Applications of a Extreme Ultraviolet 46.9 nm Capillary Discharge Laser

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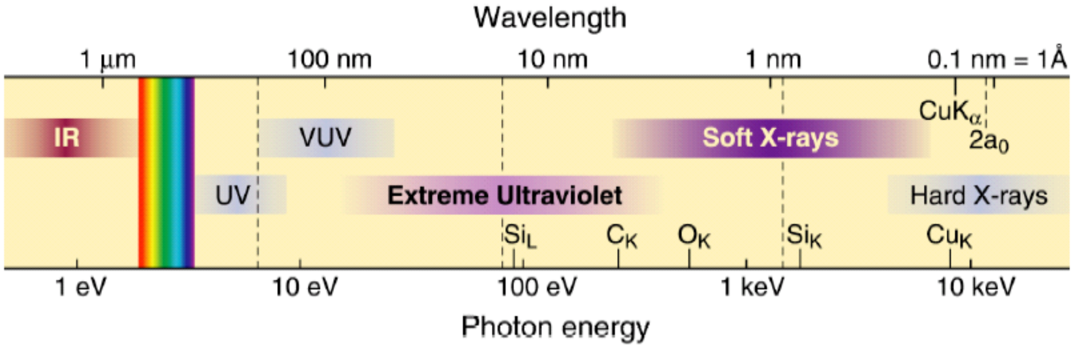
Outline

- Introduction
- Overview of the laser system
- Experiment 1: Damage to multilayer mirrors
- Experiment 2: Transmission and Reflection mode microscopy

EUV light enables nano-applications

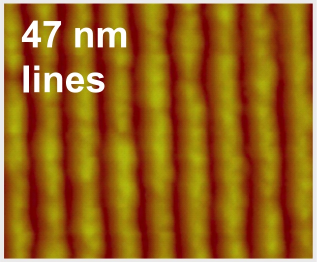


EUV and soft x-ray light

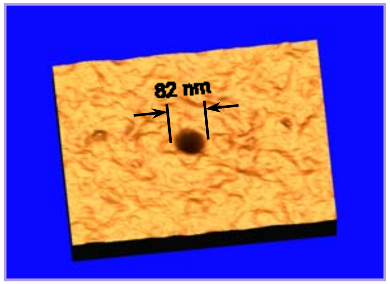
λ = 10 - 50 nm

$$\textbf{Critical Dimension} = \frac{k\lambda}{NA}$$

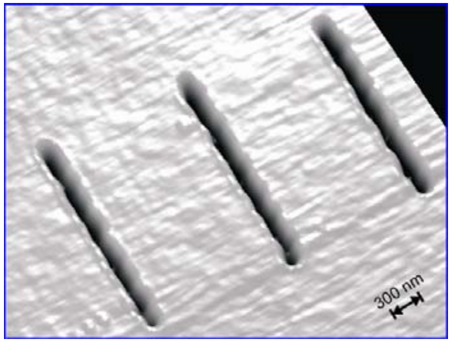
Nanopatterning



Probing at the Nanoscale



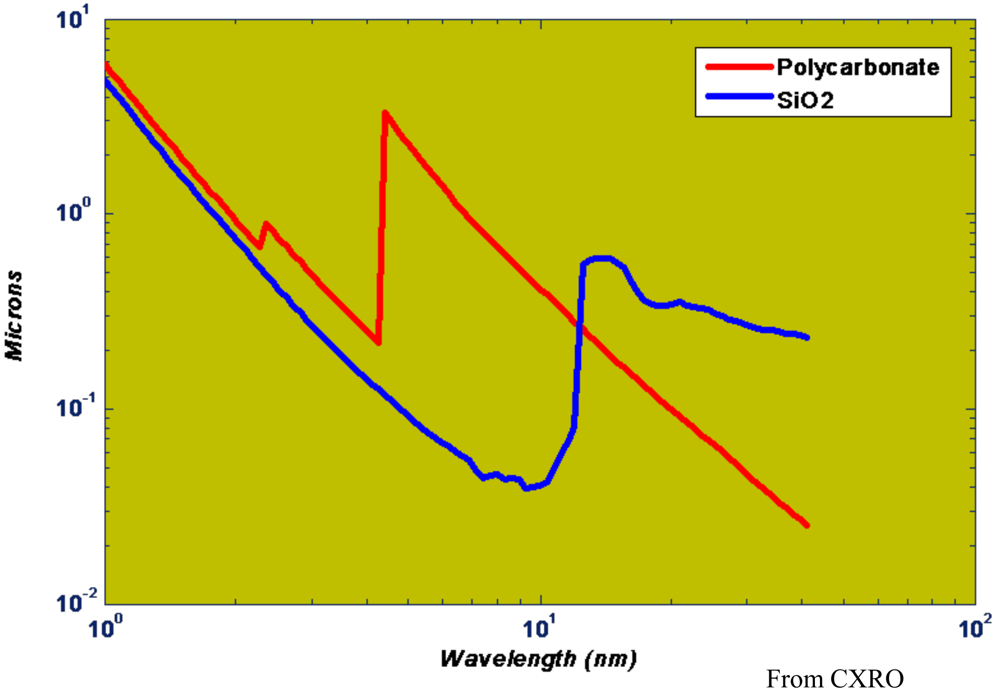
Nano-machining



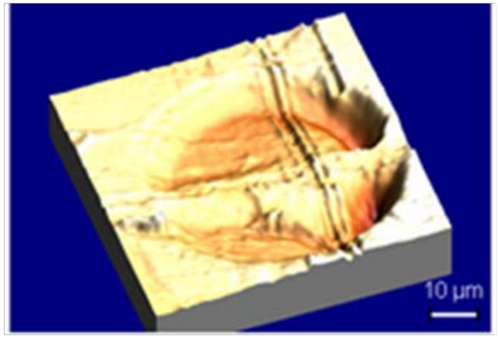
Differences in the interaction of matter

EUV and soft x-ray:

- high absorption
  - Short penetration depth
- diffractive/reflective optics

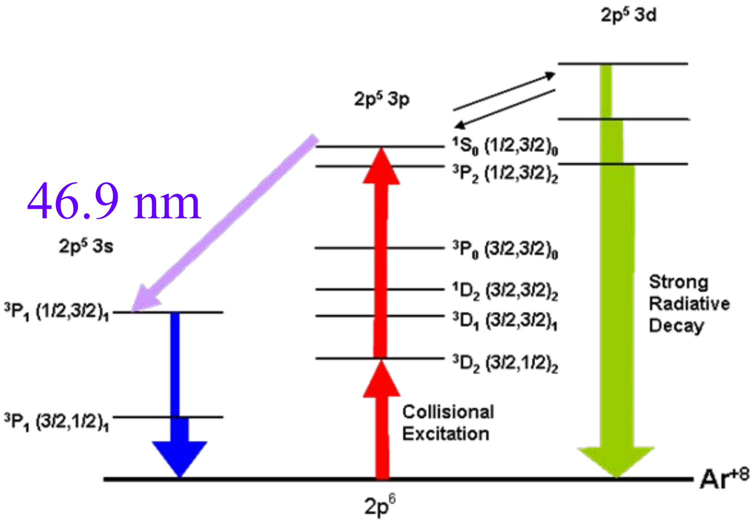


From CXRO

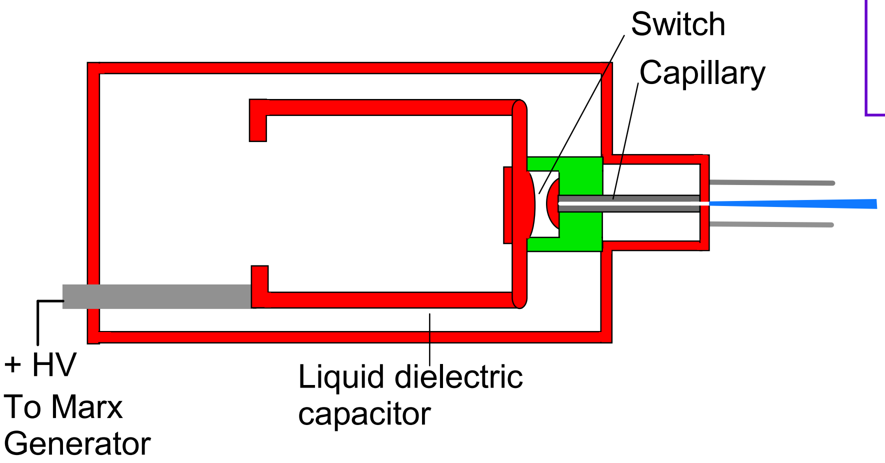


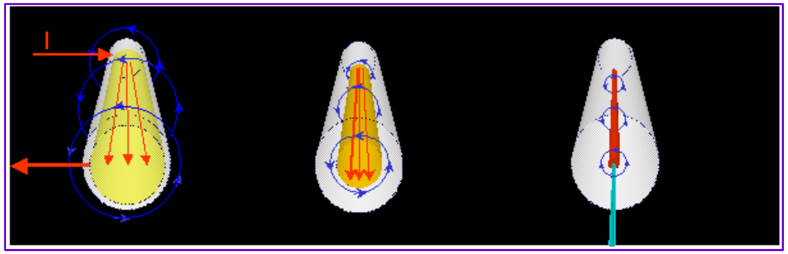
EUV Laser System

Operation of the Ne-like Ar laser



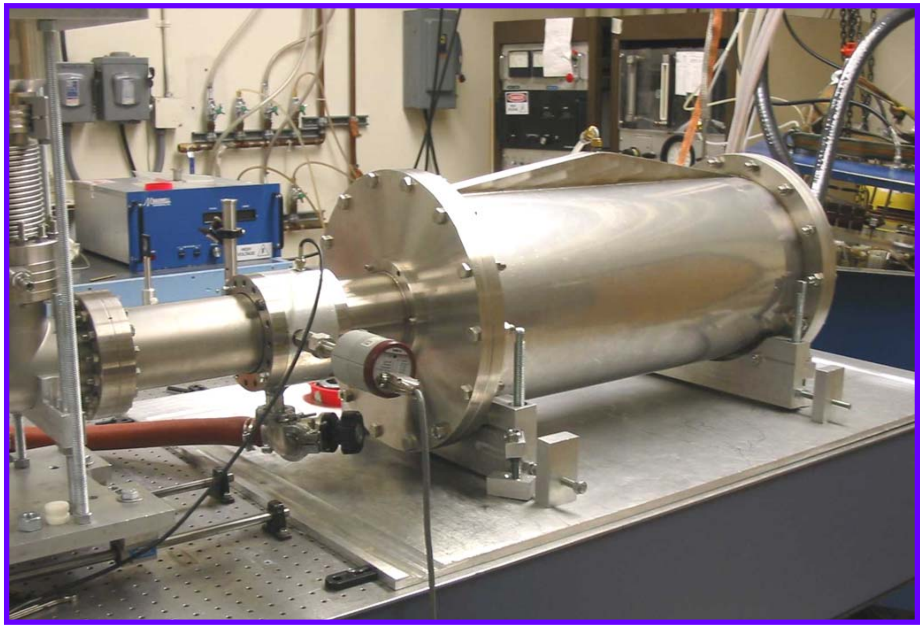
1. High voltage generator charges capacitor. Capacitor is then discharged via Ar-filled alumina capillary, creating high current pulse (25 kA)
2. Current pulse creates hot plasma that collapses into a 200 µm column due to Lorentz force.
3. Electrons collisionally ionize argon to 8+ and an additional electron collision excites the 3p laser upper level





