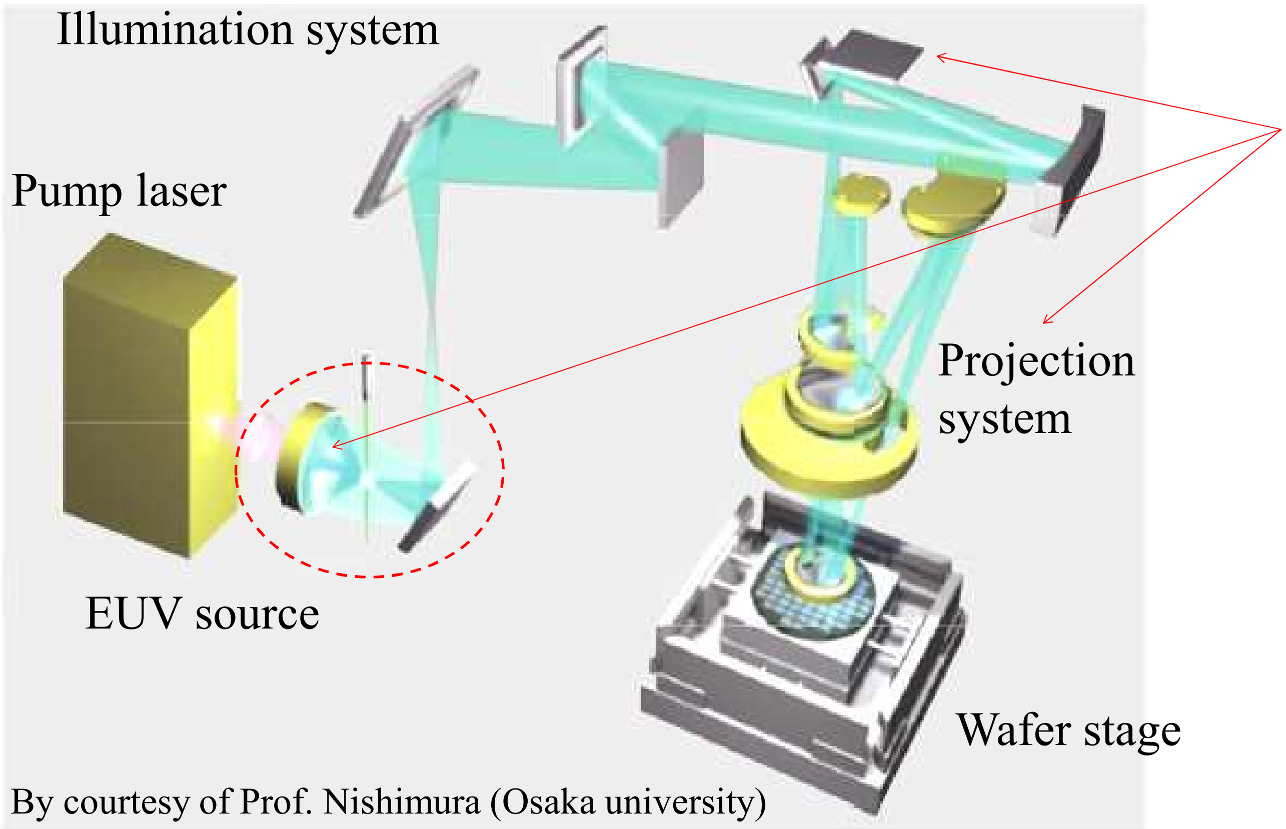
Development of damageless EUV multilayer mirrors for high intensity EUV sources

