The current status and difficulties in manufacturing multilayer mirrors for BEUV lithography

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29 January 2024, 8th EUV-FEL Workshop, Akihabara/Tokyo

Resolution of an exposure system

Rayleigh's equation

$$R = k1 \cdot \lambda / NA \propto \lambda$$

R: Resolution

λ: Wavelength

NA: Numerical Aperture

(NA=n･sinθ)

k1: process factor

The shorter the wavelength

→ The better the resolution.

Example of EUV exposure system

mask

projection optics

illuminator

intermediate focus

plasma

source

collector

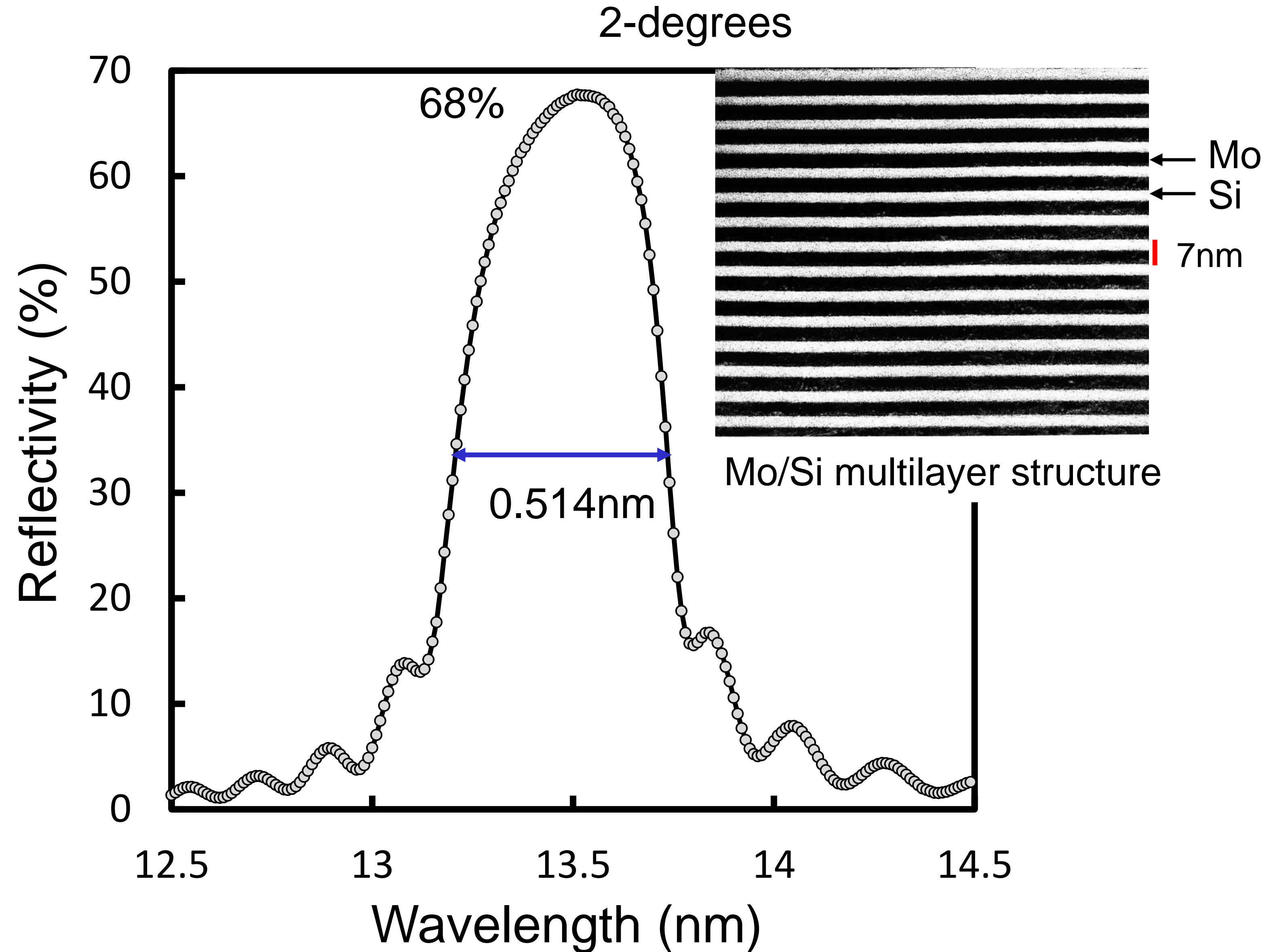
wafer

11 reflections

NA 0.33

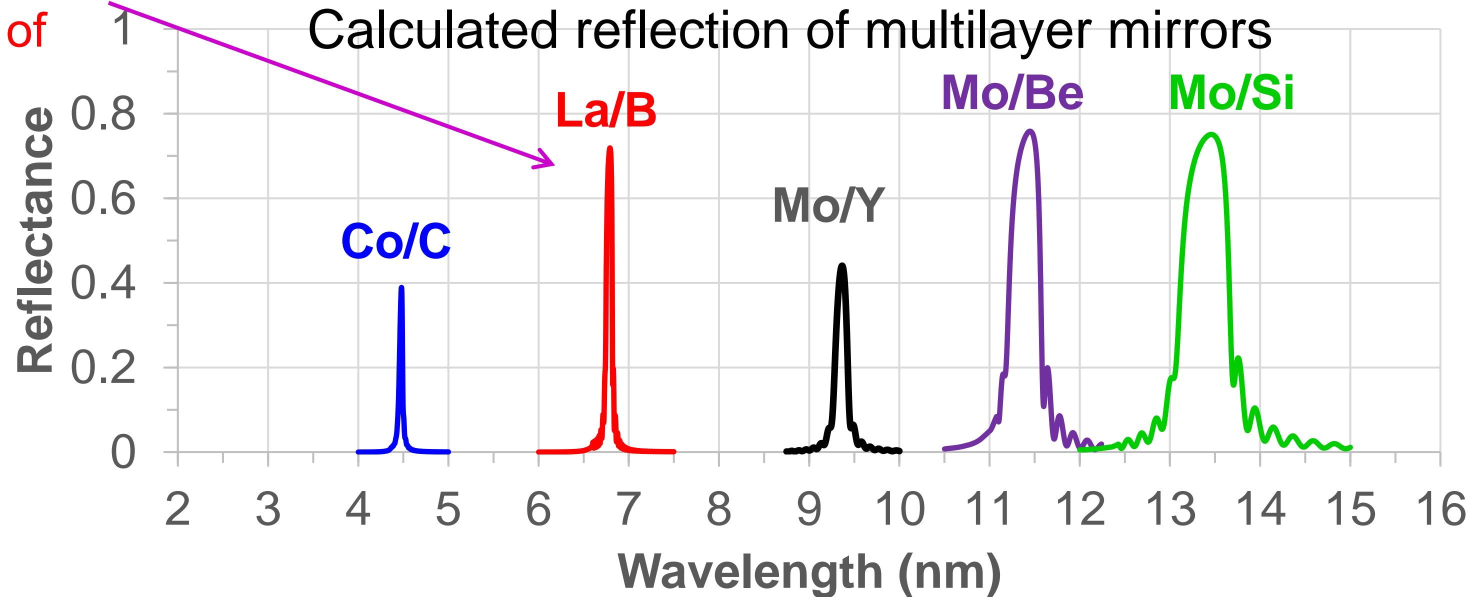
Sascha Migura, Carl Zeiss GmbH, Oberkochen, Germany, 2018 EUVL Workshop
W. Kaiser, J. van Schoot, Sematech Workshop on High-NA, 9 July 2013

