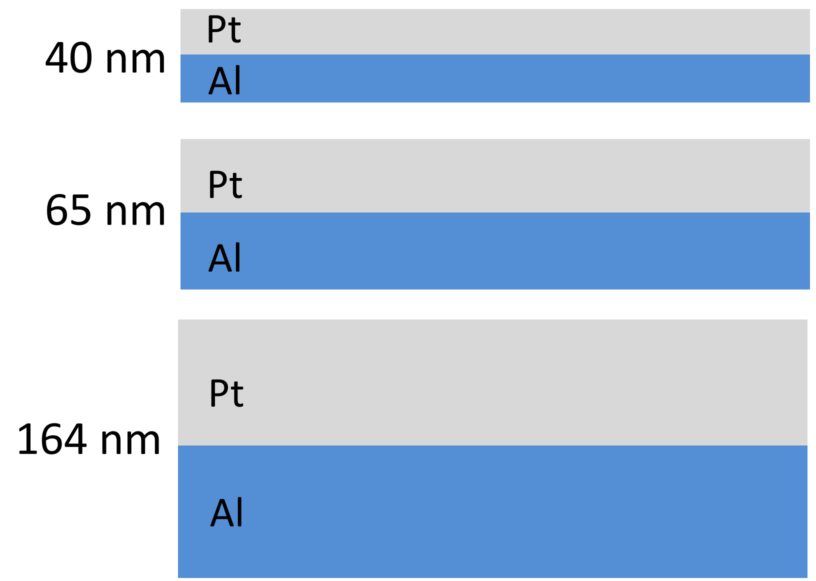
Change interaction volume

Laser Spot Size



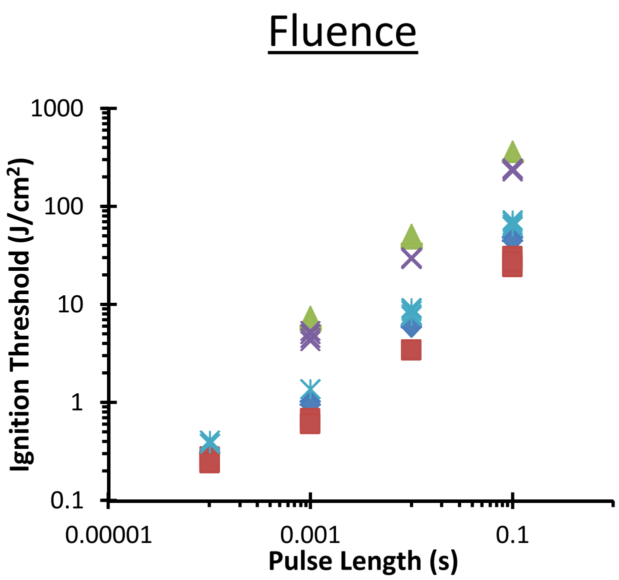
Total thickness = 1.6 µm

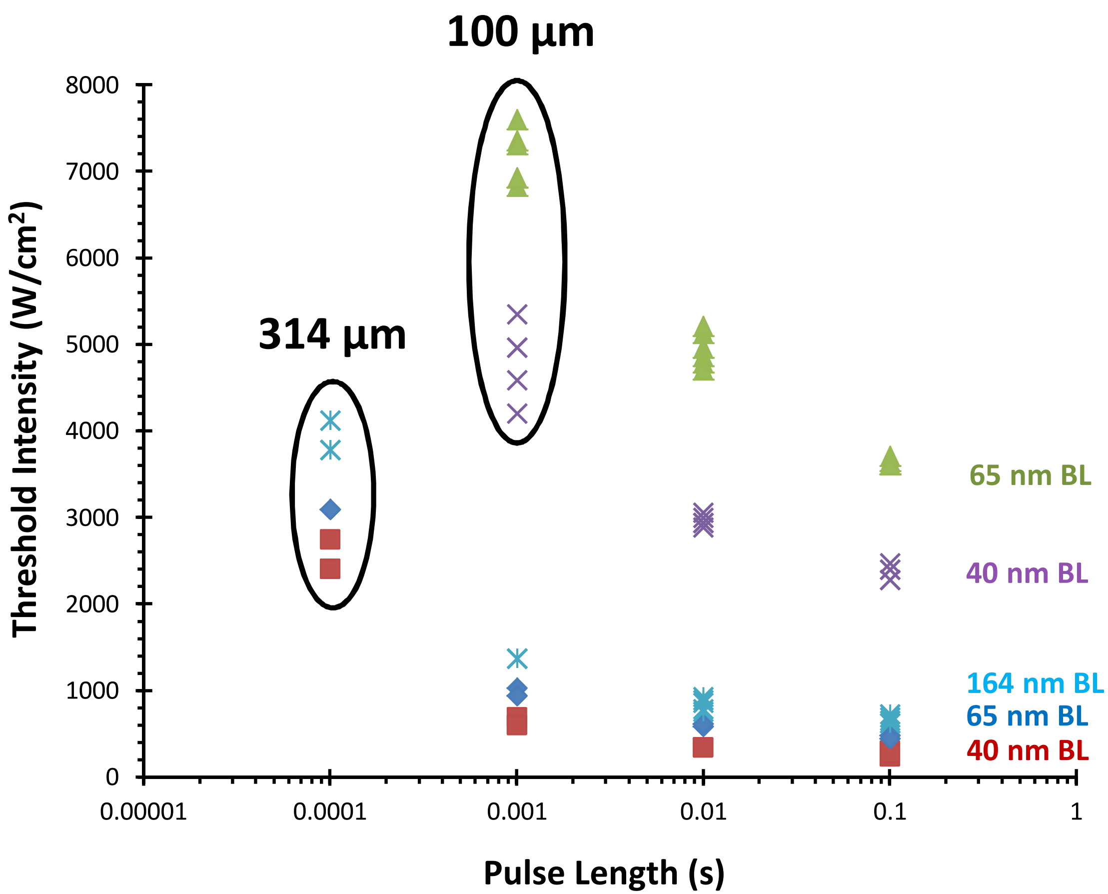
Bilayer Thickness

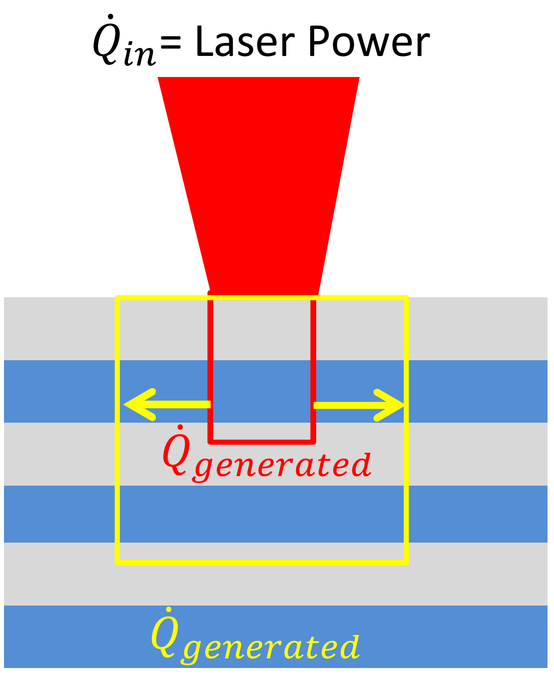


Intensity Threshold

- Intensity (W/cm^2) calculated using energy density and pulse length.
- Ignition threshold depends on intensity.
- Longer pulse lengths lower the intensity threshold.
- Longer pulse length may increase interaction volume via conduction.

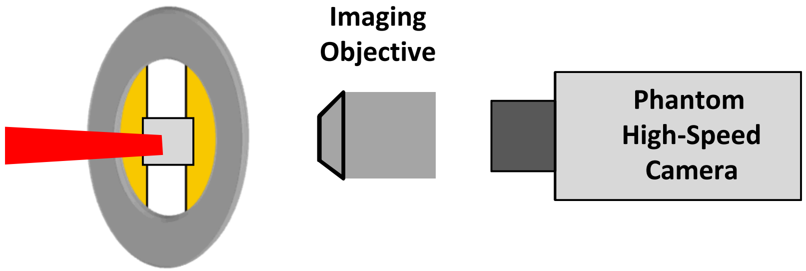






Imaging Ignition

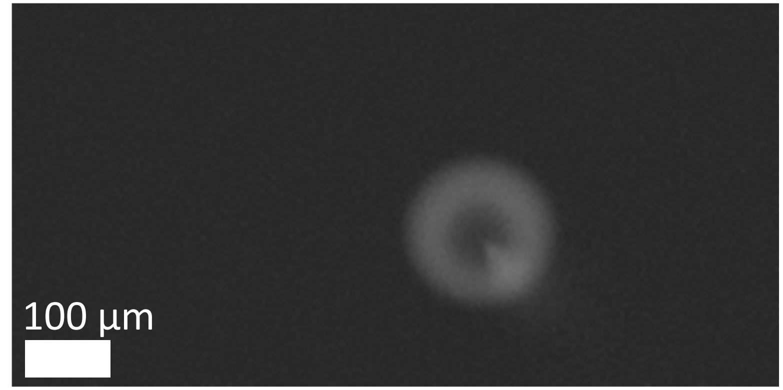
High-speed imaging of Al/Pt foil from the Al side



