FEL Irradiation Tolerance of Multilayer Optical System

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NTT AT

1. Introduction

2. Damage formation
   - Thermal process vs Non-thermal process

3. New optics for experiment improvement
   - Mirror based EUV attenuator

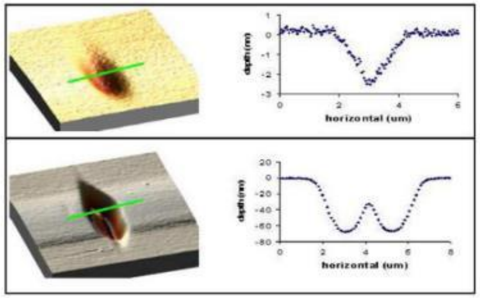
Background and previous work

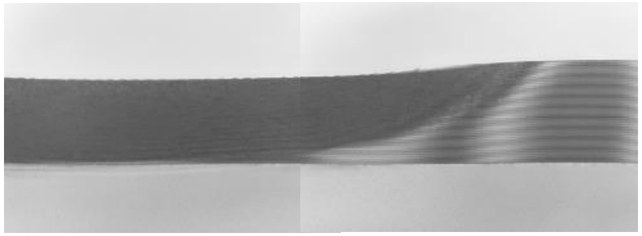
EUV lights source enhancement

- LPP source for EUV Lithography
  - 250 W stable running
  - 450 W burst mode running
- XFEL for fundamental science
  - 100 μJ/pulse @SACLA BL1
- HHG for attosecond science
  - 10 μJ/pulse @ELI attosecond

Mo/Si ablation threshold measurements

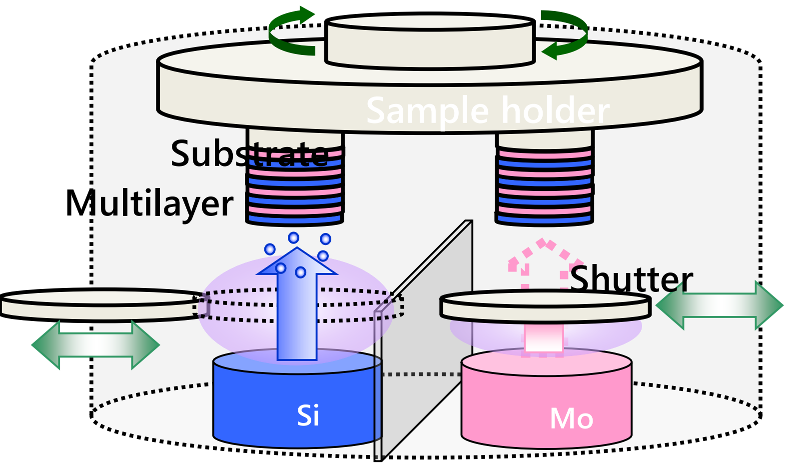
- 45 mJ/cm^2 @FLASH
  - A. R. Khorsand et al., Opt. Express, 18, 2 (2010)
- 25 mJ/cm^2 @SACLA
  - S. Ichimaru et al., SPIE EUV Lithography, (2017)
- 200 mJ/cm^2 @LPP source
  - M. Muller et al., Appl. Phys. A 108 (2012)

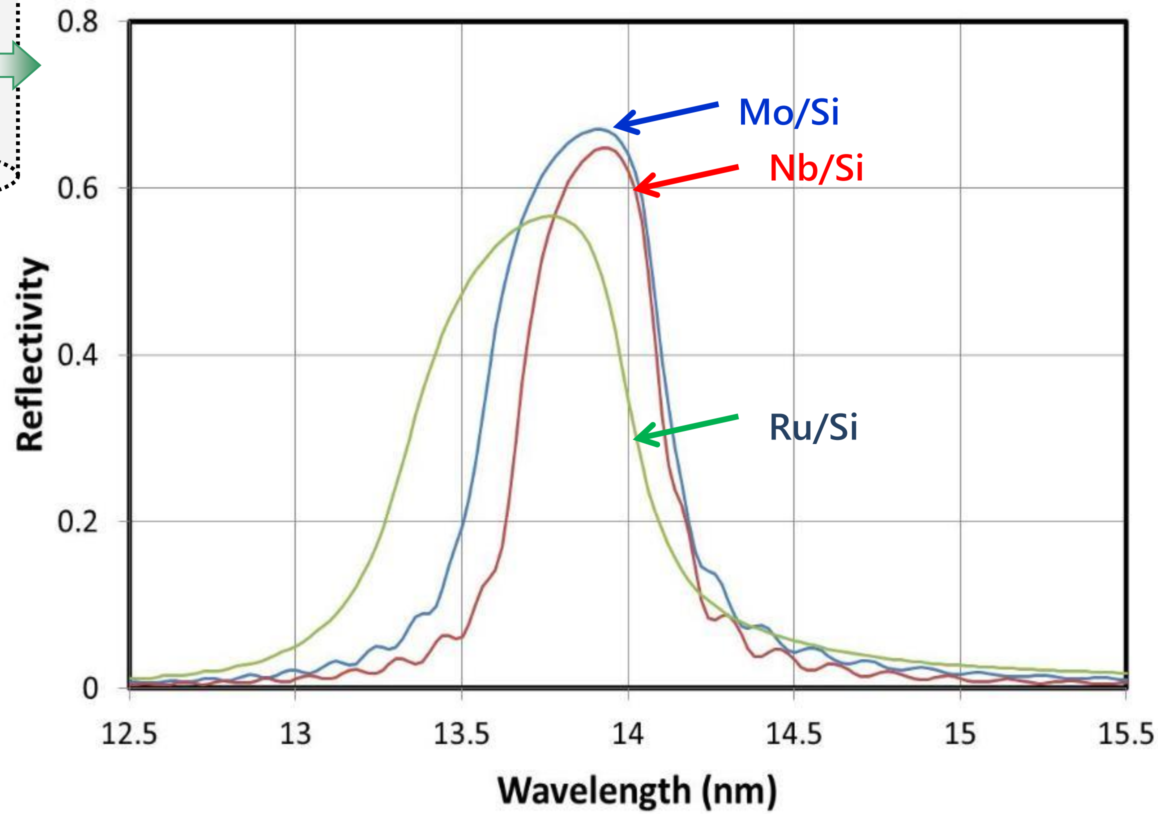




Developing a high resistance EUV multilayer mirror for high new standard EUV lights.

