# Development of Multilayer Mirrors for BEUV Reflective Optics

## — Current Status of an Ongoing Project—

**EJIMA, Takeo**

**SRIS and IMRAM, Tohoku University**

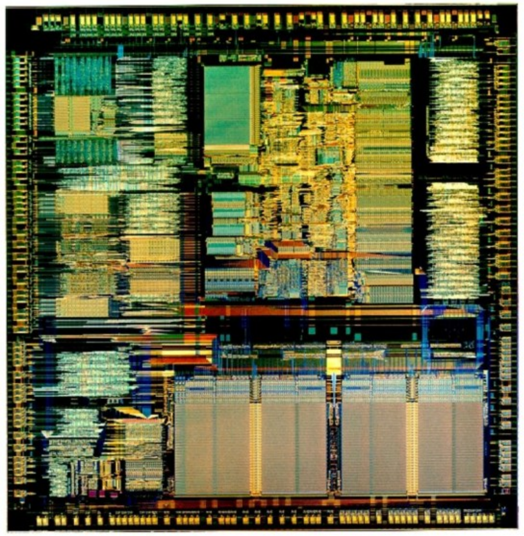
# Presentation Outline

- Overview of Reflective Multilayer Films (MLs)
  1. Microfabrication Trends in Semiconductor devices
  2. Design method for Reflective MLs

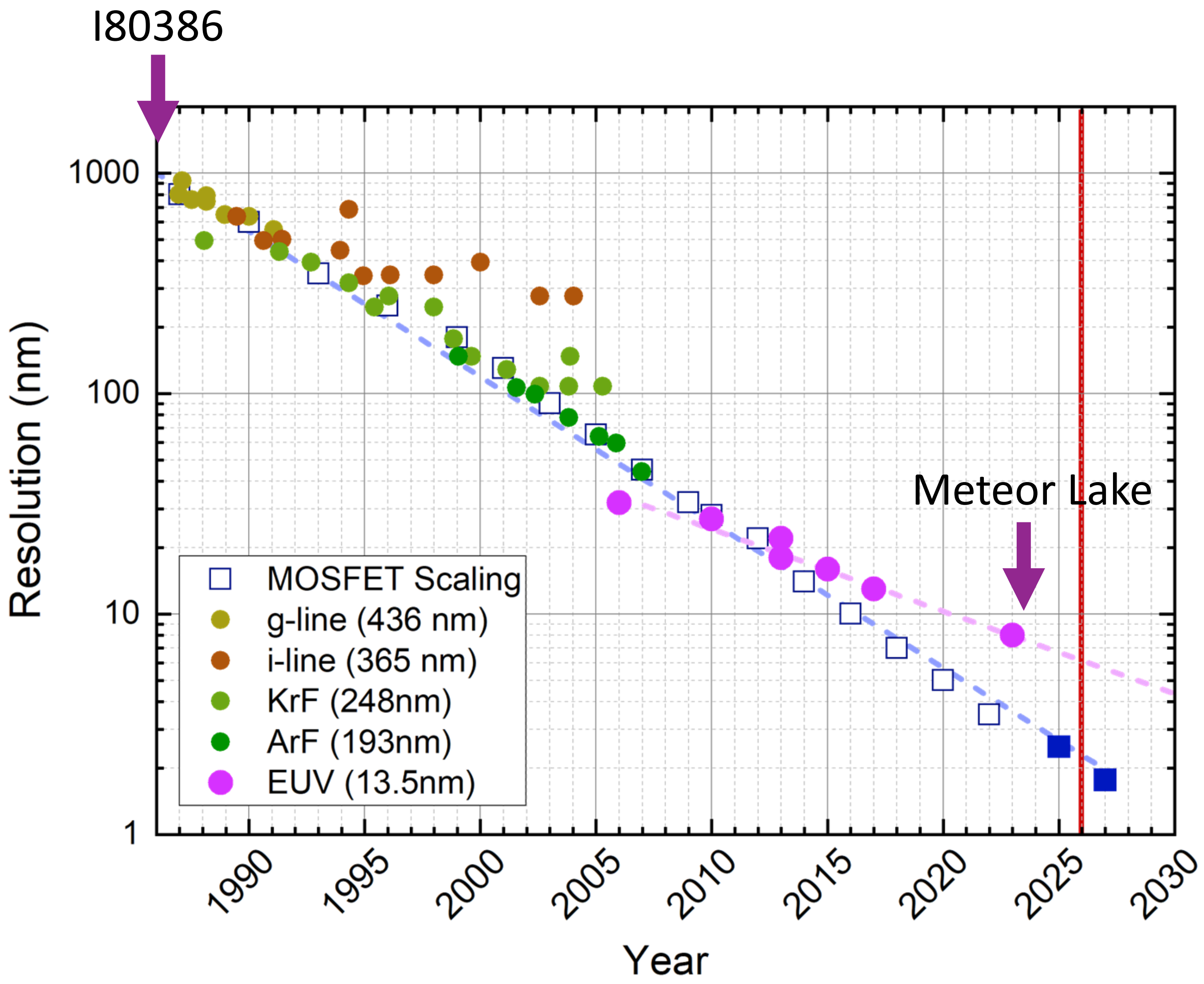
- Overview of our Project in K program
  1. Research Project
  2. Tasks and Current Status in Research Project
     - ☐ Task1: Improvement of deposition environment
     - ☐ Task2: Re-examination of BEUV ML design
     - ☐ Task3: Identification of deposition-related issues
     - ☐ Task4: Fabrication and evaluation of reflective multilayers

# Microfabrication of semiconductor devices using different type of light source

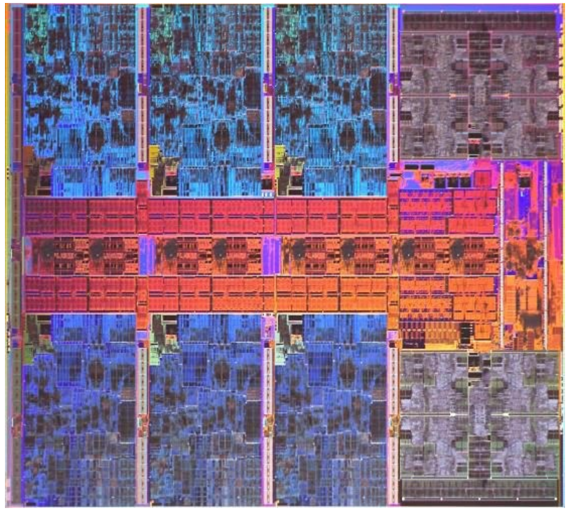
I80386 (1μm)@1985



275,000 Tr/Chip




Meteor Lake (7nm)@2023



100.8MTr/mm$^2$

- M. Kameyama, "Lithography Solutions for 32nm and Beyond", 2006 Symposia on VLSI Technology and Circuits Short Course (2006) から改変
- MOSFET Scaling: https://en.wikipedia.org/wiki/Moore%27s_law
- EUV resolution: https://www.asml.com/en/products/euv-lithography-systems

# EUV Exposure Tool NXE:3400B (ASML)

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- Present Status: ASML EXE:5000 (19, Apr. 2024)

$\delta d$ =12.3 nm ($\lambda$=13.5 nm, NA=0.55)

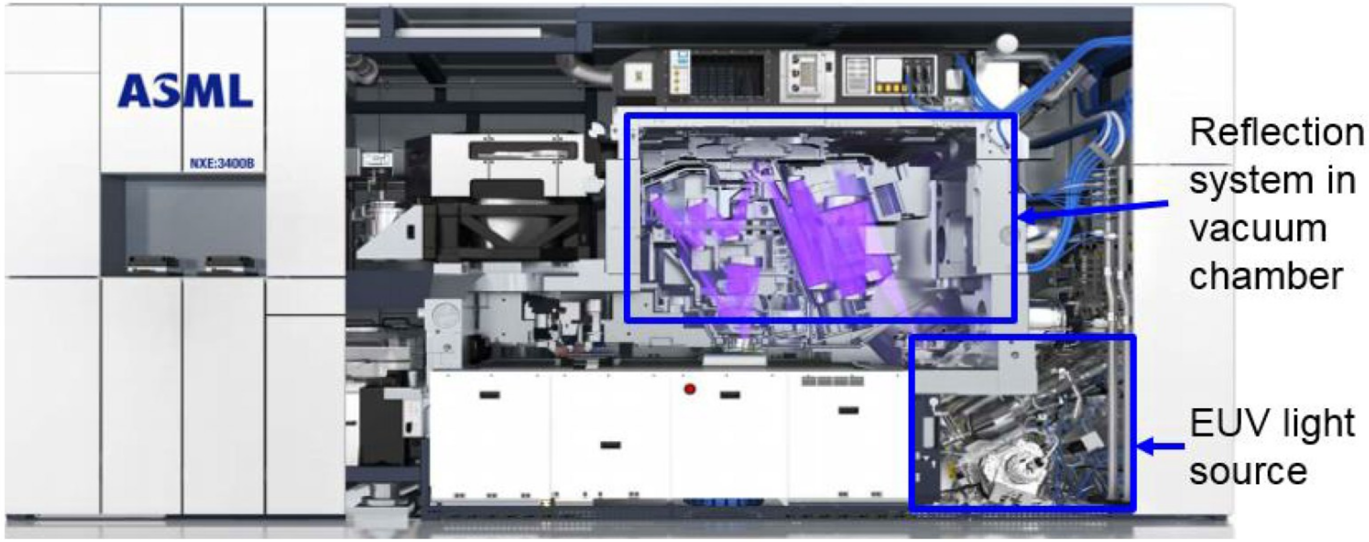


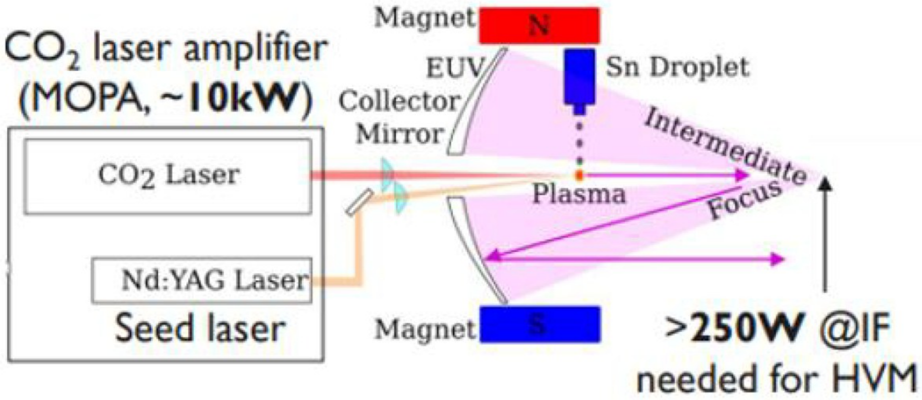

Figure 8. Internal structure of ASML NXE:3400B scanner. Source: ASML.