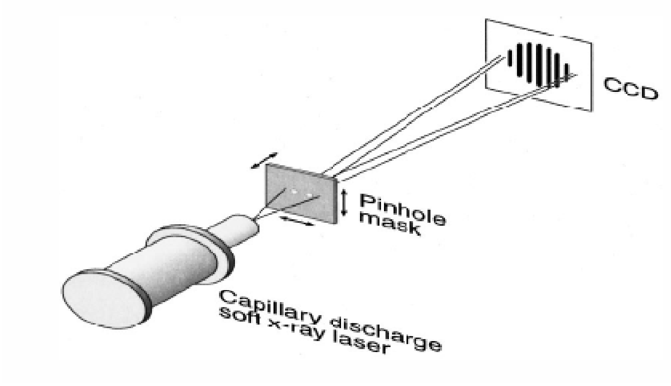
Advantages of the Ne-like Ar capillary-discharge laser

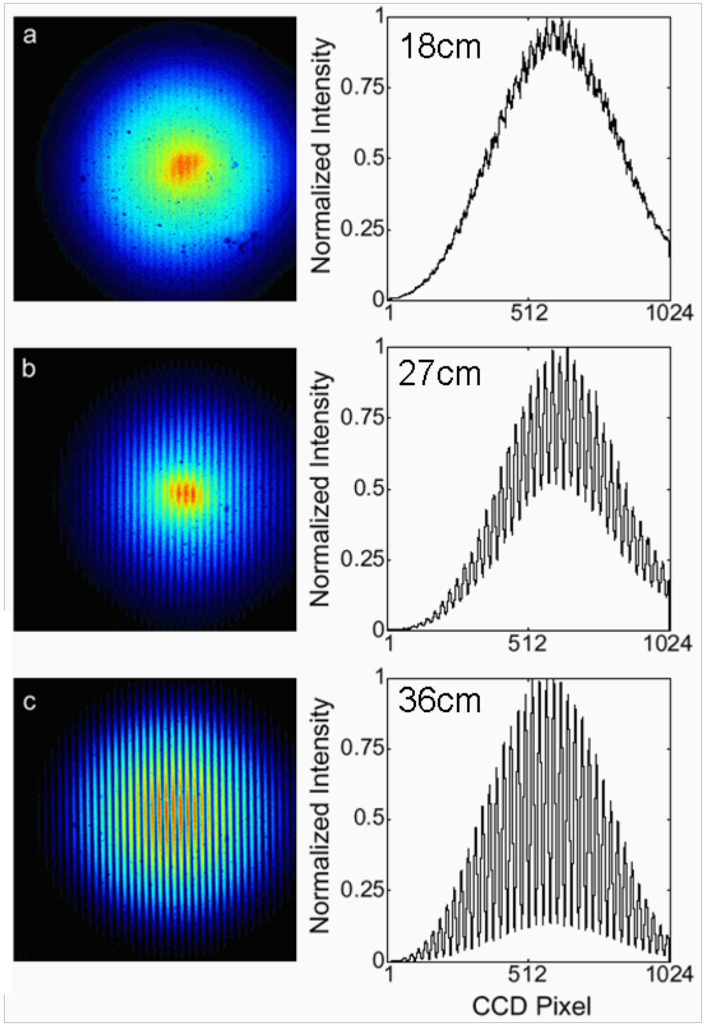
- **short wavelength:** 46.9 nm wavelength
- **high pulse energy:** 0.1 – 0.8 mJ
- **short pulses:** 1.2 ns
- **high monochromaticity:** $\Delta\lambda/\lambda \sim 10^{-4}$
- **high directionality:** $\theta = 4.6$ mrad
- **high brightness**
- **compact system**
- **repetition rate:** 1 – 4 Hz
- **capillary lifetime:** ~5-20,000 shots
- **variable coherence**



Coherence in the capillary discharge changes with capillary length

- The coherence of the laser can be varied by changing the capillary length
- Longer capillaries produce beams with more coherence and higher output





0.1 mJ - 18 cm

0.4 mJ- 27 cm

0.8 mJ - 36 cm

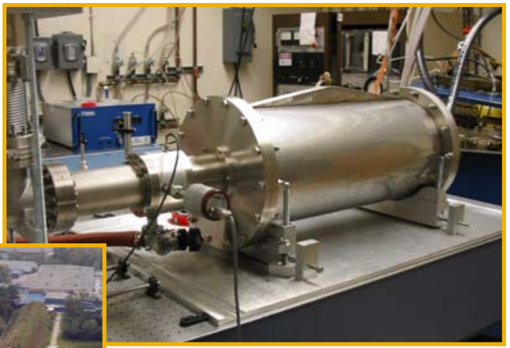
Y. Liu et al. Phys. Rev. A ***63*** *033802 (2001)*

Experiment #1

Sc/Si multilayer mirror damage threshold measurements

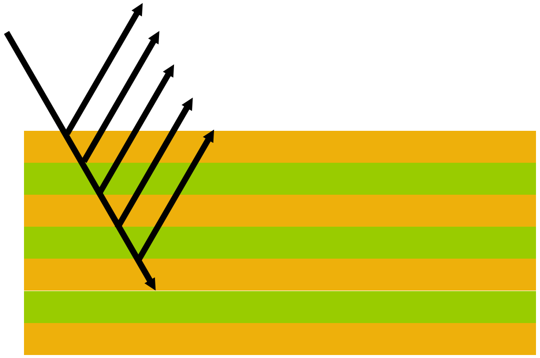
Background

- Extreme ultraviolet (EUV) coherent sources rapidly advance; radiation fluences already exceed 1 J/cm^2
- Most applications require mirrors; in the 35-50 nm range Sc/Si multilayers are used with reflectivity up to 54%
- Damage threshold of Sc/Si mirrors is unknown
- We investigated damage threshold of Sc/Si multilayers using intense laser pulses at 46.9 nm



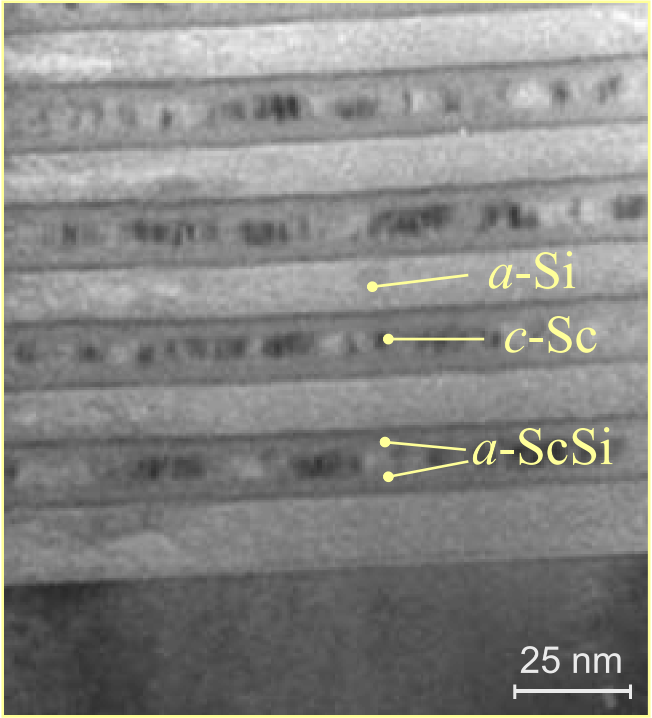
CSU laser, 46.9 nm, 1.2 ns, 100- 800 μJ

TESLA FEL, 86 nm, 100 fs, 5 μJ



Sc/Si Multilayer Mirrors

- Sc/Si multilayers deposited by dc magnetron sputtering on Si and glass
- 26.7 nm thick Sc/Si layers, ratio of layer thickness H(Sc)/H(Si) ~ 0.7
- Sc is separated from Si by ScSi interdiffusion layers (~ 3 nm)
- 33 and 10 periods
- Typical reflectivity 30 – 40% @ 46.9 nm
- Samples were cut in small pieces



Cross-section TEM image of a typical Sc/Si coating

Goal: Irradiating Sc/Si multilayer mirror with different fluences to find damage threshold

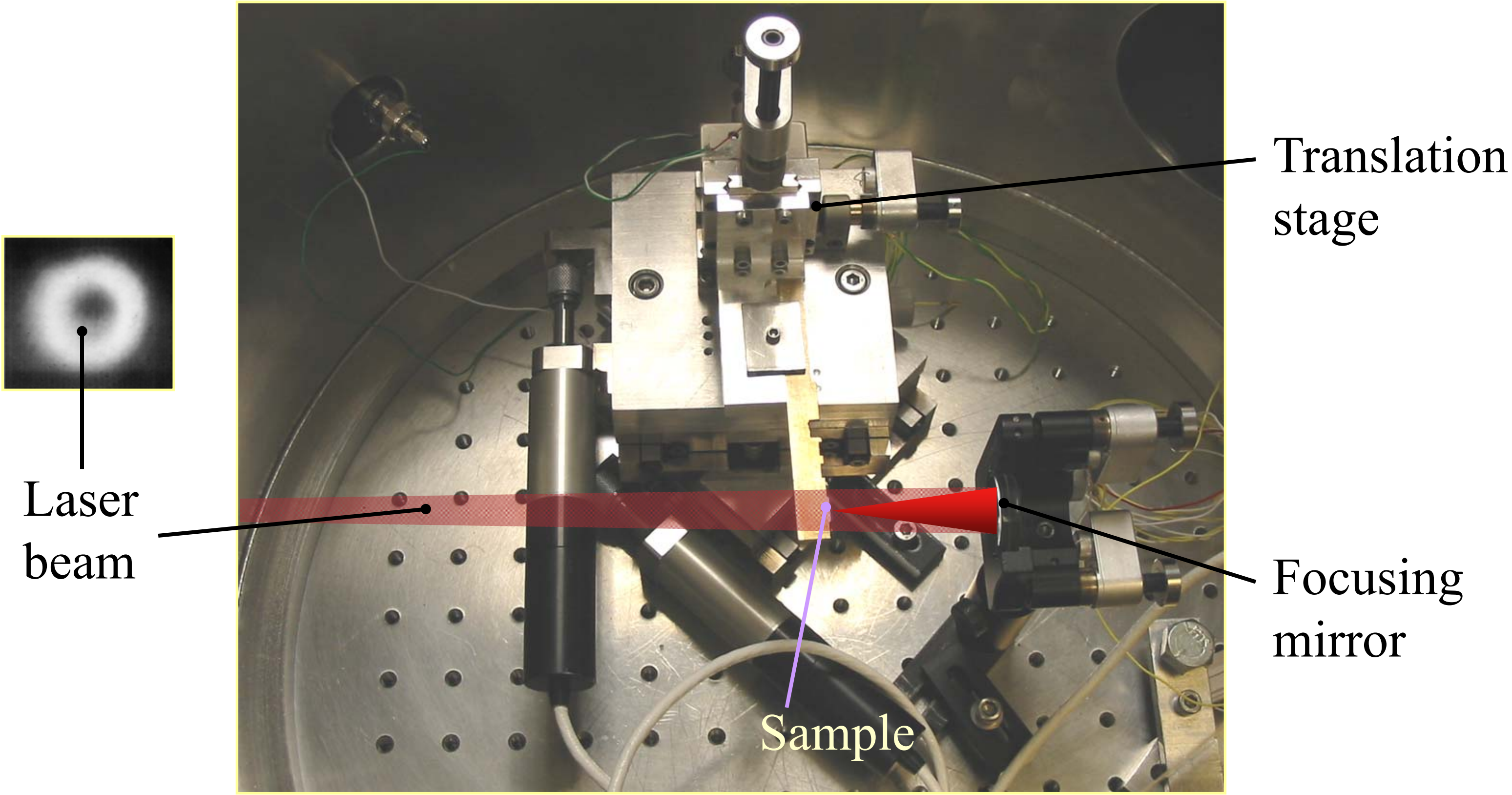
Analysis techniques

- Optical Microscopy
- Scanning Electron Microscopy (SEM)
- Transmission Electron Microscopy (TEM)
- X-ray diffraction (XRD, λ=0.154 nm)
- Electron diffraction