NEW Multilayer material combination



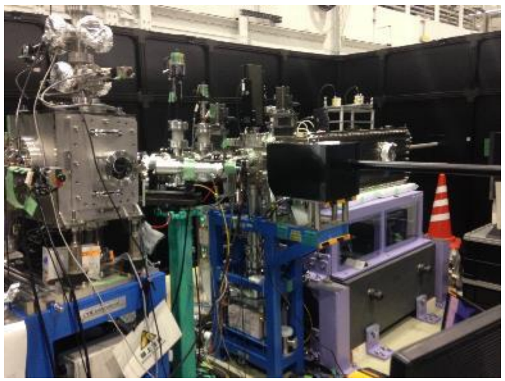


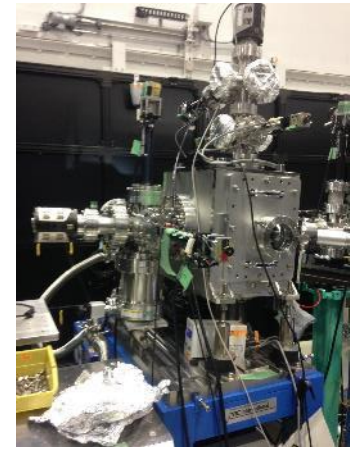
Mo/Si: 68%

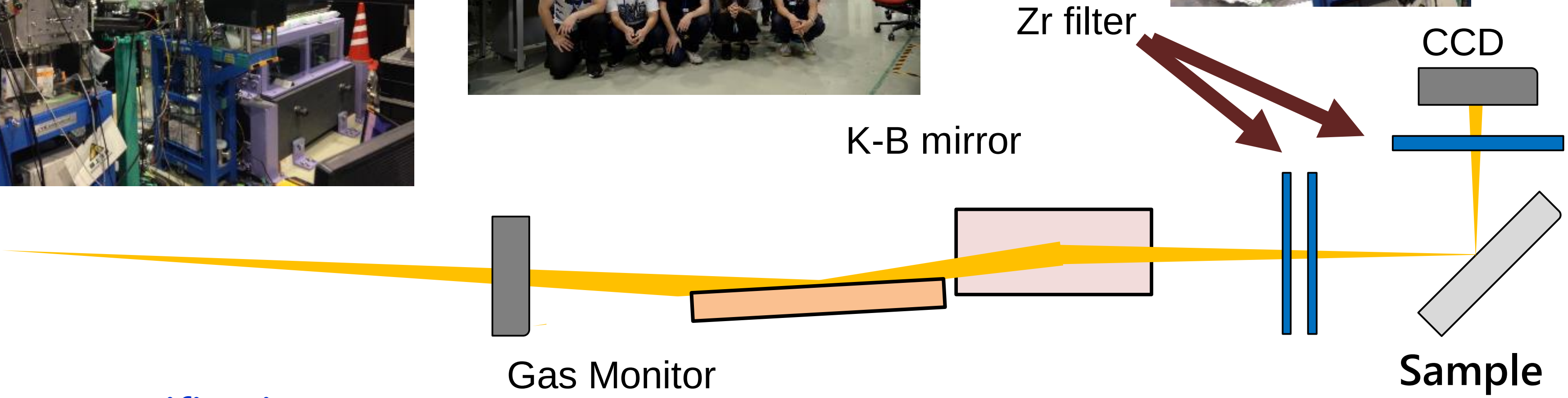
Nb/Si 64%

Damage test by using XFEL light

Schematics of irradiation damage test







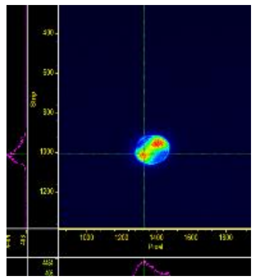
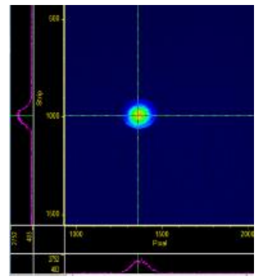
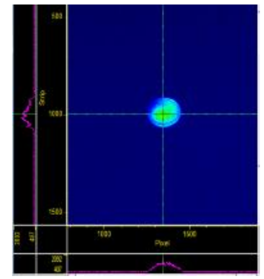
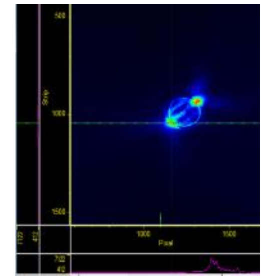
Beam specifications

- pulse duration : 100 fs
- Wavelength : 13.5 nm
- Peak fluence : 5 mJ/cm^2 – 120 mJ/cm^2
  (variable by changing Zr filter thickness)

Damage test summary

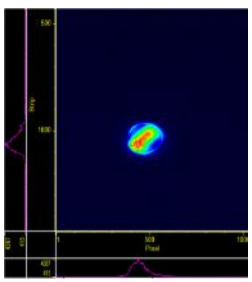
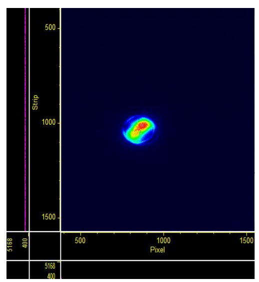
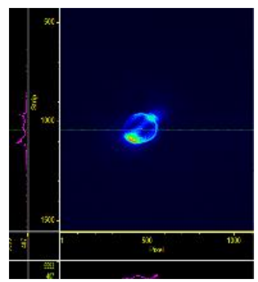
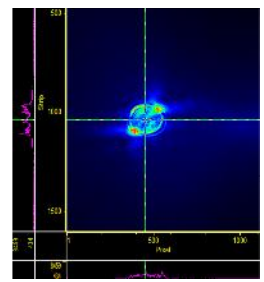
Damage threshold of Nb/Si ML is 2-3 times higher than that of Mo/Si ML

Nb/Si

~5 mJ/cm^2 ~25 mJ/cm^2 ~60 mJ/cm^2 ~80 mJ/cm^2 ~120 mJ/cm^2

Mo/Si

Estimated damage threshold

- Mo/Si: ~25 mJ/cm^2
- Nb/Si: >80 mJ/cm^2
- (Ru/Si < Mo/Si @QST X-ray Laser)

Mo vs Nb (vs Ru)

Material		Mo	Nb	Ru
Atomic number		42	41	44
Atomic weight		95.96	92.91	101.07
Density	g/cm3	10.28	8.57	12.4
Optical constant @13.5 nm	δ (10^{-2})	7.64	6.64	11.4
	β (10^{-2})	0.65	0.52	1.72
Melting point	deg	2623	2477	2334
Boiling point	deg	4639	4744	4150
Heat of fusion	kJ/mol	37.48	30	38.59
Heat capacity @25 deg	J/mol·K	24.06	24.6	24.06
Thermal Conductivity @27 deg	W/m·K	138	53.7	117
Expansion coefficient @25 deg	μm/m·K	4.8	7.3	6.4