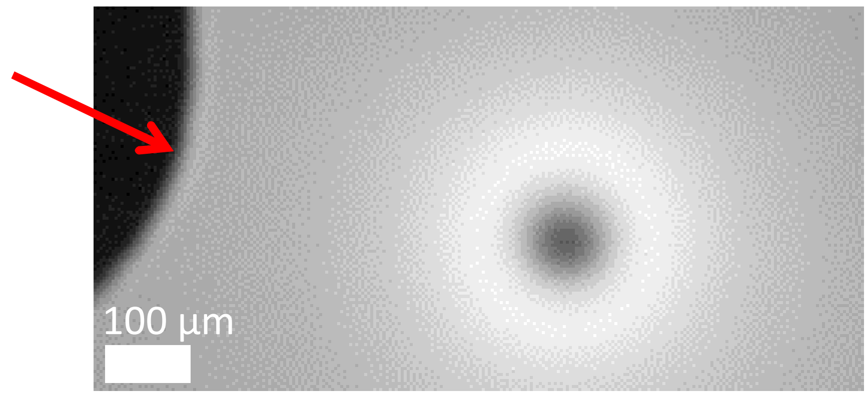
10 ms Incident Pulse
65 nm Bilayer
619 W/cm^2

t = 0 ms Laser Turns On

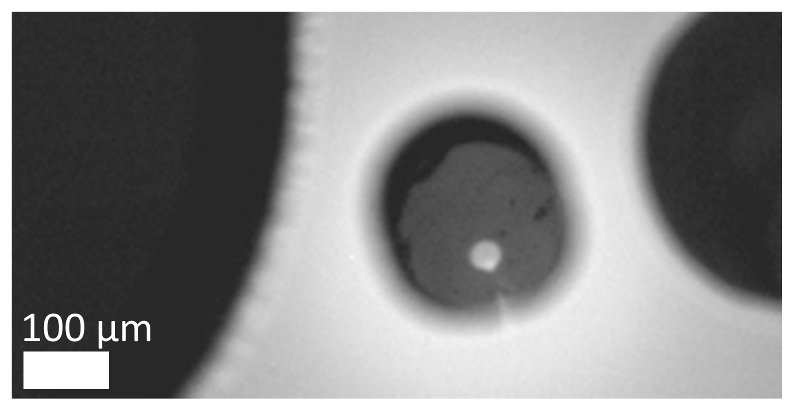
t = 2.88 ms Foil Ignites



t = 2.89 ms Entire Foil Melts

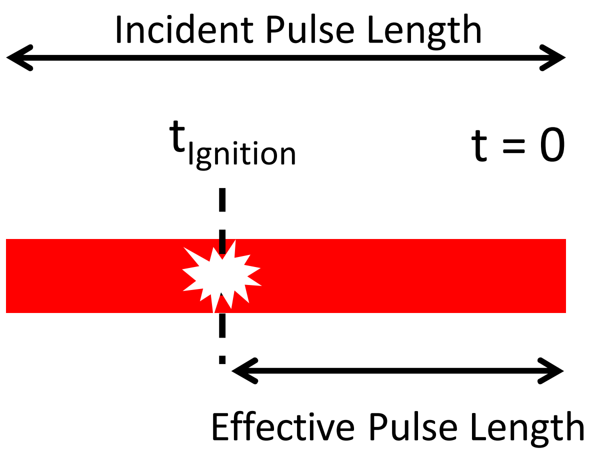


t = 2.91 ms Laser Penetrates Foil

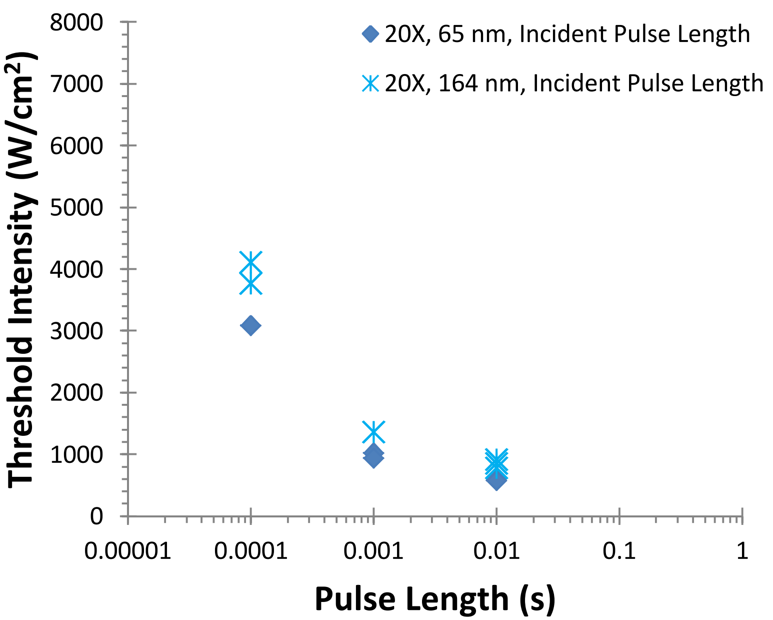


Laser-Foil Interaction Time

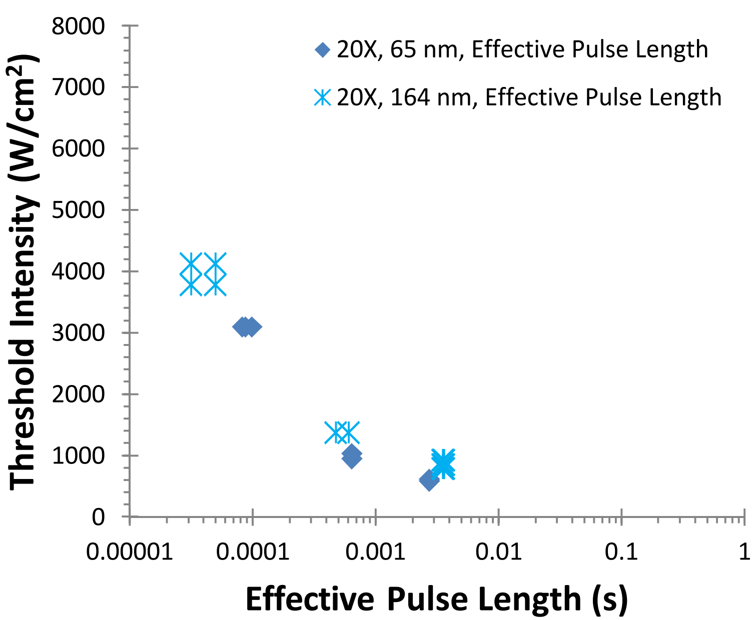
- Effective pulse length calculated by observing when ignition begins.
- Effective pulse length is usually shorter than incident pulse length.
- *Shorter pulses require energy to be delivered at a higher rate (power).*