Damage threshold is defined as visible damage to the surface of the multilayer mirror with a single shot of the EUV laser

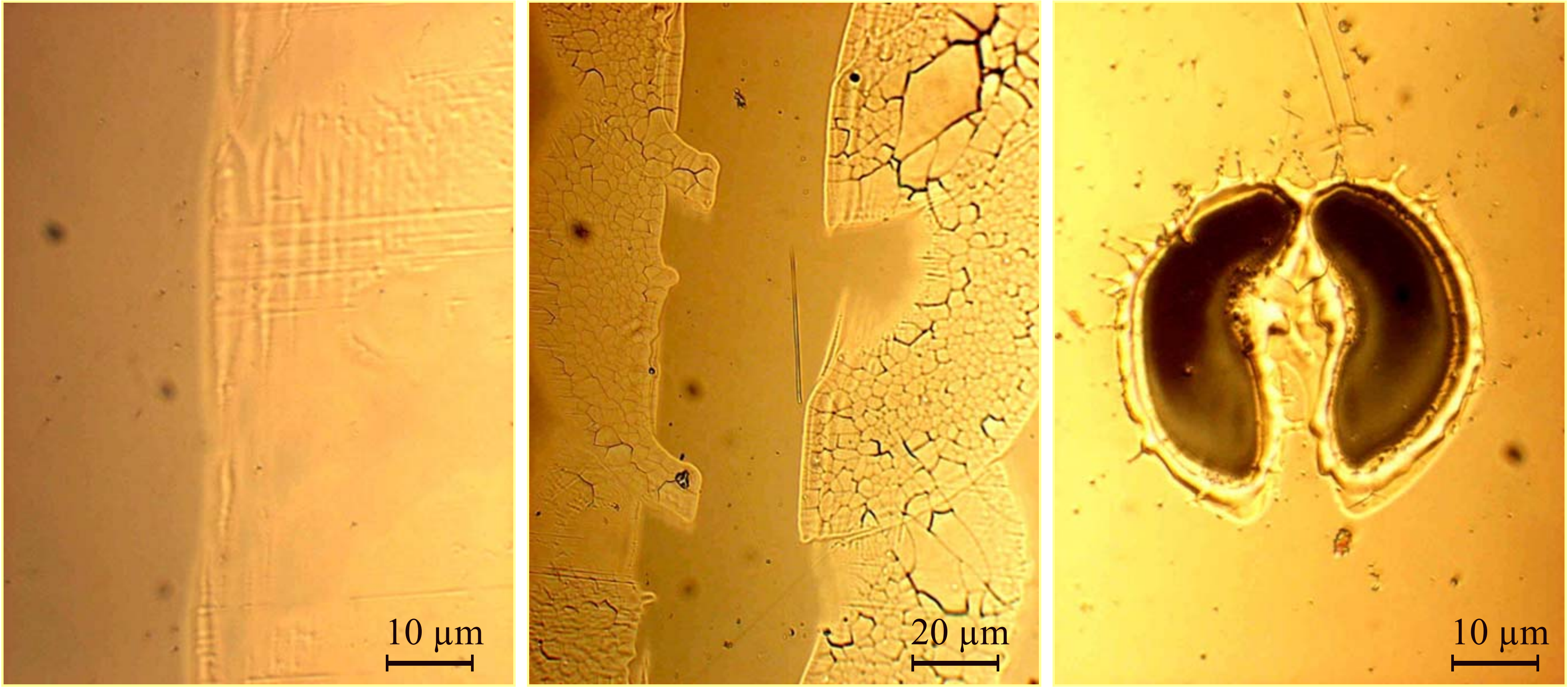
Experimental set-up

Capillary-discharge Ne-like Ar laser $\lambda = 46.9$ nm, operated at $E = 0.13$ mJ, $\tau = 1.2$ ns
Fluence ~ 0.01 – 10 J/cm^2



Results: Damage vs Fluence

Optical micrographs of damaged areas



0.12 J/cm^2 0.5 J/cm^2 5.0 J/cm^2

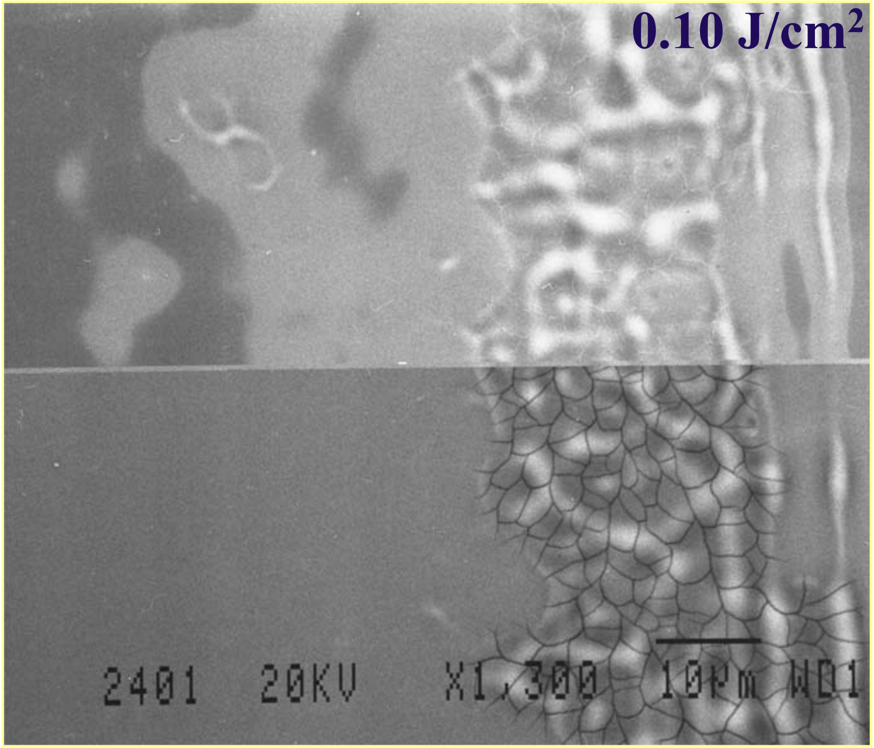
Damage threshold $\sim$ 0.08 J/cm^2 is found for Sc/Si multilayers

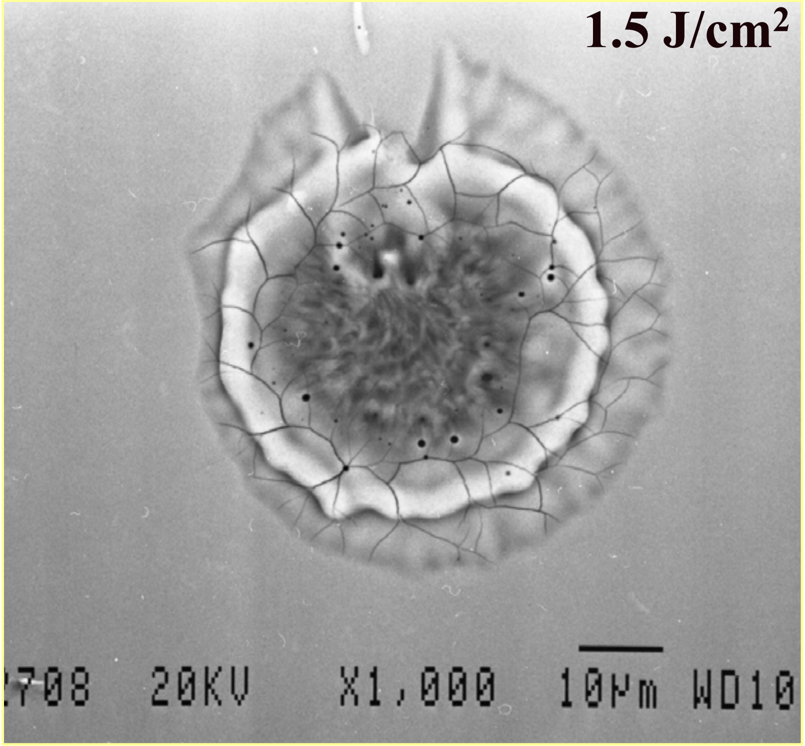
M. Grisham et al., Optics Letters 29, 620 (2004).

Results: SEM Analysis

Scanning Electron Microscope (SEM) images of damaged areas reveal change in the apparent color of the coating, cracks, and pits