Advantage
Disadvantage

1. Introduction

2. Damage formation
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3. New optics for experiment improvement
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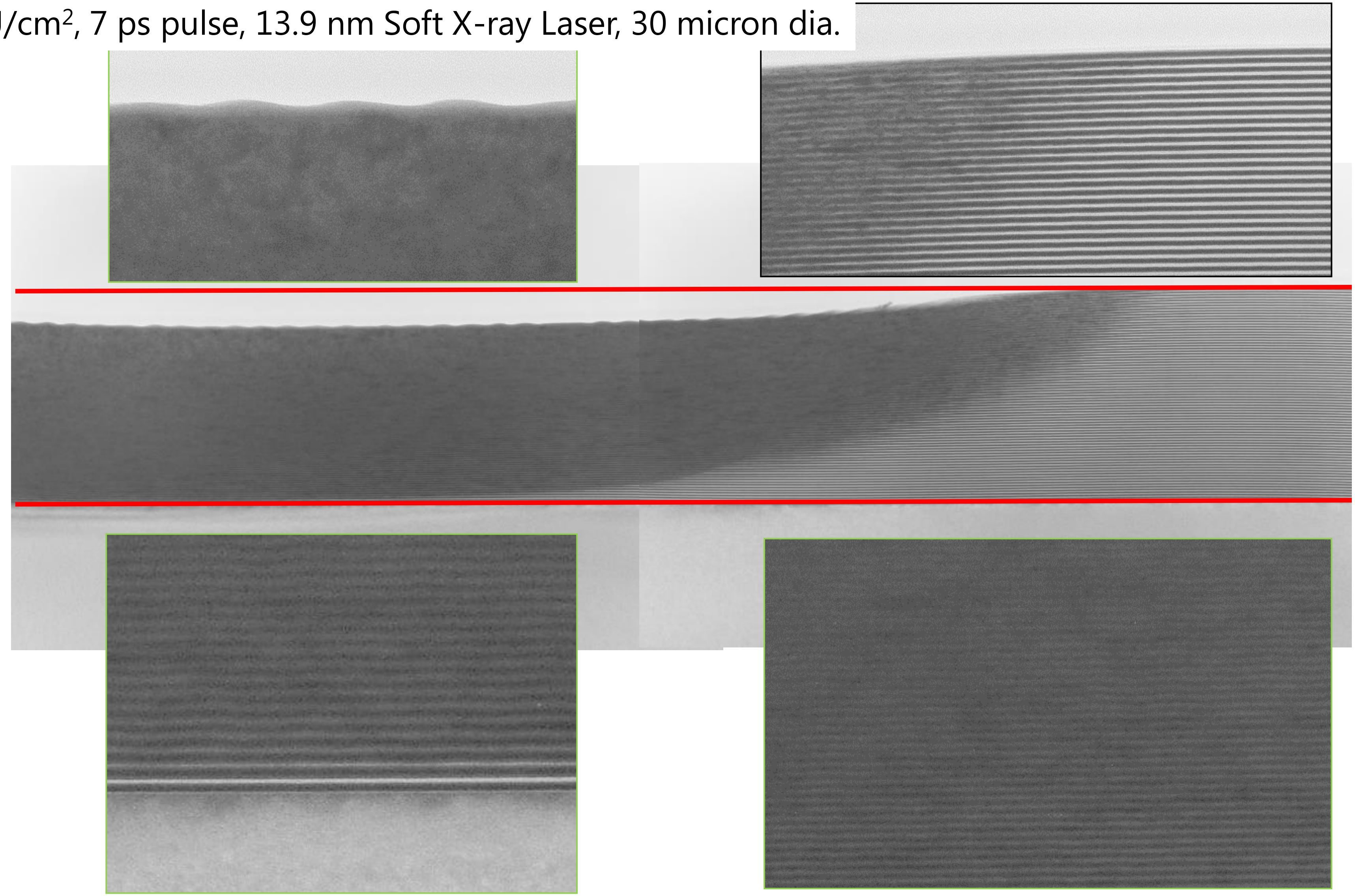
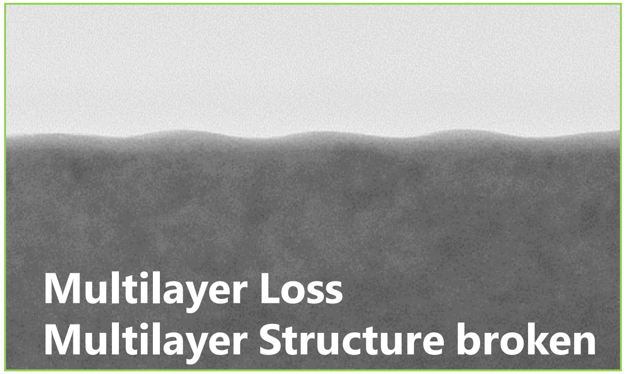
TEM image of Mo/Si ML damage

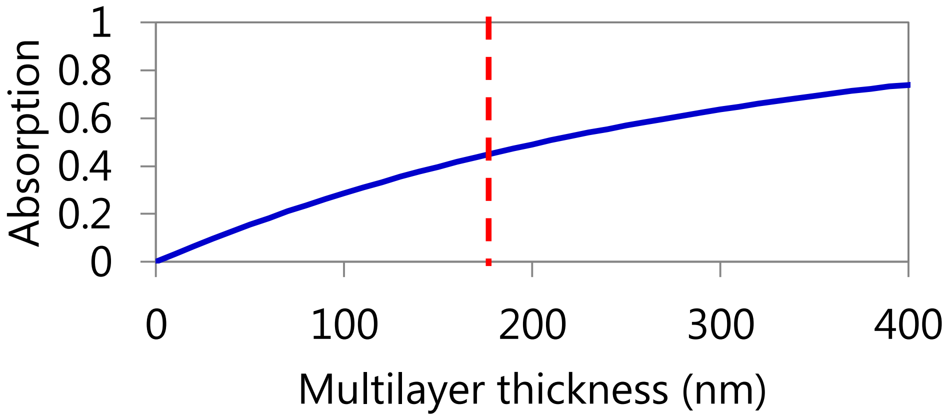
25 mJ/cm^2, 7 ps pulse, 13.9 nm Soft X-ray Laser, 30 micron dia.



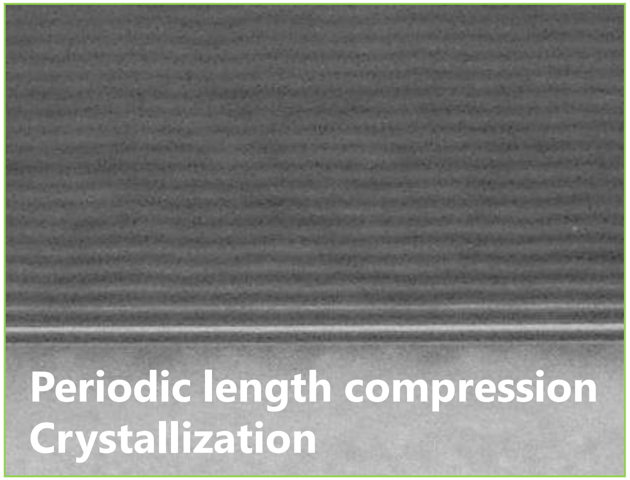
Absorption and Thermal expansion

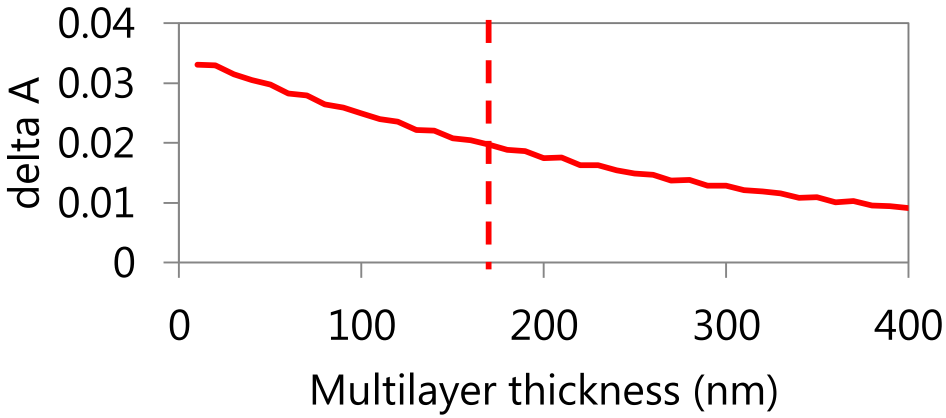
TOP stacks





BOTTOM stacks

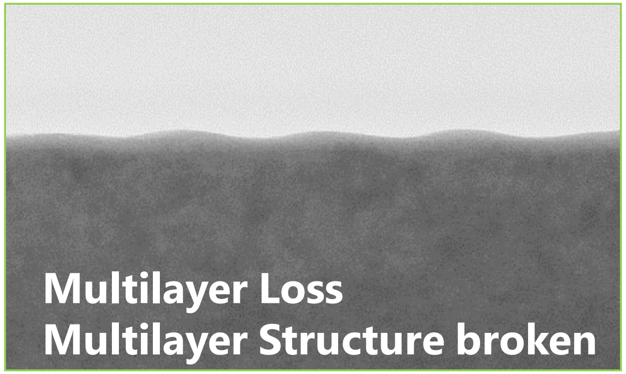




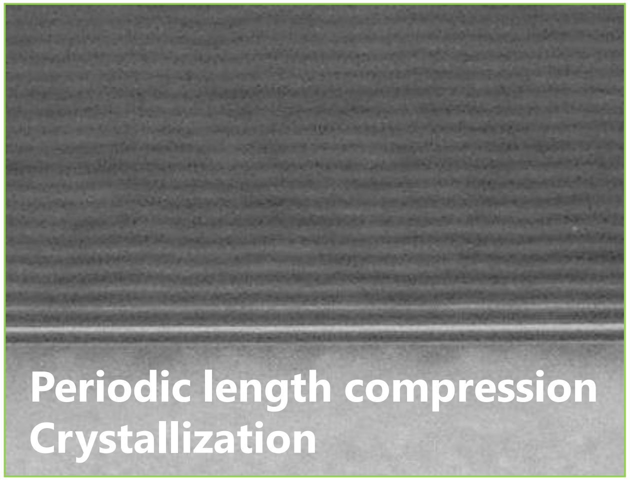
Multilayer periodic length: ~10 nm
Reflectivity @13.9 nm and 6 deg.: ~0