Satoshi ICHIMARU

NTT Advanced Technology Corporation

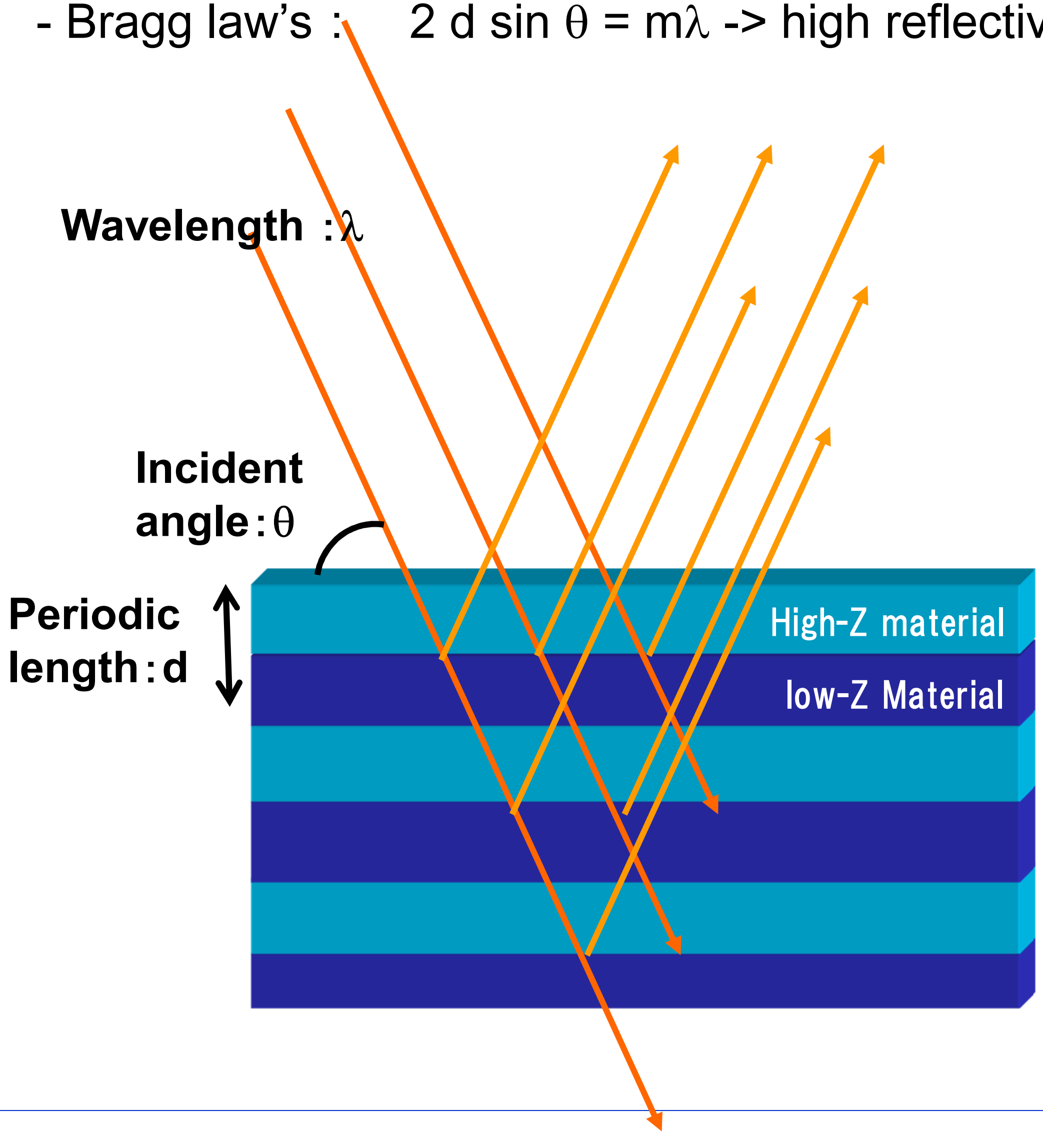
EUV Lithography



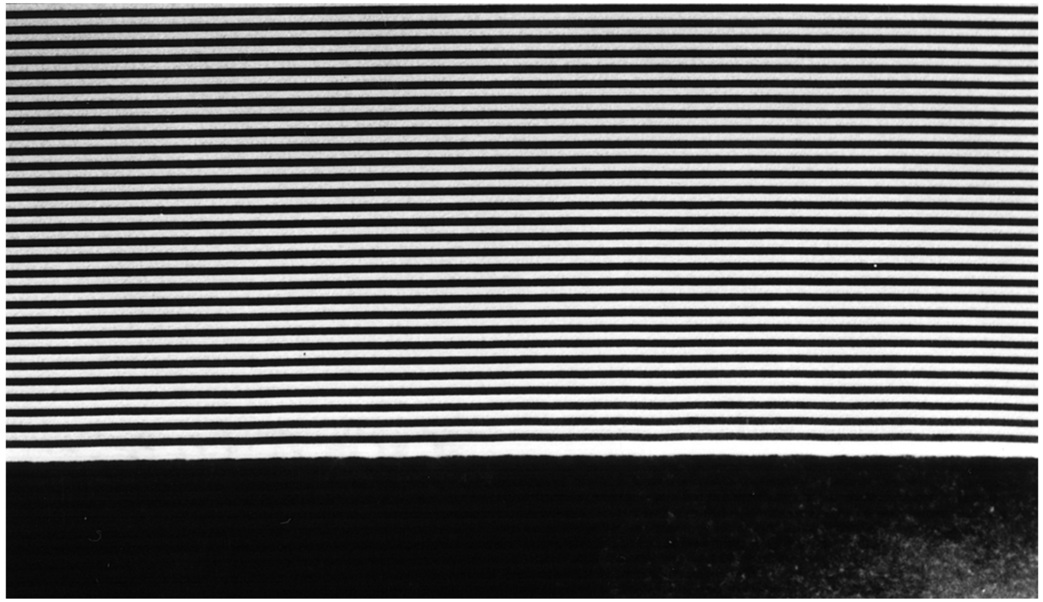
What is EUV multilayer ?

EUV multilayer

- Structures consisting of alternating layers of high- and low-*Z* materials, with individual layers having thicknesses of the order of nanometers, can be fabricated on suitable substrates.
- Bragg law's : $2\,d\,\sin\theta = m\lambda$ -> high reflectivity.



TEM cross sectional TEM image of Mo/SiC multilayer



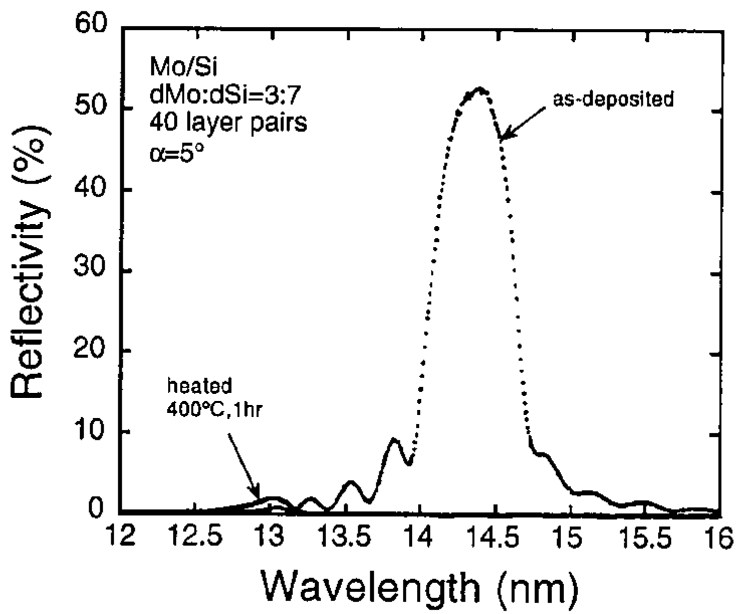
History of EUV multilayer

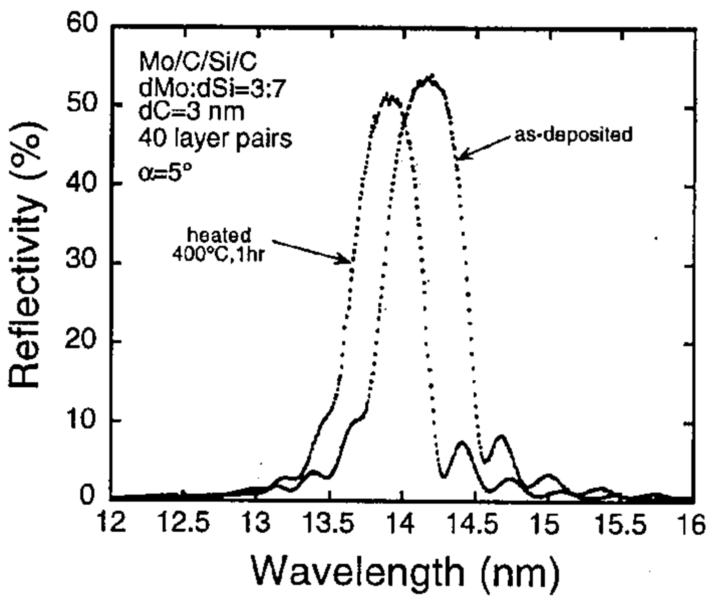
- Start of EUV multilayer research: 1970s～
- Research for thermal stability of EUV multilayer 1990s～

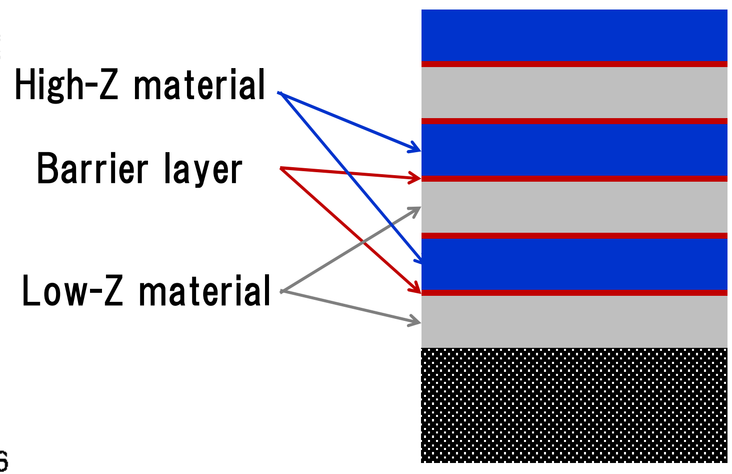
  ：for X-ray sources such as SR, X-ray laser

  ⇒ Thermal effects make serious problems for EUV multilayer.