<u>Incident Pulse Length</u>



<u>Effective Pulse Length</u>

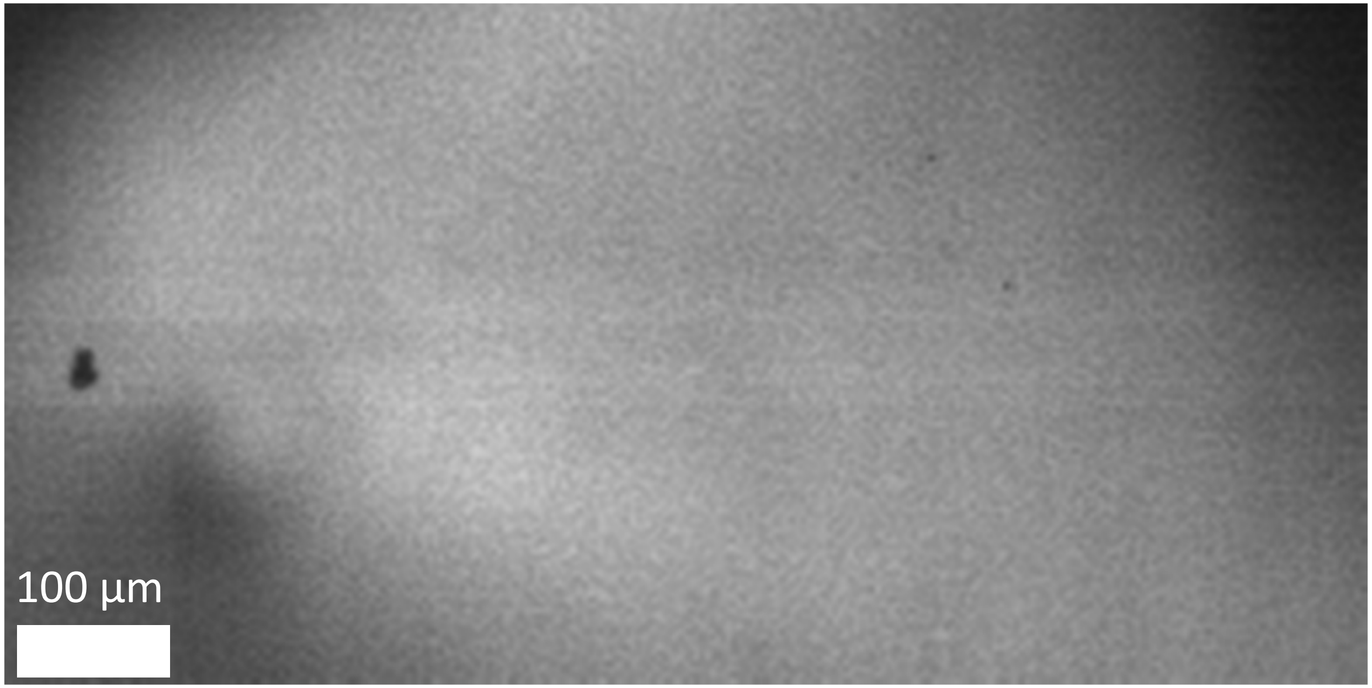


Sub-threshold Irradiation

95% Ignition Threshold

2.94 ms Incident Pulse
65 nm Bilayer

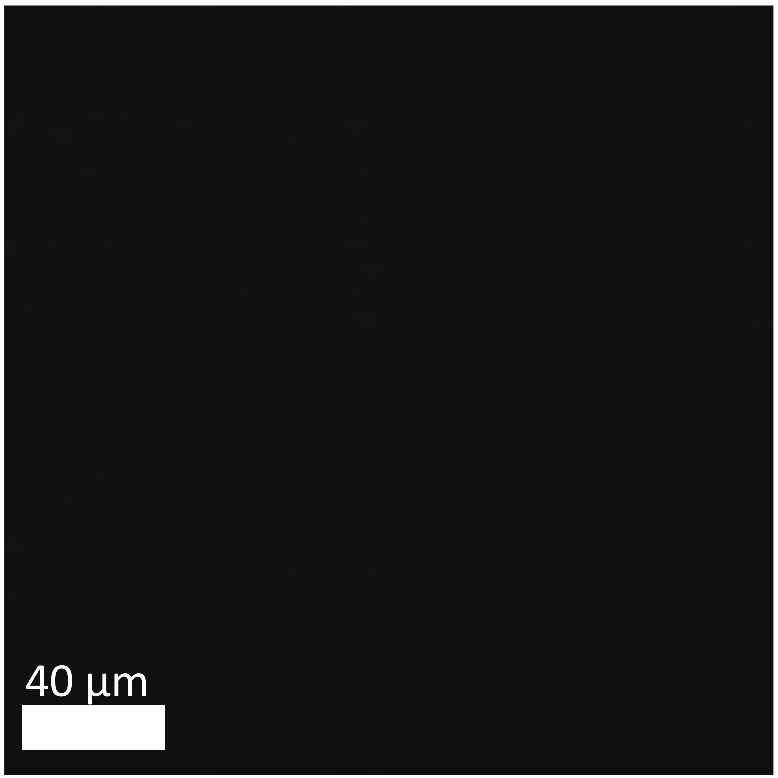
10 μs/frame



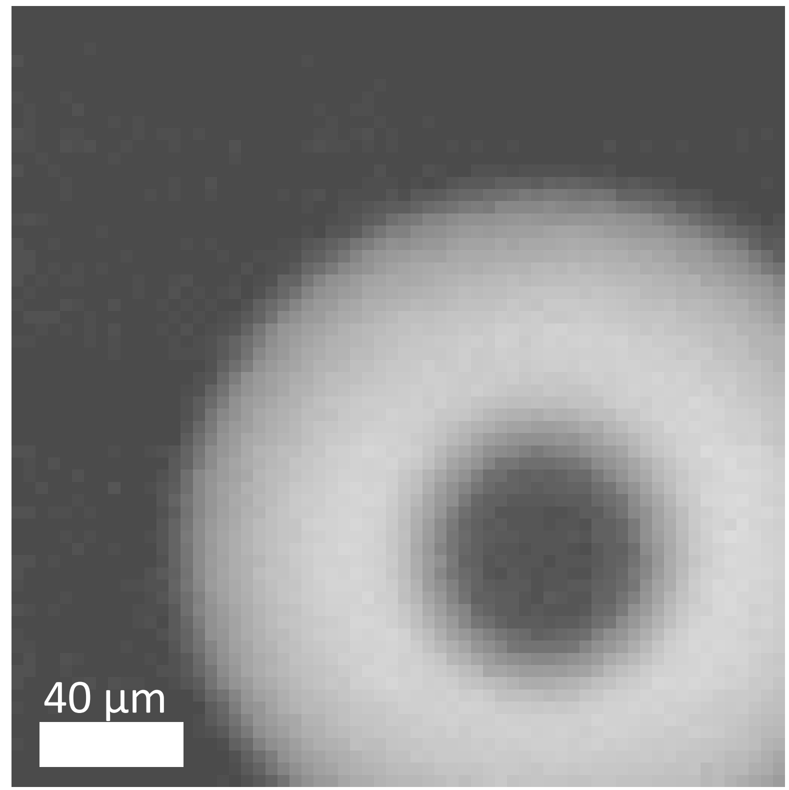
Self-Propagating Reaction after Ignition

10 ms Incident Pulse
164 nm Bilayer
894 W/cm^2

4 μs/frame

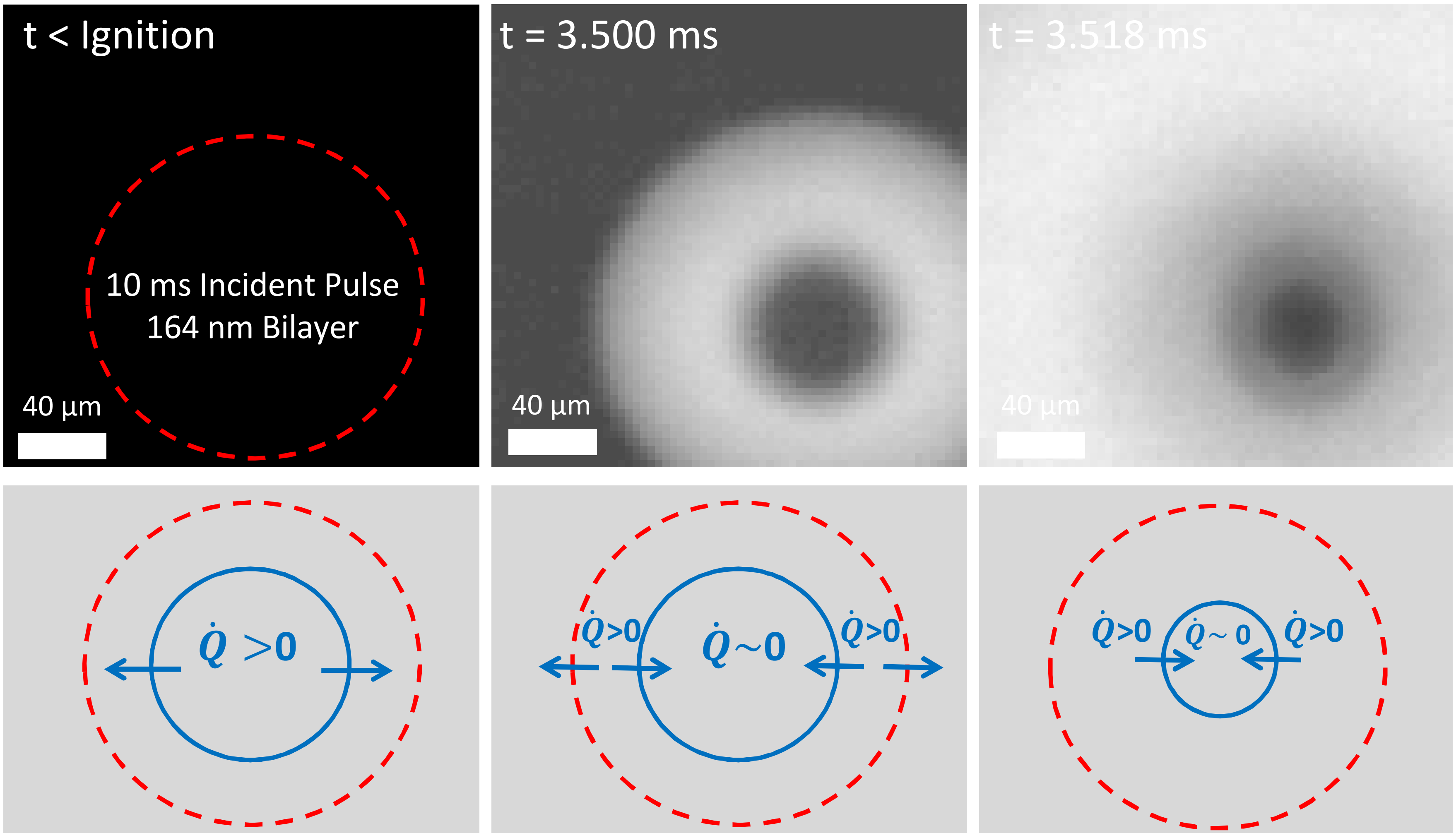


Ignition ~ 3.500 ms after laser turn on



Solid-State Reaction vs. Self-Propagating Reaction

- Dark center suggests ignition begins as a slow, non-propagating reaction.
- Bright annulus suggests these regions are hotter than surrounding regions.

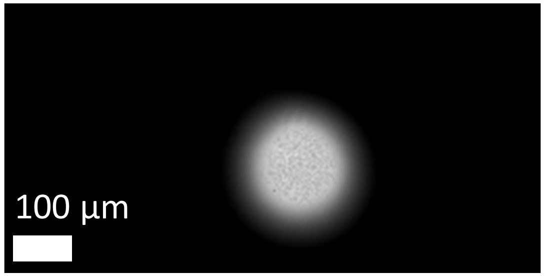


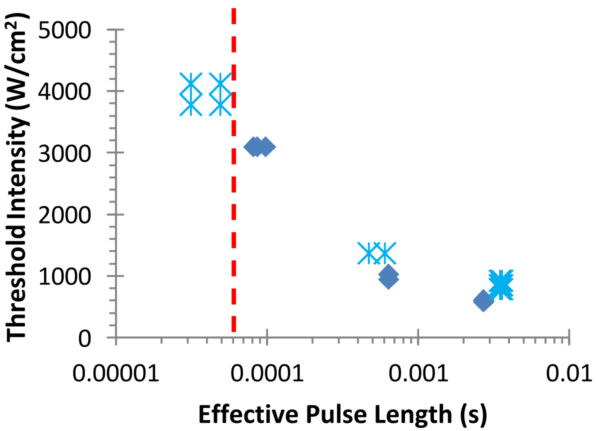
Shorter Pulses – Mechanisms Change

100 μs Pulse

- Ignition occurs – no annulus observed.
- Central, irradiated area ignites.
- Mechanisms are *intensity* dependent

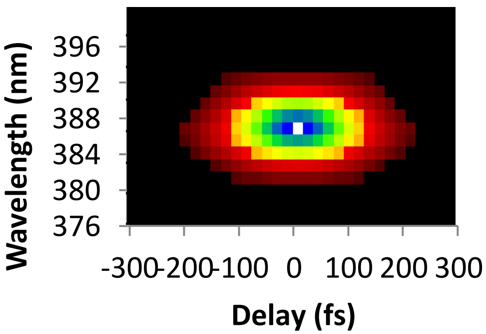
<u>100 μs Incident Pulse</u>
164 nm Bilayer
3.8 kW/cm²
t = 49 μs

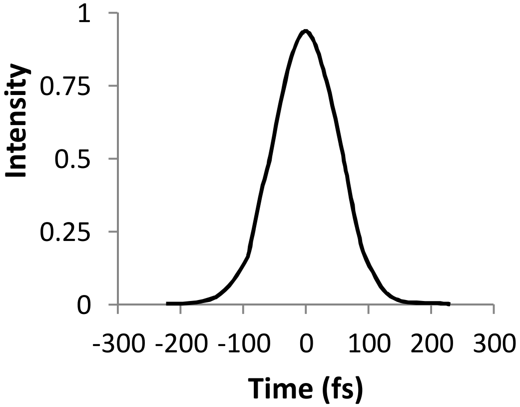




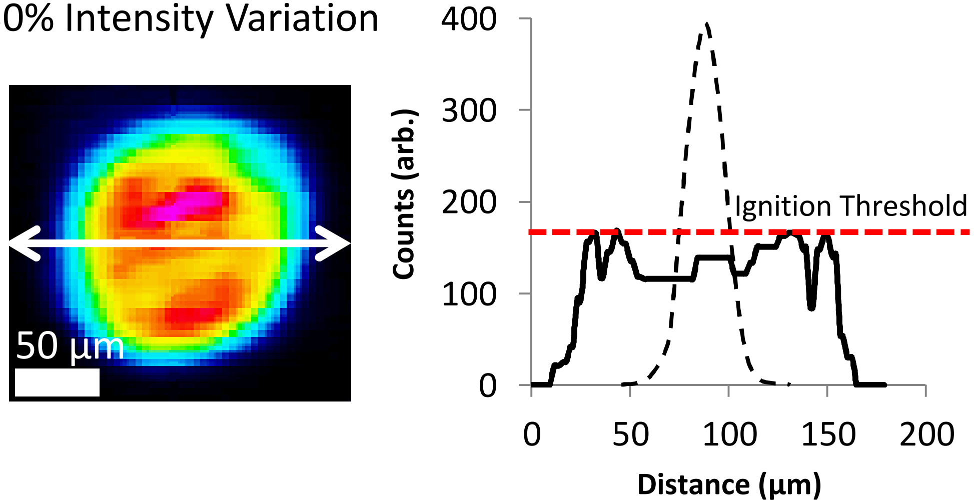
150 fs Pulse

- Measured *temporal* distribution is Gaussian.
- "Flat-top" *spatial* distribution.