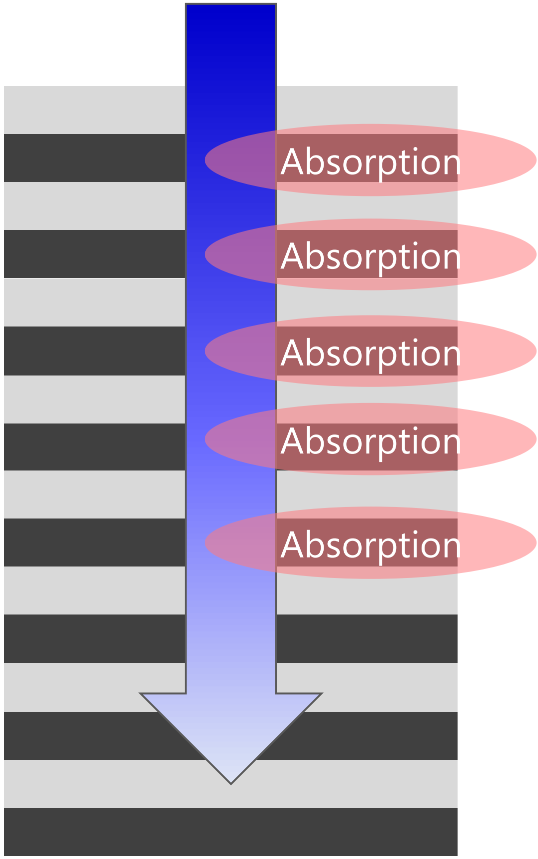
Instantaneous Temperature Estimation

TOP stacks: 450 – 500 deg



BOTTOM stacks: <300 deg

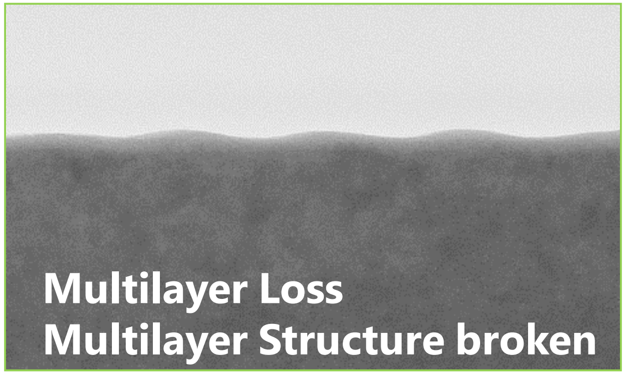




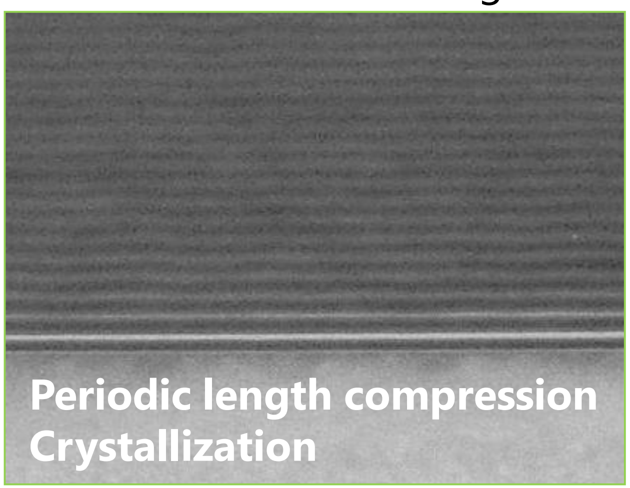
Estimation model

Irradiation damage vs thermal effect

TOP stacks: 450 – 500 deg

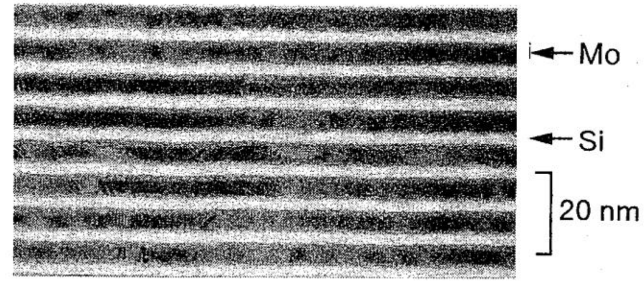


BOTTOM stacks: <300 deg

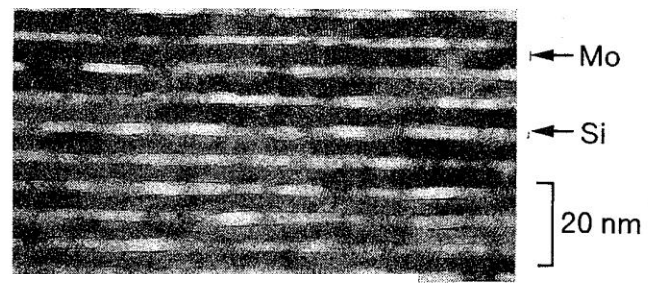


Annealing in Ar atmosphere

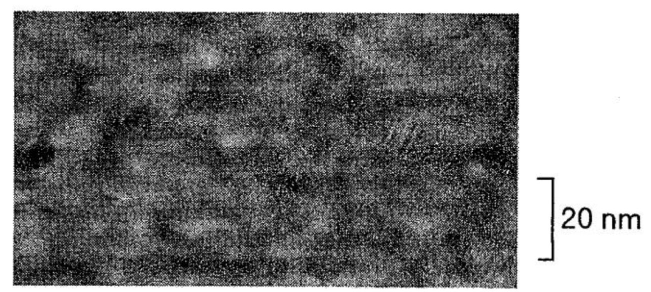
(a) as-depo



(b) 600 deg x 1 hour



(c) 700 deg x 1 hour

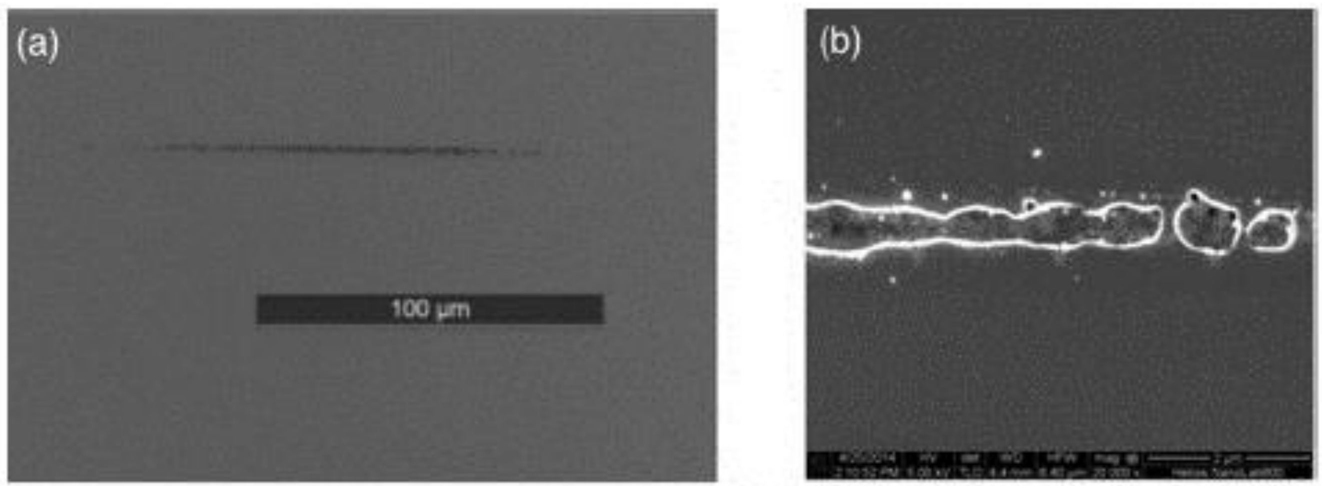


H. Takenaka, et al, J. Appl. Phys. **78**, 5227 (1995)

Non-thermal process?