<u>One example of high thermal stability EUV multilayer:</u> Mo/Si multilayer with C barrier layer





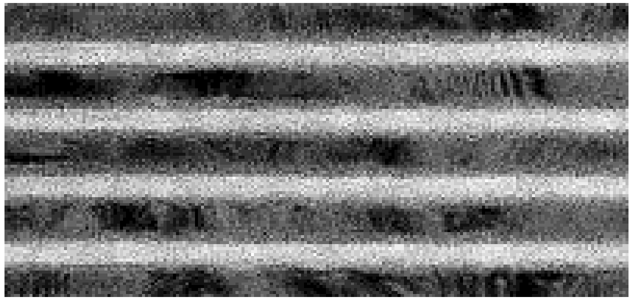


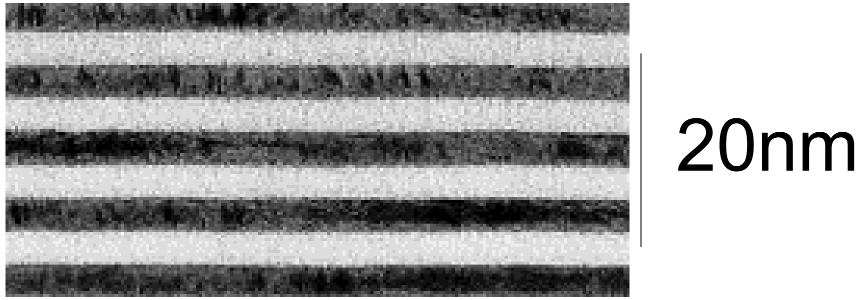
H. Takenaka, T. Kawamura, J. Elec. Spec. and Rel. Phenom. 80(1996),p.381

TEM Cross Sectional TEM image of Mo/Si multilayer

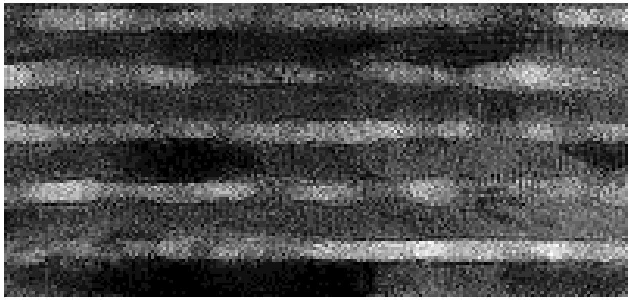
Mo/Si | Mo/C/Si/C(C:0.5nm)

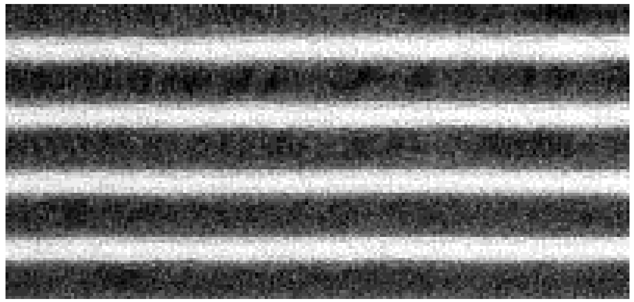
as-depo





Heating
- 600℃
- 1 hour
- Ar





H. Takenaka, T. Kawamura, J. Elec. Spec. and Rel. Phenom. 80(1996),p.381

In order to elongate a lifetime of EUV multilayer mirrors

Examples of previous works

a) High resistance multilayer mirror

- ✓ Mo/Si multilayer with a barrier layer — Takenaka OSA TOPS on EUVL, 4, 169 (1996)
- ✓ Mo/Si multilayer with a capping layer — Bajt, Proc. SPIE 4506, 65 (2001)
- ✓ High stacked Mo/Si Multilayer — Ichimaru, Proc. SPIE, 965814, 9658 (2015)

b) the damage reduction mechanism

- ✓ cooling substrate — Bozec, Proc. SPIE 7969, 79690A (2011)
- ✓ low energy prepulses — Tao, J. Appl. Phys. 101, 023305 (2007)
- ✓ gas curtain — Bollanti, Appl. Phys. B 76, 277 (2003)
- ✓ magnetic fields — Ueno, Appl. Phys. Lett. 92, 211503 (2008)

c) Cleaning of EUV mirror — Oizumi, 3rd EUVL Sympo., Co09 (2004, Miyazaki JAPAN)

These methods are useful for the protection of EUV mirrors from thermal effect, ion attack, and contamination.

High power EUV light sources and ablations of EUV multilayers

Development of High power EUV sources

LPP

- Output250 W （Gigaphoton;2016）

FEL

- FLASH2 started to drive @ λ = 4-60nm （DESY;2014）
- LCLS-II project:10 kW EUV source（SLAC;2014）
- SXFEL@12-30nm（SACLA;2015-）
- Compact-ERL（KEK;2009-）& EUV-FEL light source based on ERL

HHG

- 20.8 MHz cycle （MPI;2011）
- Photon ring project （Univ. of Tokyo, RIKEN;2010-）

High power and fluences EUV light sources, not only FELs but also LPPs, make some several problems.
→ One of them is ablations of EUV multilayer.

Past estimations for damage threshold of EUV multilayer for 13.5nm

- A. R. Khorsand et al., Opt. Express, 18, 2 (2010) p.700
  Mo/Si ML： 45 mJ/cm^2 @～10 fs
- R. Sobierajski et al., Opt. Express, 19, 1 (2011) p.193
  MoN/SiN ML： 48 mJ/cm^2 @～10 fs
- M. Muller et al., Appl. Phys. A 108 (2012), p.263
  Mo/Si ML： 200 mJ/cm^2 @～8.8 ns
  Mo/C/Si/C ML： 260 mJ/cm^2 @～8.8 ns

⇒ Development of a high intensity EUV lights irradiation damageless multilayer for 13.5nm is needed.

Collaboration of QST & NTT-AT

QST (National Institutes for Quantum and Radiological Science and Technology) & NTT-AT collaborates for the development of high damageless EUV multilayer from Dec. 2014.

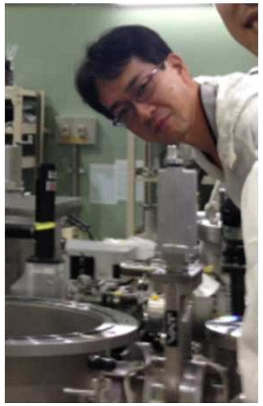
→ We reported some conferences.

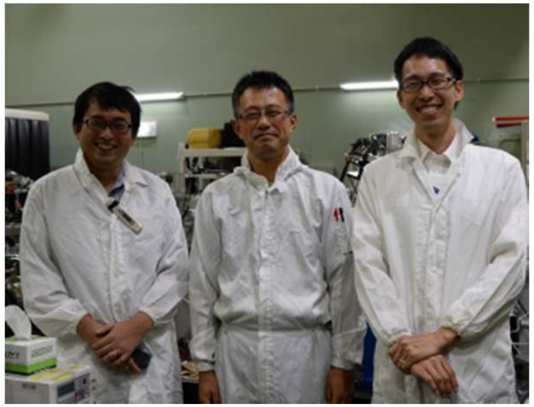
- M. NIshikino, SPIE Optical Engineering + Applications 2015
- M. Ishino et. al., OPIC-XOPT 2016
- M. Nishikino, et.al., 15th ICXRL
- S. Ichimaru et. al., EUVL Sympo. 2016