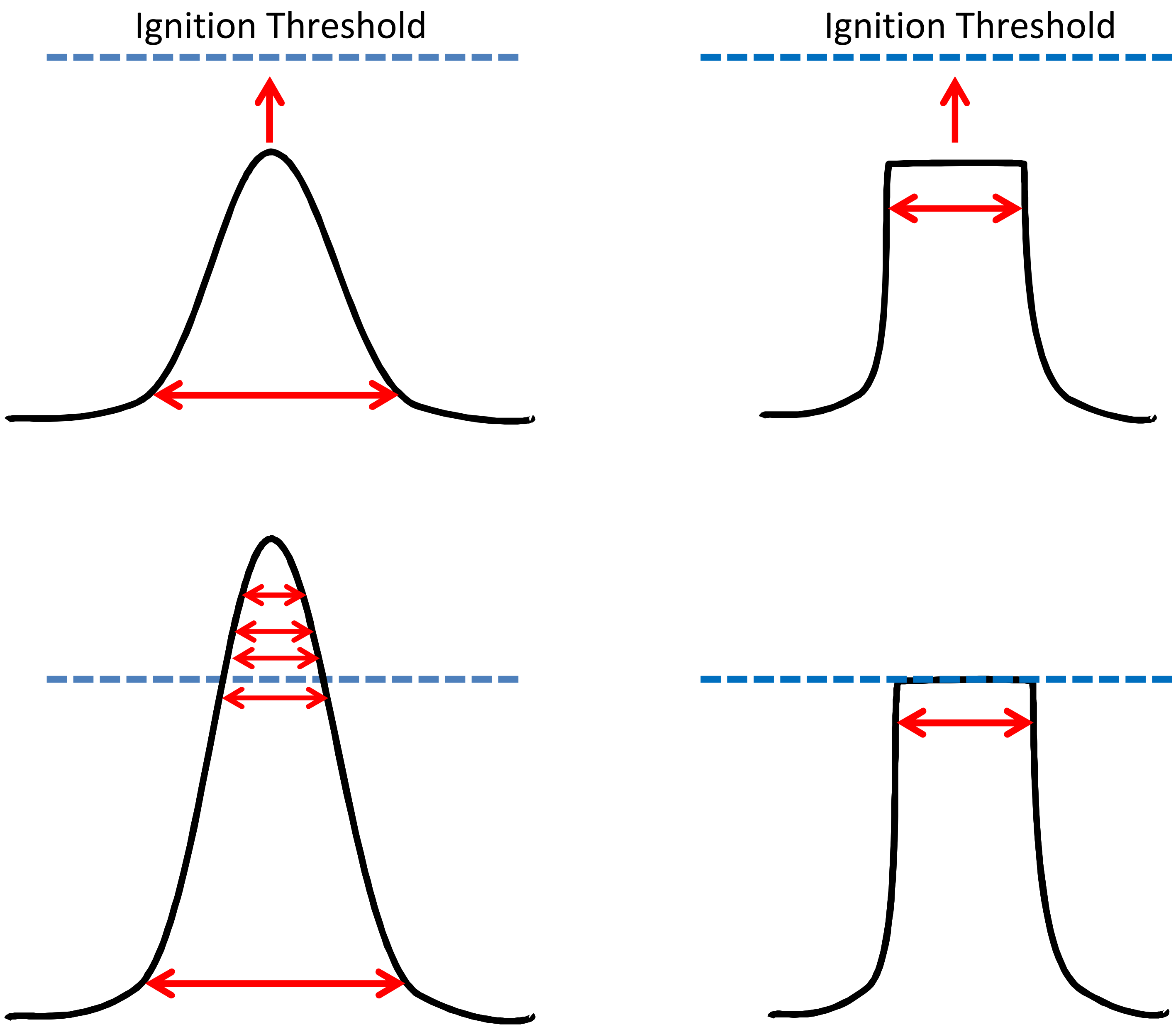




~ 30% Intensity Variation

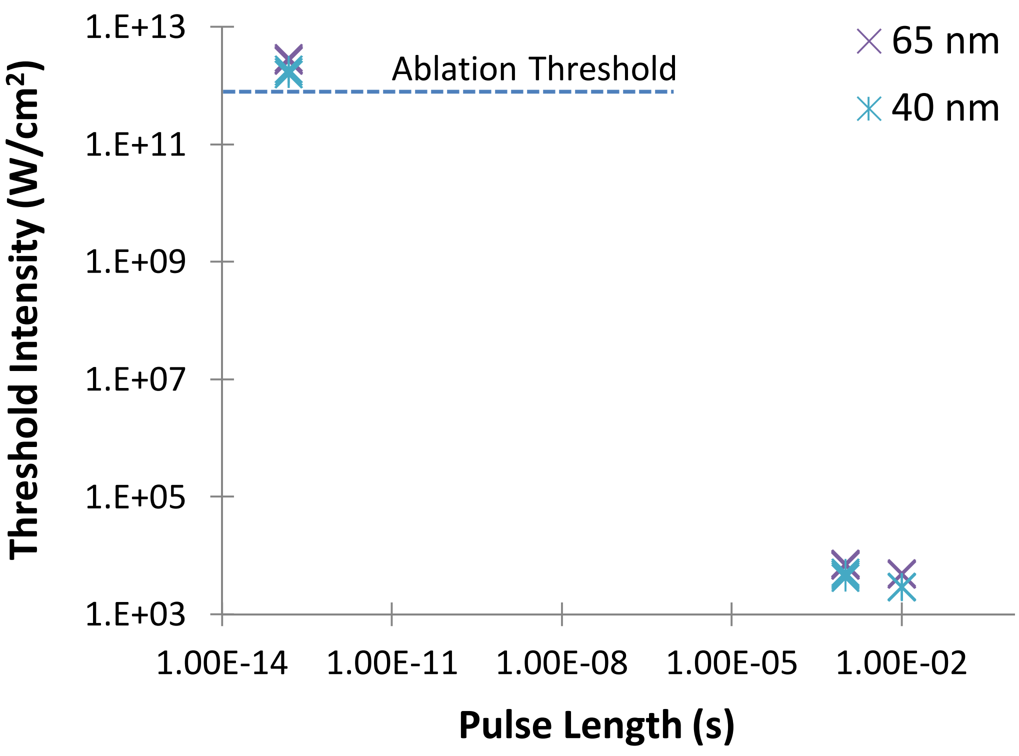


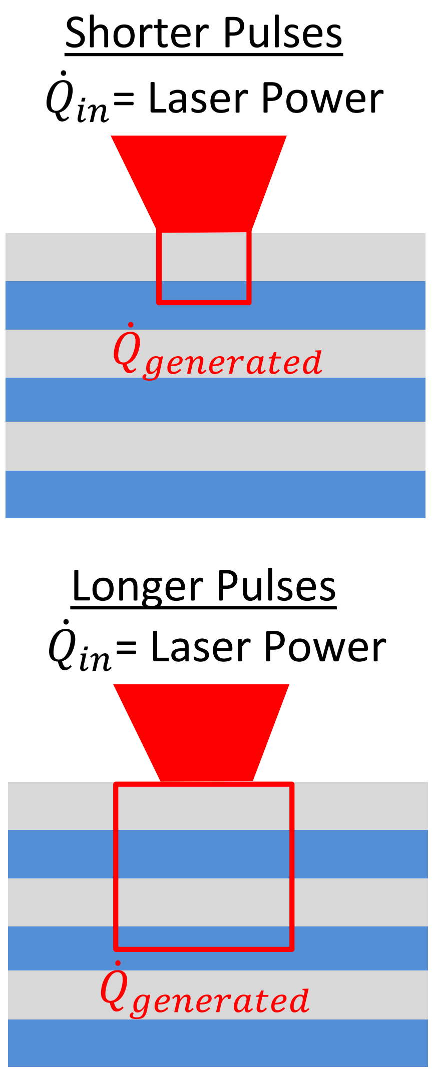
Fixed Interaction Volume



Ignition Threshold

- "Flat-top" beam is used for all pulse lengths – defines the interaction area
- 150 fs: mechanism changes from solid-state ignition to laser-induced melting and ablation.



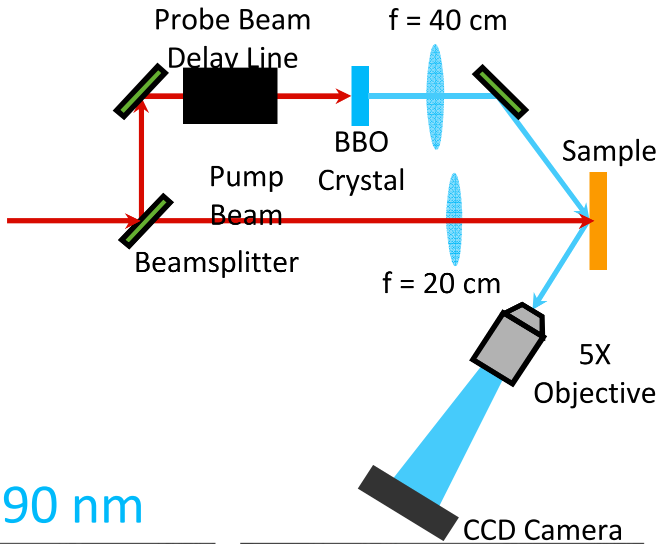


Conclusions

- Material removal occurs at interfaces
- Void nucleation linked to surface roughness
- LIPSS formation is affected by surface features
- Diffraction and surface plasmons are responsible for LIPSS formation
- LIPSS begin forming on same time scales as material removal
- Laser pulse lengths ranging from femtoseconds to milliseconds can ignite foils.
- Laser ignition threshold depends on pulse duration, laser spot size, and foil bilayer thickness.
- Ignition mechanism depends on the laser pulse length.