Example of the measured reflectivity of Mo/Si multilayer

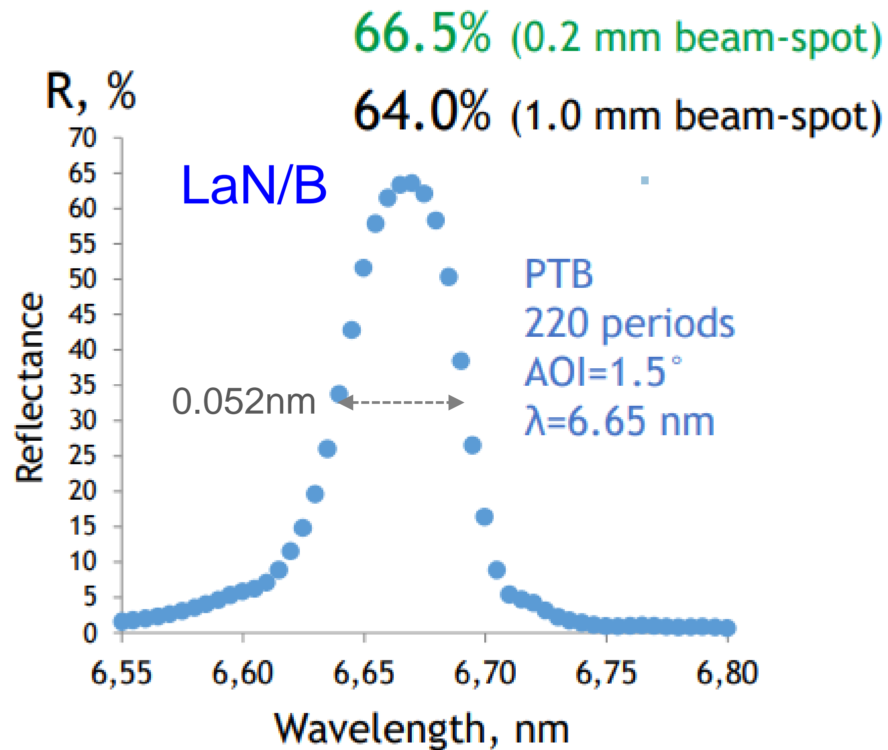


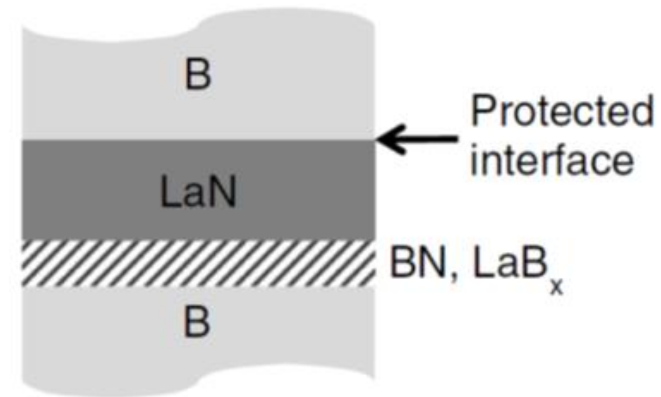
Reflectivity of multilayer - Calculated R for ideal ML (zero roughness)

La/B has high reflect. at 6.x nm which is half of the peak λ of Mo/Si.



Measured reflectivity of LaN/B





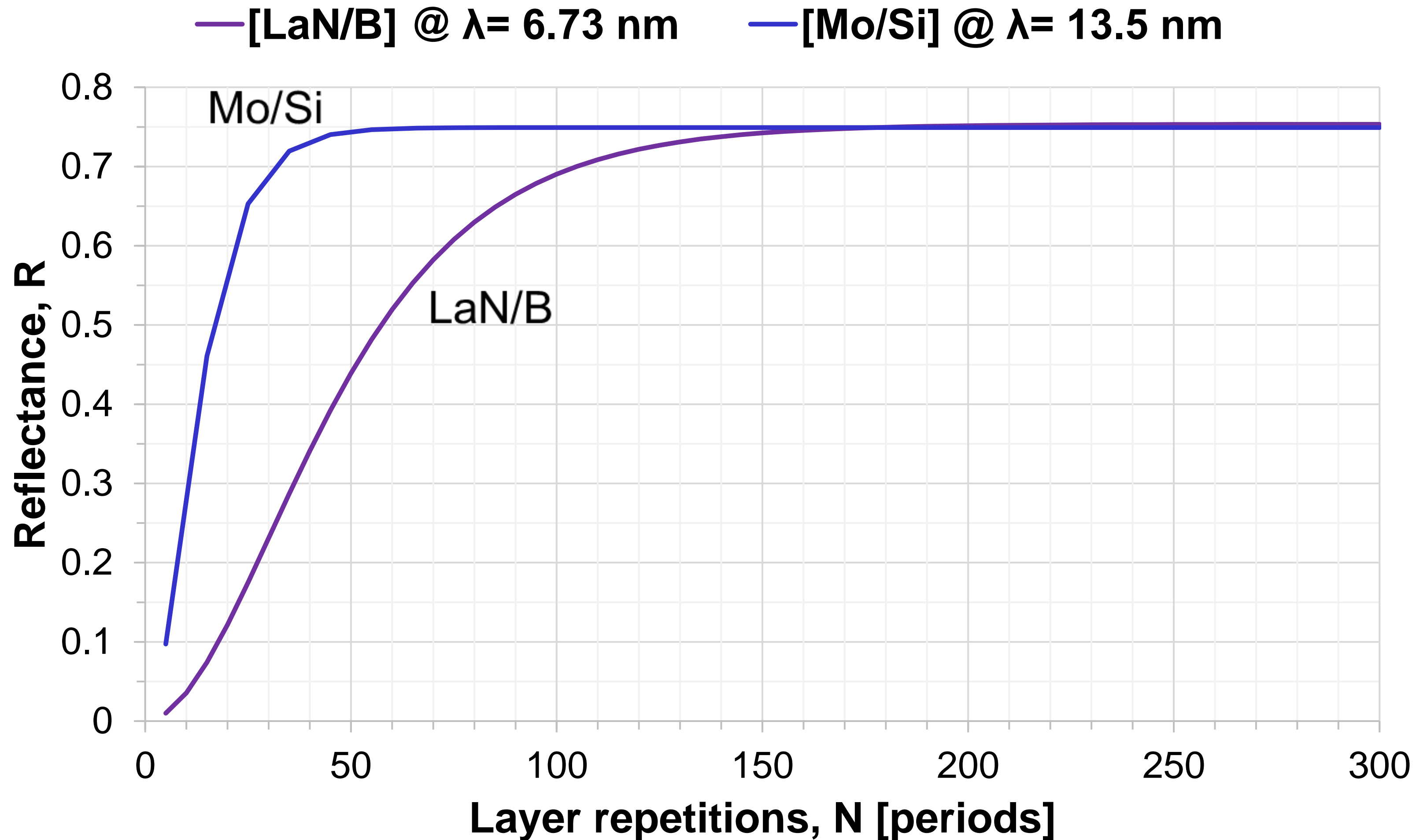
Structure of LaN/B ML

Kuznetsov group fabricated LaN/B and measured reflectivity.
LaN/B exhibited a high reflectivity of 64.1% at 6.67nm.

La/B-based MLs are expected to be used as BEUV.