- Spatial Resolution:

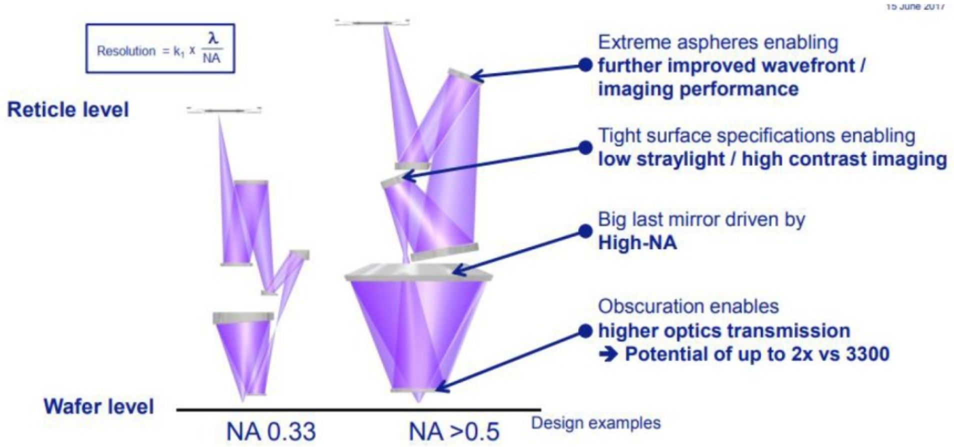
$$\delta d = \mathrm{K}\,\frac{\lambda}{\mathrm{NA}}$$

K=0.5
$\lambda$: 13.5 nm
NA: numerical aperture

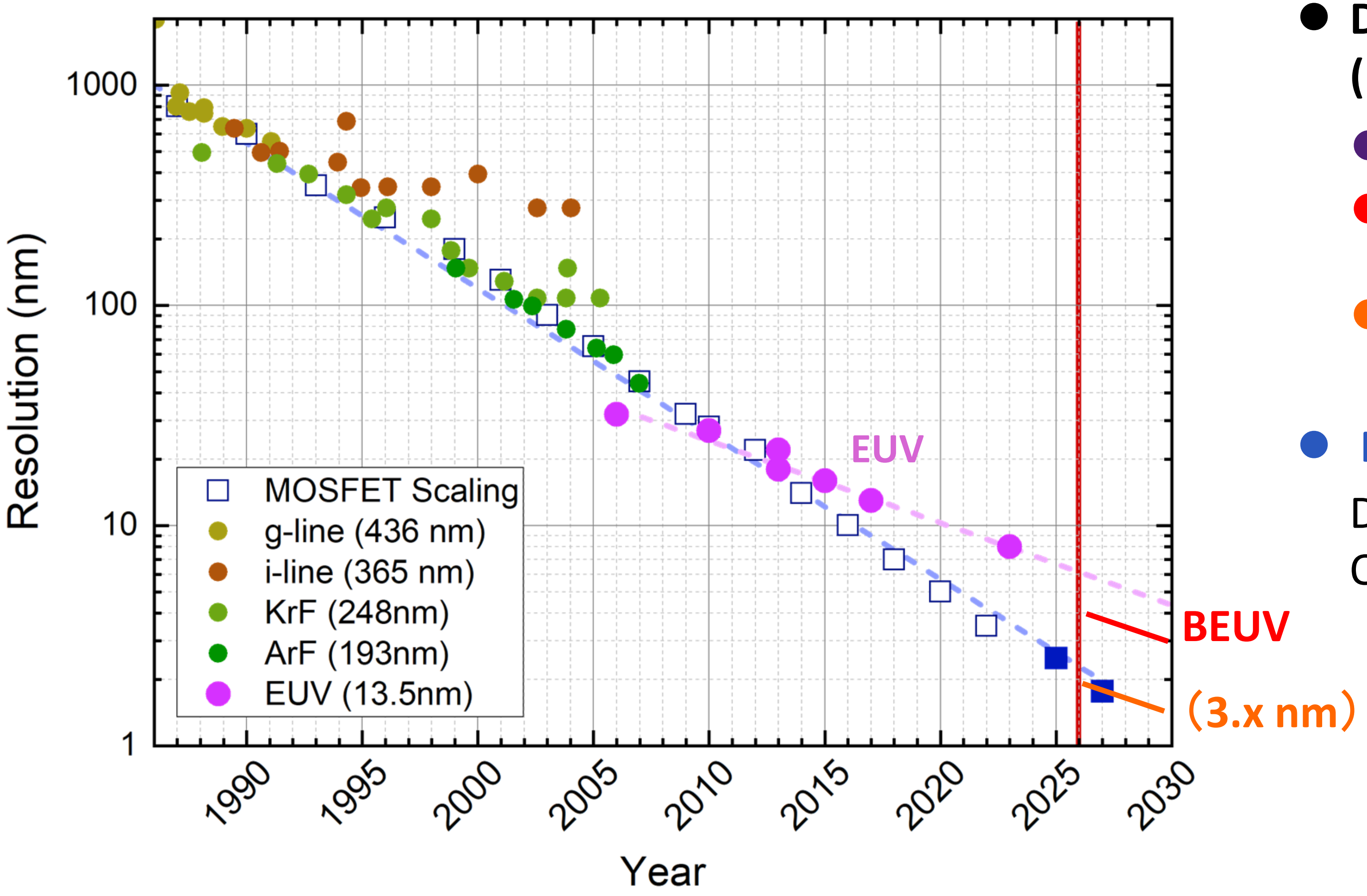
- Light source (Laser Produced Plasma):




- Reflection System:



# Discrepancy between Spatial Resolution & Process node




- **Development roadmap in Exposure Tools (IRDS 2024)**
  - hyper-NA: NA ≥ 0.75
  - BEUV: **λ = 6 ～ 7 nm**
  - **( Water window: λ = ～ 3. x nm ? )**

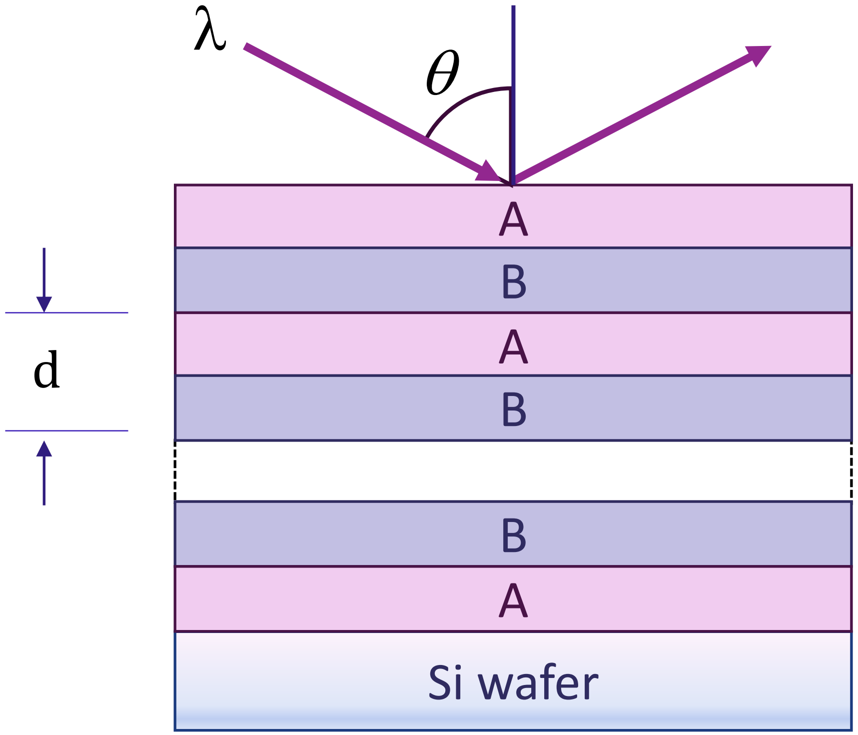
- **Research Objectives:**

  Development of BEUV Multilayer Film Optics in Japan.