Collaborator

QST： Masaharu Nishikino, Masahiko Ishino, Noboru Hasegawa, Tetsuya Kawachi

NTT-AT：Satoshi Oku, Masatoshi Hatayama, Takashi Maruyama, Kazuhito Inokuma, Mika Zenba

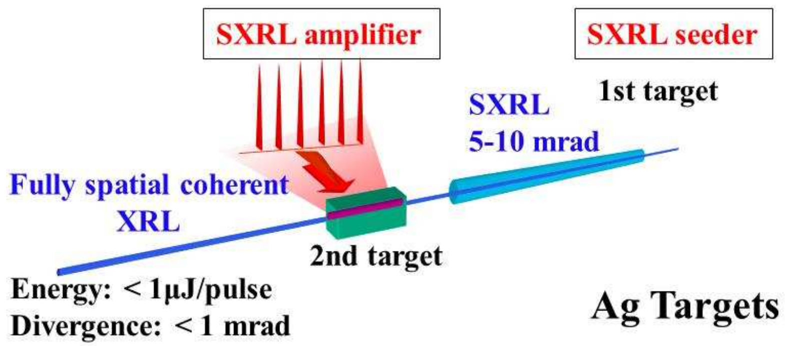




Soft X-Ray Laser system @ QST

The features of SXRL are

(a) the short time scale for 7 pico-second
(b) narrow bandwidth of ~10^{-4}
(c) small divergence beam
(d) highly brightness

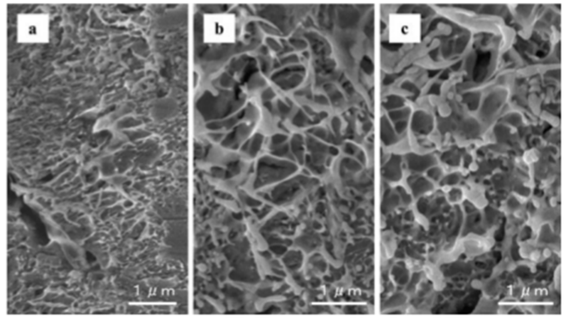


The wavelength of 13.9nm from Ag targets was used for irradiated damage tests for EUV MLs. Our final target is the development of high resistance multilayer for the wavelength of 13.5nm. The difference for the optical constants of materials for 13.5nm and 13.9nm are a little.

This system is already used for the irradiated damage test for several materials.

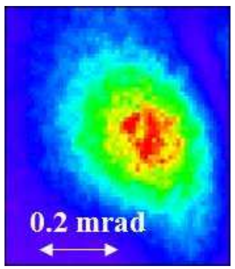
Al, Au, Cu, Si and LiF

M. Ishino *et al*., J. Appl. Phys. **109**, 013504 (2011).
M. Ishino *et al*., J. Appl. Phys. B, **116**, 183302 (2014).
M. Ishino *et al*., Appl. Phys. A **110**, 179 (2013).

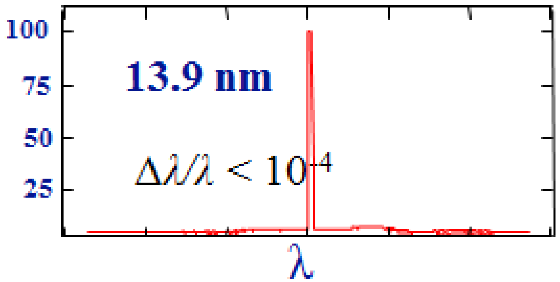


SEM image of irradiated Au surface
M. Ishino *et al*., Appl. Phys. A **110**, 179 (2013).