Secondary electron image



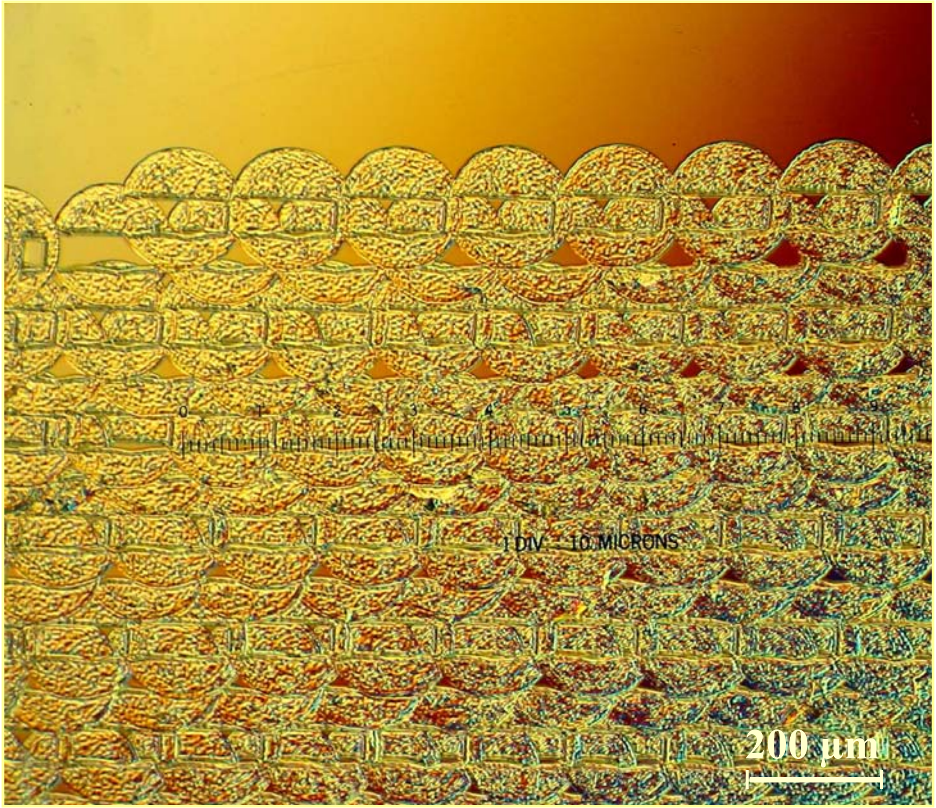


Primary electron image

Results: Large-area Irradiation

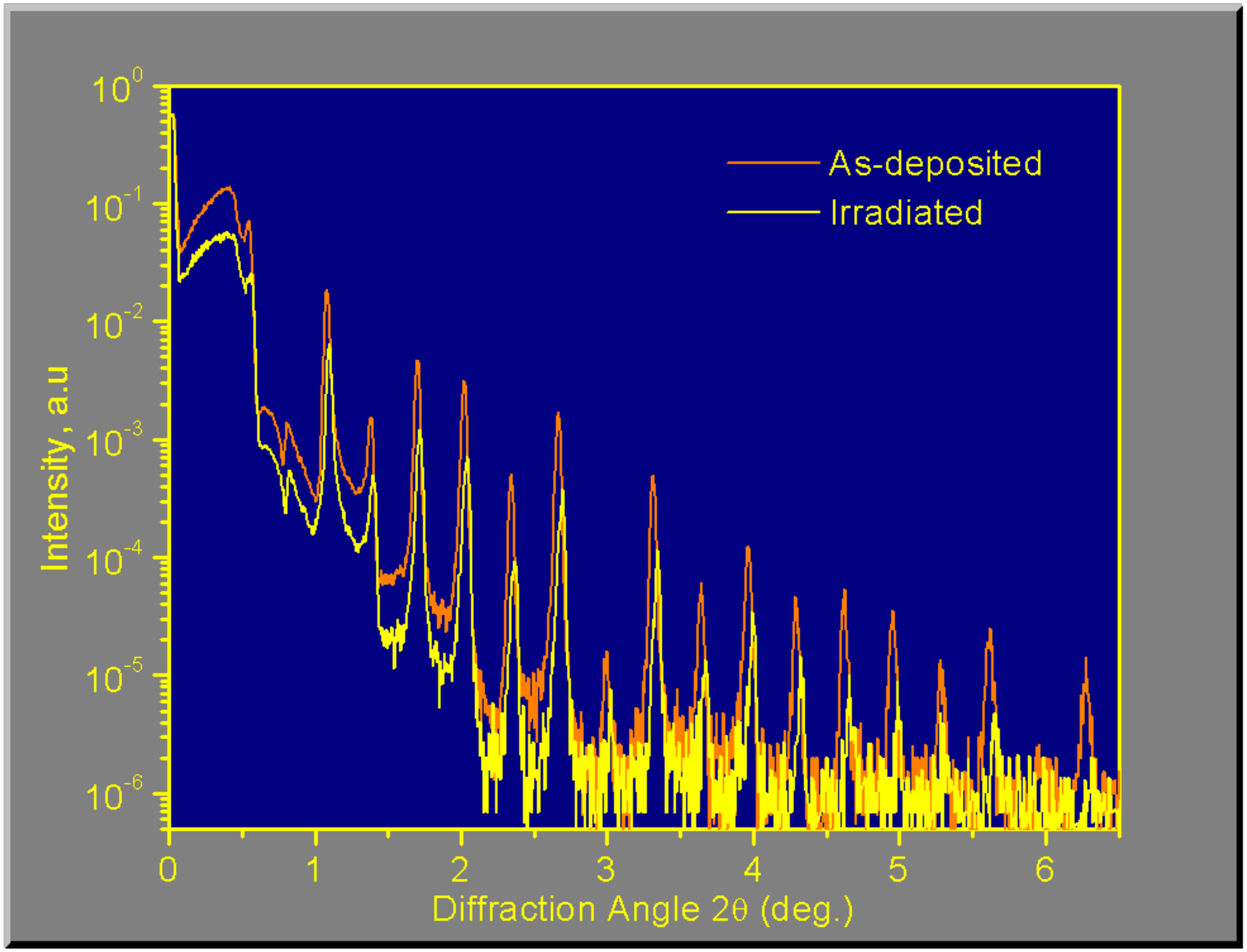
Large area irradiation made possible by high repetition rate and large laser pulse energy of capillary discharge laser

Spot diameter ~ 160 µm (~ 0.21 J/cm^2), 2 × 2 mm area is irradiated



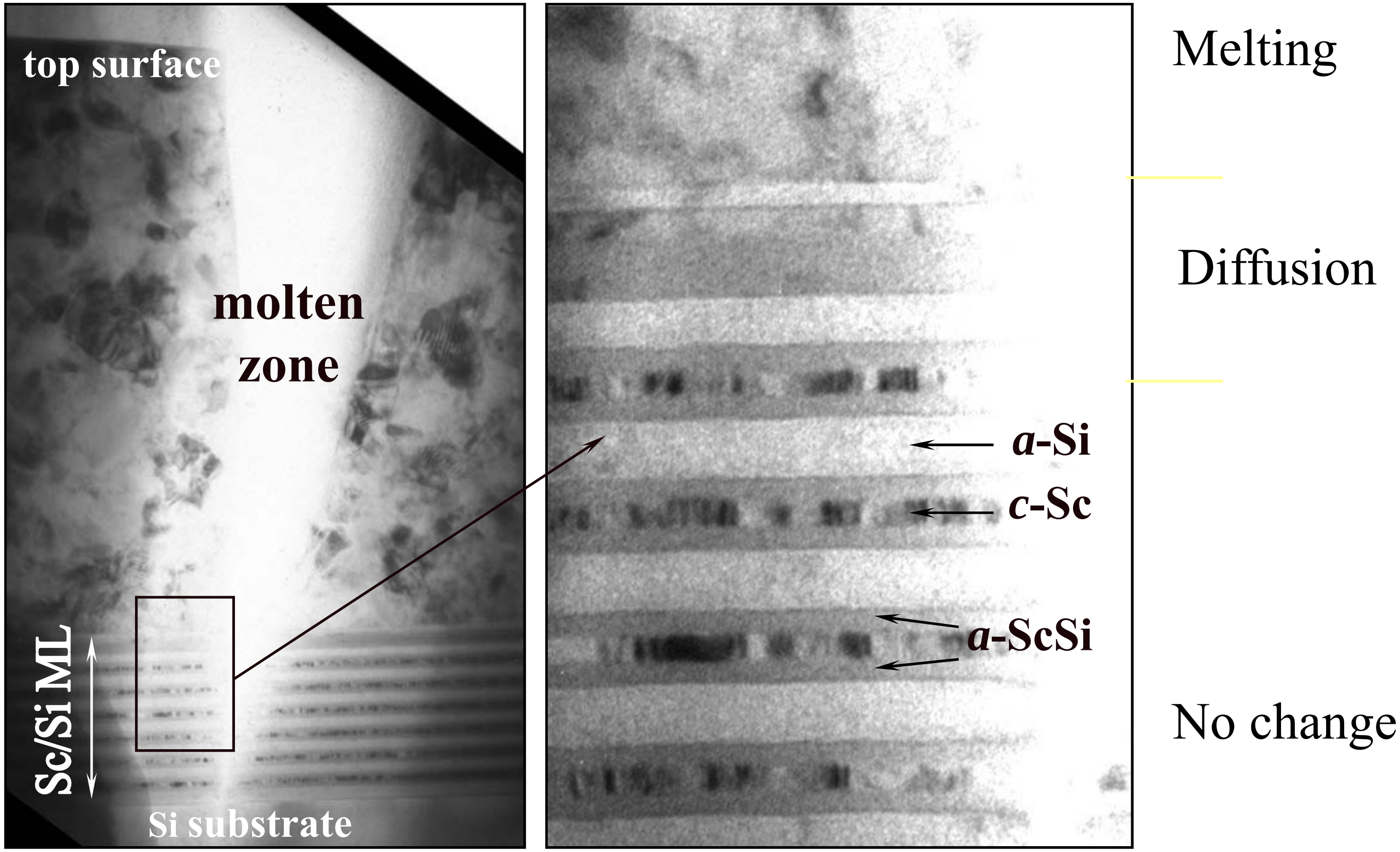
Results: XRD analysis

Small angle X-ray ($\lambda = 0.154$ nm) diffraction of large-area irradiation sample (0.21 J/cm^2 fluence). Only top layers are damaged.



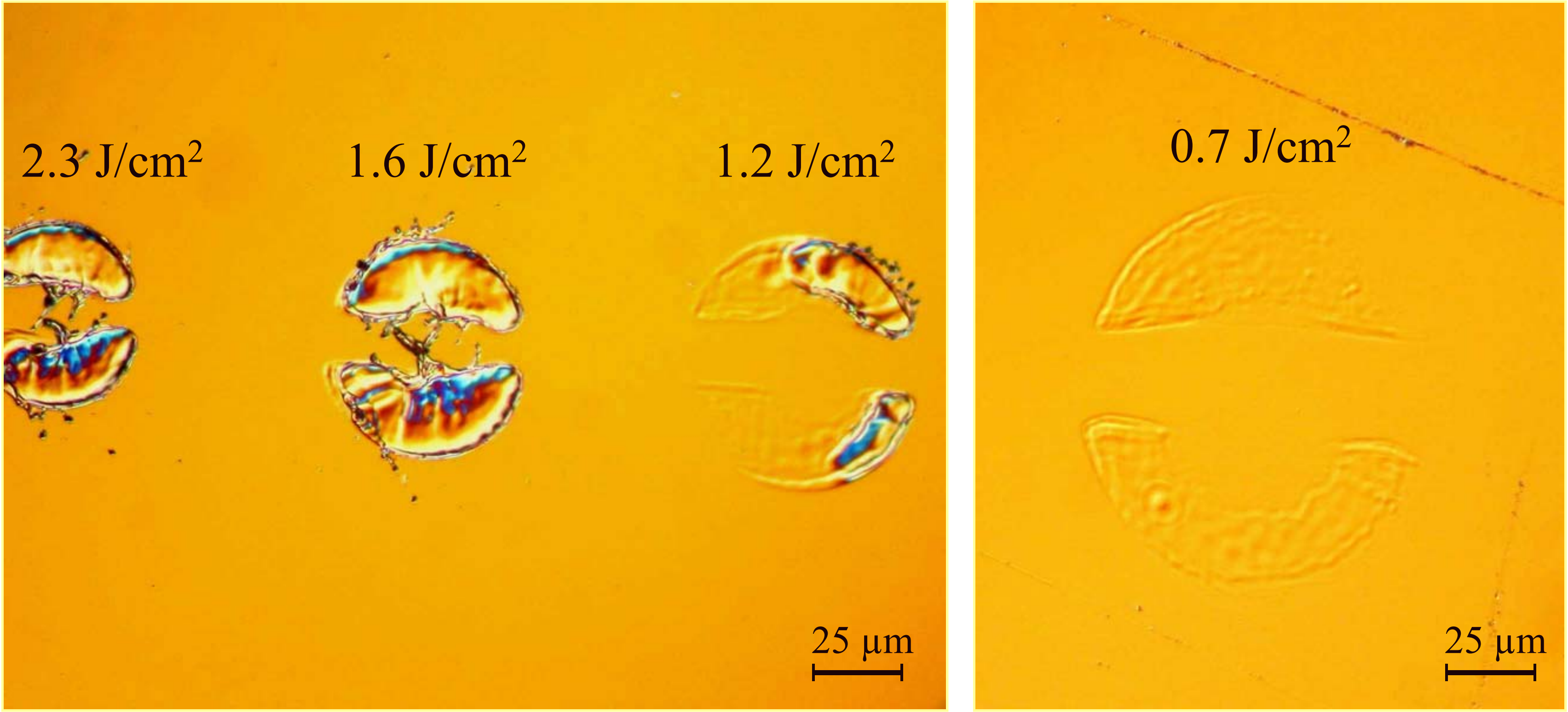
Results: TEM analysis

Transmission Electron Microscopy reveals surface modifications of the Sc/Si multilayers (0.21 J/cm^2 fluence)