Extra Slides

Pump-Probe Microscopy: Time Scales



Pump Beam

0.60 J/cm^2

Probe beam wavelength = 390 nm

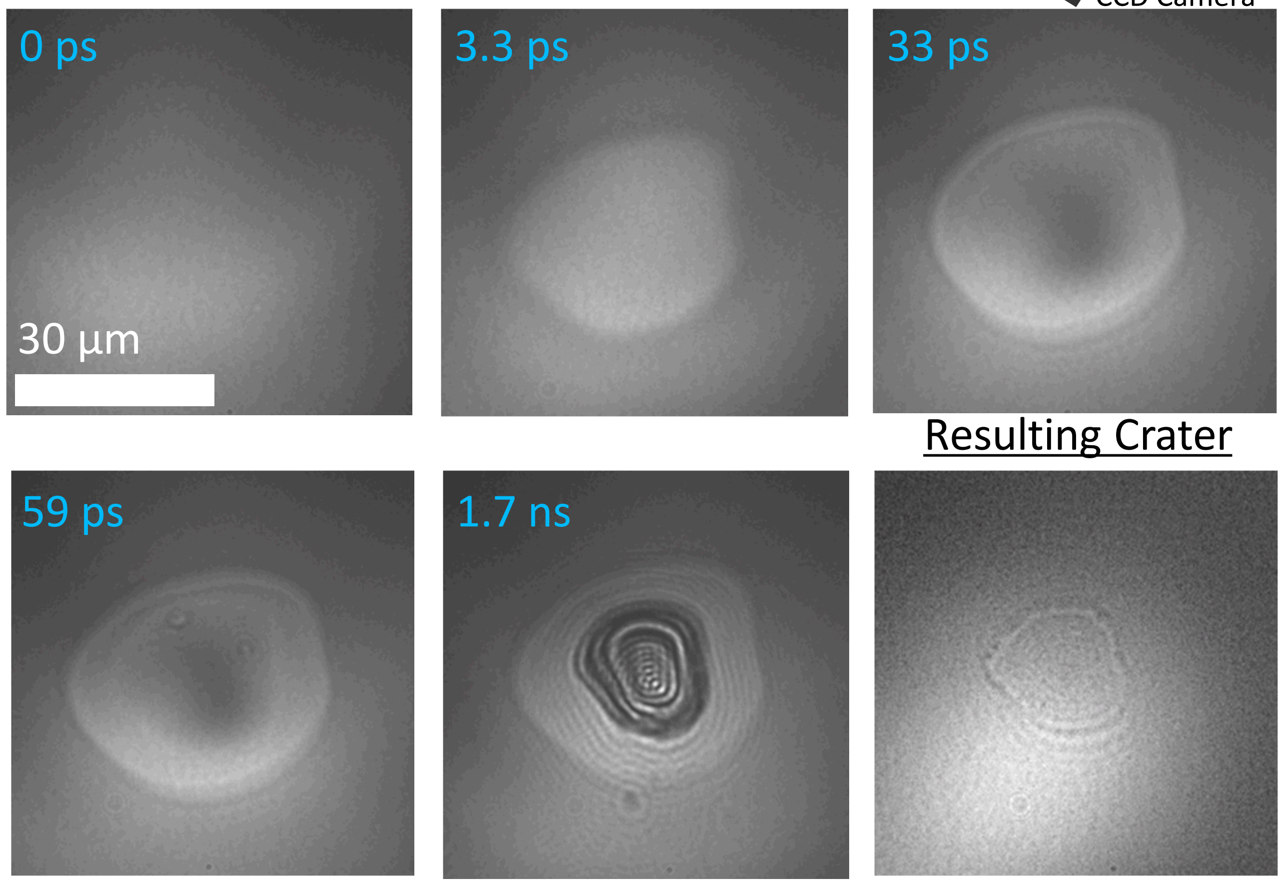
Silicon Substrate

Crater threshold

0.32 J/cm^2

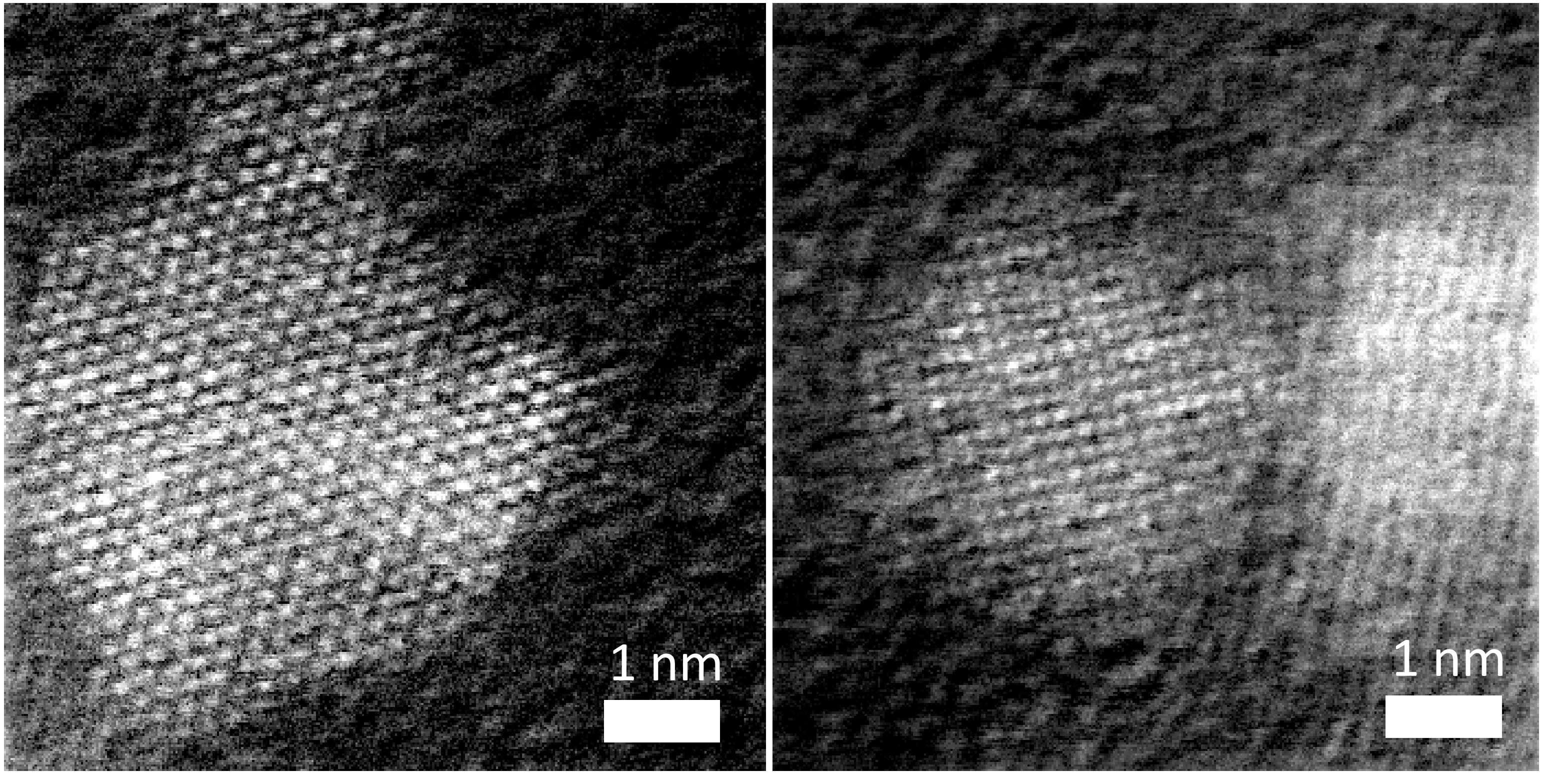
Melt threshold

0.20 J/cm^2

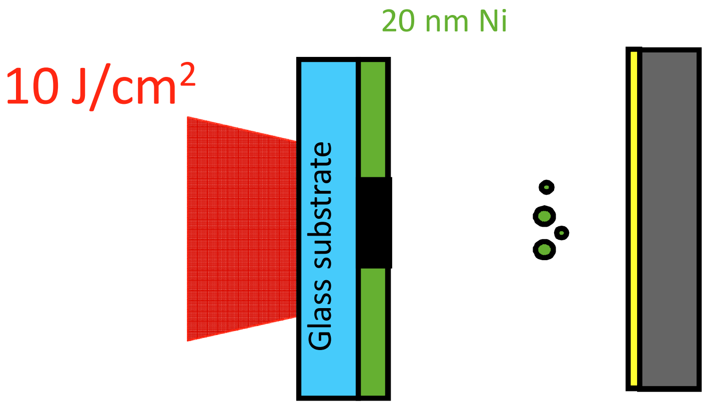


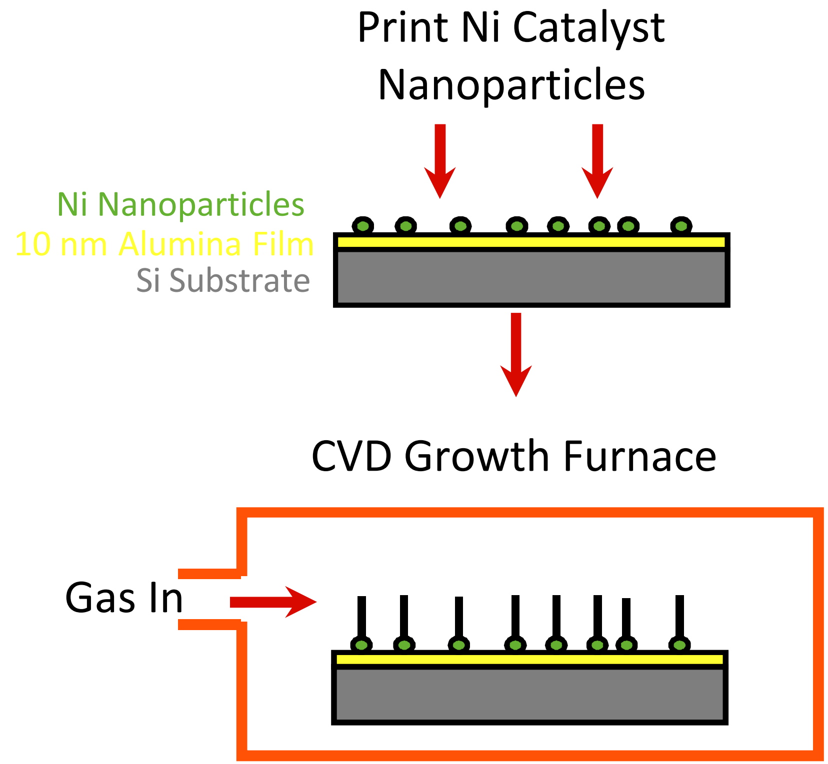
Faceted Nanoparticles

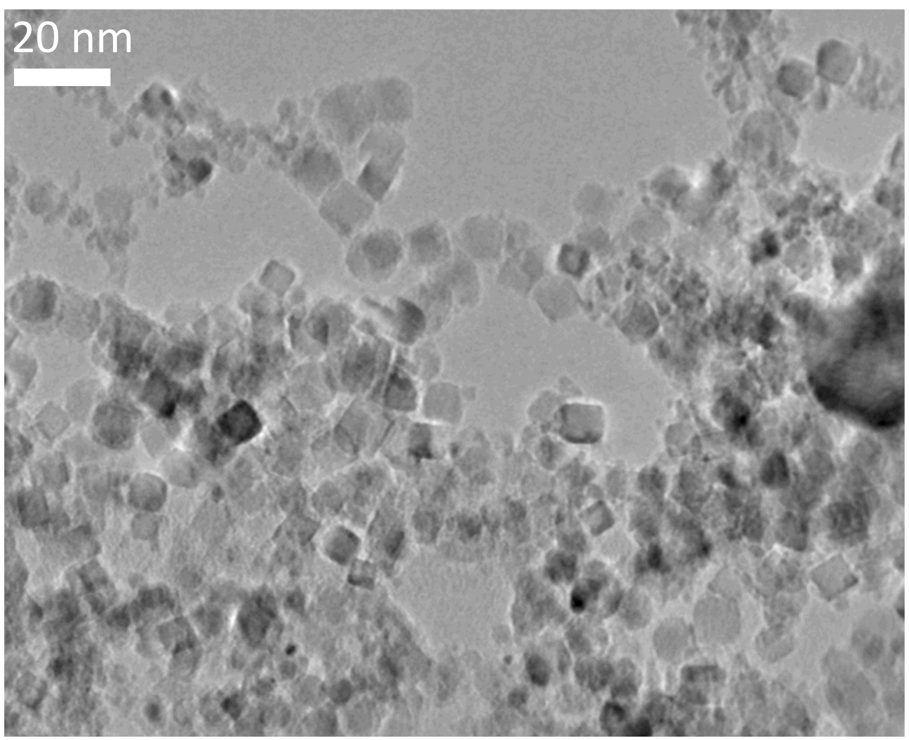
Atomic Resolution

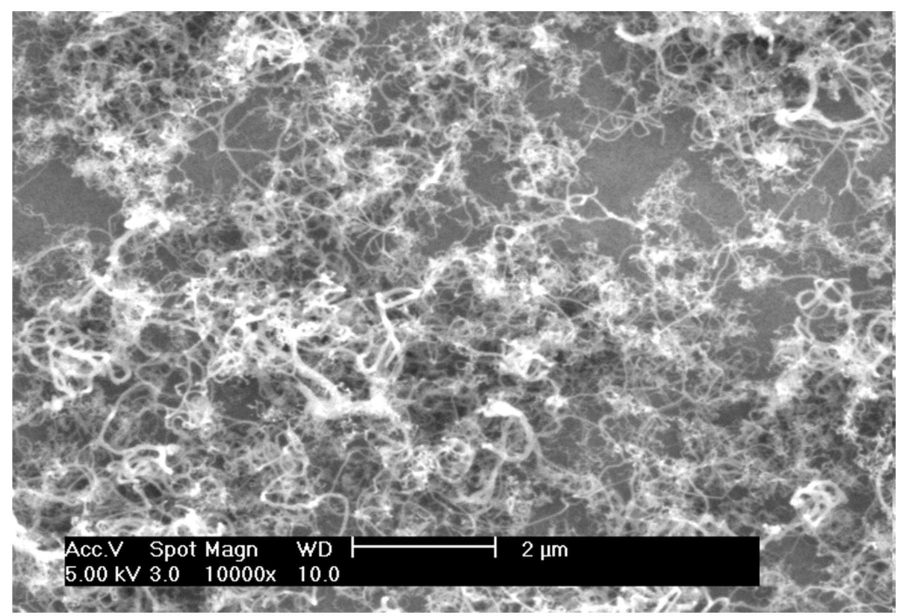


Ni Nanoparticle Printing



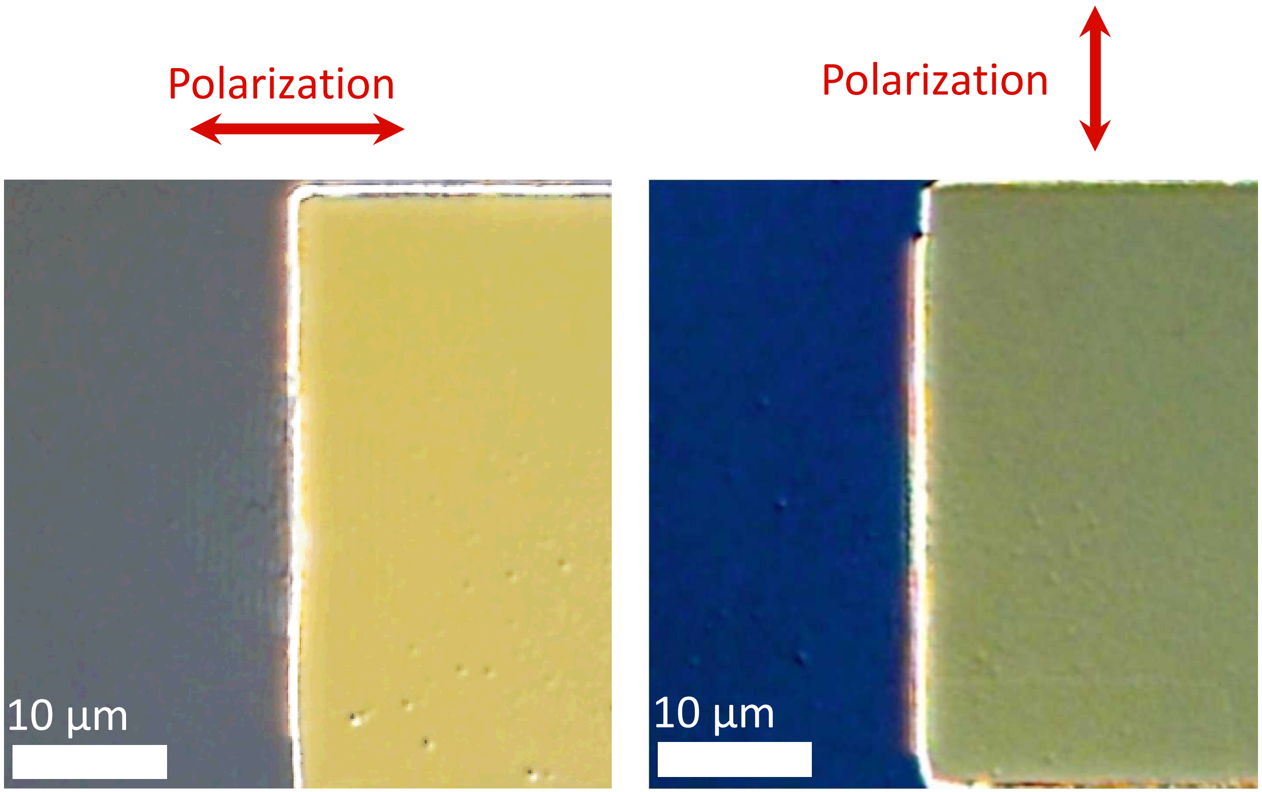