310 J/cm^2, AOI=4.5 mrad,
R=89.9%, 7 keV

4700 J/cm^2, AOI=3.0 mrad,
R=95.0%, 12 keV



The incorporation of energy transport and dissipation via keV level energetic photoelectrons accounts for the observed damage threshold

A. Aquila et. al., Appl. Phys. Lett. 106, 241905 (2015).

Non-thermal process?

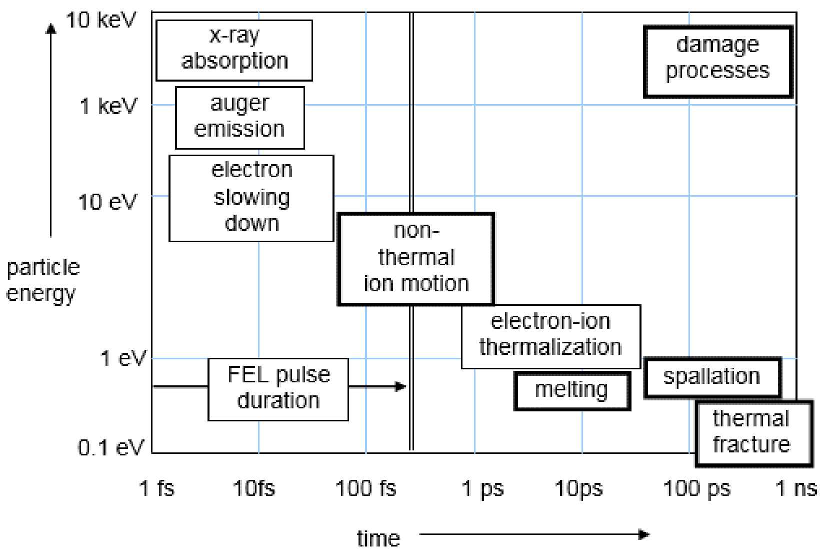


Figure 4. Energy-time plot of processes associated with high intensity x-ray-matter interaction.

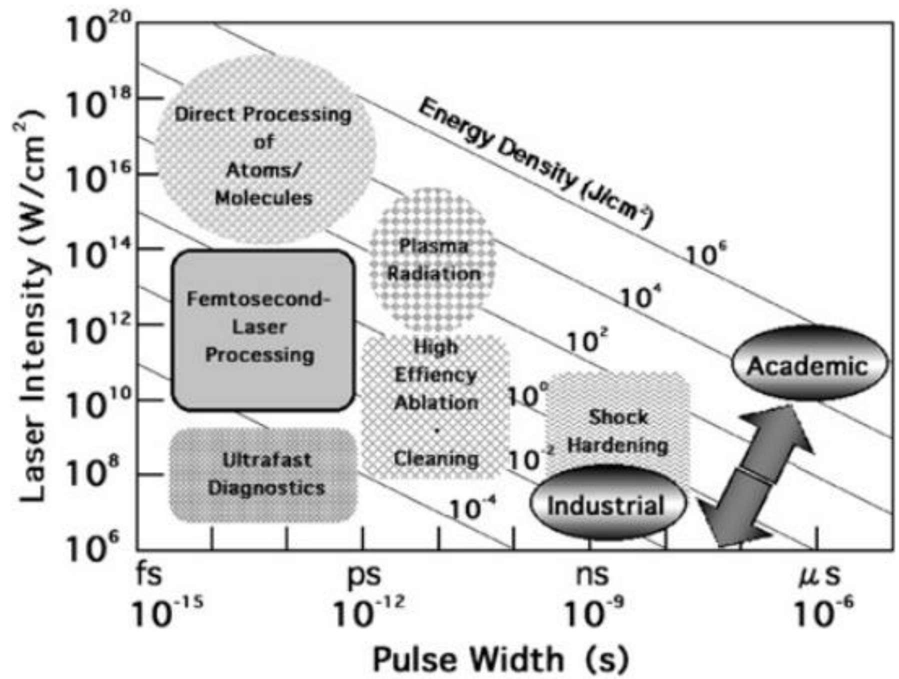
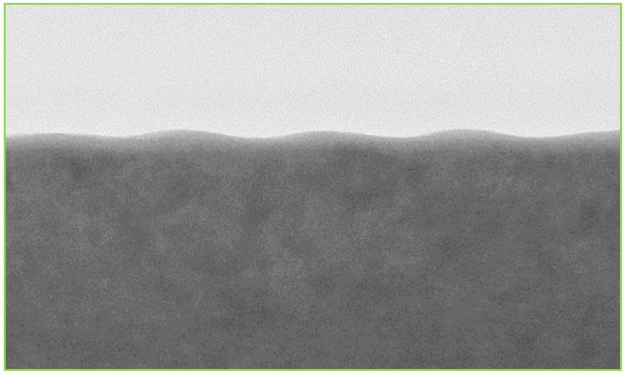


Fig. 1 Industrial applications of the short pulse lasers.

Richard A. London et. al., Proc. SPIE 4500, 51 (2001)

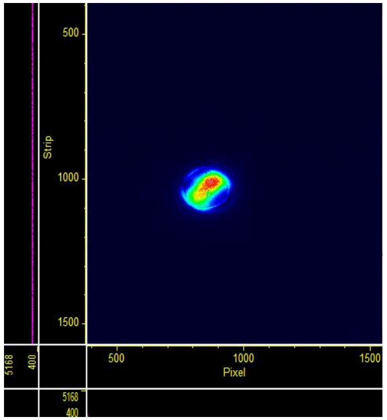
M. Fujita and M. Hashida, J. Plasma and Fusion Research 81, 195 (2005)