Kuznetsov, D.S.; Yakshin, A.E.; Sturm, J.M.; van de Kruijs, R.W.E.; Louis, E.; Bijkerk, F. High-reflectance La/B-based multilayer mirror for 6.x nm wavelength. Opt. Lett. 2015, 40, 3778–3781.

Effect on N (the number of repeating layers)



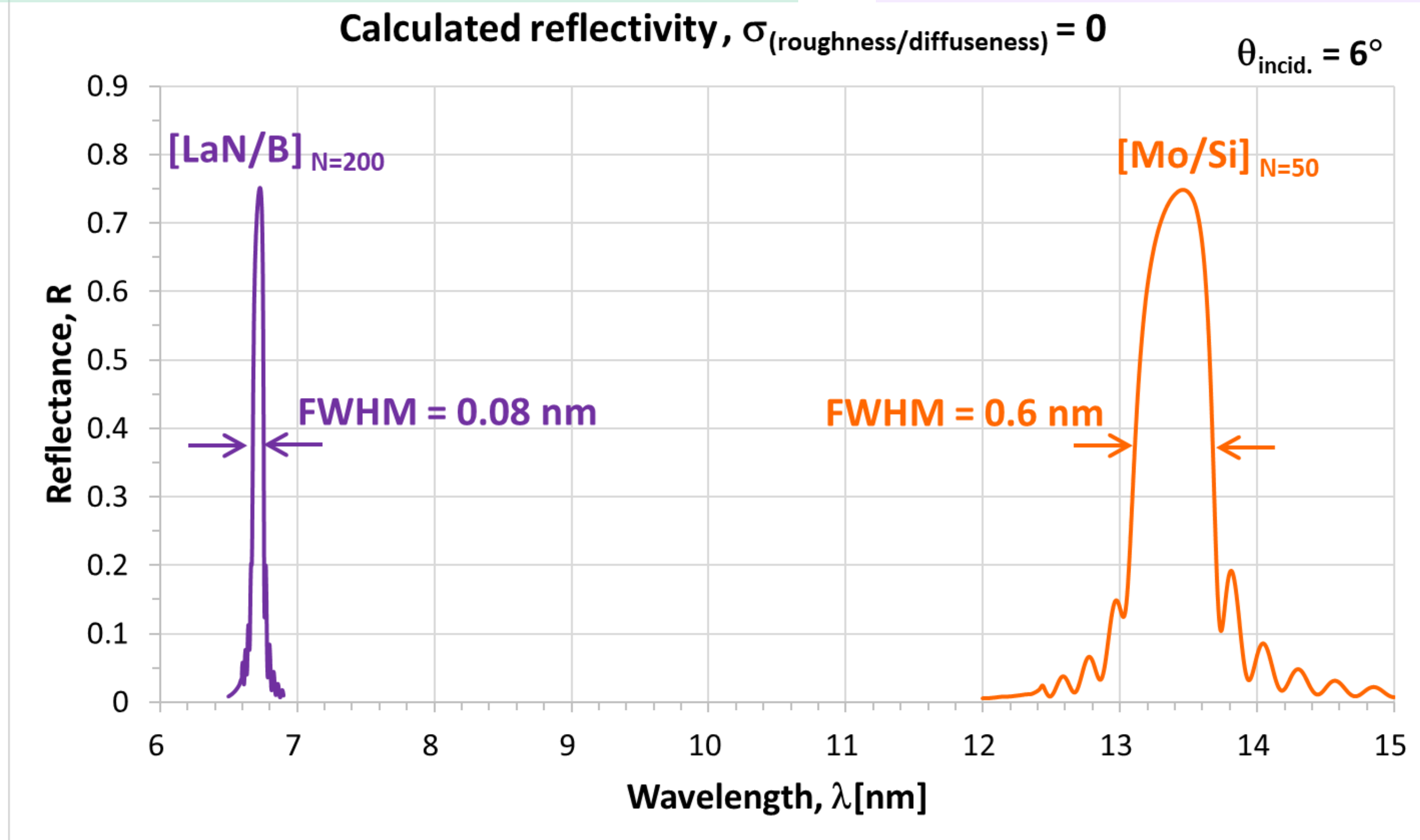
Reflectance dependence of No. of repeating layers for EUV (Mo/Si) and BEUV (LaN/B) @ 6°

In the case of BEUV, it is almost saturated when the repeating layers is above 150 pairs.
→ In the following discussion, N of 200 pairs is used in the calculation of BEUV MLMs.

Calculated reflectances of LaN/B and Mo/Si

[LaN/B]N=200 @ 6.73 nm, d=3.4 nm, Γ=0.4

[Mo/Si]N=50 @ 13.5 nm, d=6.7 nm, Γ=0.35

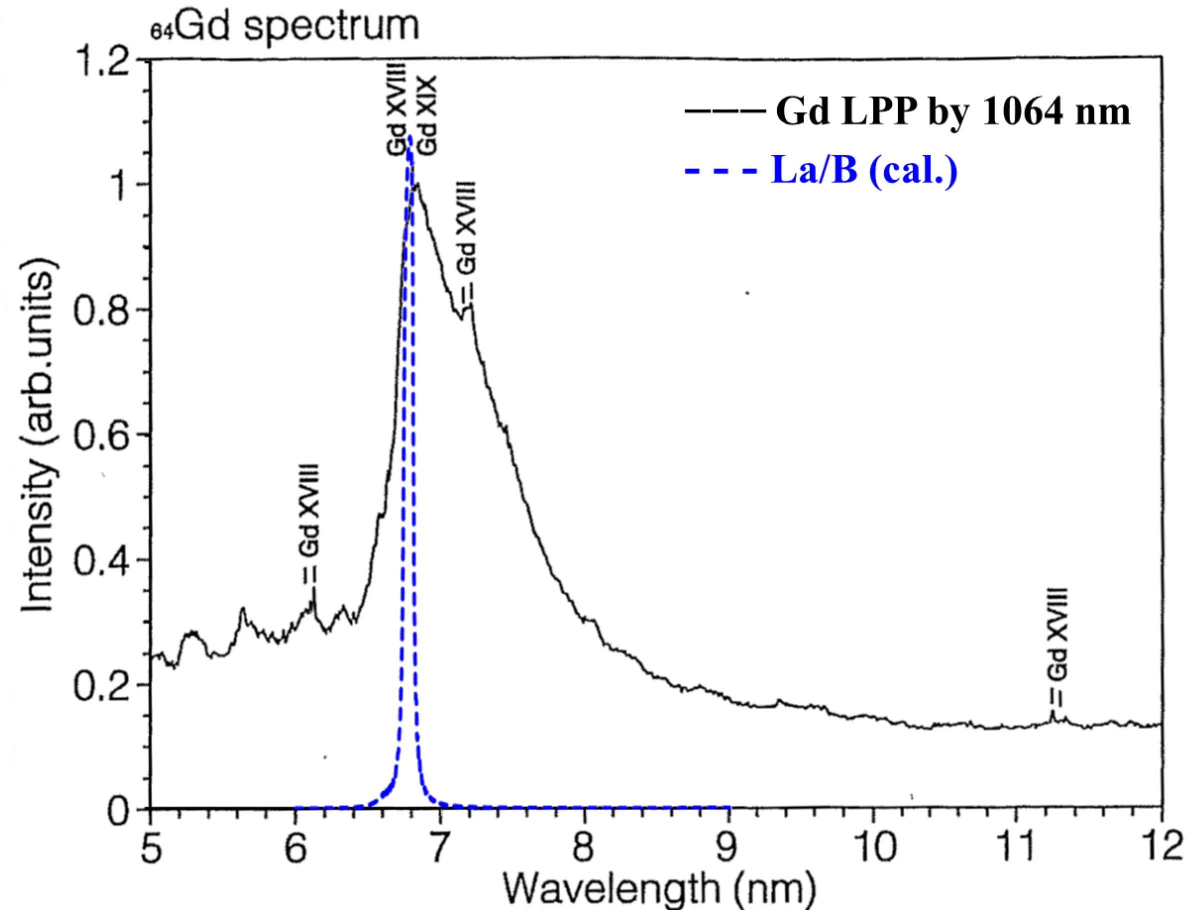


Calculated reflectance of La/B-based ML is high at 6.7 nm

The reflectance bandwidth of LaN/B ML is an order of magnitude narrower than that of Mo/Si ML.