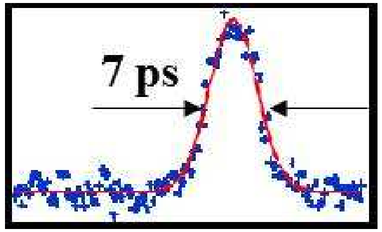
Far-field pattern



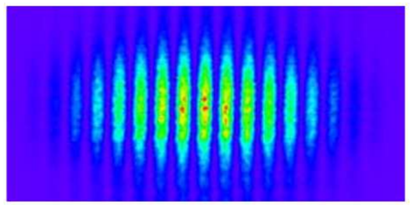
Bandwidth



Pulse Duration

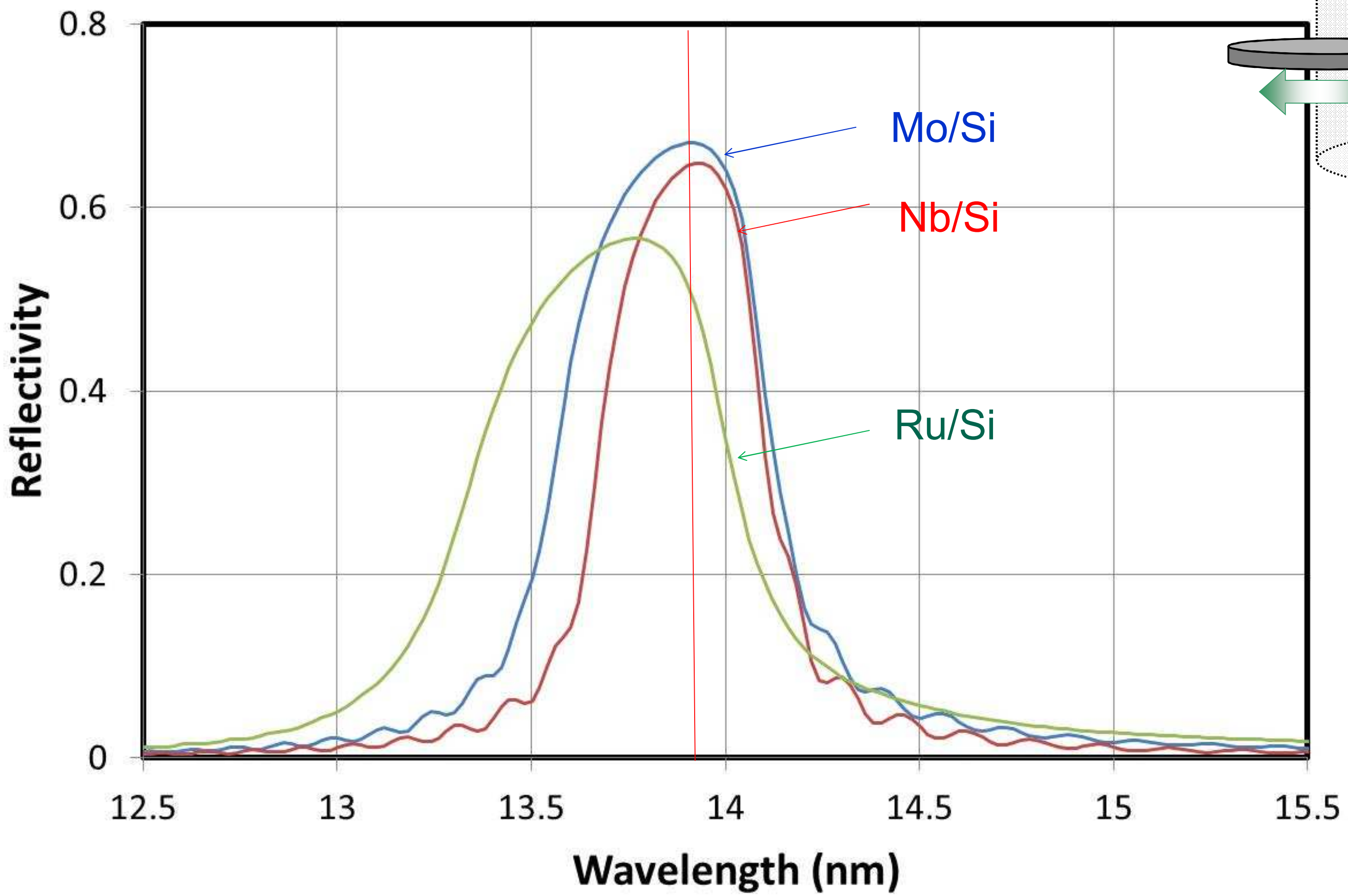


Spatial coherence

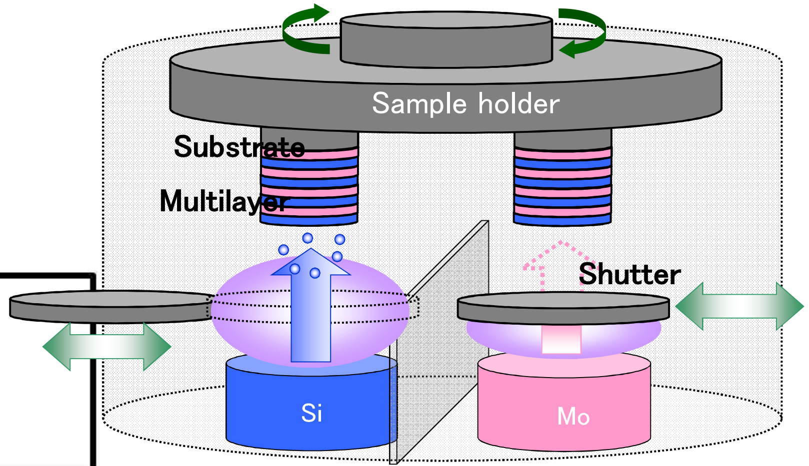


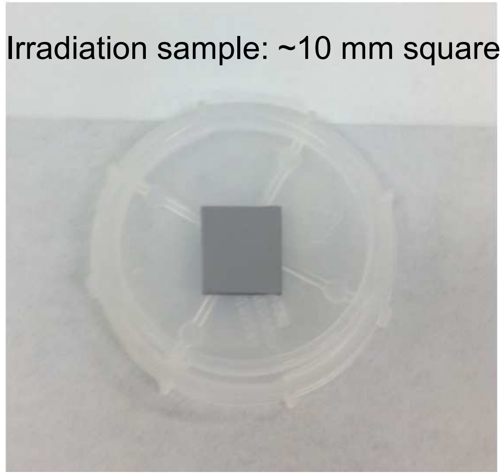
Fabrication of Multilayer mirror

- Method: Magnetron sputtering
- Coating: Mo/Si, Ru/Si and Nb/Si
- Substrate: Commercial silicon wafers.



Measured reflectivity profiles by ALS BL.6.3.2

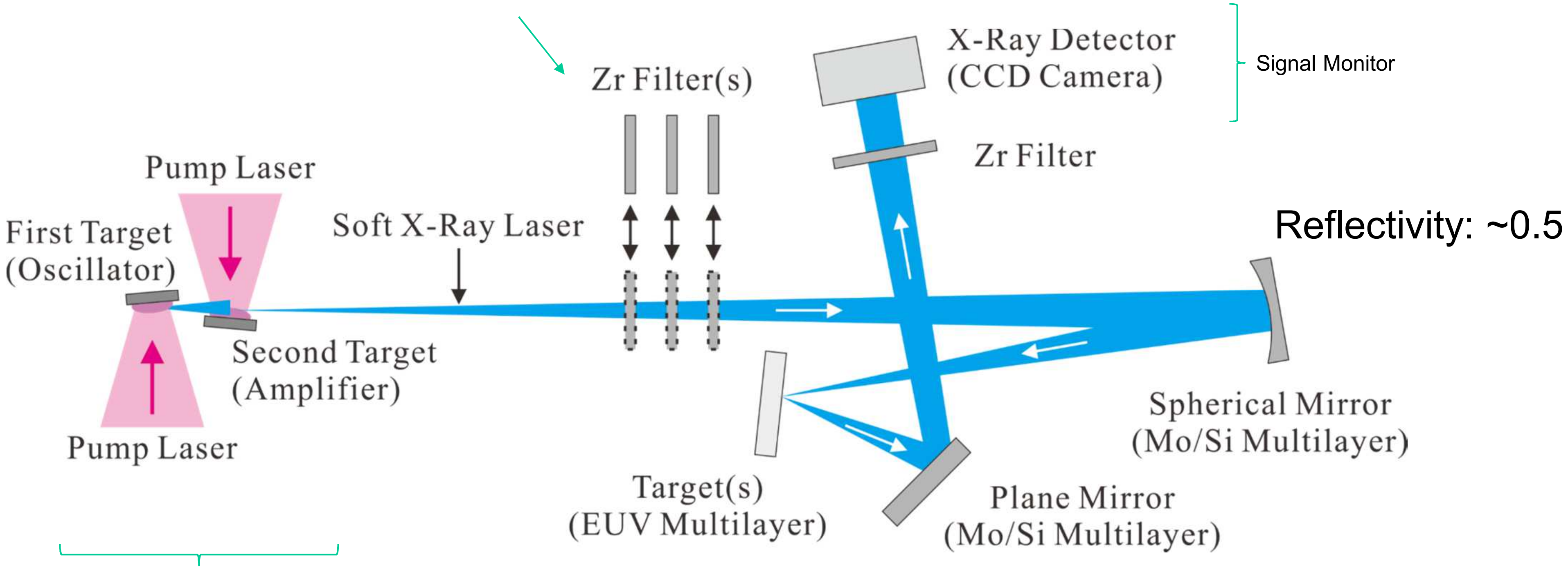




Experimental Setup for irradiation test

- Beam size: on the sample: φ30 μm
- Beam intensity: 20~30mJ/cm^2 @ Zr filter 0.2μm

Total Thickness (μm): 0.1, 0.2, 0.3, 0.4, …
SXRL Transmission: 0.69, 0.48, 0.33, 0.16, …

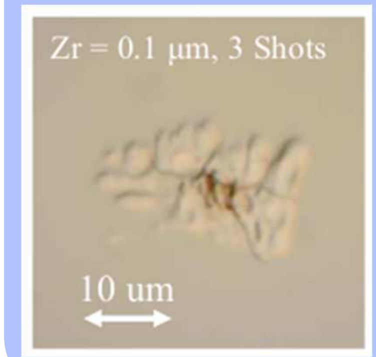


SXRL Source
Output Energy: ~200 nJ/shot

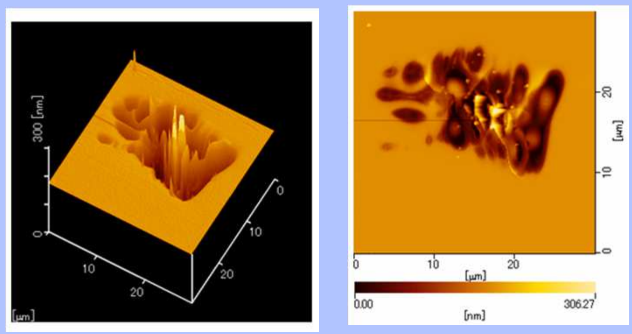
Characterization of irradiation damaged structure of Mo/Si multilayer samples

- Multilayer: Mo/Si
- Zr filter thickness: 0.1 μm.
- Shot number: 3shot.