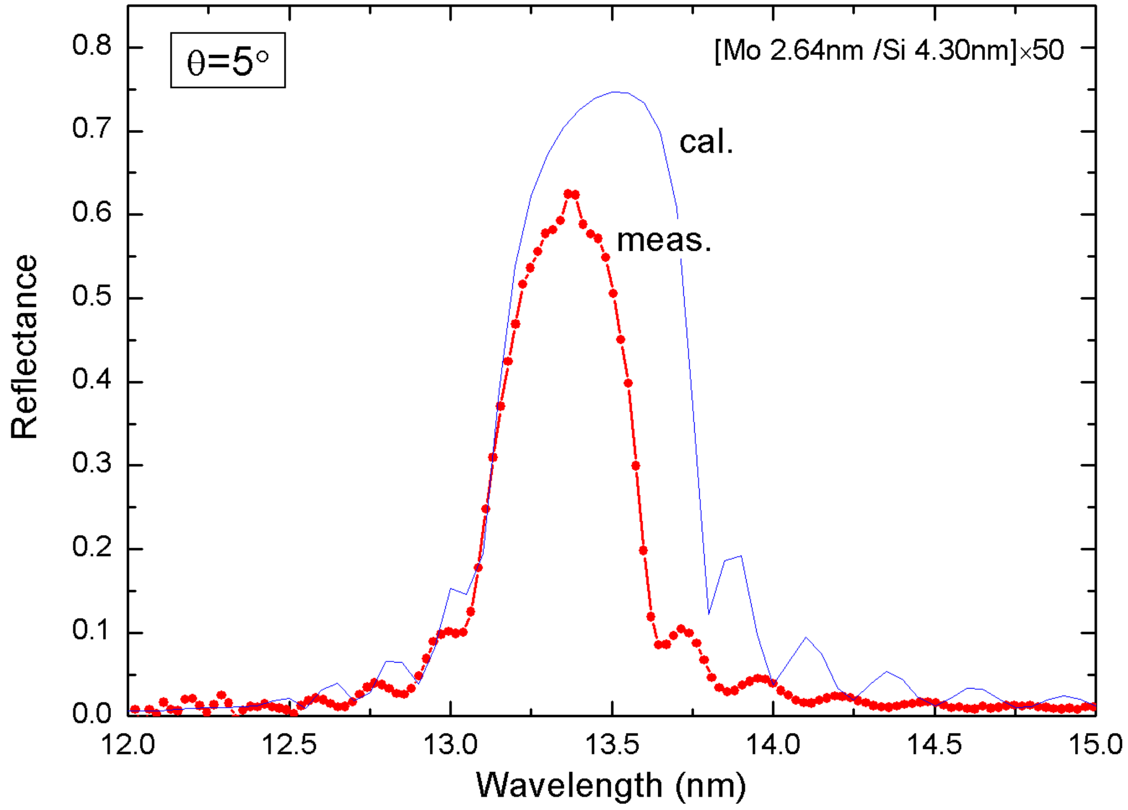
- M. Kameyama, "Lithography Solutions for 32nm and Beyond", 2006 Symposia on VLSI Technology and Circuits Short Course (2006) から改変
- MOSFET Scaling: https://en.wikipedia.org/wiki/Moore%27s_law
- EUV resolution: https://www.asml.com/en/products/euv-lithography-systems

# Overview of Reflective multilayer film (ML)

- ML Features:
  - Periodic Structure by 2 materials
  - Bragg Condition: $m\lambda = 2\mathrm{d}\ \cos\theta$

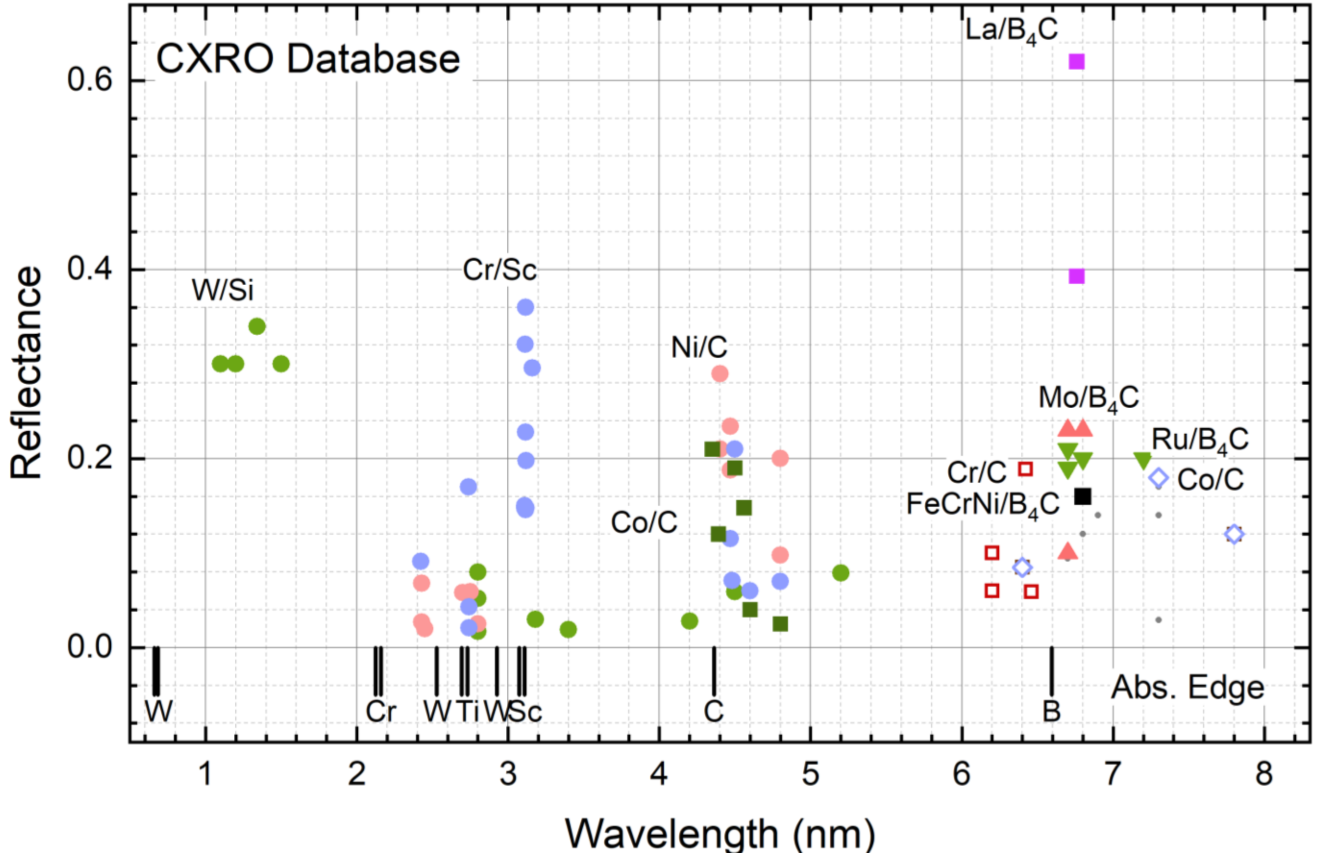



- Ex) Mo/Si reflective ML




Meas. Data from T. Harada, D. Thesis, (Tohoku University, 2007).

# **Design method:** 1. Empirical guidelines for selecting materials



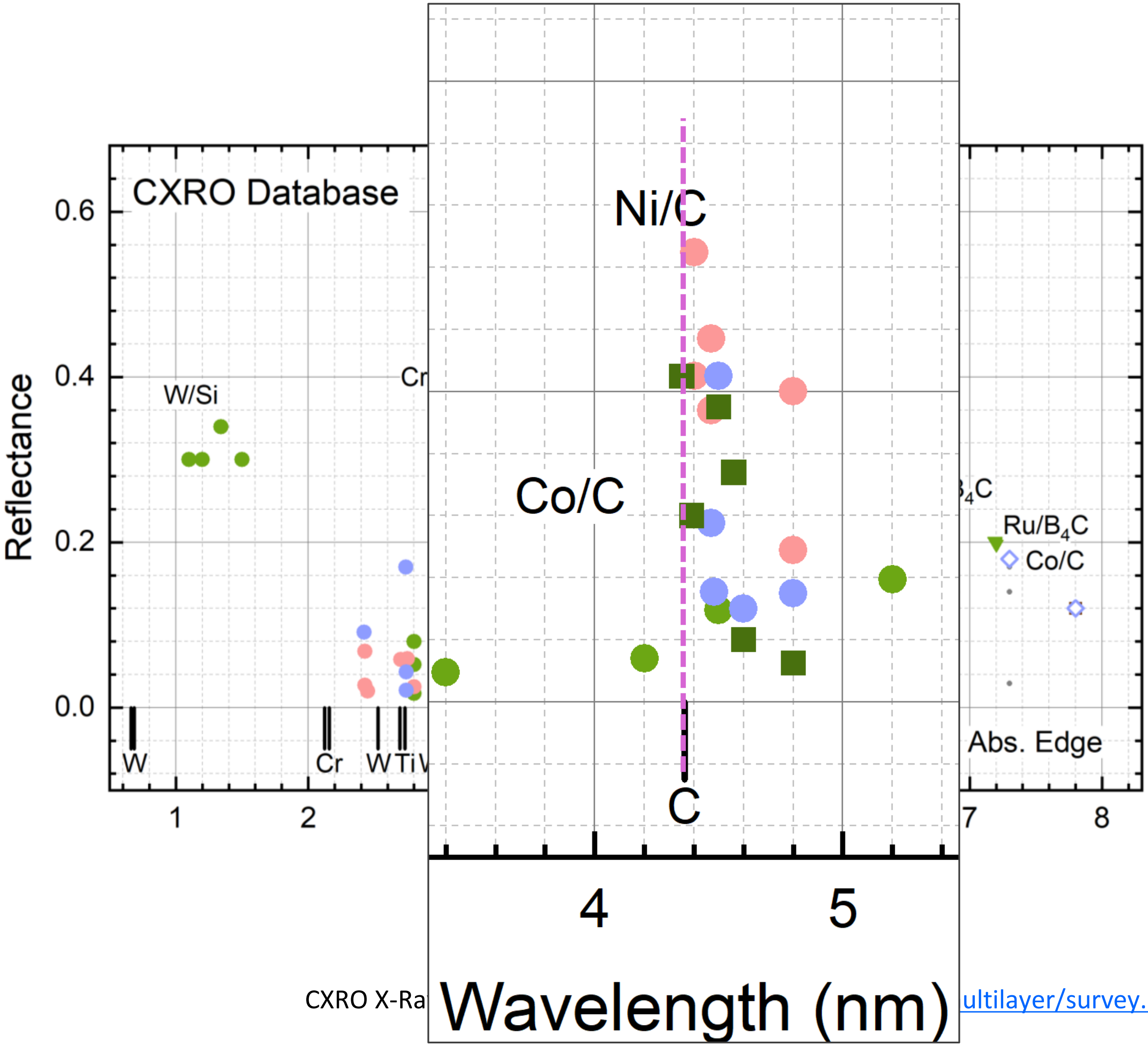

Empirical guidelines for selecting materials from reflective MLs with high reflectance.