Amorphous Si Formation

0.20 J/cm^2

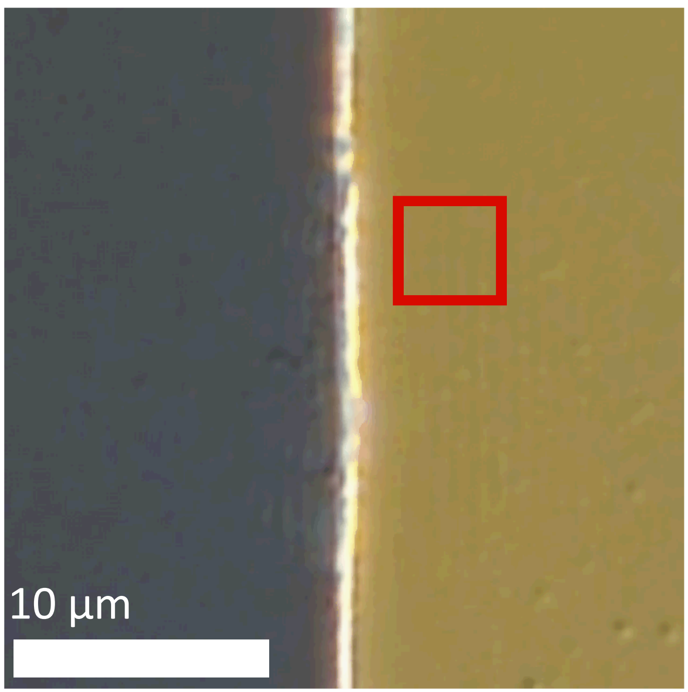


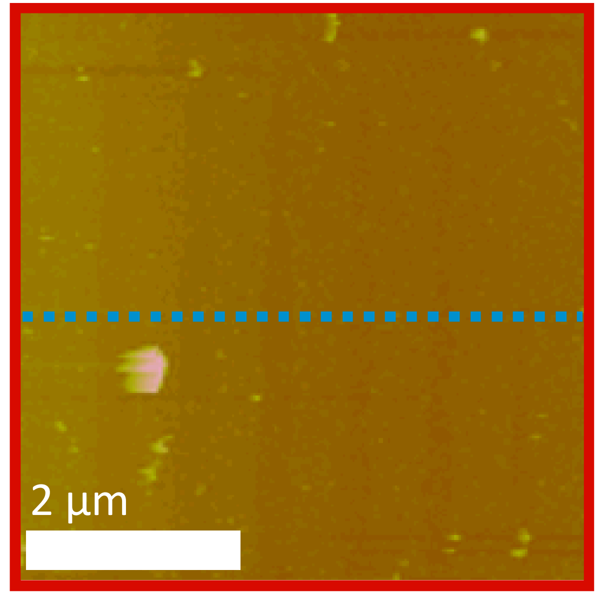
SPP Excitation

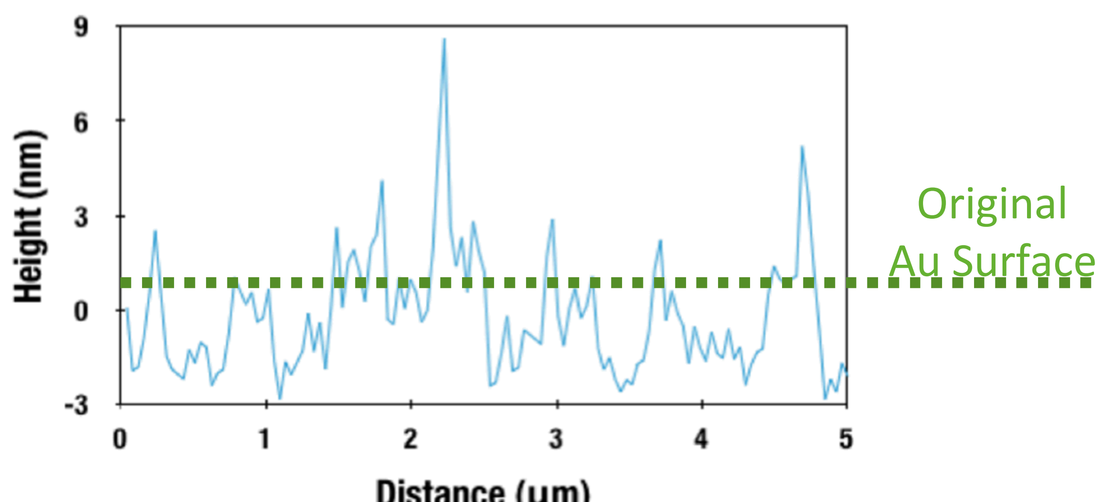
Au melt threshold ~ 0.55 J/cm^2

0.20 J/cm^2

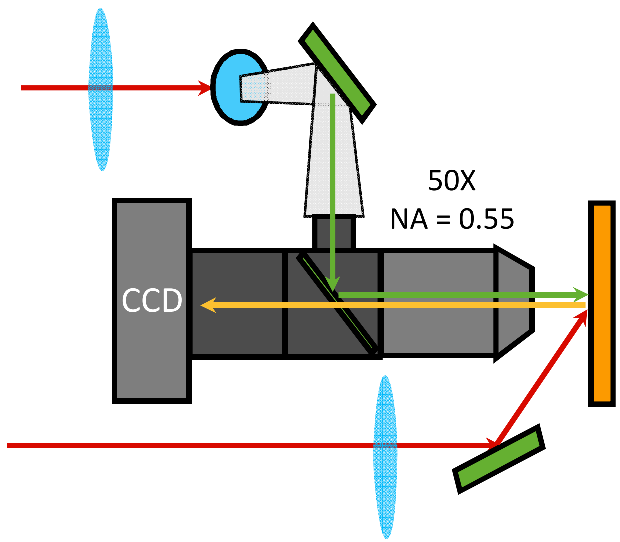
Polarization

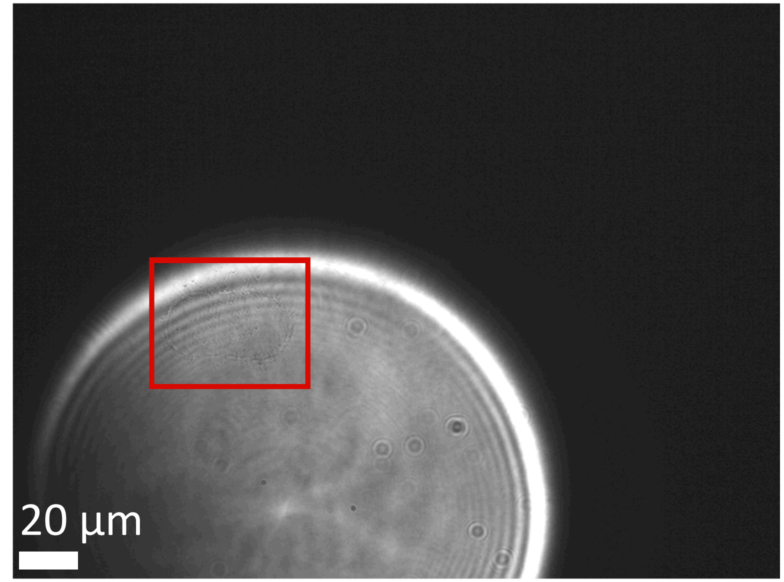




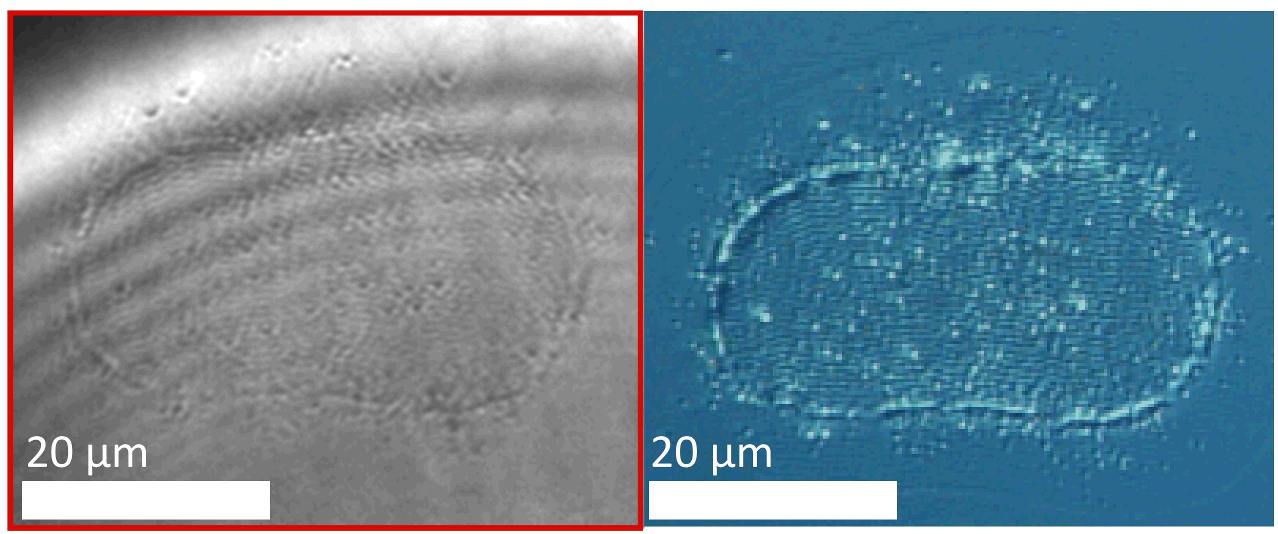


White Probe Light





Polarization

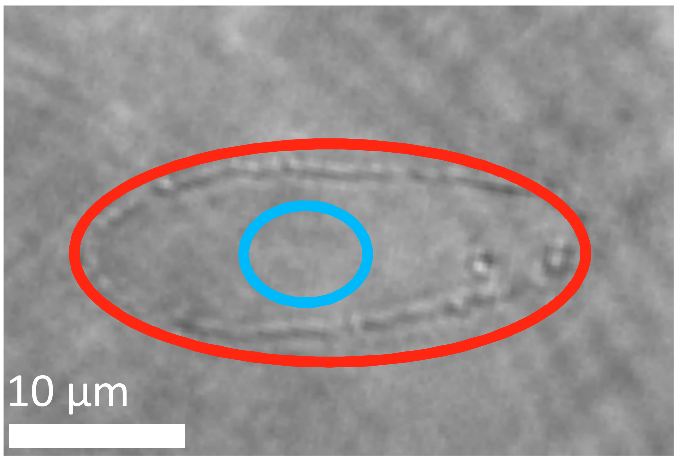


LIPSS Formation Dynamics

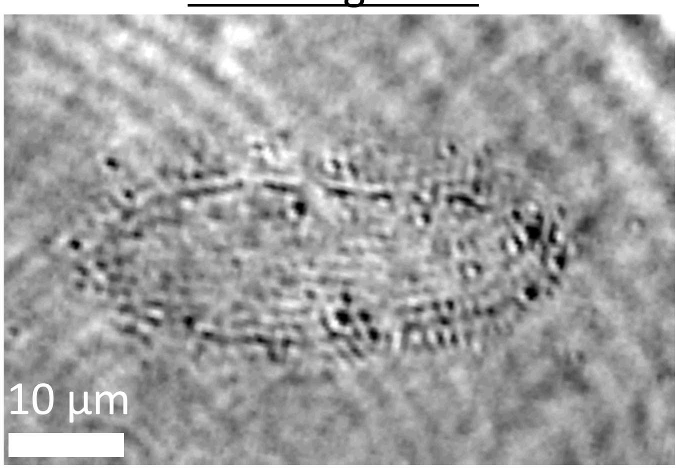
Polarization