DIC

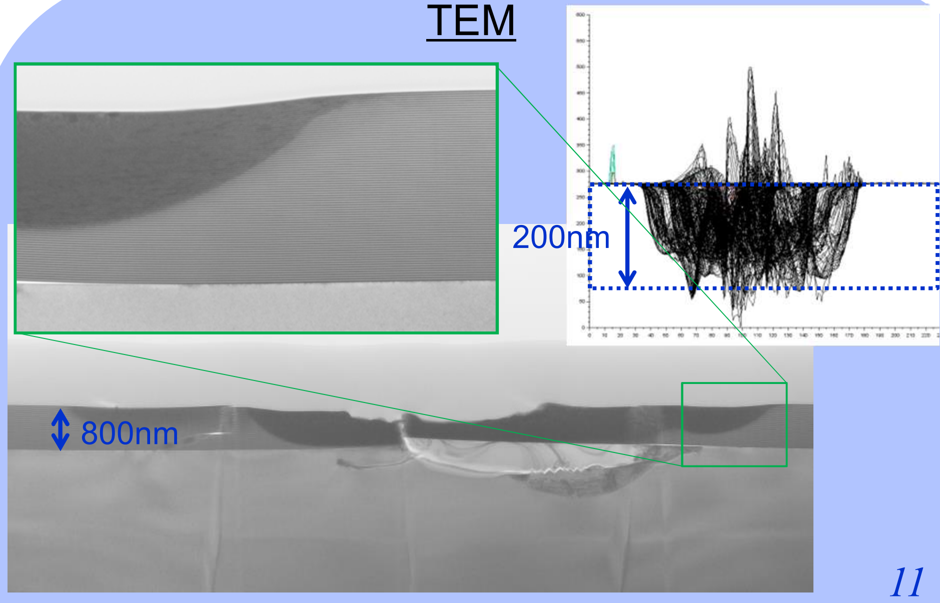


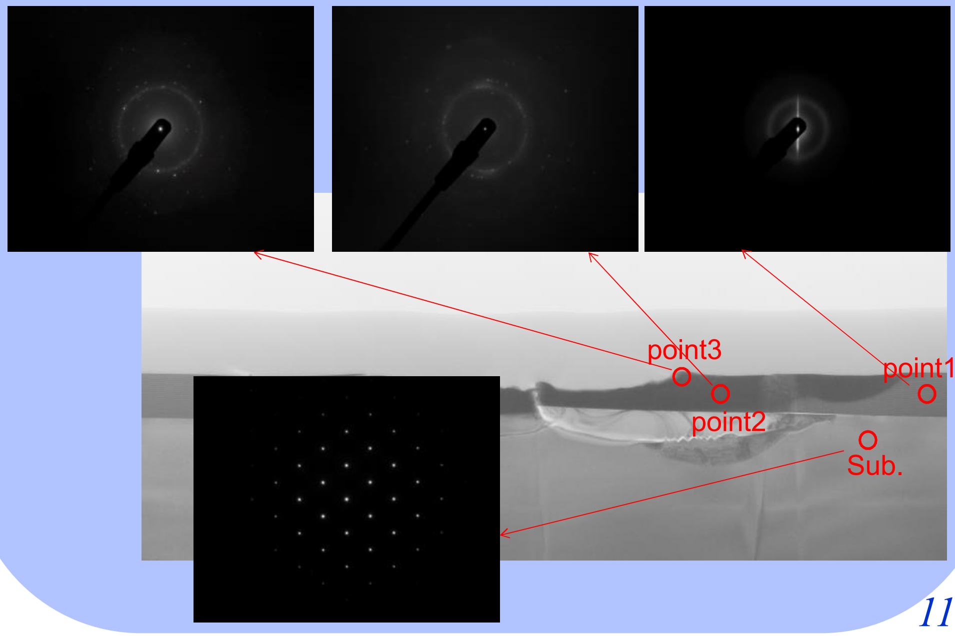
AFM



SEM

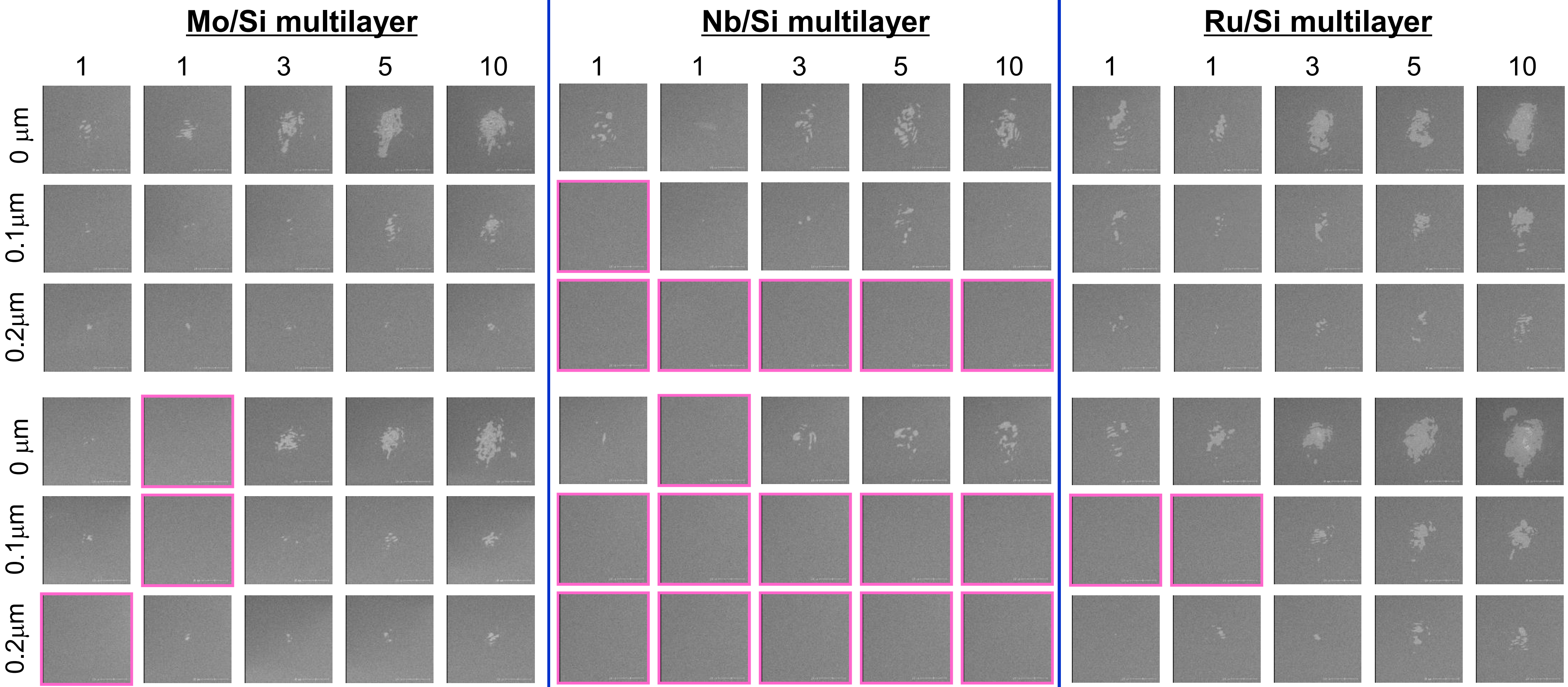
TEM





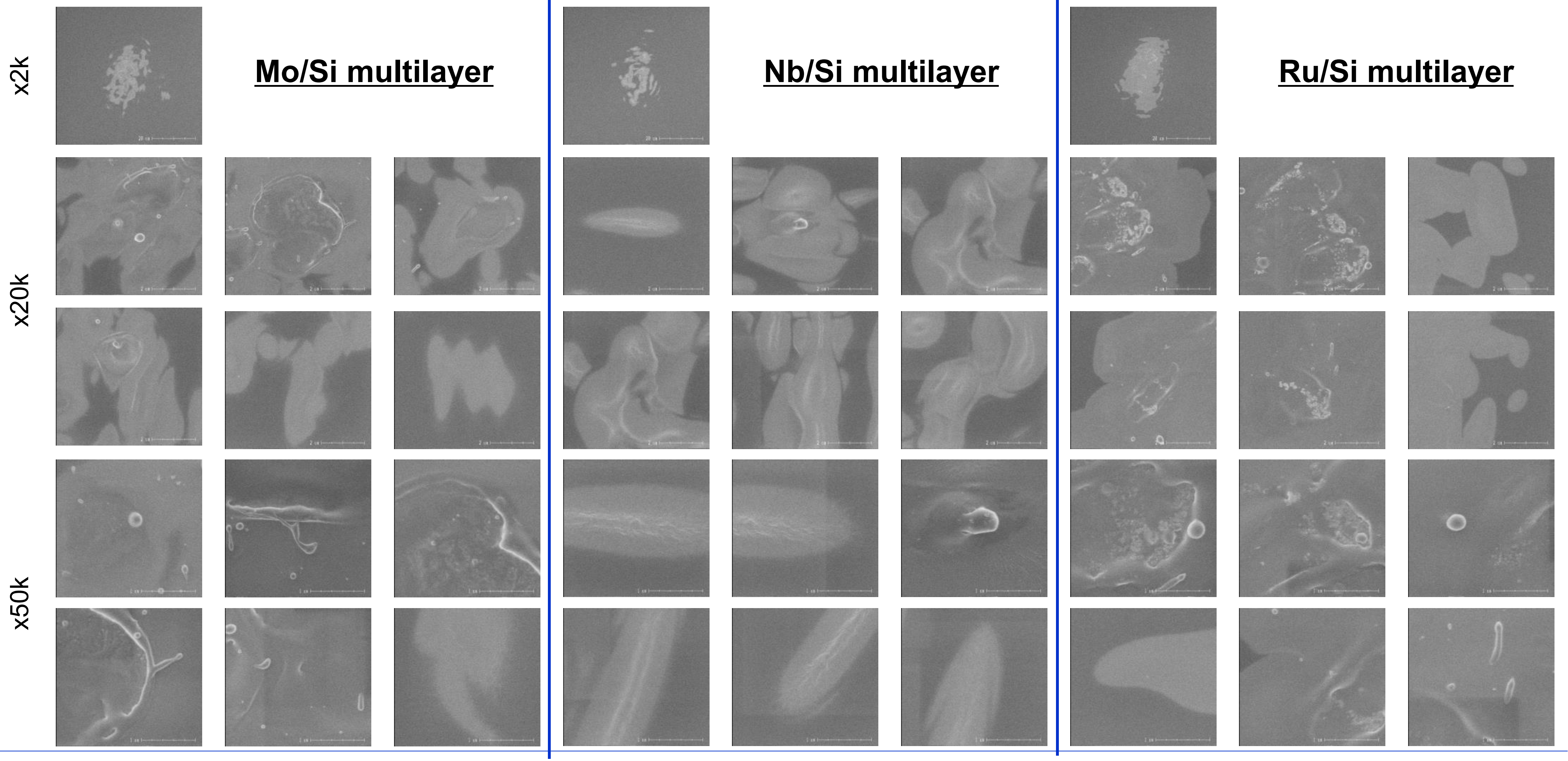
Comparison for irradiated damage structure of Mo/Si, Nb/Si and Ru/Si multilayer samples

- Multilayer: Mo/Si, Nb/Si and Ru/Si multilayer
- Zr filter thickness: 0, 0.1, 0.2, 0.3 and 0.4 μm.
- Shot number: 1shot, 1 shot, 3 shots, 5 shots and 10 shots x 2 cycles
- Irradiated damaged structure was observed by SEM → Nb/Si is superior than the other multilayers for irradiation damage and thus X-ray multilayer.