1. One material should be chosen from elements located near an absorption edge.
2. The second material should exhibit relatively low absorption and provide sufficient refractive index contrast.

CXRO X-Ray Multilayer Database, https://henke.lbl.gov/multilayer/survey.html


J. H. Underwood and T. W. Barbee, Appl. Opt. **20**(17), 3027–3034 (1981).
DOI: 10.1364/AO.20.003027

# **Design method:** 1. Empirical guidelines for selecting materials




CXRO X-Ra ultilayer/survey.html

Empirical guidelines for selecting materials from reflective MLs with high reflectance.

1. One material should be chosen from elements located near an absorption edge.
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J. H. Underwood and T. W. Barbee, Appl. Opt. **20**(17), 3027–3034 (1981).
DOI: 10.1364/AO.20.003027

# Design method: 2. Material Selection Rules for Reflective MLs

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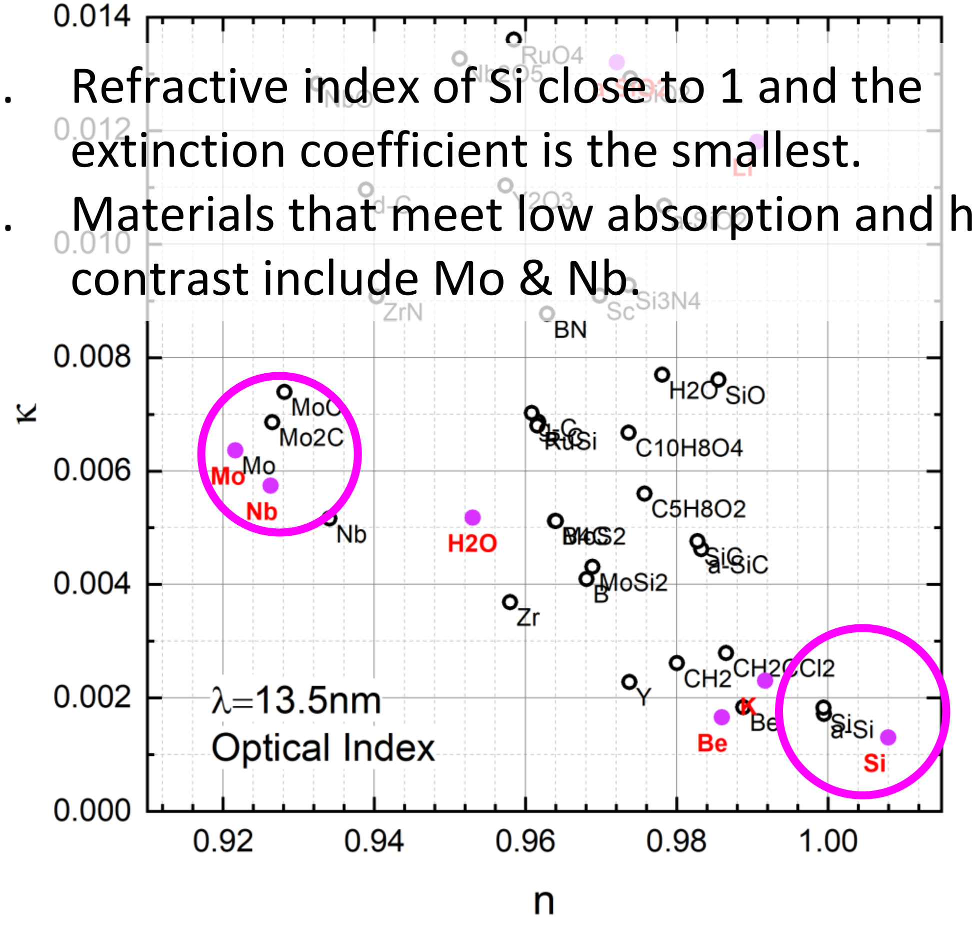
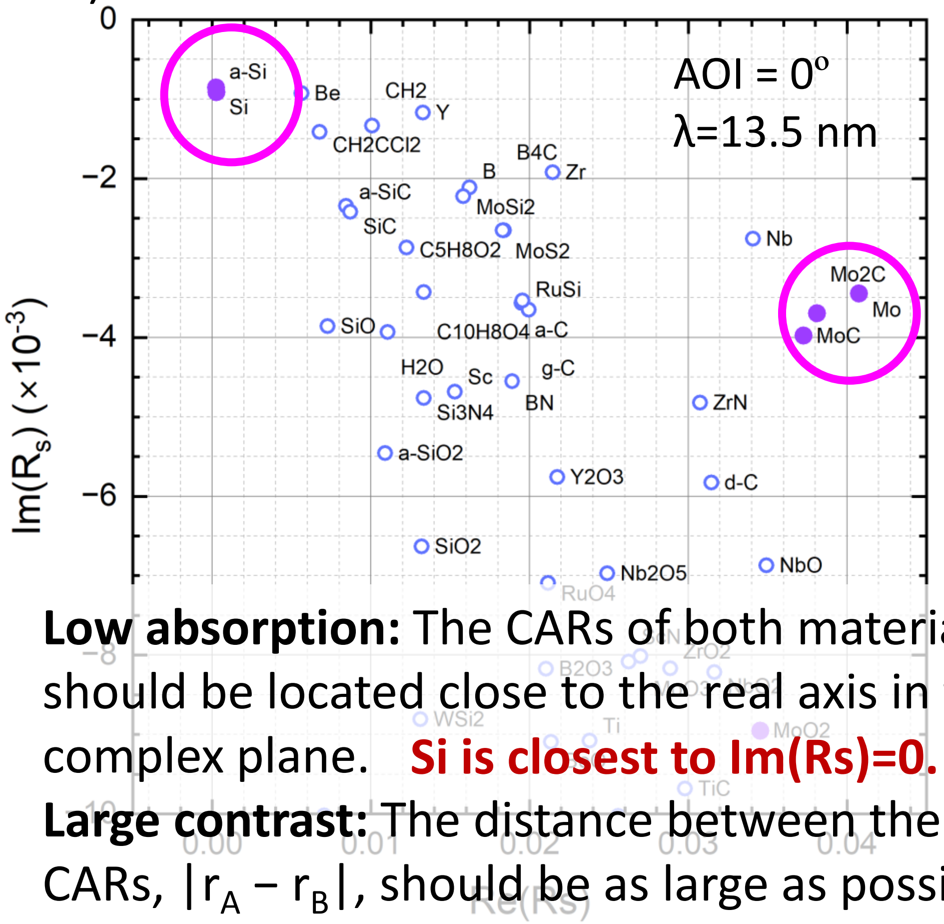
- Empirical guidelines using Optical Constants




1. Refractive index of Si close to 1 and the extinction coefficient is the smallest.
2. Materials that meet low absorption and high n contrast include Mo & Nb.

- Selection rules using Complex Amplitude Reflectance (CAR)




1. **Low absorption:** The CARs of both materials should be located close to the real axis in the complex plane. **Si is closest to Im(Rs)=0.**
2. **Large contrast:** The distance between the two CARs, $|r_A - r_B|$, should be as large as possible. **Mo compounds.**

- CXRO: http://www-cxro.lbl.gov
- 'Handbook of Optical Constants of Solids I, II, and III', Ed. by E. D. Palik, Academic Press, Inc.

# 3. Determining the Optimal film thickness for high reflectance

CAR trajectory
when changing the film thickness

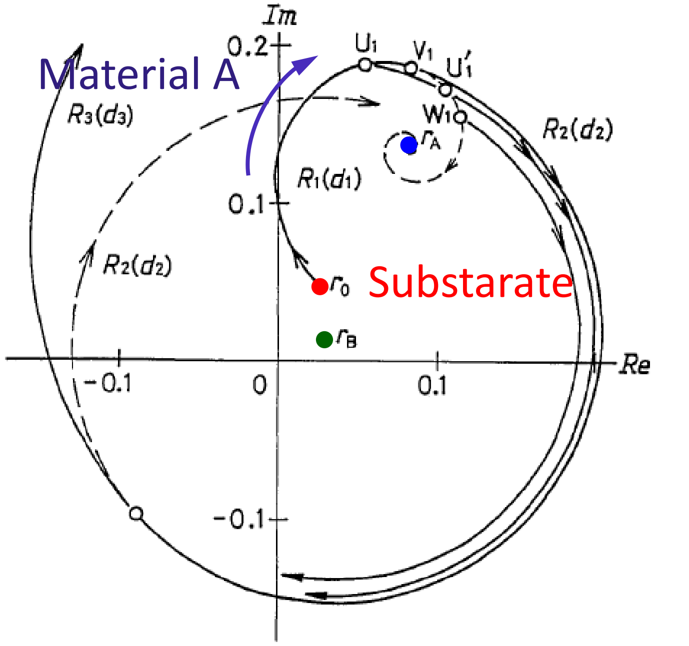
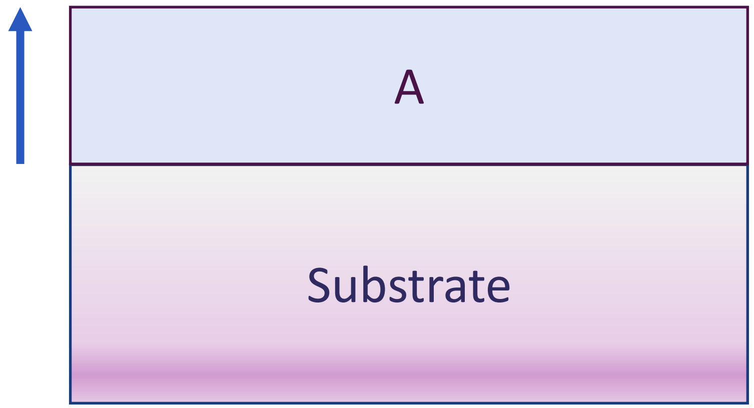



Fig. 3. Complex plane plot of amplitude reflectances $R_j$'s of the first three layers of a multilayer composed of materials A and B. Points $r_0$, $r_A$, and $r_B$ are the Fresnel reflection coefficients of the substrate, material A and material B, respectively. Points $U_1$, $V_1$, $U'_1$ and $W_1$ are various switching points.