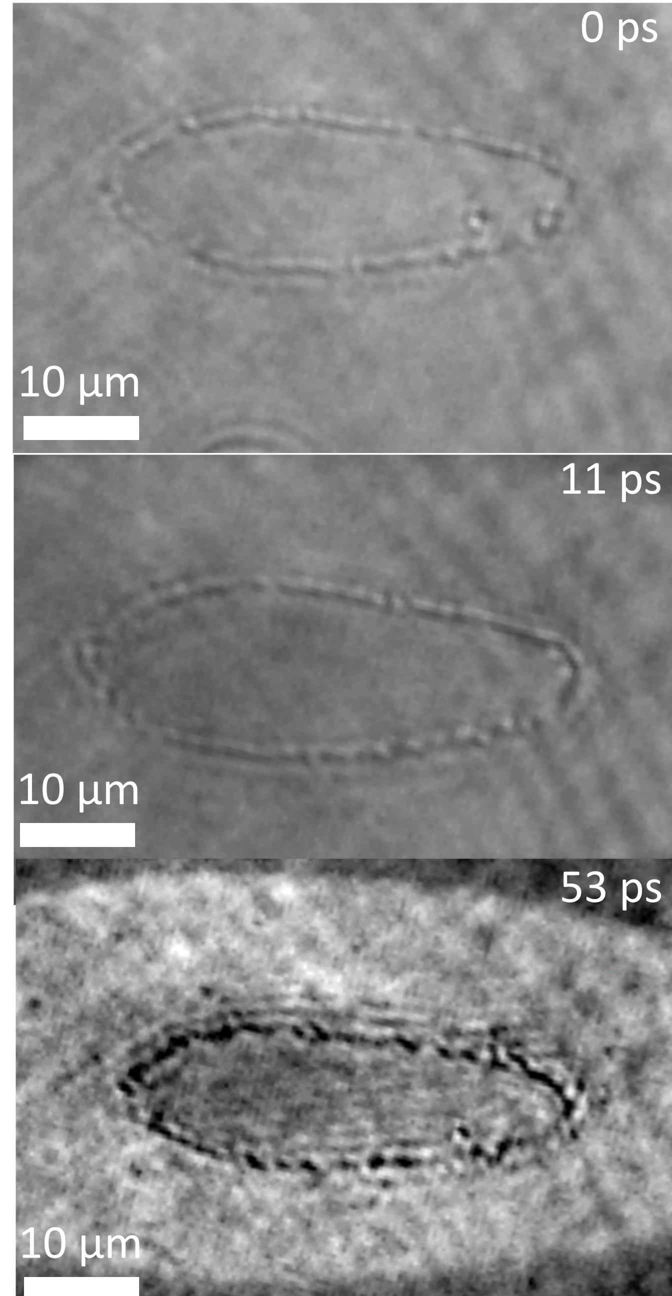
1st shot 0.45 J/cm^2

2nd shot 0.32 J/cm^2

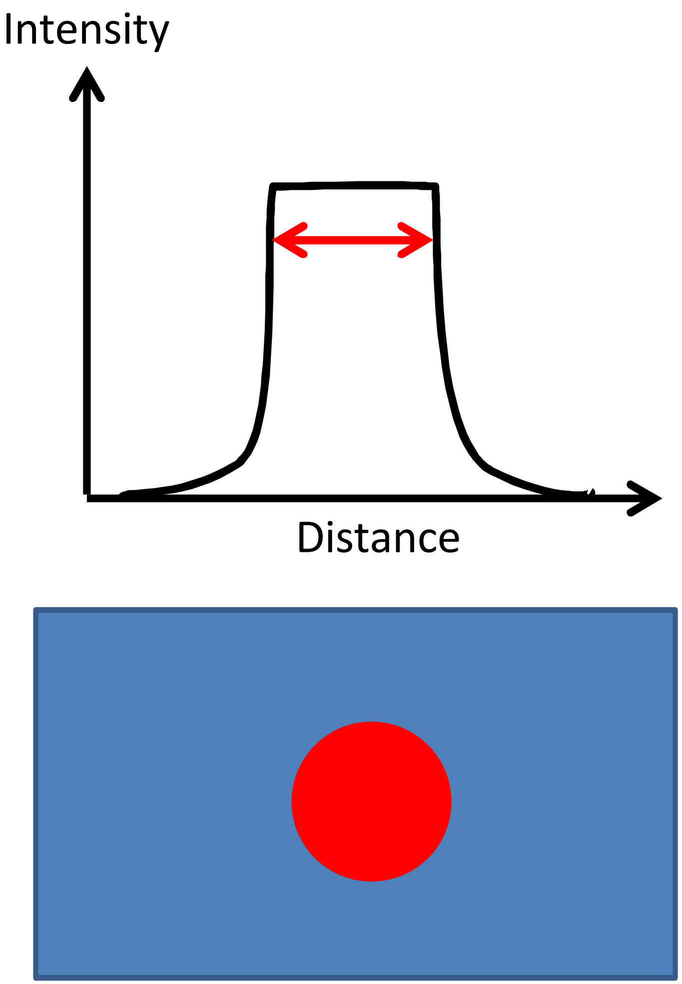


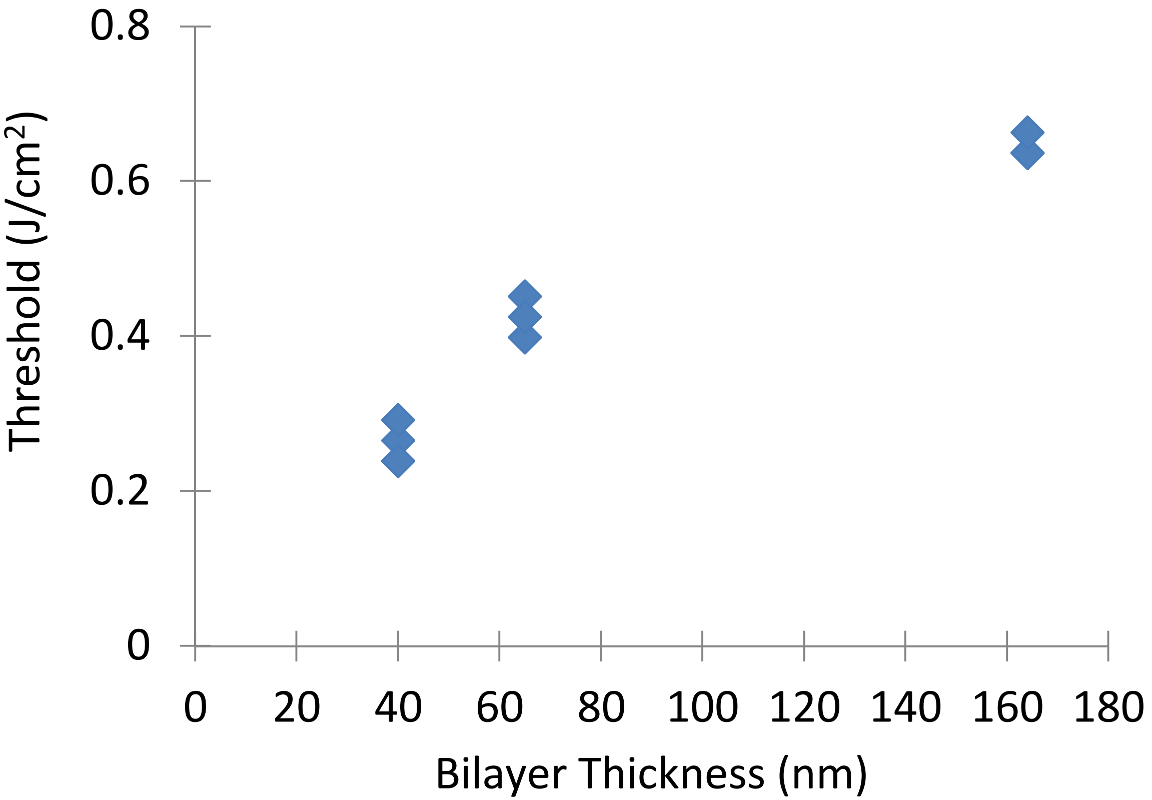
Resulting LIPSS





150 fs Ignition Threshold





Effective Pulse Length Depends on Intensity

1 ms Incident Pulse
65 nm Bilayer

% Above Threshold	Effective Pulse Length (ms)
0	0.892
49	0.440
100	0.300

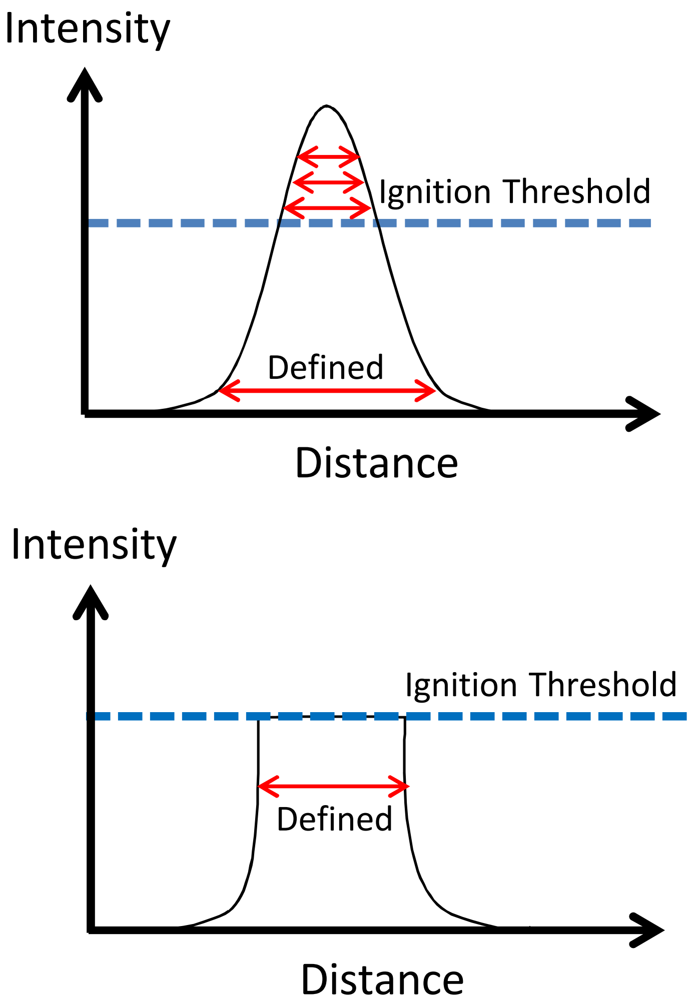
Diffusion Zone Size Depends on Pulse Length

65 nm Bilayer

Incident Pulse Length (ms)	Diffusion Zone Diameter (µm)