Instantaneous Temperature Estimation



Absorption Fluence: 25 mJ/cm^2
Pulse duration: 7 ps

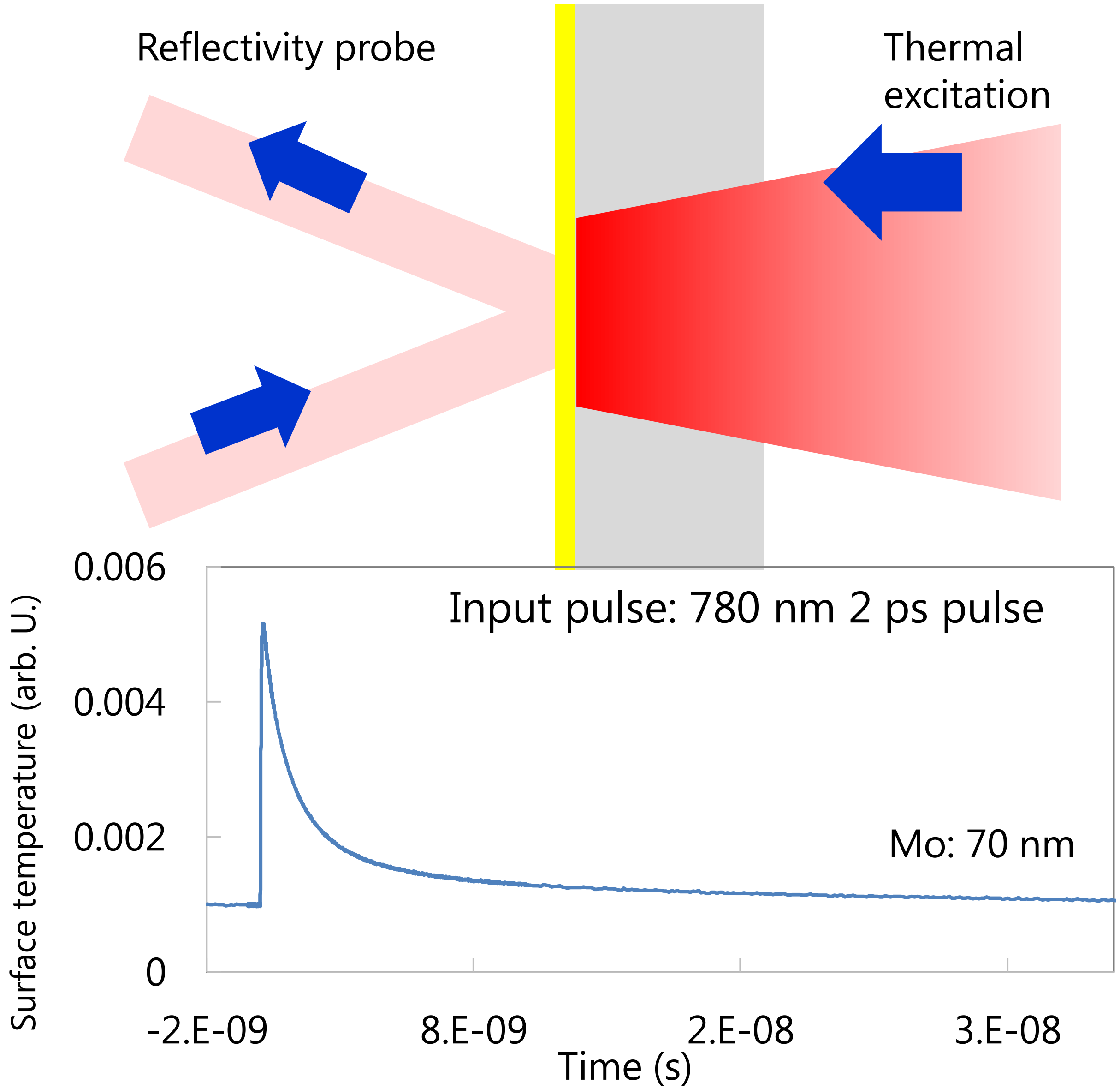
<u>**Estimated Temperature of top Mo: 500 deg**</u>
Irradiation Intensity: 4 × 10^9 W/cm^2



Absorption Fluence: 10 mJ/cm^2
Pulse duration: 100 fs

Estimated Temperature of top Mo: 400 deg
<u>**Irradiation Intensity: 1 × 10^{11} W/cm^2**</u>

Thermal reflectance measurement



Pico-therm. Co.

Multilayer Capability

Fluence
- Irradiation fluence: < 25 mJ/cm^2

Decay time
- Acceptable repetition rate: ~10 MHz

Peak intensity
- Acceptable peak intensity: $<1\times10^{11}$ W/cm^2

	ERL
Power	10 kW
Repetition rate	162 MHz

Assuming beam size of 1 cm and pulse duration of 100 fs at mirror surface
Fuluence: ~0.1 mJ/cm^2, Intensity: $\sim1\times10^9$ W/cm^2

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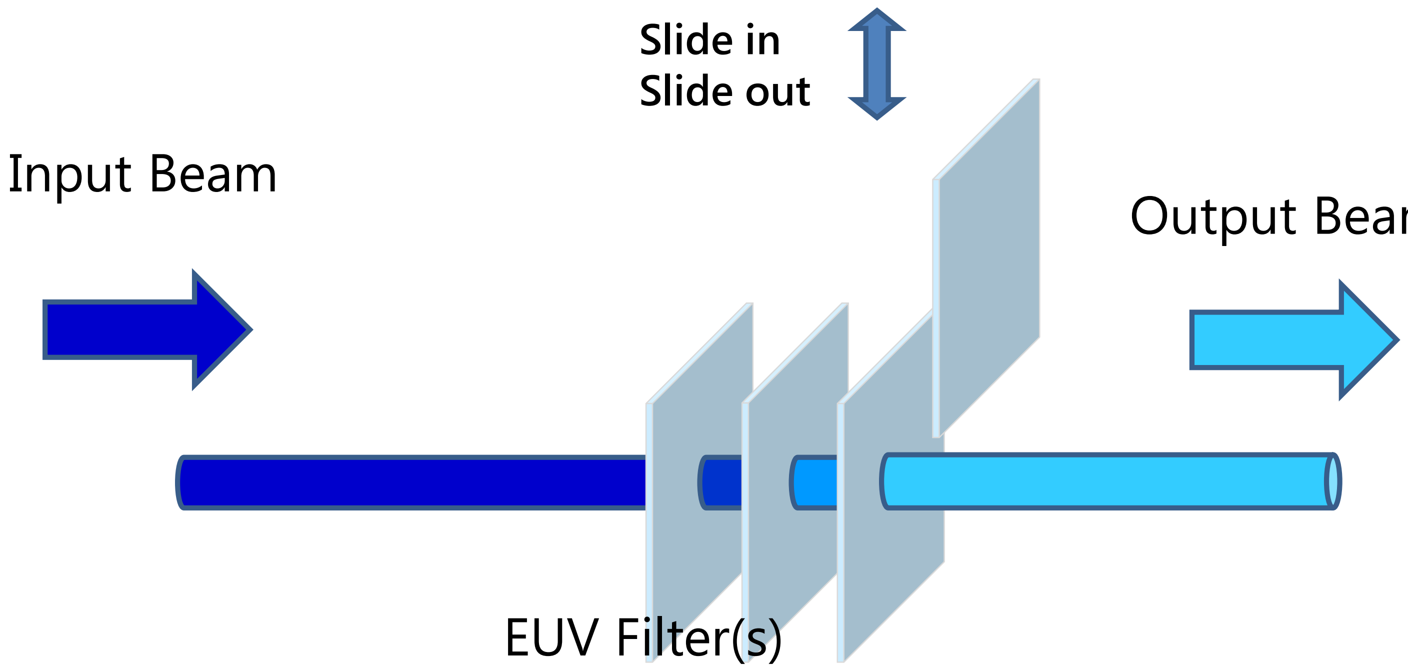
2. Damage formation
   - Thermal process vs Non-thermal process