M. Yamamoto and T. Namioka, Appl. Opt. **31**(10), 1622–1627 (1992). DOI: 10.1364/AO.31.001622




- Complex amplitude reflectance of the film changes as the film thickness increases.
- As the increase of film thickness, the trajectory follows a spiral path centered around $r_A$, and approaches $r_A$.

## CAR trajectory
## when changing the film thickness

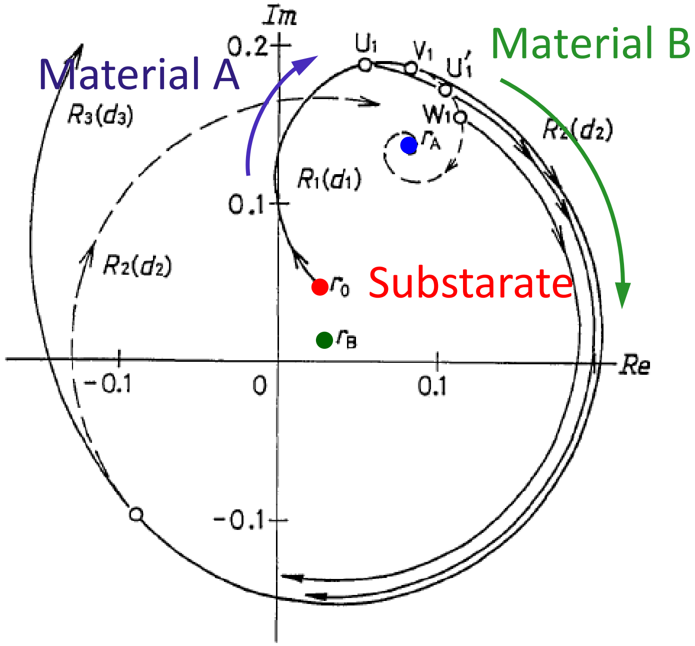



Fig. 3. Complex plane plot of amplitude reflectances $R_j$'s of the first three layers of a multilayer composed of materials A and B. Points $r_0$, $r_A$, and $r_B$ are the Fresnel reflection coefficients of the substrate, material A and material B, respectively. Points $U_1$, $V_1$, $U'_1$ and $W_1$ are various switching points.

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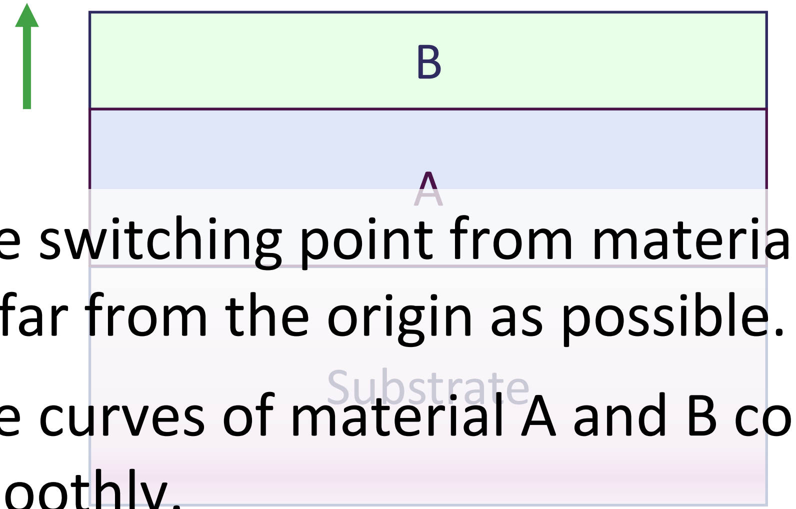


- The switching point from material A to B is as far from the origin as possible.
- The curves of material A and B connect smoothly.
  - Complex amplitude reflectance of the film changes as the film thickness increases.
  - As the increase of film thickness, the trajectory follows a spiral path centered around $r_A$, and approaches $r_A$.

# 3. Example of the Optimal film thickness: Mo/Si ML

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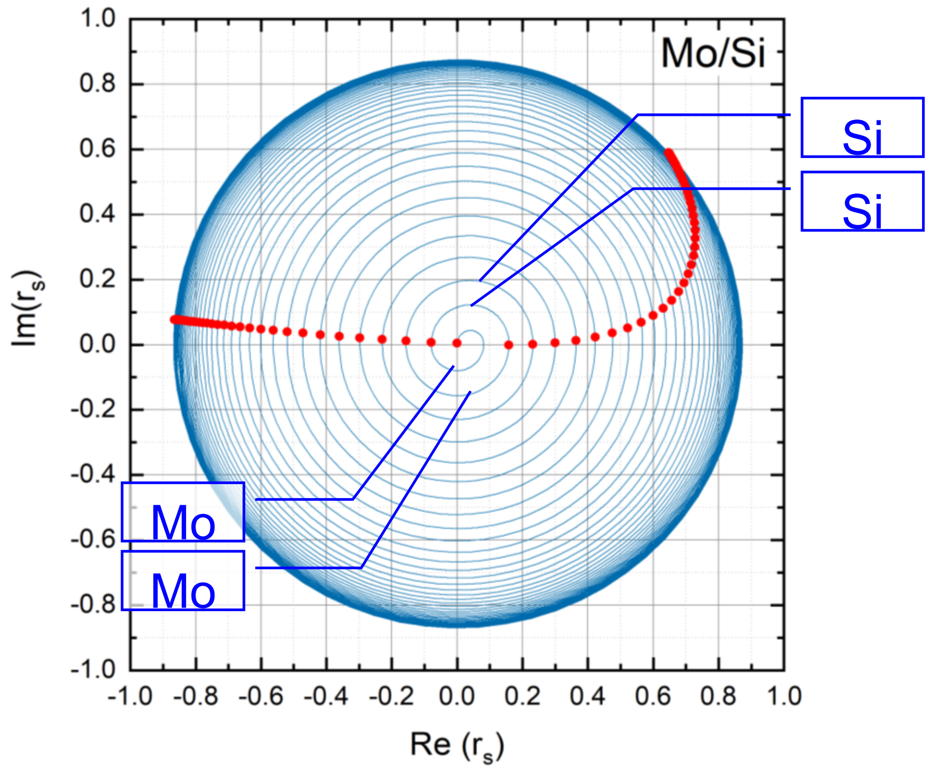
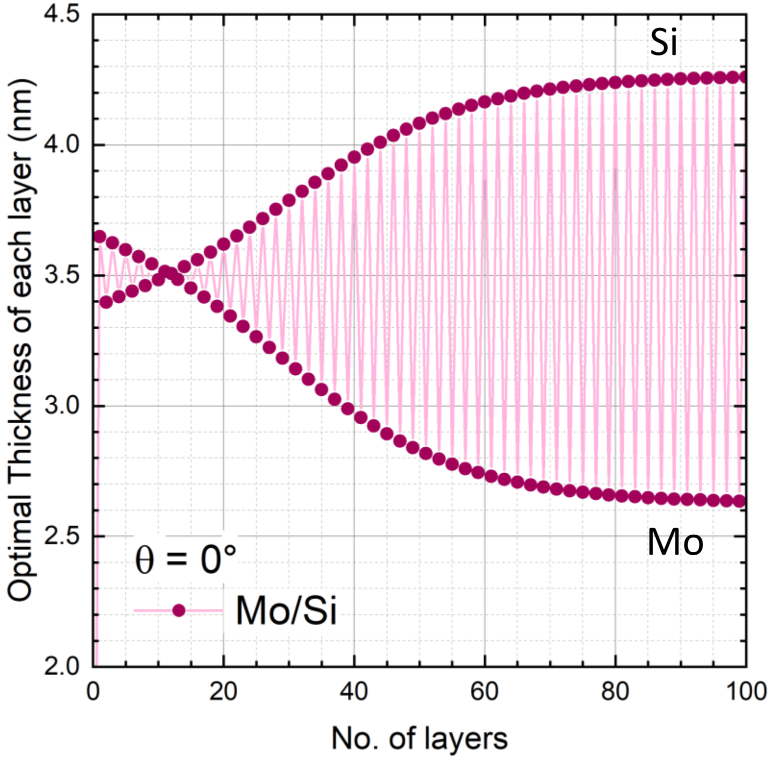
CAR trace for Mo & Si
@ 13.5nm & 0deg




Optimal Thickness of each layer




$N_{Layer}$ < 80: Different spacing
$N_{Layer}$ > 80: Even spacing

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        - ☐ Task1: Improvement of deposition environment
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# Overview of our Project in the K Program: BEUV Reflective ML Optics

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- **Project (Apr. 2025 – Mar. 2030 ) :**
  Development of BEUV ML Mirrors Using Ion Sputtering with Quantum Ellipsometry-Enabled Precise Thickness Control

- **Member:**

PI: EJIMA, T.
Tohoku Univ.