Emission spectrum of Gd LPP and reflectance curve of La/B

Comparison between the emission spectrum of Gd LPP and the reflectance curve of La/B.



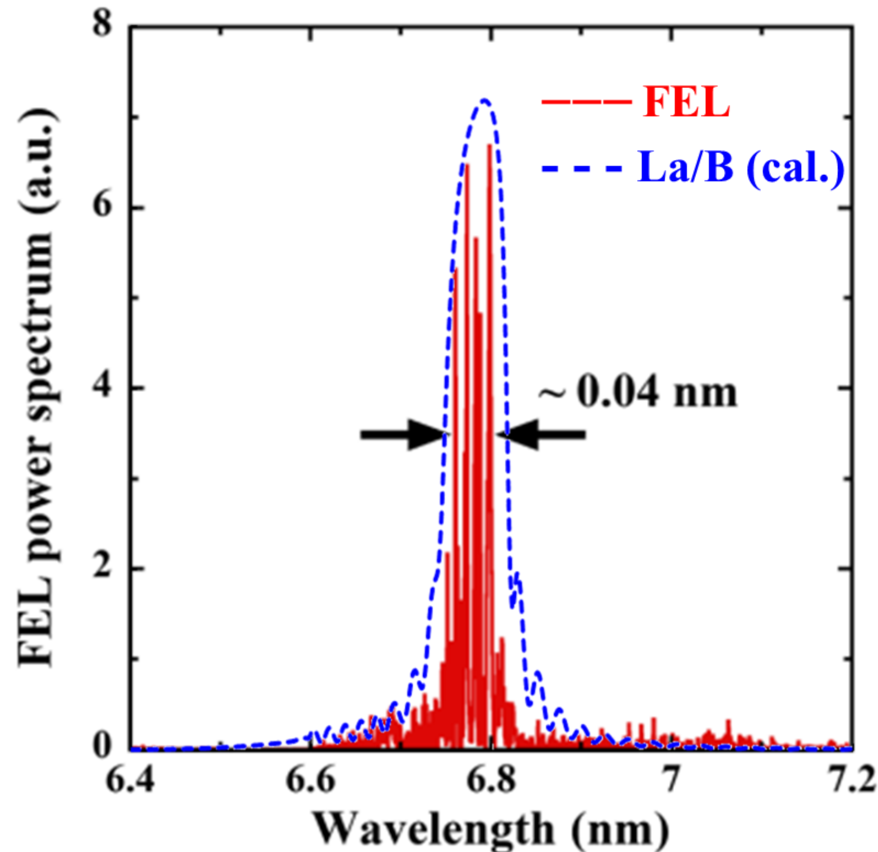
Reflection width of MLM is too narrow

→ Only a small amount of photon flux of the EUV LPP light can be extracted.

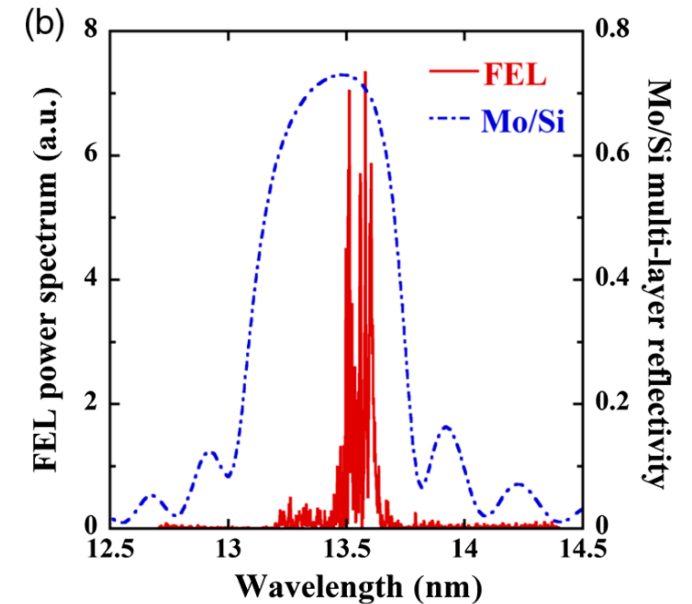
Gerry O'Sullivan, Pardraig Dunne, Takashi Higashiguchi, Takanori Miyazaki, Fergal O'Reilly,, Emma Sokell,
Photon Sources for Lithography and Metrogy, Ch. 2, Fig.2.8,

FEL spectrum and reflection shape of La/B multilayer

Comparison between the bandwidth of La/B and the λ spread of FEL



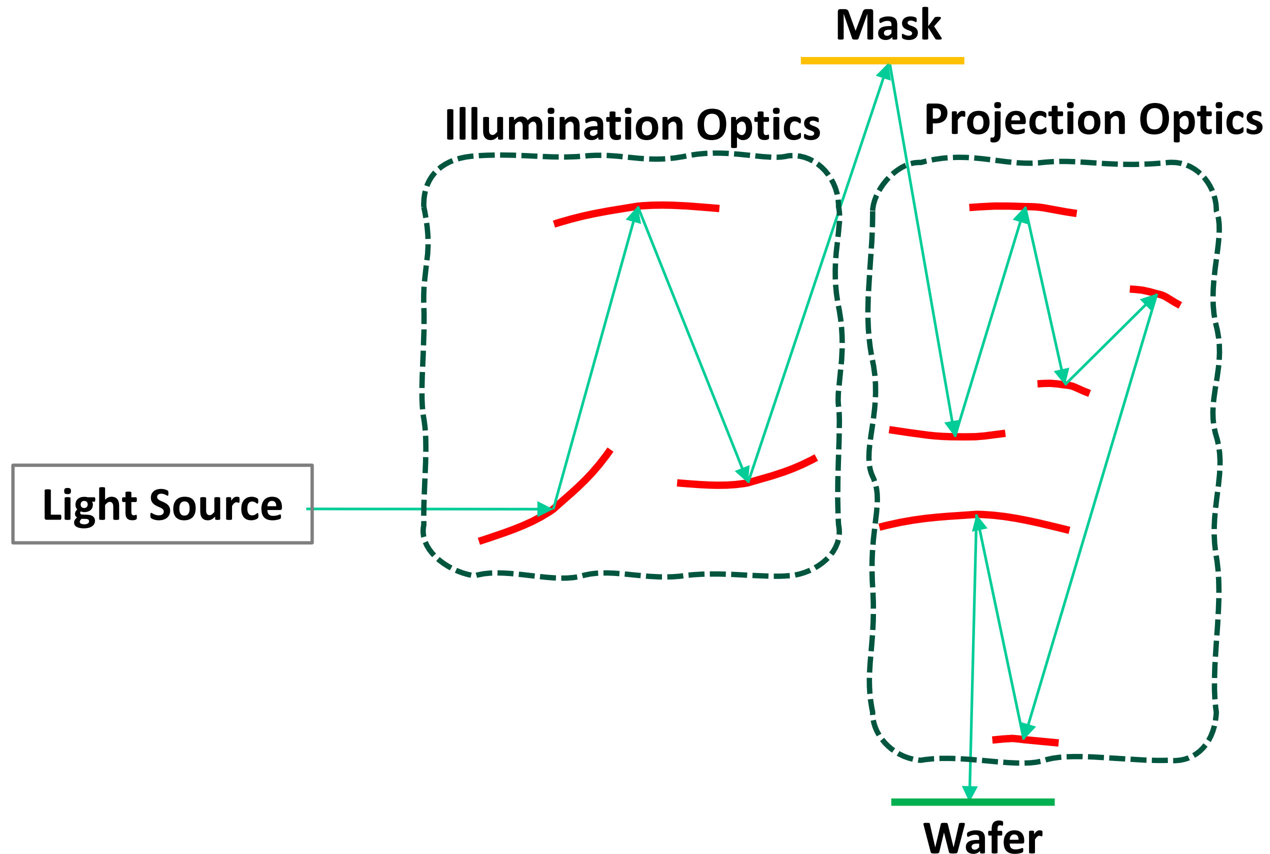
Wavelength spread of FEL spectrum at 6.75-nm.
FWHM is ~0.04 nm, which is narrow enough to match the acceptance of La/B.