3. New optics for experiment improvement
   - Mirror based EUV attenuator

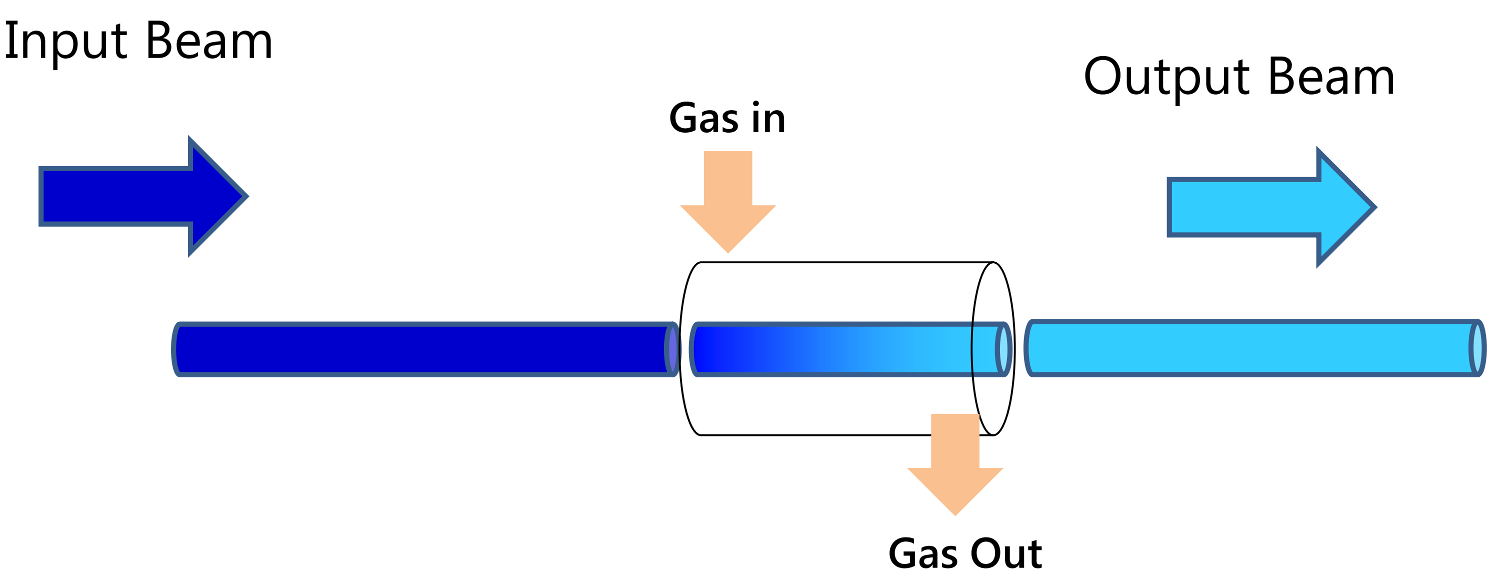
EUV Light Attenuation by using thin-film filter



<u>Advantage</u>
- Keep beam direction
- Easy alignment

<u>Disadvantage</u>
- Discrete Attenuation
- Beam quality losing
- Low damage threshold

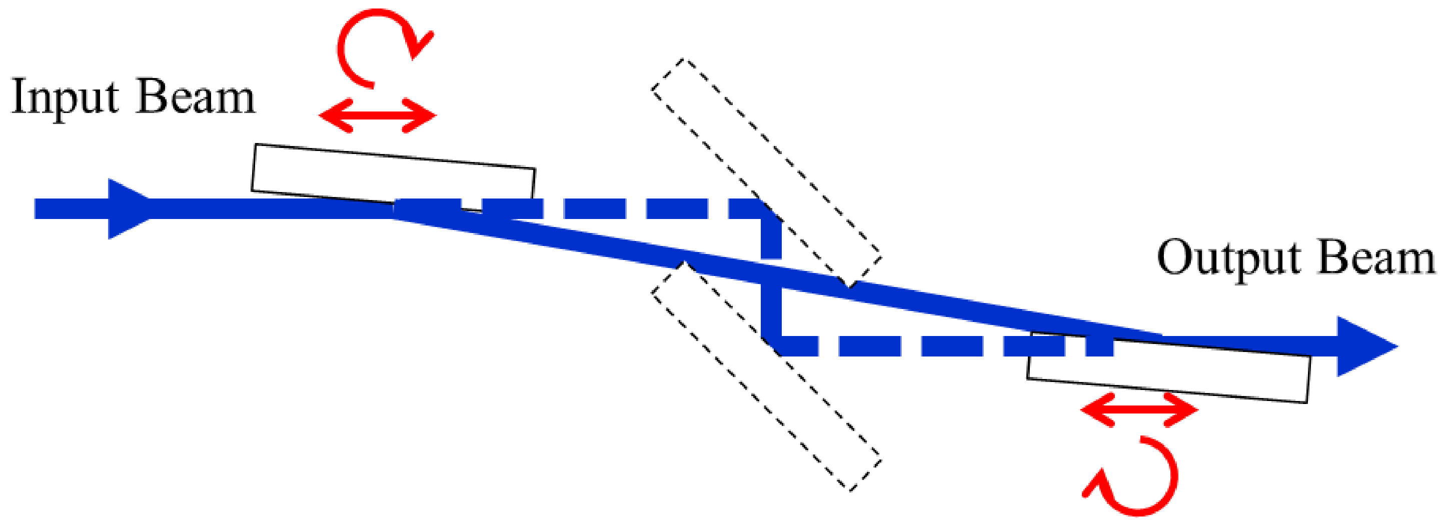
EUV Light Attenuation by using gas-cell



Advantage
- Keep beam direction
- Continuous attenuation

Disadvantage
- Required thin window
- Low stability
- (little bit) large system

EUV Light Attenuation by using Total reflective mirror



Advantage

- Continuous Attenuation
- Static and High damage threshold
- Broadband Attenuation