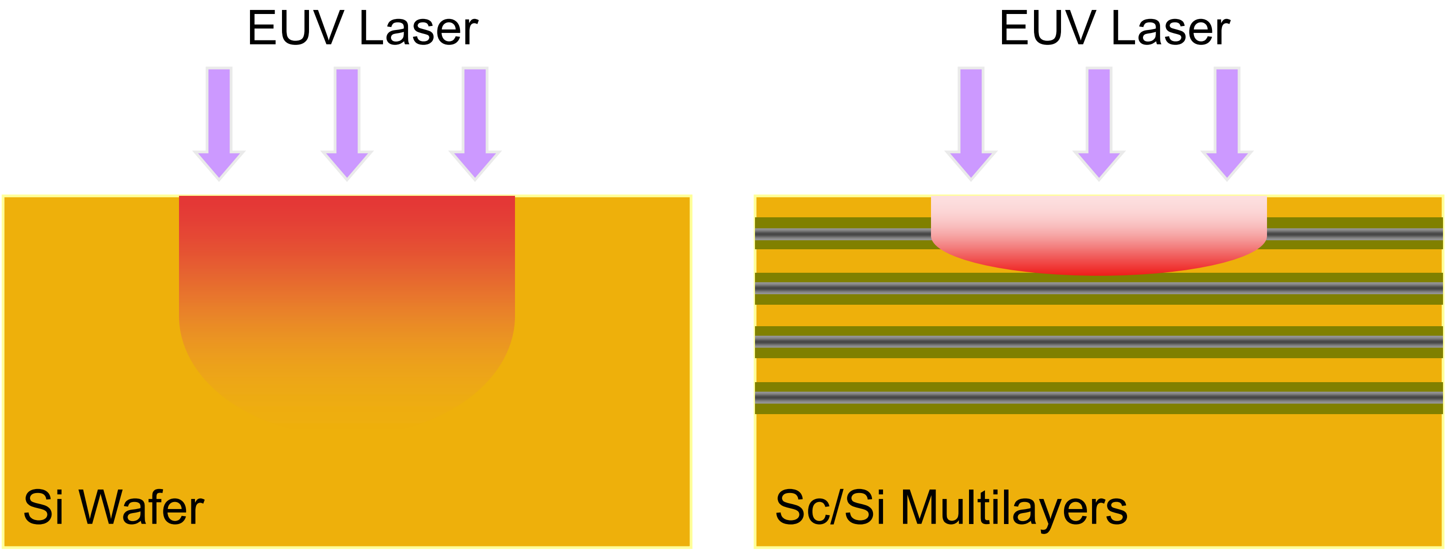
Results: Damage to Si

Optical micrographs of damaged areas on silicon wafer; the damage threshold fluence is ~ 0.7 J/cm^2, significantly higher than in Sc/Si multilayers



Explanation

- Inter-phase boundaries (Sc-ScSi, ScSi-Si) reduce thermal conductivity of the multilayers
- Under pulsed irradiation the heat is localized in the surface layers
- The low damage threshold of the multilayers is set by the interdiffusion in the surface layers, and not by the melting and evaporation as in a crystal Si


EUV Laser

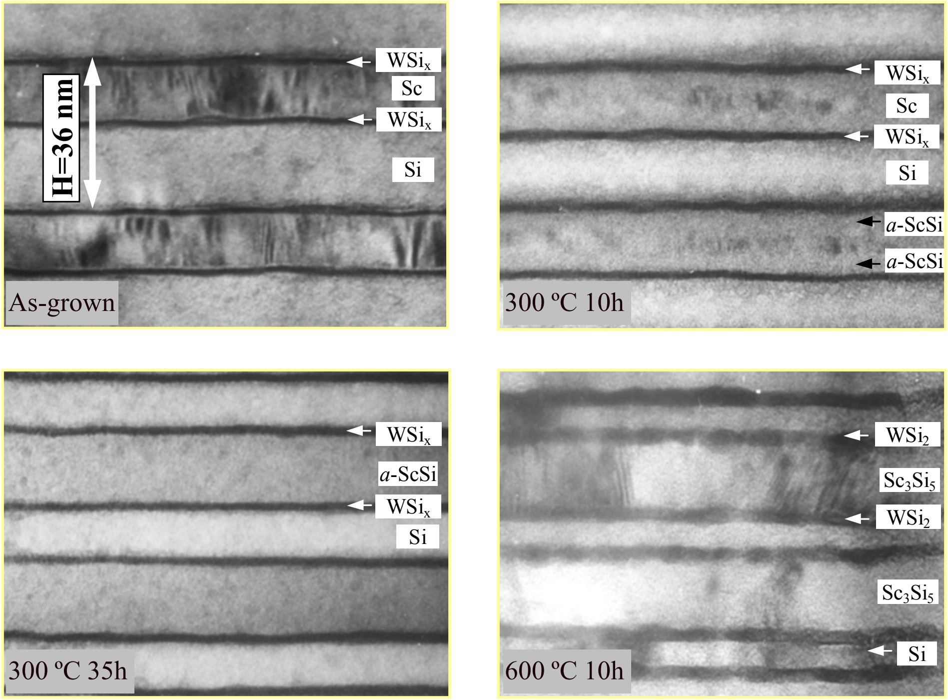
EUV Laser

Si Wafer

Sc/Si Multilayers

Suggested Improvements

- To improve radiation resistance one may consider using ScSi/Si multilayers instead of Sc/Si
- Interdiffusion barriers (i.e. ~ 0.2 - 1 nm W layers) between Sc and Si may also improve damage resistance:



TEM image of the Sc/Si multilayer coating with W barriers under isothermal heating at 300 and 600 ºC

D. L. Voronov et al., AIP Conf. Proc. 641, 575 (2002).

Important Findings

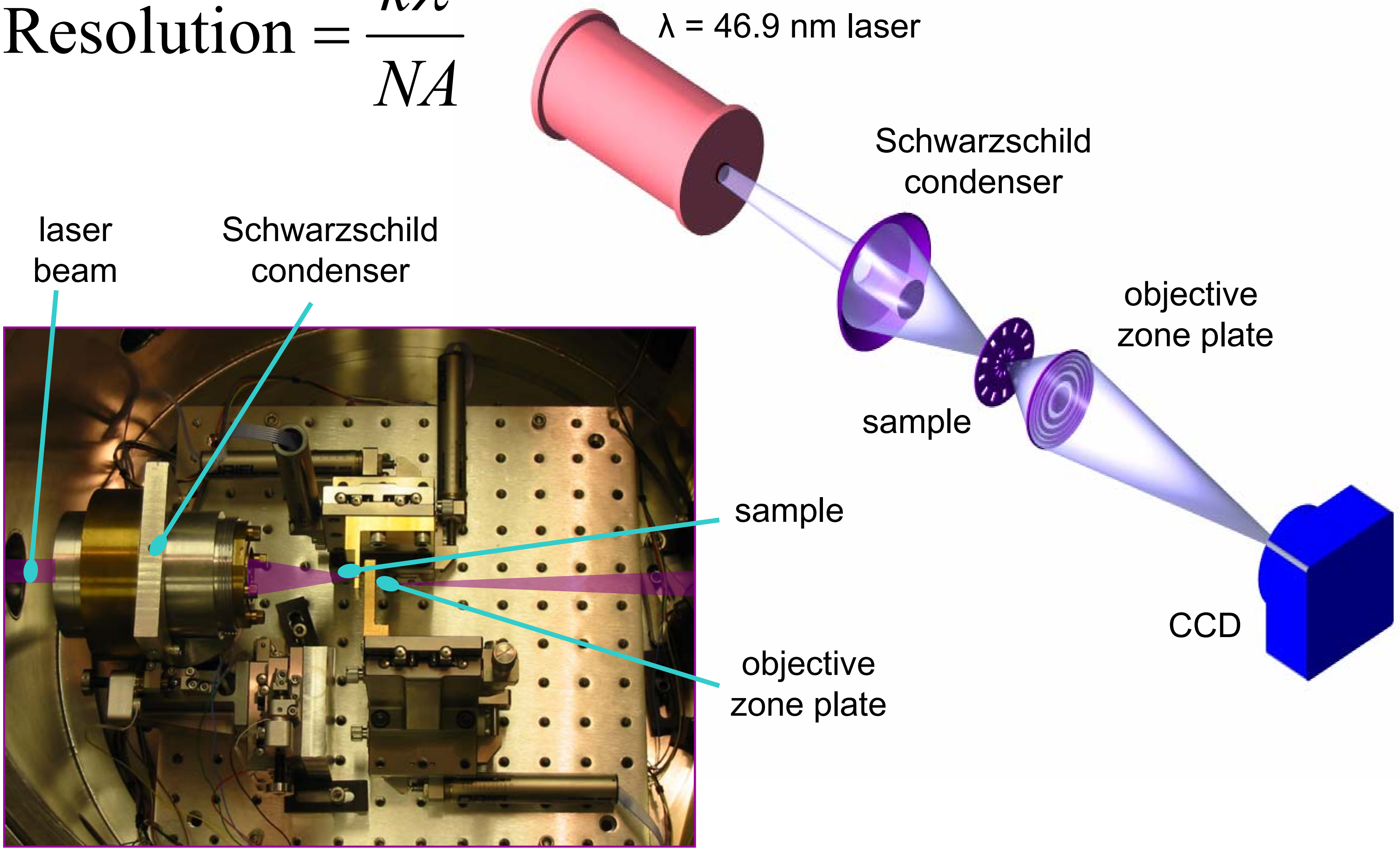
- **The damage threshold of Sc/Si multilayer mirror is ~ 0.08 J/cm^2 is found, significantly lower than that in Si (0.7 J/cm^2)**
- Damage to Sc/Si produced by nanosecond pulses at 46.9 nm is thermal in nature
- Three distinct zones in the damaged areas: molten layer, heat affected zone (diffusion), and unchanged layer
- Radiation damage is strongly affected by the reduced thermal conductivity of the multilayers; Sc/ScSi phase boundaries contribute to this effect
- To improve radiation resistance one may consider using ScSi/Si multilayers instead of Sc/Si
- Interdiffusion barriers (i.e. ~ 0.5 nm tungsten layers) between Sc and Si may also improve damage resistance