The calculated FEL power spectrum for 2% linear undulator tapering at FEL exit and the Mo/Si refl. curve.

Hiroshi Kawata, Norio Nakamura, Hiroshi Sakai, Ryukou Kato, Ryoichi Hajima,
Journal of Micro/Nanopatterning, Materials, and Metrology, Vol. 21, 021210 (2022).

Requirements for multilayers used in EUVL exposure systems



In exposure system, many MLMs are used in the illumination optics, mask, and projection optics.

For these MLMs, it requires:

1. The peak wavelength of reflectance must match between each MLM.

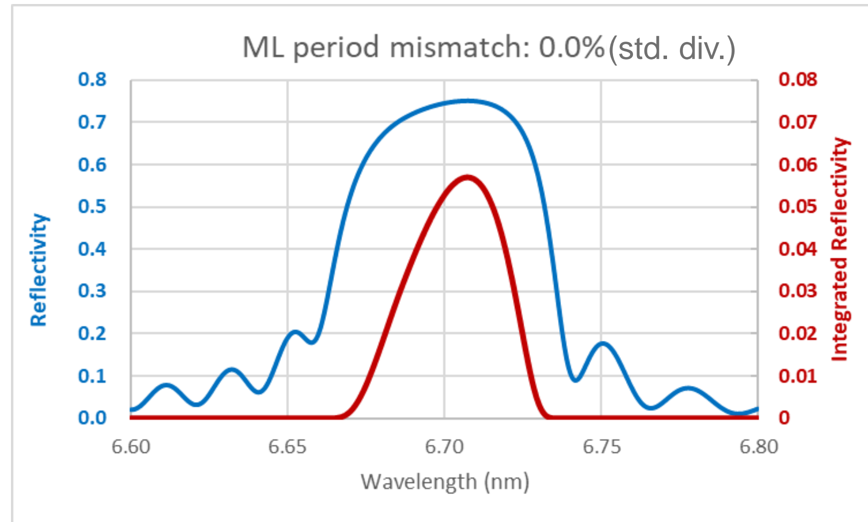
2. In-plane film thickness distribution of MLM matches design value.

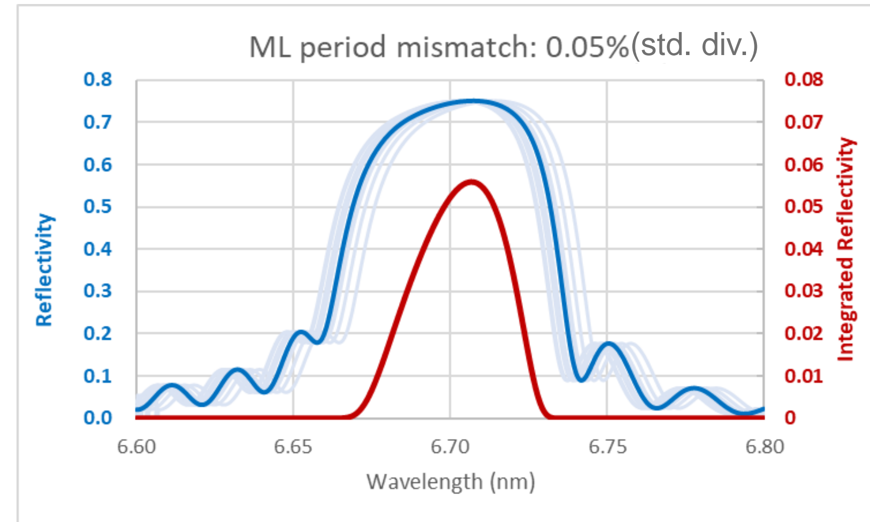
How about the reflectance characteristics of BEUV MLMs ?

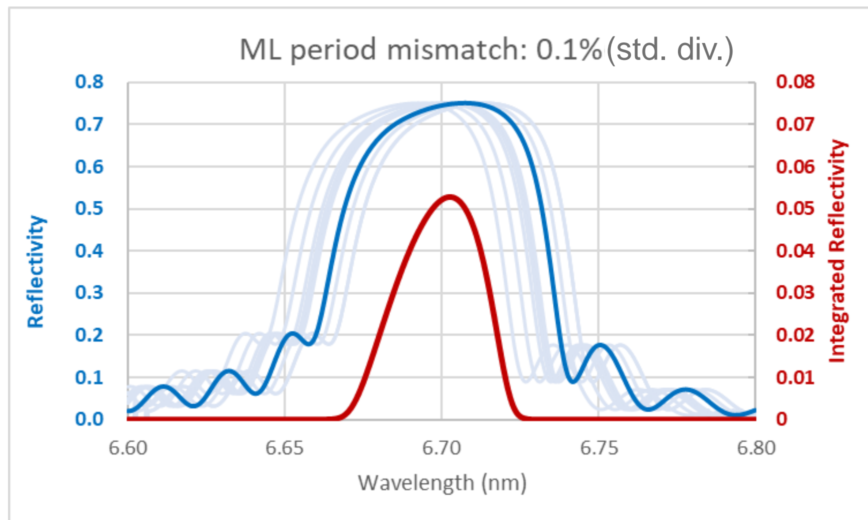
Center wavelength matching accuracy between multilayer mirrors

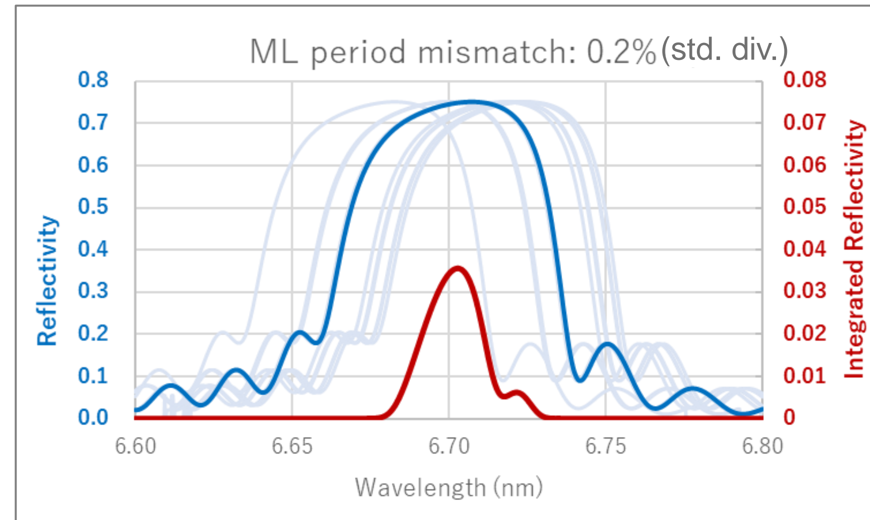
Assume that there are 10 MLMs with different deviations in d of each mirror, the total reflectivity are calculated with the incidence angle of 10 deg.