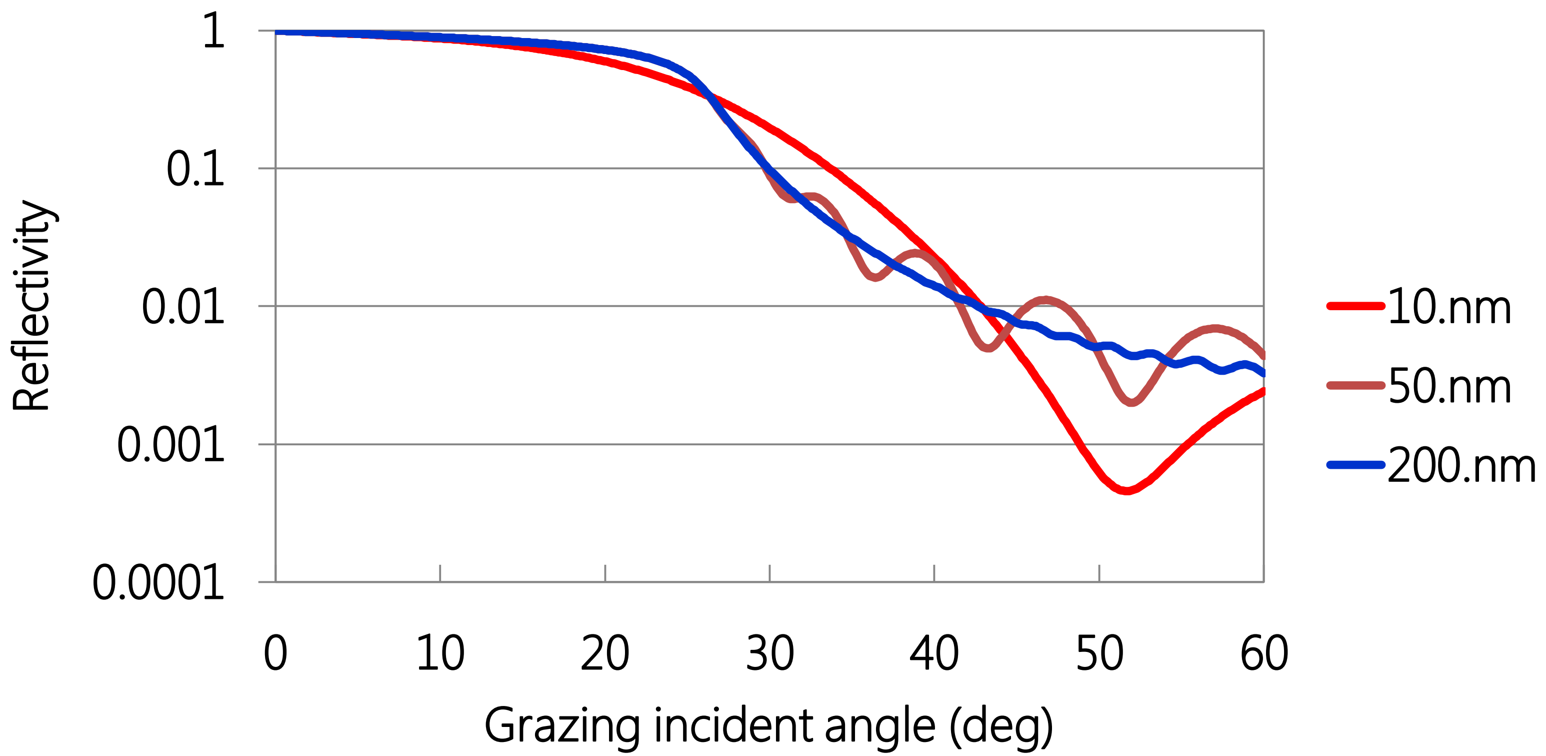
Material Survey

- Low absorption and High melting point
  - Expected high damage threshold
- High-Ionization energy
  - Expected low surface oxidation to obtain high reflectivity

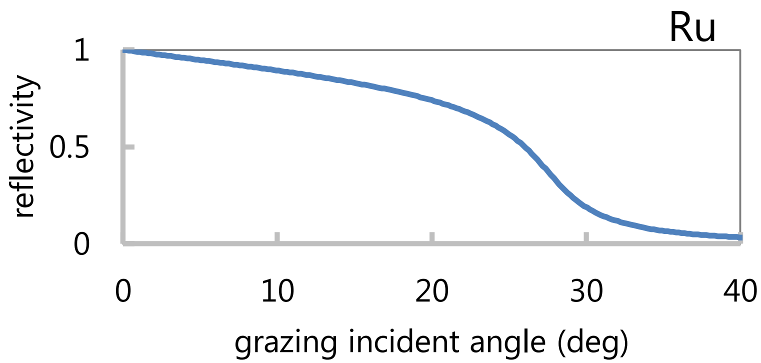
Material	Absorption coefficient*	Melting Point (deg. C)	Ionization energy (kJ/mol)
Ru	**0.016**	**2334**	**710.2**
Zr	**0.0038**	1855	640.1
Mo	**0.0065**	**2623**	684.3
Hf	0.035	2233	658.5
W	0.033	**3422**	**770.0**
Au	0.052	1064	**890.1**

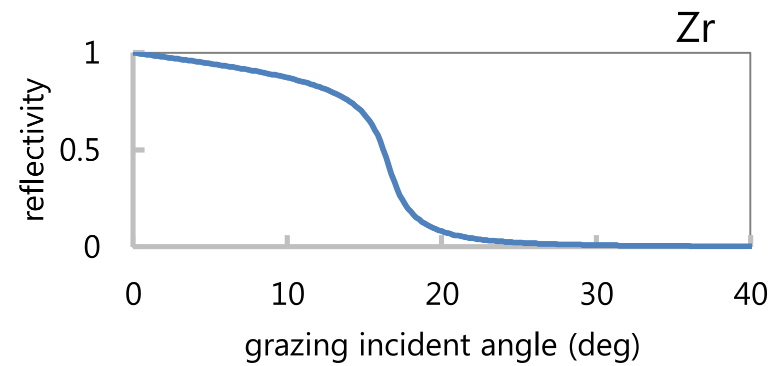
* @13.5 nm, LLNL and CXRO

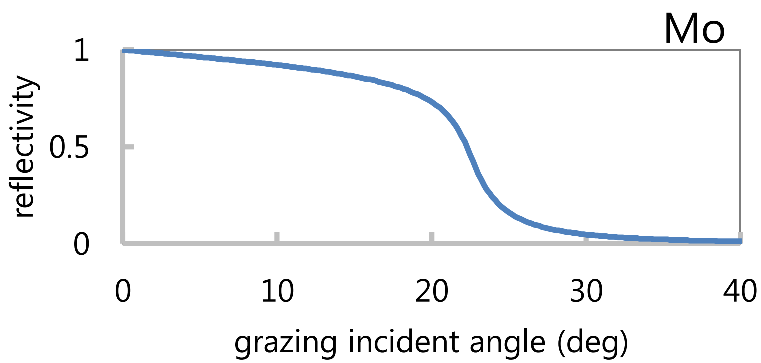
Thickness Optimization

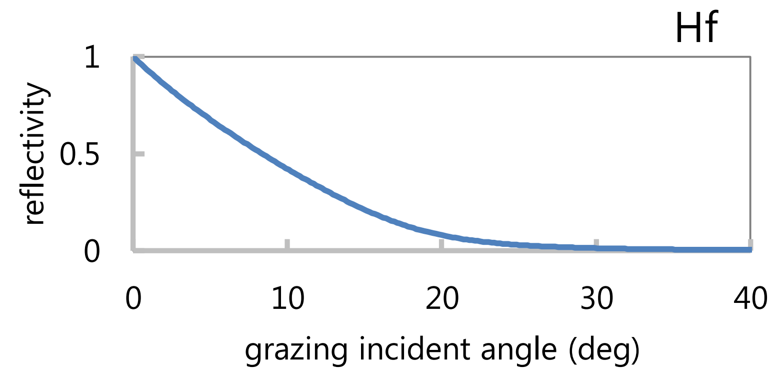


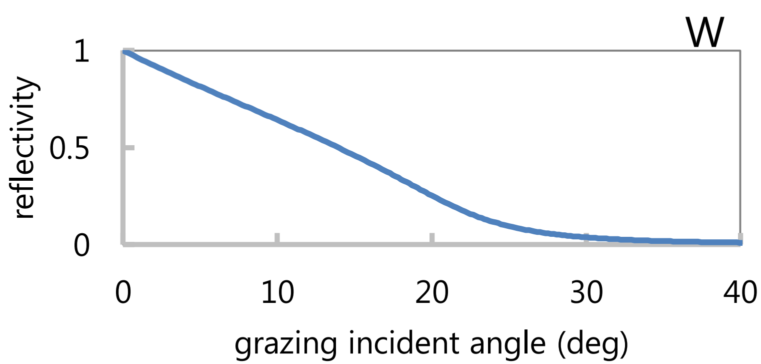
Calculated reflectivity profile of several materials

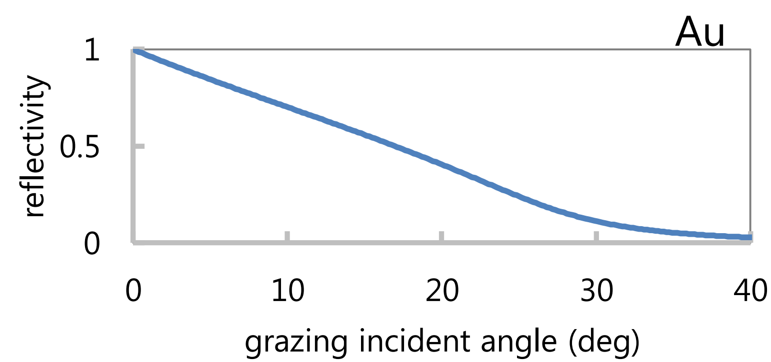












Summary

- Discussion of damage formation of multilayer system
  - Estimated multilayer temperature was 500 deg

- Acceptable parameters were estimated
  - Fluence < 25 mJ/cm^2
  - Peak intensity < 1×10^{11} W/cm^2
  - Repetition rate ~10 MHz

- New optics for experimental improvement
  - Mirror based EUV continuous attenuator was proposed