Experiment #2

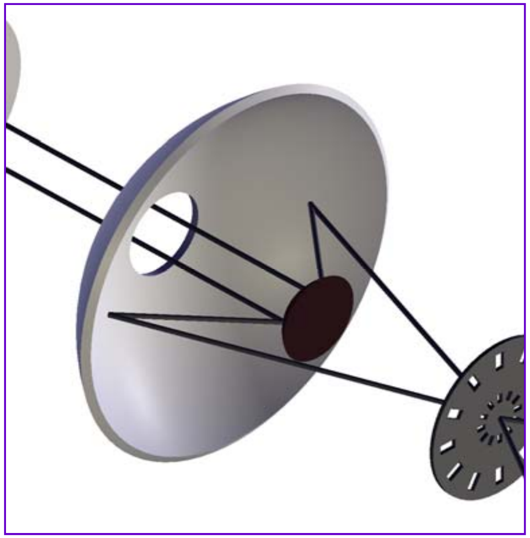
Transmission and Reflection mode microscopy

Compact transmission-mode microscope setup

$$\text{Resolution} = \frac{k\lambda}{NA}$$



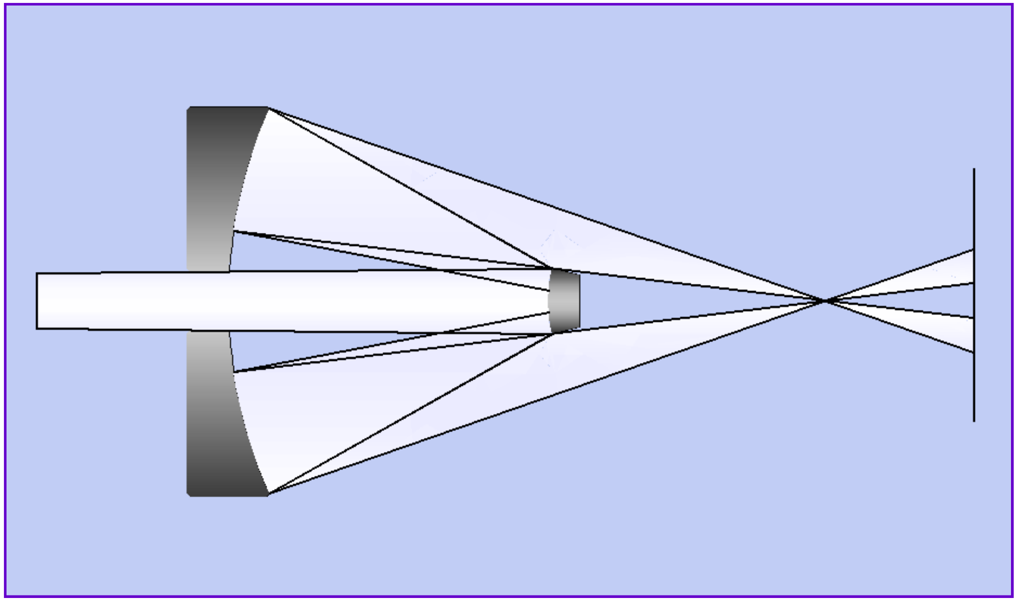
Schwarzschild condenser



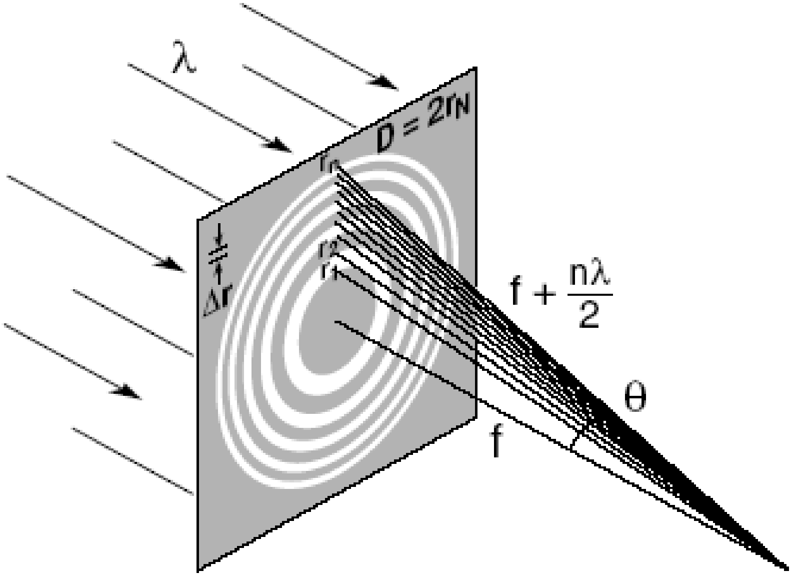
- Two Sc/Si multilayer coated mirrors.
- Produces a hollow cone of light focused onto the sample.

Specifications:

Diameter M_1	D_1 = 50 mm
Diameter M_2	D_2 = 10.8 mm
Focal distance	f = 27 mm
Num. Aperture	NA = 0.18
Throughput	T = 1% (16%)



The resolution of a zone plate based microscope depends on the outer zone width

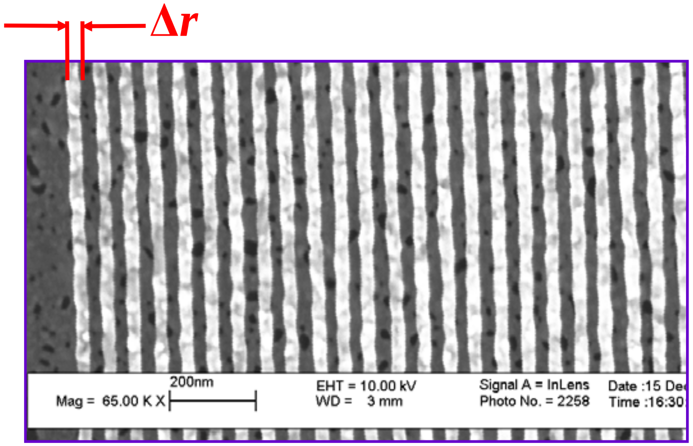


Outer zone width	200 nm
NA	0.12
Diameter	0.5 mm
Number of zones	625
Focal distance	2.14 mm
Depth of focus	± 1.76µm

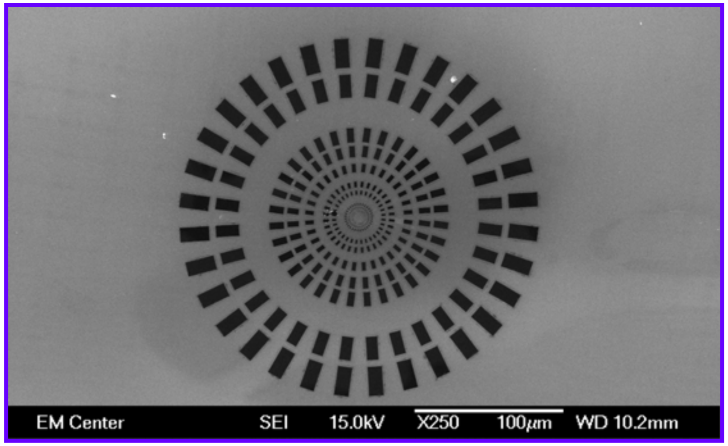
$$D = 4N\,\Delta r \qquad f = \frac{4N(\Delta r)^2}{\lambda}$$

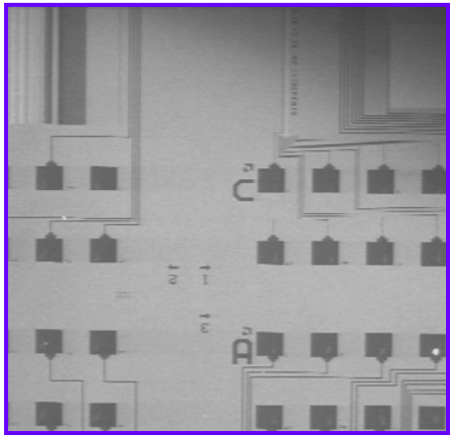
$$\mathrm{NA} = \frac{\lambda}{2\,\Delta r} \qquad \mathrm{DOF} = \pm\frac{1}{2}\frac{\lambda}{(\mathrm{NA})^2} = \pm\frac{2(\Delta r)^2}{\lambda}$$

- $$\boxed{\mathrm{Res} = \frac{k\lambda}{NA} = 2k\quad\Delta r}$$



Samples used to characterize the microscope





circular test pattern:

- diameter = 200 μm
- smallest features = 100 nm
- substrate = Ni foil

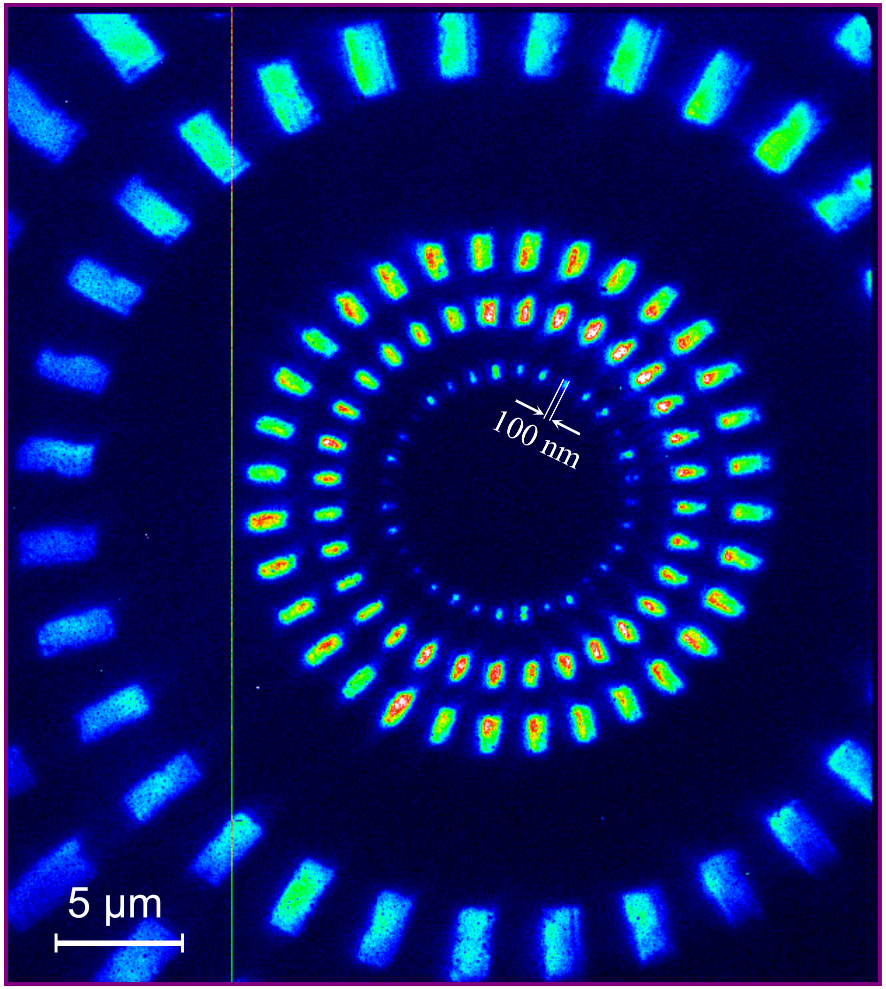
Si wafer with polysilicon lines:

- smallest features = 100 nm
- grating with 250 nm half pitch

Freestanding zone plate:

- smallest features = 200 nm
- substrate = Ni foil

First Results - Transmission mode image of a nickel test pattern



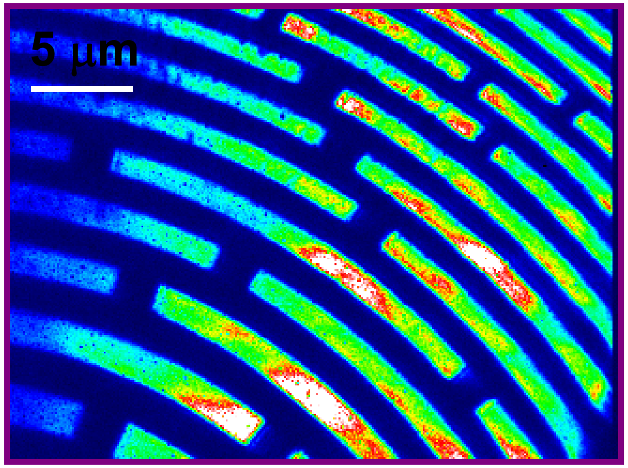
- 10 sec exposure

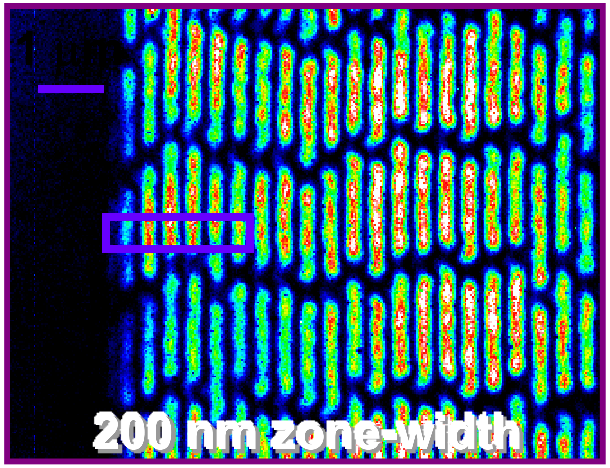
(10 laser shots at 1 Hz)

- ×470 magnification
- 100 nm wide features in innermost ring

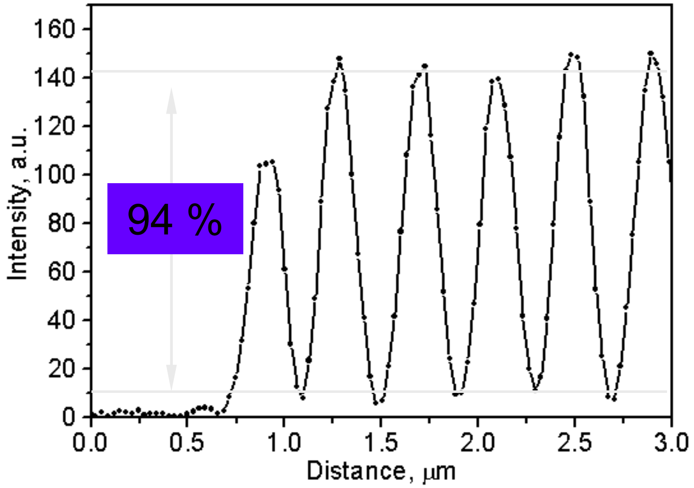
Resolution better than 200 nm obtained

Images of a zone plate

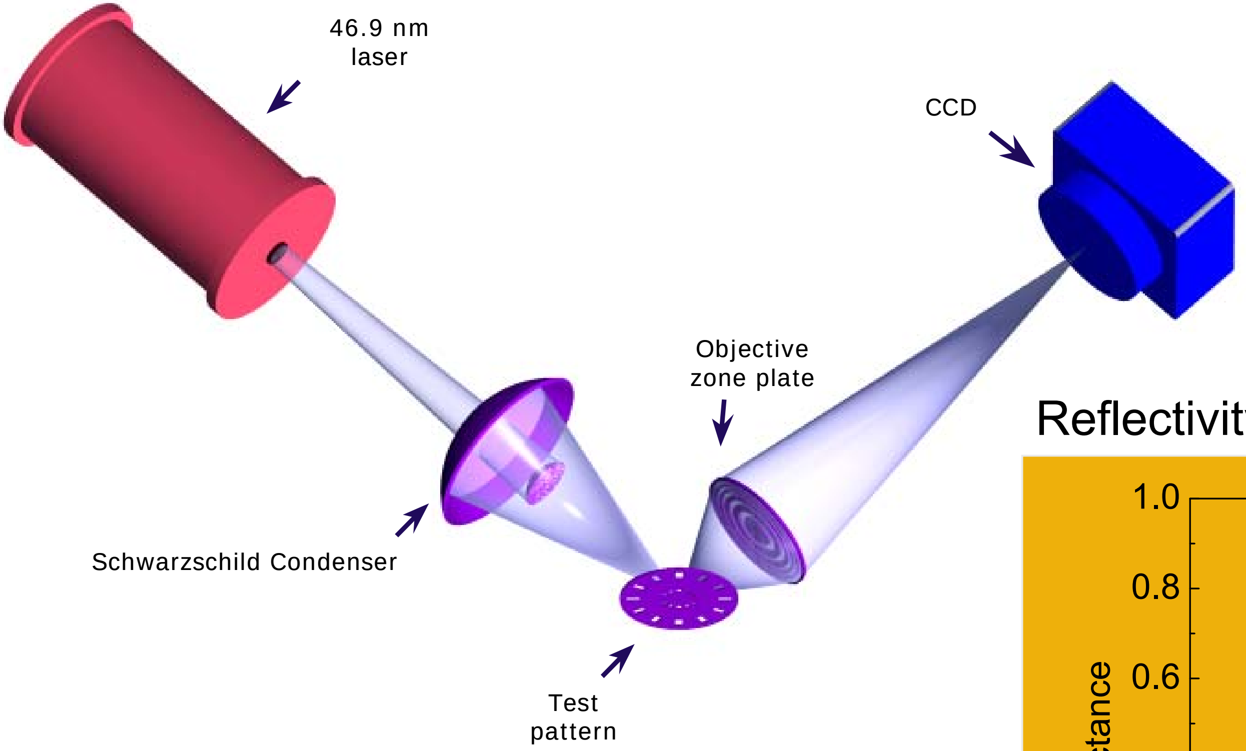




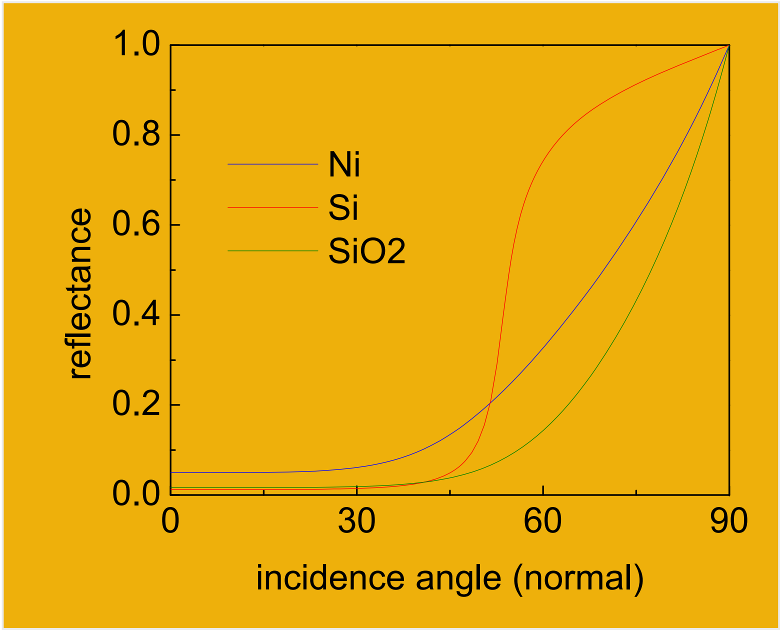
- ~ 94 % modulation >> 26.5 % (Rayleigh-like modulation)
- Predicted 120 - 150 nm spatial resolution.