[LaN/B]N=200





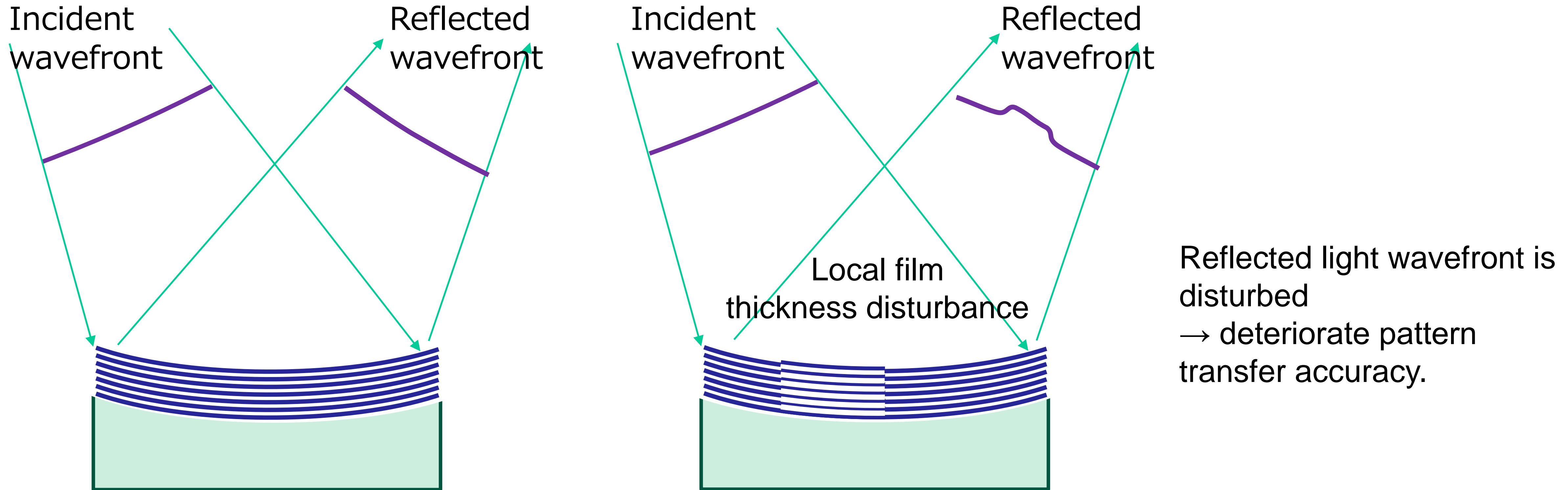




In order not to diminish the total reflectivity after 10 reflections, d of each mirror must match the design value within 0.1%. (std. div.)

Film thickness accuracy within the plane of MLM

Local deviation from designed film thickness distribution



Reflected light wavefront is disturbed
→ deteriorate pattern transfer accuracy.

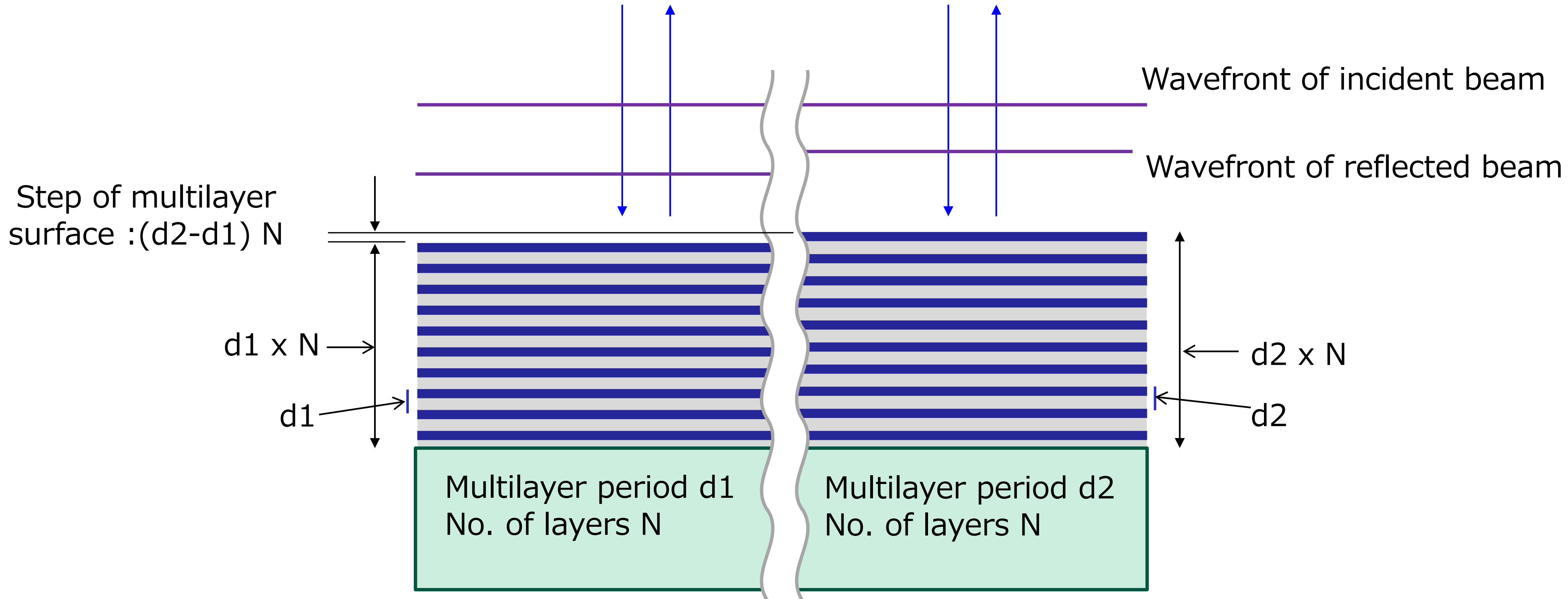
To keep wavefront aberration of entire 6-mirror projection system within 0.07λ rms (Marechal criterion), if ML and other error factors are divided equally, wavefront aberration due to ML of one mirror is required to be 0.02λ rms (0.07/√12) or less.

In practice, more stringent conditions than the Marechal criterion are used.

Film thickness accuracy within plane of MLM

Local deviation from the designed film thickness distribution

Reflection occurs approximately at the outermost surface of MLM.