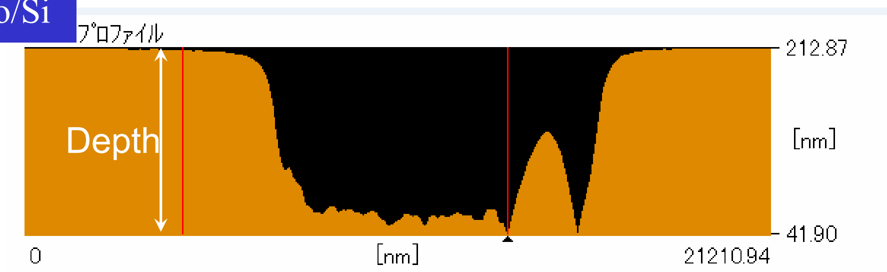
Comparison for irradiated damage structure of Mo/Si, Nb/Si and Ru/Si multilayer samples (2)

- Enlarged SEM images of damages: damages caused by no filter and 10 shots
- Damage of all area of Nb/Si is similar to surrounding damages of Mo/Si and Ru/Si.
- The center damage of Mo/Si and Ru/Si is not almost shown in damage of Nb/Si.
- Irradiated damaged structure was observed by SEM → Nb/Si is superior than the other multilayers for irradiation damage.