Reflection mode microscope



Reflectivity vs. of angle of incidence

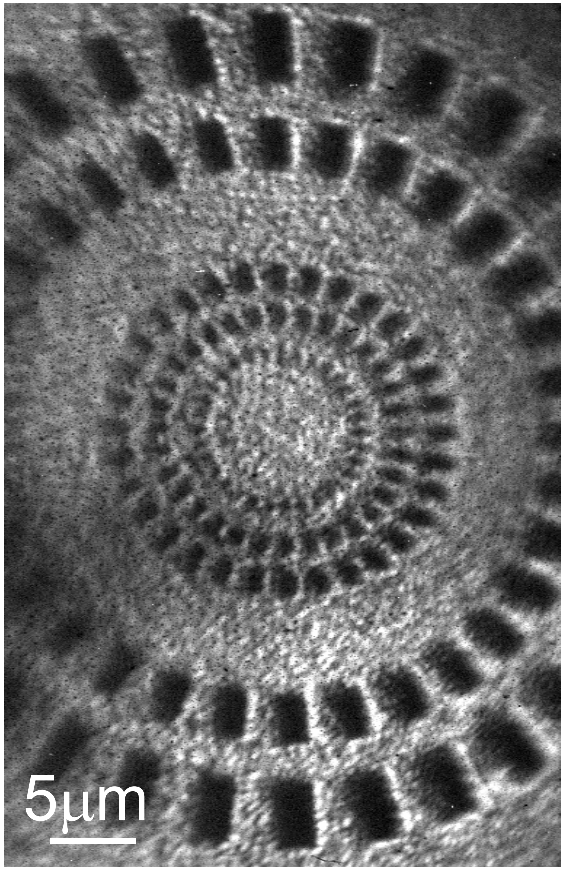


From CXRO database

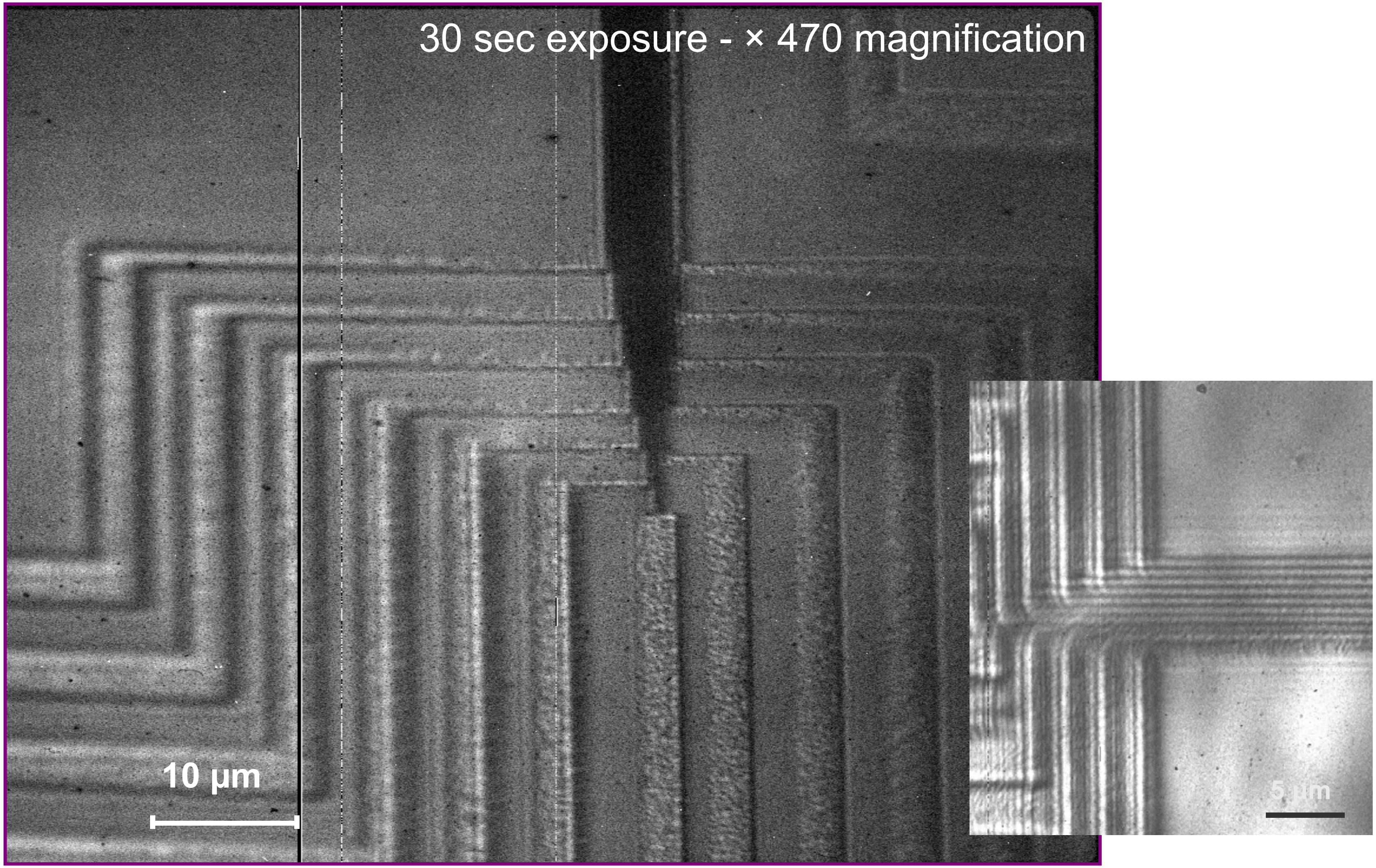
- Sample at 45^o with respect to the beam.
- Objective at 90^o with respect to the beam

Image of the nickel test pattern in reflection mode

- 70 sec exposure
(70 laser shots at 1 Hz)
- ×480 magnification
- Sample at 45 degrees
- 100 nm wide features in innermost ring



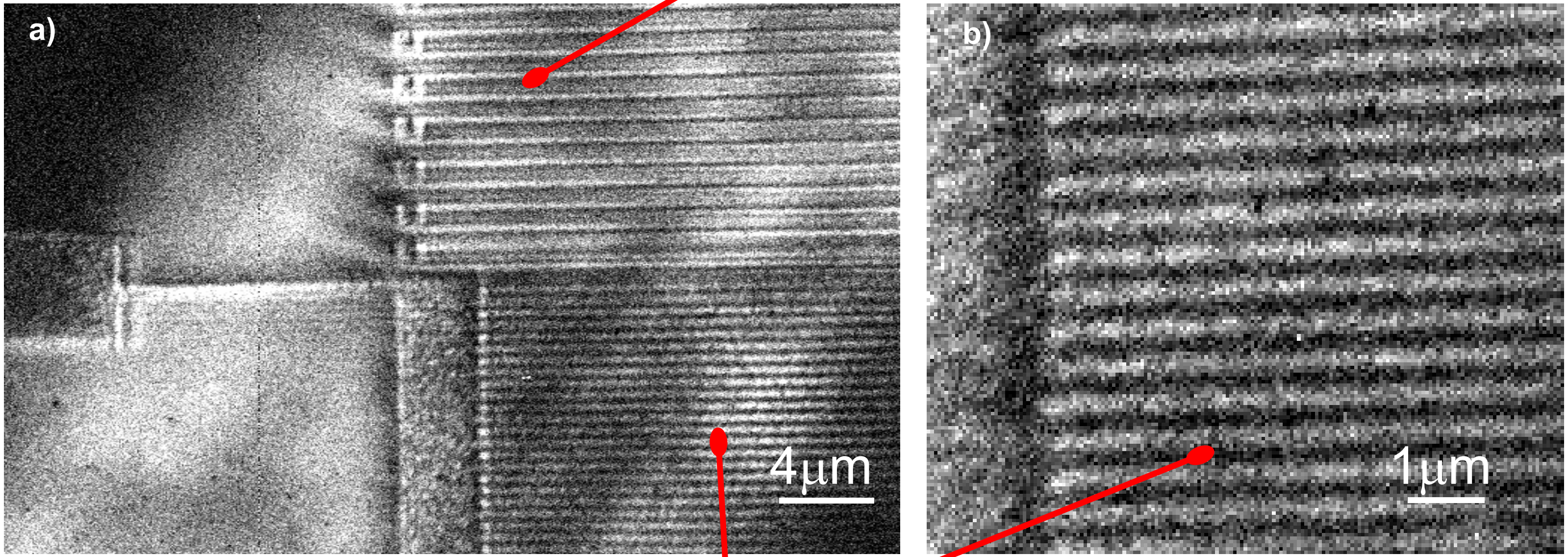
Images of Si wafer with polysilicon lines


30 sec exposure - × 470 magnification

250 nm lines are resolved – 100 nm lines are visible

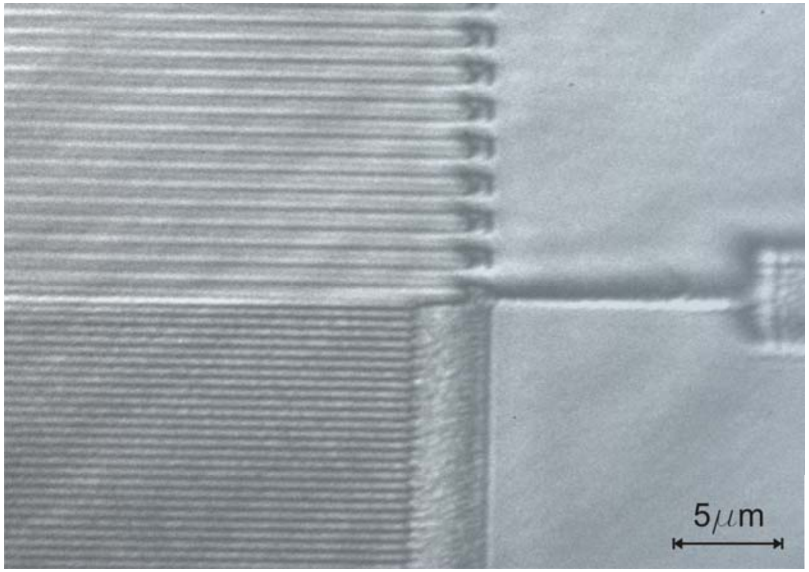
60 sec exposure (1 Hz) - ×750 magnification

100 nm lines - 800 nm spaces

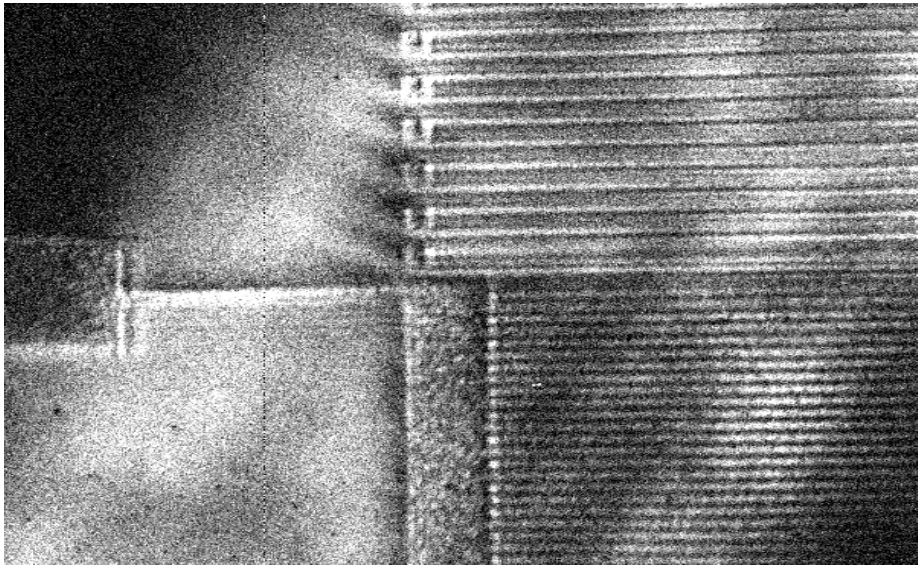


250 nm lines - 250 nm spaces

Current state of the microscope



F. Brizuela stunning image of the same polysilicon lines using the desktop capillary laser system.



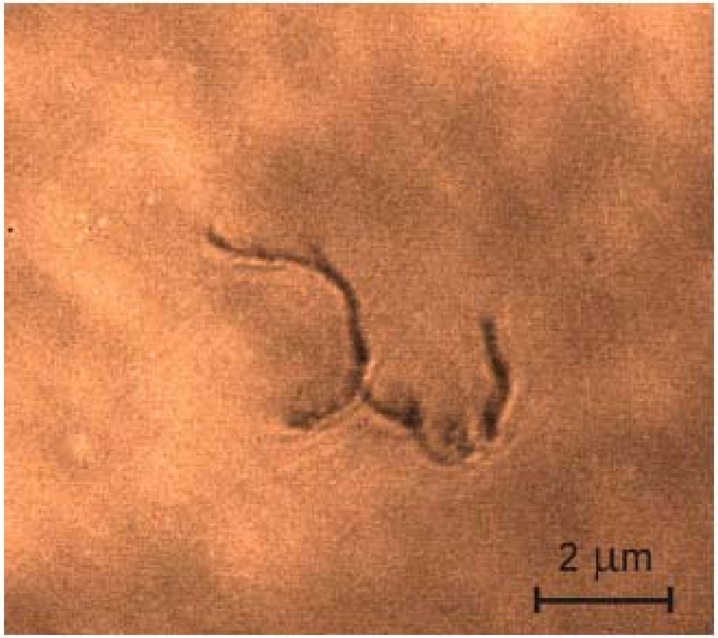
Conclusions

- We have constructed an optical microscope based on a compact extreme ultraviolet laser.

- High resolution images were obtained operating in transmission and reflection mode.

- The images show a spatial resolution better than 200 nm

- These results have lead to further developments that resulted in 54 nm resolution of carbon nanotubes with a single shot in transmission mode



C. Brewer et al., Opt. Lett. 33, 518-520 (2008).

Questions

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