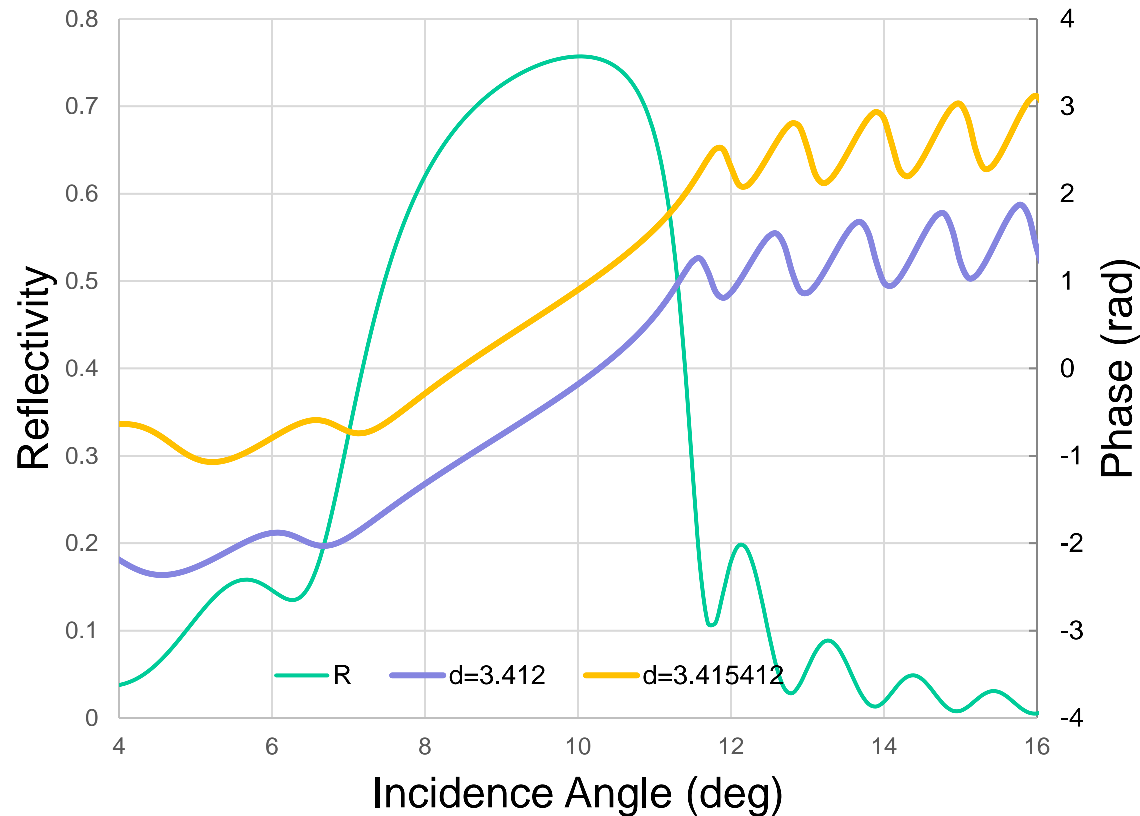
To reduce the wavefront aberration cause by one multilayer down to 0.02λ rms or less

→ Film thickness disturbance must be less than 0.01% rms

Film thickness accuracy within plane of MLM

Local deviation from designed film thickness distribution

Calculation of the total reflection of the entire MLM surface.



When d changes by 0.1%, the phase of the reflected light changes by approximately 1.1rad (0.17λ)

To reduce the wavefront aberration caused by one MLM down to 0.02λrms or less, film thickness disturbance must be less than 0.012%rms

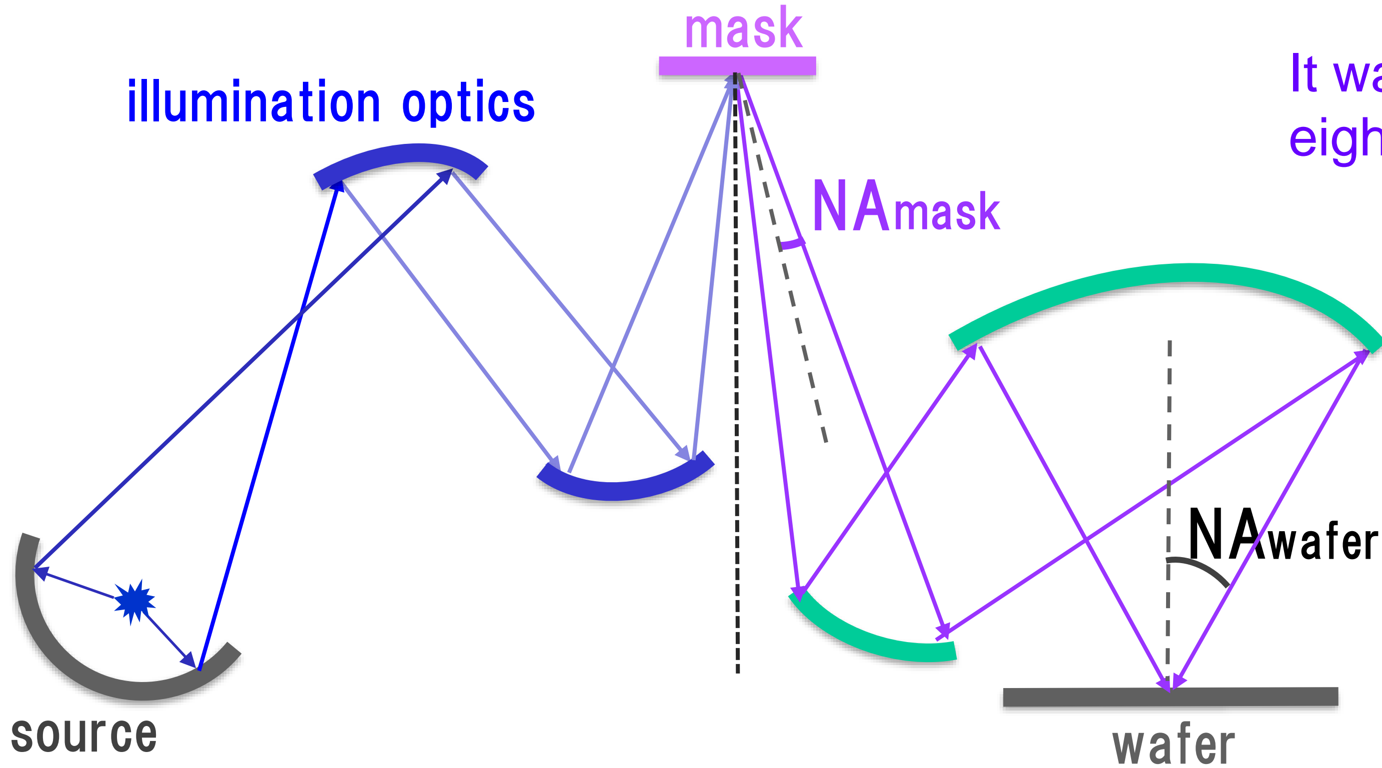
A. Miyake, et al. , “Phase measurement of reflection of EUV multilayer mirror using EUV standing waves,” J. Vac. Sci. Technol. B 22, 2970–2974 (2004)