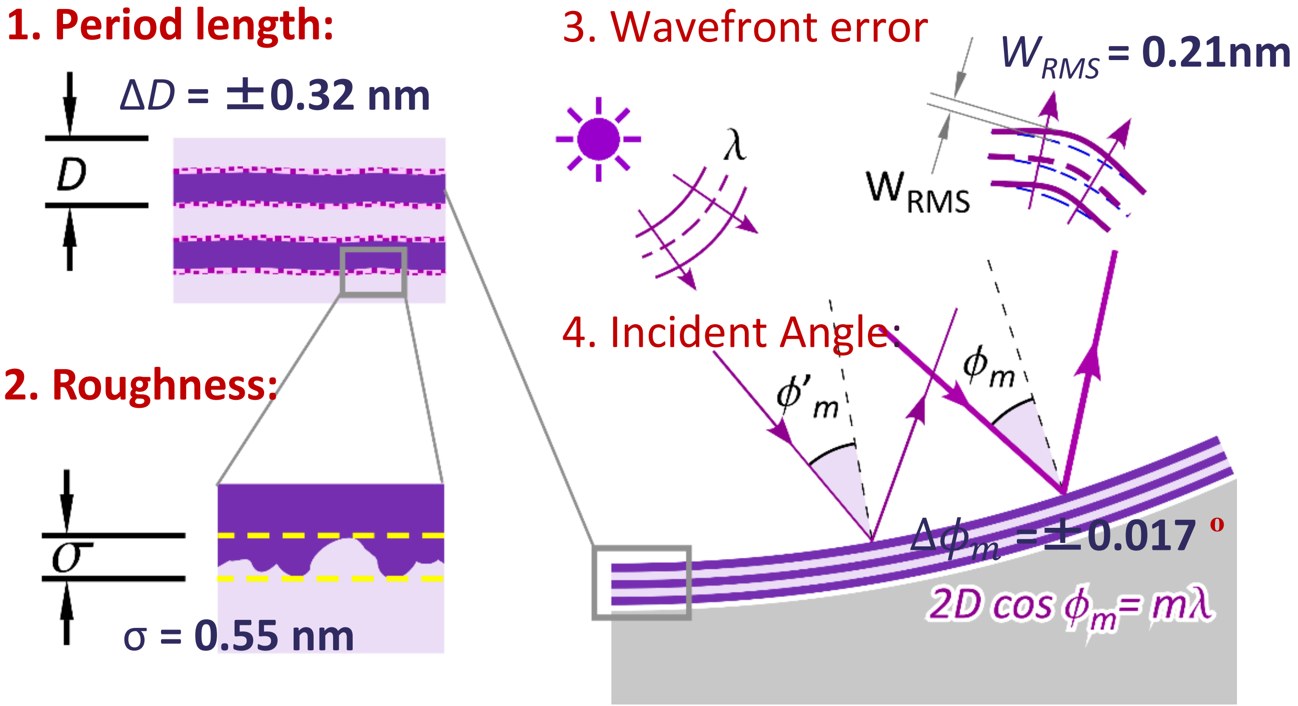
Co-PI: MIZUTANI, Y.
Osaka Univ.

HATANO, T.
Tohoku Univ.

- **Research Objectives:**
  1. Development of BEUV Multilayer Films (ML) via Ion Sputtering
  2. Development of a Monitoring System for In-Situ Film Deposition (Quantum ellipsometry)

- **Errors & Tolerance of BEUV Multilayer Mirror (λ=6.8 nm)**

Achieving **$R=0.6R_T$** requires all fabrication errors within **±5%** of target values.




**$\Delta D$ , σ, $W_{RMS}$, $\Delta\phi_m$** : Estimated values of fabrication errors at **60%** of theoretical reflectance, **$R_T$** assuming that errors contribute equally.

# Overview of our Project in K Program: Tasks in Research Objectives

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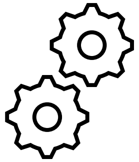
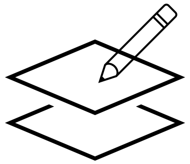
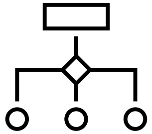
- Tasks in the research objectives



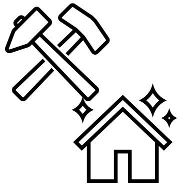
**Task 1.** Improvement of deposition environment
Introduce a deposition system different from conventional magnetron sputtering in order to improve the deposition environment.



**Task 2.** Re-examination of BEUV ML design
Revisit the design of reflective multilayers and explore suitable material combinations.



**Task 3.** Identification of deposition-related issues
Identify critical issues in multilayer fabrication based on the results of Task 2.



**Task 4.** Fabrication and evaluation of reflective multilayers
Fabricate and evaluate actual reflective multilayer samples in relation to the issues identified in Task 3.

# **Task 1.** Improvement of deposition environment

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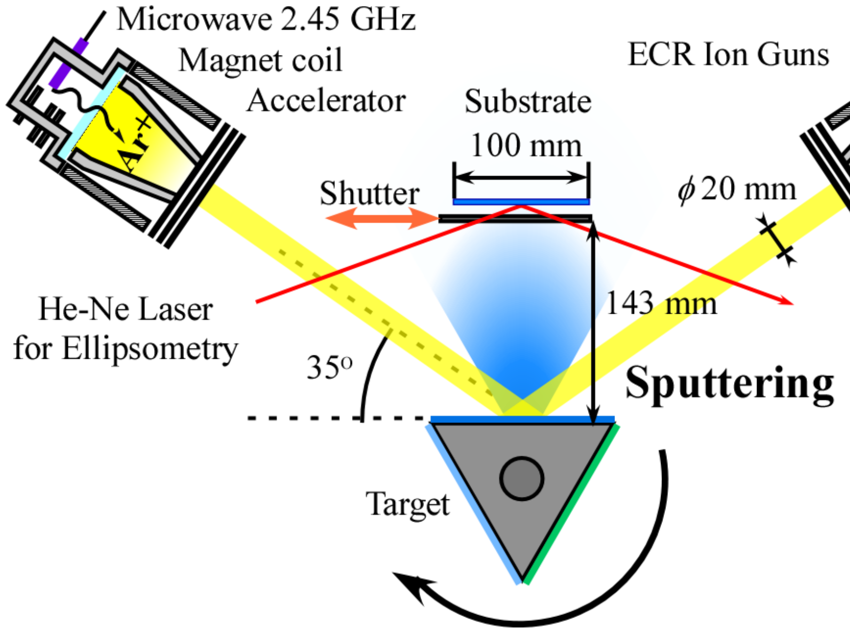
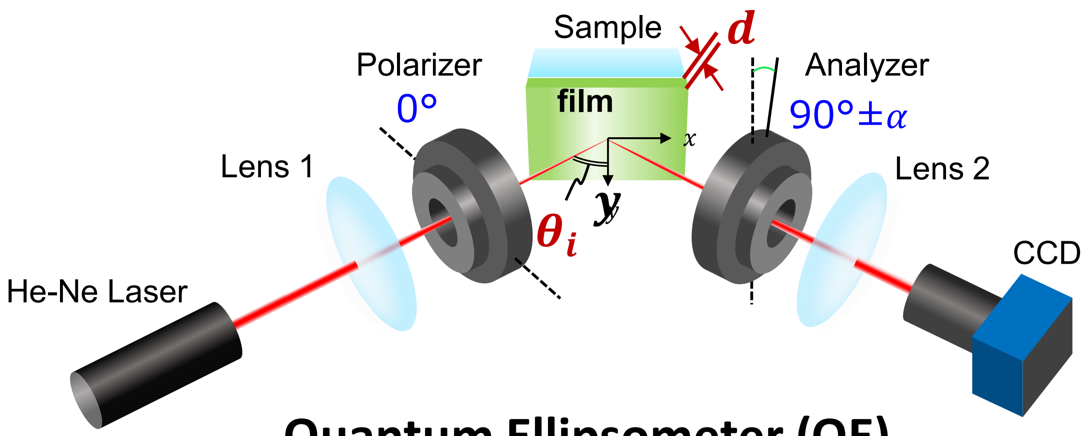
1. Ion Sputtering System with Thickness Monitor and Control of Film Thickness Distribution



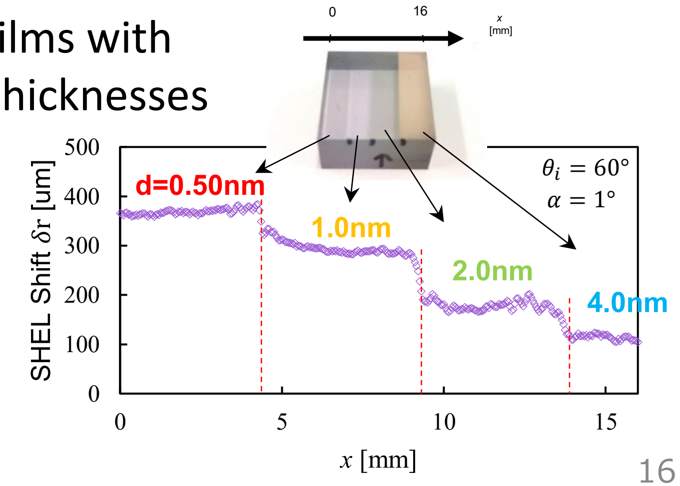

- Advantages of the Sputtering System:
  - Reducing the deposition pressure by two orders of magnitude
  - Reactive Sputtering
  - Precise Control of Film Thickness Distribution

2. Monitoring of film growth using the **S**pin **H**all **E**ffect of **L**ight (SHEL)




- QE monitor can precisely determine film thickness.