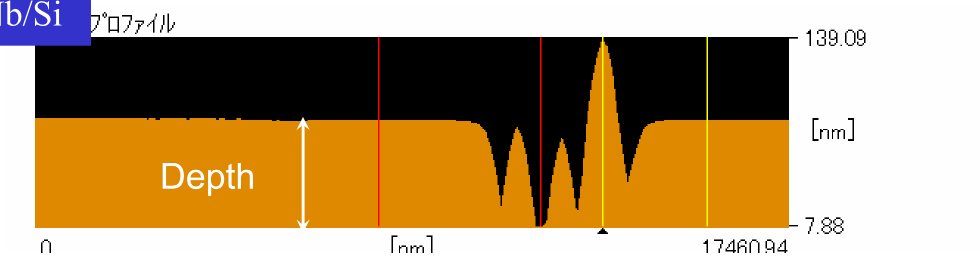


Damage depth of Mo/Si and Nb/Si multilayers

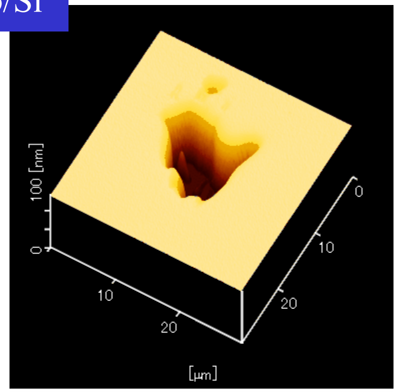
Mo/Si



Nb/Si

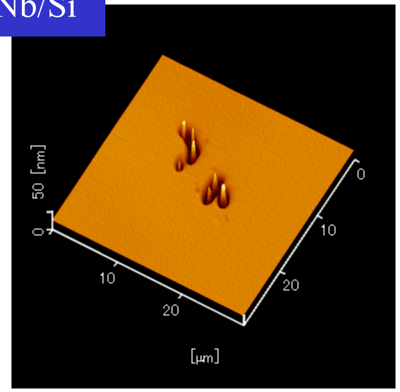


Mo/Si

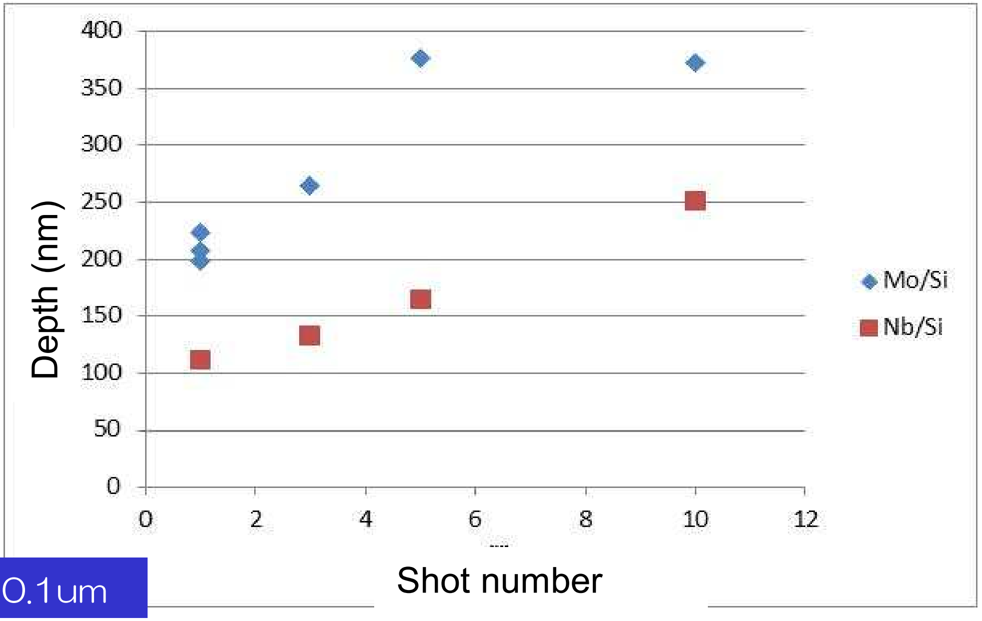


ファイル名: 150324-049f.xqd
コメント 1 : Mo/Si XRL Zr=0.2um
コメント 2 : F=BEST 3Shots
コメント 3 : 30um 0.25Hz

Nb/Si

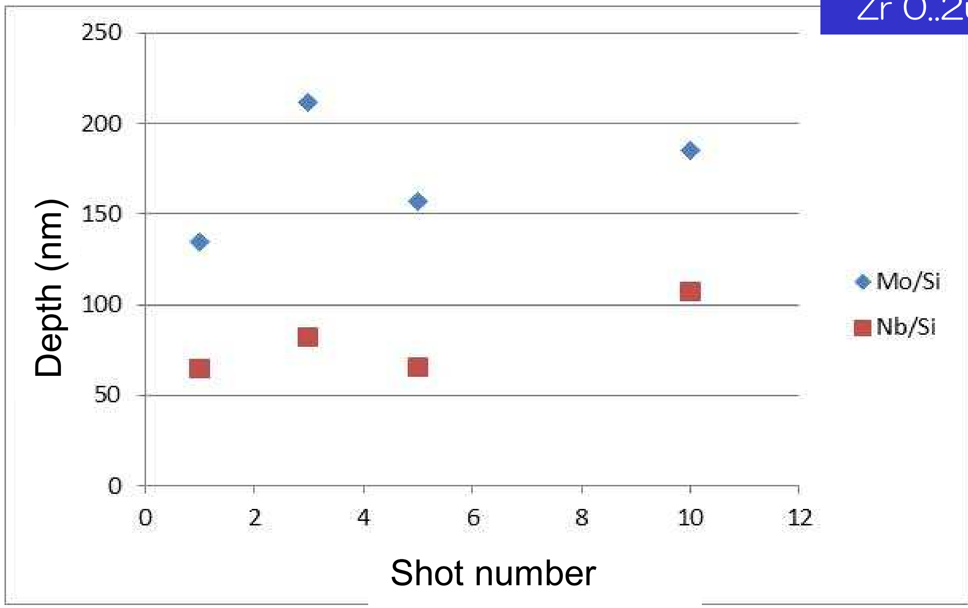


ファイル名: 150401-025f.xqd
コメント 1 : Nb/Si XRL Zr=0.2um
コメント 2 : 3Shots
コメント 3 : 30um 0.25Hz



Zr 0.1um

Zr 0..2um



NTT AT

Summary

The irradiation damage tests for Mo/Si, Ru/Si and Nb/Si multilayer were carried .

<u>Final target: the development of high resistance EUV multilayer mirror for the high fluences EUV lights</u>

Recently, as becoming higher fluences of EUV lights

→ becoming a serious problem of irradiation damages of EUV MLs.

→ This damage makes a non-stability and an unproductiveness of productions using these EUV MLs.

.

<u>Experiment</u>

- ✓ Samples; Mo/Si, Ru/Si, Nb/Si multilayers
- ✓ Irradiation damage test: 13.9nm EUV lights from SXRL
- ✓ Evaluation: A DIC, a SEM, an AFM, and a TEM were used

<u>Results</u>

- ✓ The irradiated damages of all multilayers were observed .
- ✓ TEM imaged of Mo/Si MLs shows not only a crater structure but also the destruction of the ML structure.
  → The area of a reduction for reflectivity of Mo/Si ML is larger than the area of creater.
- ✓ The irradiation damages of Mo/Si and Ru/Si MLs were observed using the 0.2 μm Zr filter, but that of Nb/Si MLs were not observed.
- ✓ The depth profile also shows that the damages of Nb/SI ML are smaller than Mo/Si ML.

→ This result indicates that Nb/Si ML is superior than the other multilayers for irradiation damage.

Future

Nb/Si MLs is the major candidate as a damageless EUV multilayer for for high intensity EUV sources, but we need more experiments.

- Estimation of damage threshold
- Why is the damage is caused ?
- Are there damages in multilayer when damage on the surface is not found ?
- High-Repetition
- Dependency of pulse duration.
- Actual usage
- In order to develop higher damageless EUV multilayer
    -> Ex. Selection of barrier layer