Other issue : NA matching

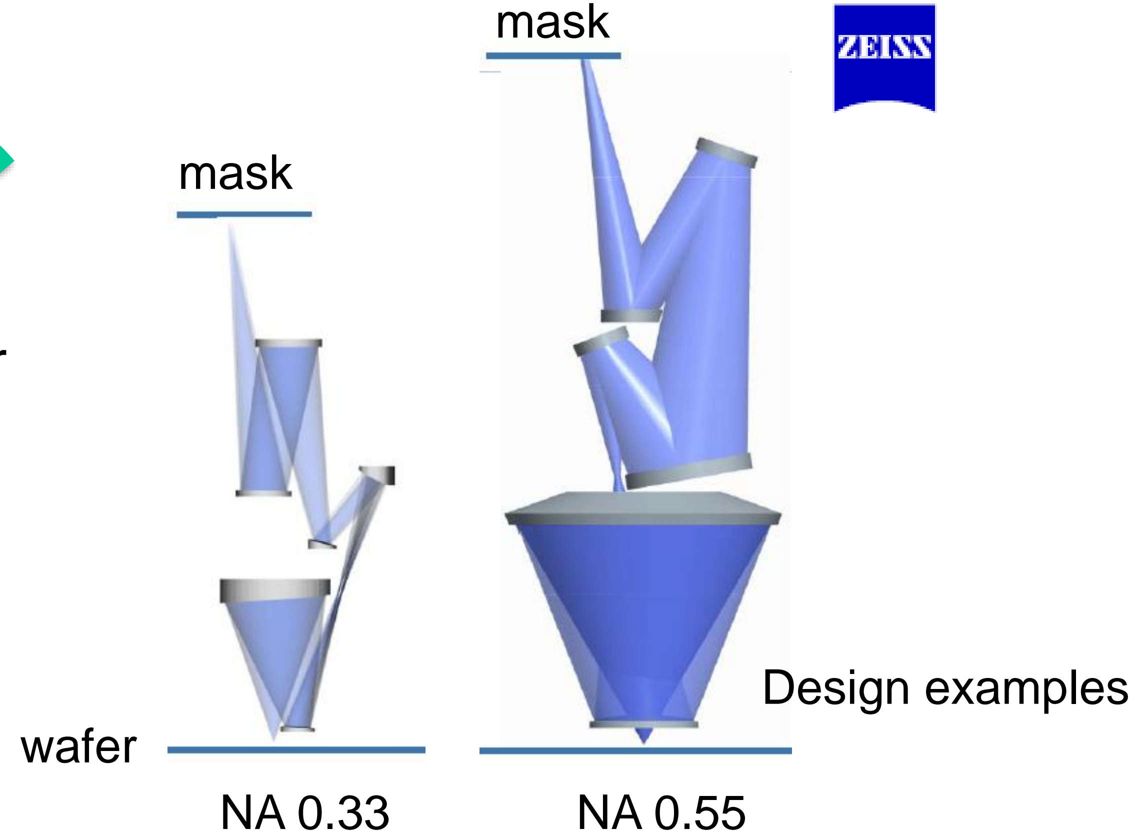
$$NA_{mask} = \frac{NA_{wafer}}{Magnification}$$

In the current EUVL, NA of wafer is 4 times higher than NA of mask (NA wafer = 0.33).

It was announced that this number will increase eightfold (NA wafer = 0.55).

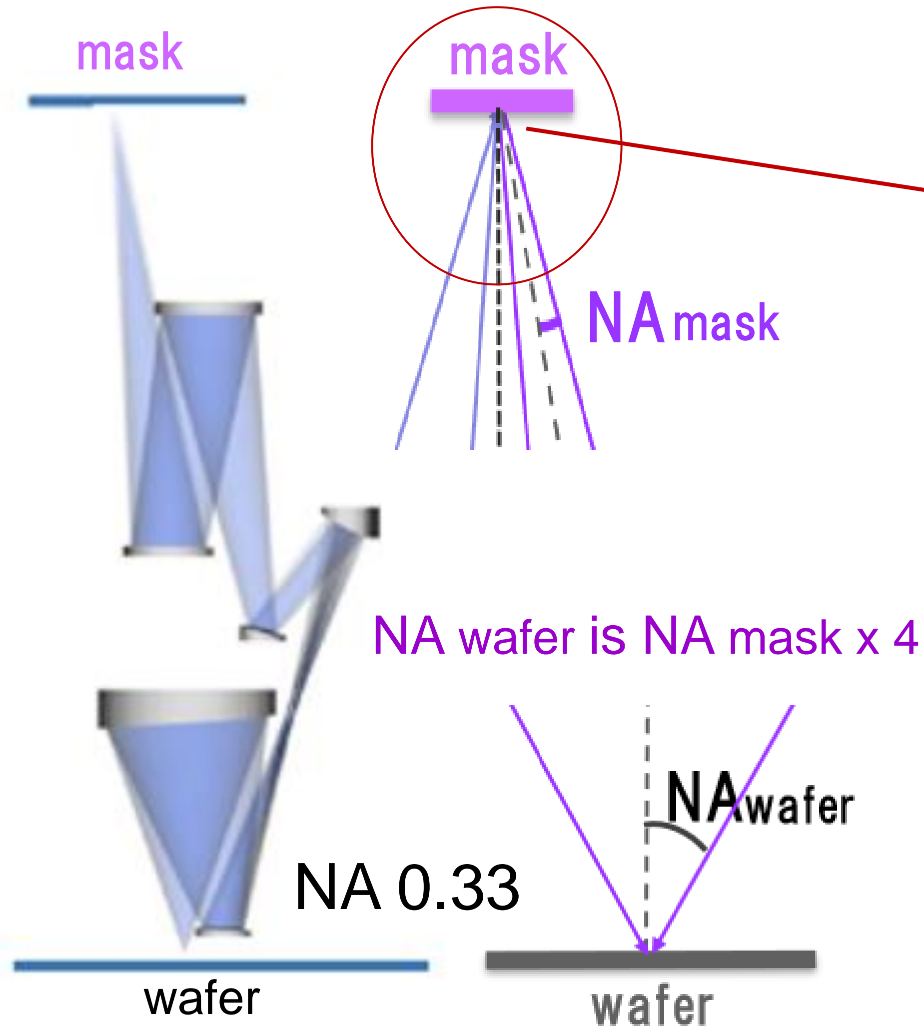


Simple model of the exposure system



Design examples

Reflection angle width of LaN/B and Mo/Si at mask surface



Current EUV exposure system

NA wafer is 4 times higher than NA mask

[LaN/B] @ λ= 6.73 nm

[Mo/Si] @ λ= 13.5 nm

Reflectance, R

0.8, 0.7, 0.6, 0.5, 0.4, 0.3, 0.2, 0.1, 0

Incidence Angle, θ [deg.]

0, 2, 4, 6, 8, 10, 12, 14, 16, 18, 20

NAwafer=0.33

→ NAmask=0.0825 =4.73°

Chief-ray angle = 6°

Reflection angle width of LaN/B is narrower than that of Mo/Si

Very low reflectivity (LaN/B)

BEUV mask and mirrors can easily produce non-uniform intensity distributions due to the narrow angular width of the reflection

Dependence of reflectance of LaN/B and Mo/Si on reflection angle at mask surface

(Reflection peak value at a reflection angle of 6°)

Conclusion

1． The wavelength of the reflectance peak must match between each MLM.

→ Each ML, the deviation of d from the designed value should be less than 0.1% (std. dev.) .

For near normal incidence, the required deviation of d is at least ~0.003nm or less

2． Film thickness distribution within the plane of MLM should match the design value.

→In-plane film thickness accuracy (dev. from designed in-plane film thickness distribution) is at least 0.012% or less (within ~0.0004nm for near normal incidence)

3． Other issue

For near normal incidence, range of reflection angle of BEUV ML is narrower than that of EUV ML.

→ How to design optics to achieve High-NA with BEUV is a challenge!

Special thanks to

Akira Miyake
Eric M. Gullikson
Hiroo Kinoshita
Hiroshi Kawata
Katsuhiko Murakami
Satoshi Ichimaru
Suit Yi Liu
Takeo Ejima
Yuya Iwamoto

Thank you for your kind attentions