**Sample:** Au films with varying film thicknesses



# Task 1: Principle of the Quantum Ellipsometry

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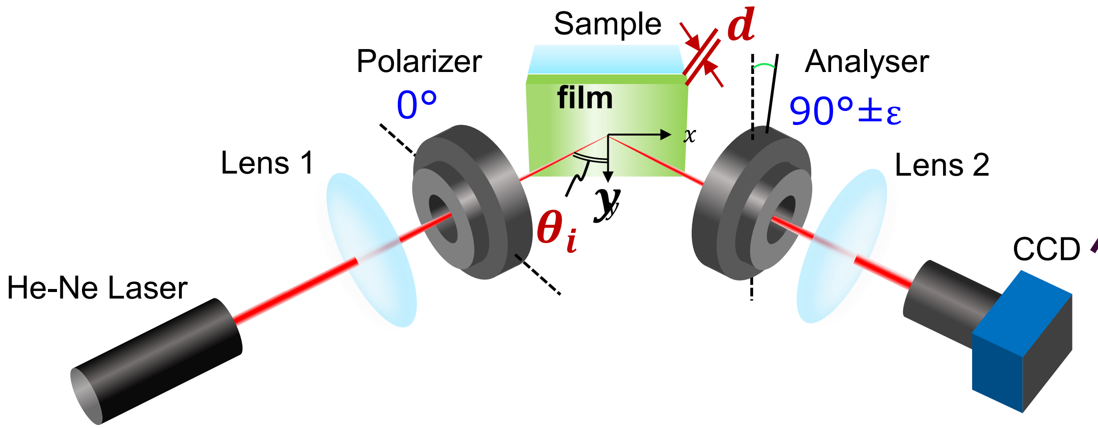
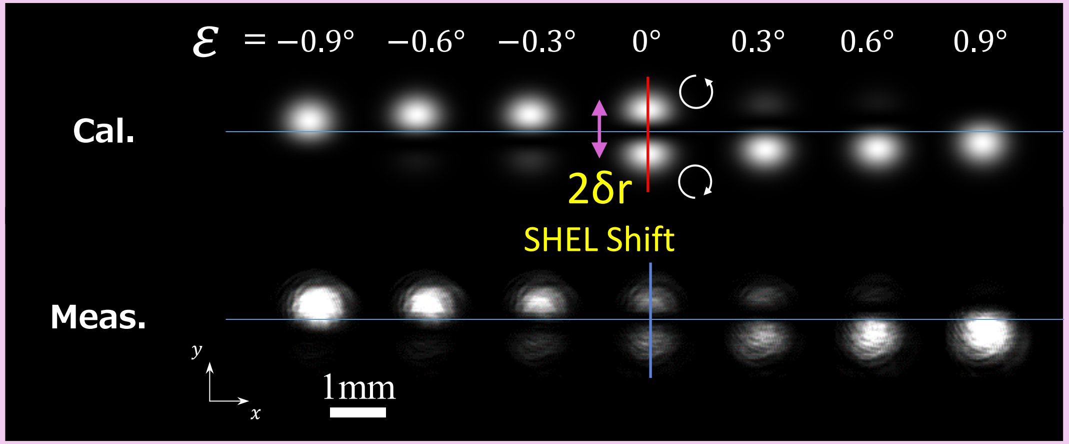
MIZUTANI, Y., private comm.

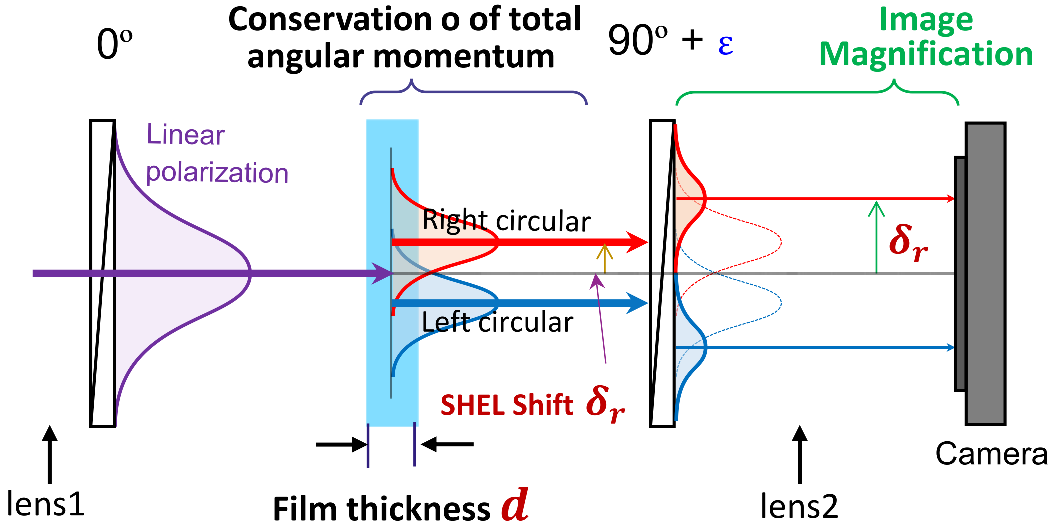
**S**pin **H**all **E**ffect of **L**ight (SHEL):
Conservation of total angular momentum in reflection




SHEL Shift, 2δr, changing the analyzer angle $\varepsilon$

Sample：BK7 prism（SiO2）




Film thickness change $\delta d$ in monolayer film is represented using the SHEL shift, $\delta_r$, the film thickness $d$, and the reflection phase $\Delta$.

- Film thickness change: $\delta d \sim \dfrac{d}{\Delta} \delta_r$

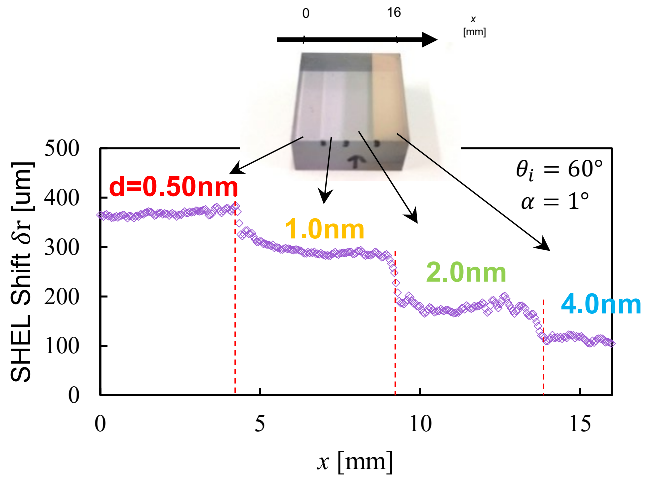
- Reflection phase: $\Delta = \dfrac{2\pi}{\lambda} n_i d \cos\theta_i$

# Task 1: Present Status of the Quantum Ellipsometer 1

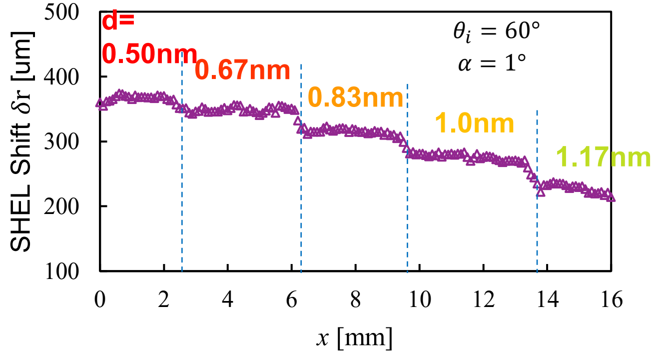
MIZUTANI, Y., private comm.

## Thickness sensitivity in Au film on a glass substrate

**Sample:** Au films with varying film thicknesses




Film thickness step:
**0.5 nm**




Film thickness step:
**0.17 nm**

→ SHEL shift was confirmed with sub-nanometer sensitivity.

## Surface Roughness of Optical Flat

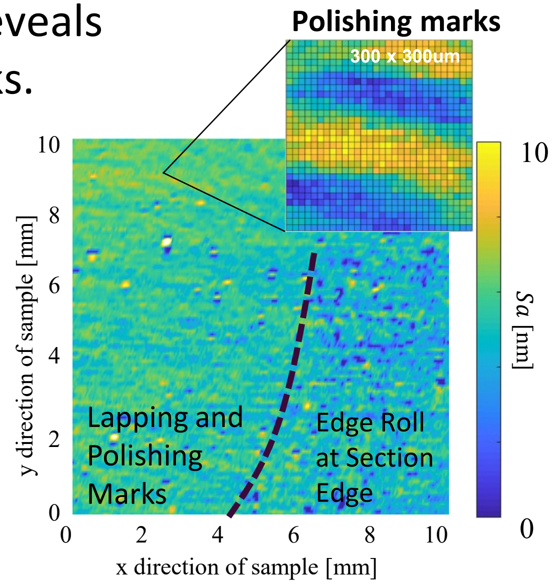
**Sample:**

Material: synthetic quartz
$n+i\,\kappa$: 1.457 + 0 $i$
Size: ϕ 30 mm

Surface roughness (AFM value):
$Sa = 6.65 \pm 3.89$ nm

**Measurement results: SHEL shift converted to 2D map.**

The 2D map reveals polishing marks.