0.1, 9 mW 0.1, 9 mW	18 18
1, 9 mW 1, 4.5 mW 1, 5.5 mW 1, 5.5 mW	42 44 28 22
10, 36 mW 10, 36 mW 10, 36 mW	73 36 44

164 nm Bilayer

Incident Pulse Length (ms)	Diffusion Zone Diameter (µm)
0.1, 12 mW 0.1, 12 mW	0 0
1, 8 mW 1, 8 mW	18 22
10, 52 mW 10, 52 mW	49 52

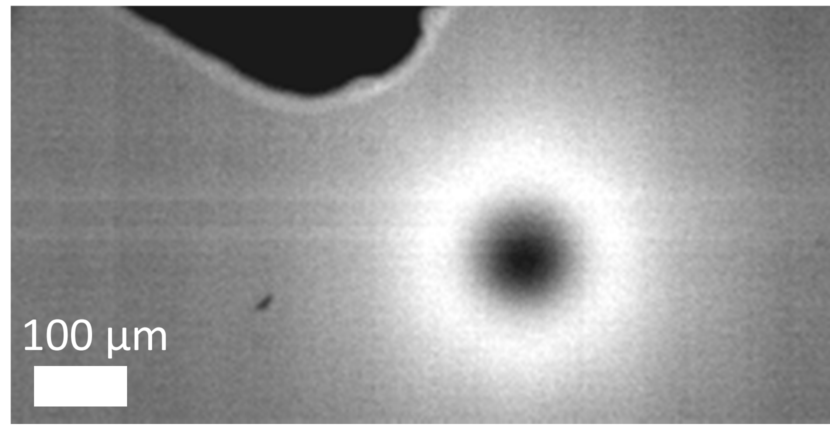

Intensity
Ignition Threshold
Defined
Distance
Intensity
Ignition Threshold
Defined
Distance

Ignition and Melting

10 ms Incident Pulse
65 nm Bilayer
36 mW

~ 2.60 ms after laser turns on

~ 2.61 ms after laser turns on



Reflectance Measurements