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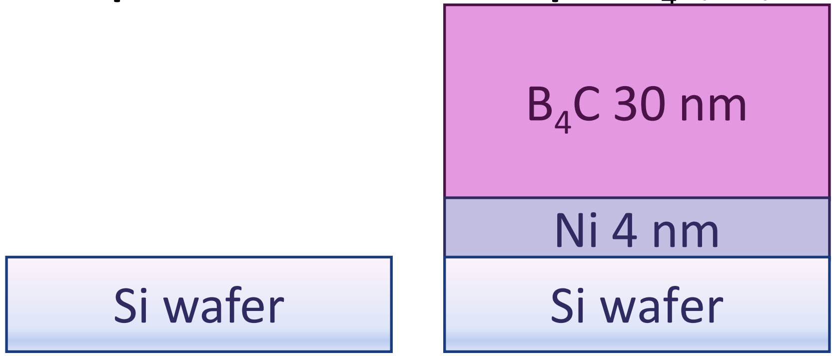
## Preliminary Experiments for Application to Sputtering System

Zahara, N. & MIZUTANI, Y. et al., to published in Proc. Of OPTM2026.

**Sample:** Si wafer **Sample:** $B_4C$/Ni/Si

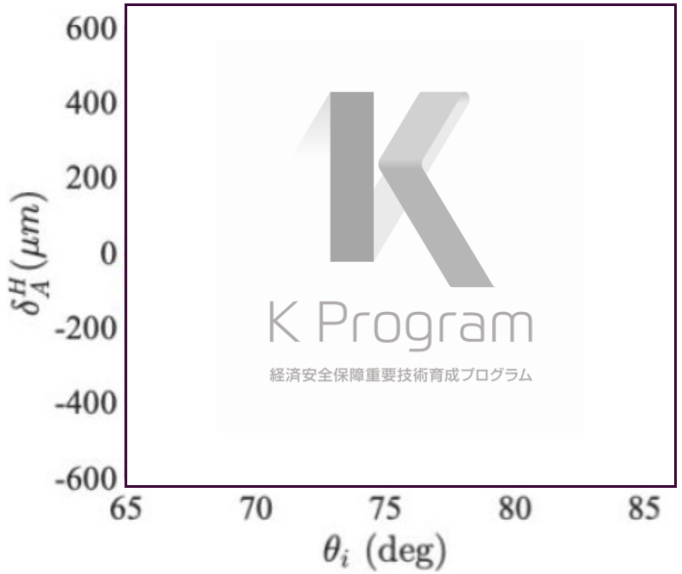



**Meas.:** SHEL shift $\boldsymbol{\delta_r}$ vs Incident Angle $\boldsymbol{\theta_i}$

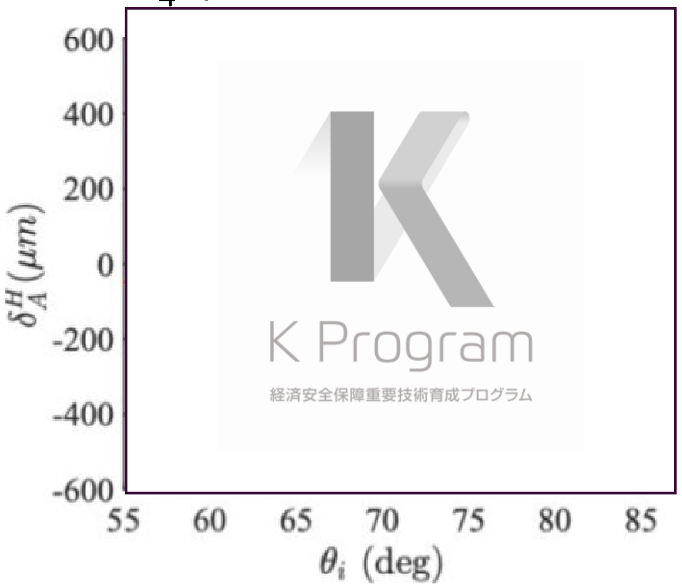
**Conditions:** in the Atmosphere, λ=633 nm

| Medium | Refractive index |
|---|---|
| Air | 1.0003 + 0i |
| $B_4C$ | 3.186 + 0.414i |
| Ni | 1.990 + 4.114i |
| Si | 3.882 + 0.019i |

Si wafer




$B_4C$/Ni film on Si wafer




→

- The Si substrate measurements were well reproduced by optical calculations,
- The $B_4C$/Ni bilayer film was clearly distinguishable,
- The SHEL shift was largest when the Analyzer Offset Angle ε was 0.5° .

# Task 2. Re-examination of BEUV ML design

T. Ejima, submitted to JJAP

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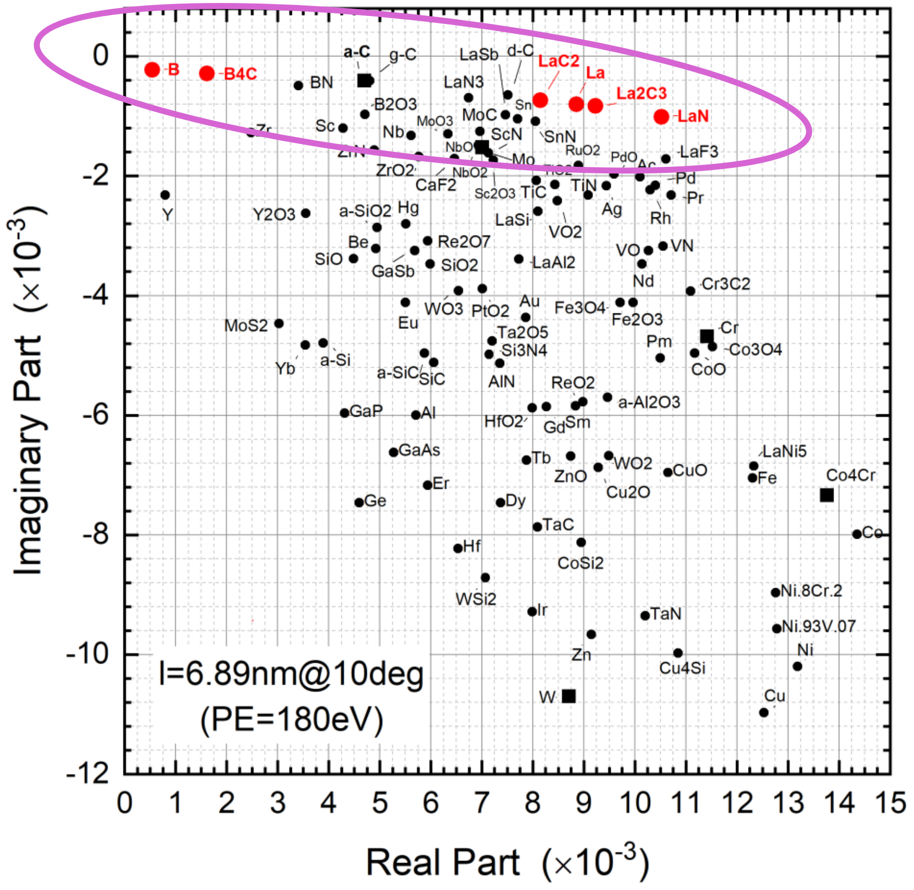
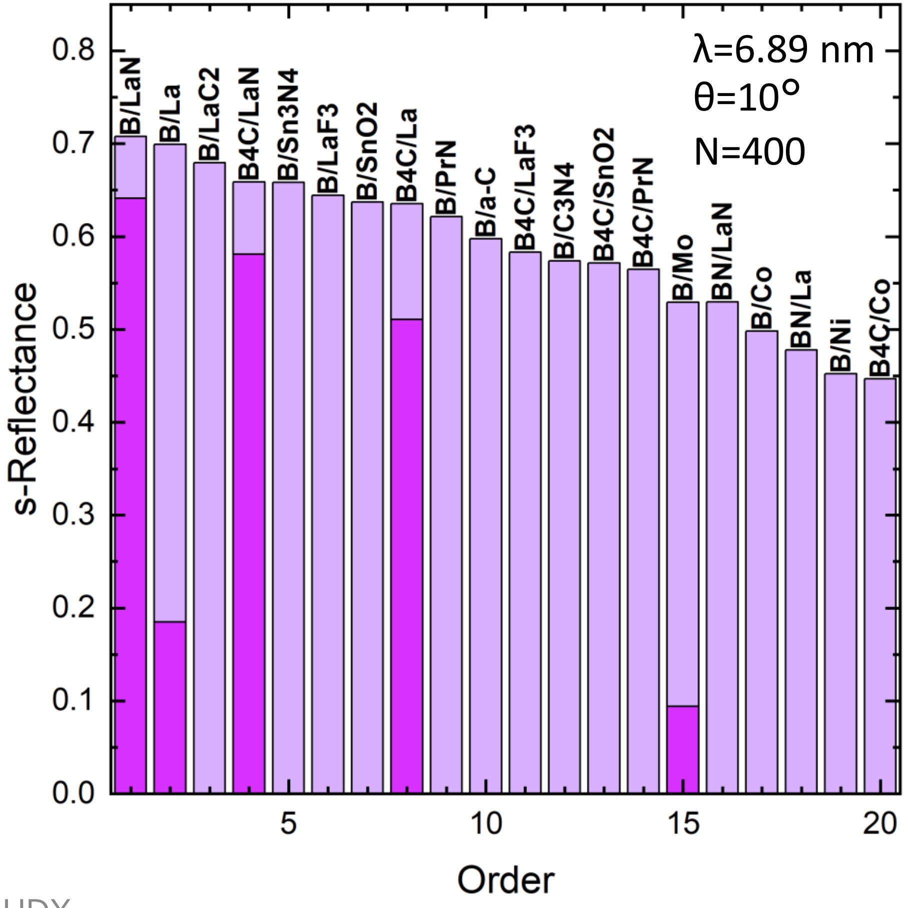
- **Selecting material pair in λ=6.89 nm & AOI=10°**
  - Rule 1 ( small Im(ρ) ): B & $B_4C$ close to the origin
  - Rule 2 (large separation ): the red ellipse,
    La compounds show largest distance from B pos.



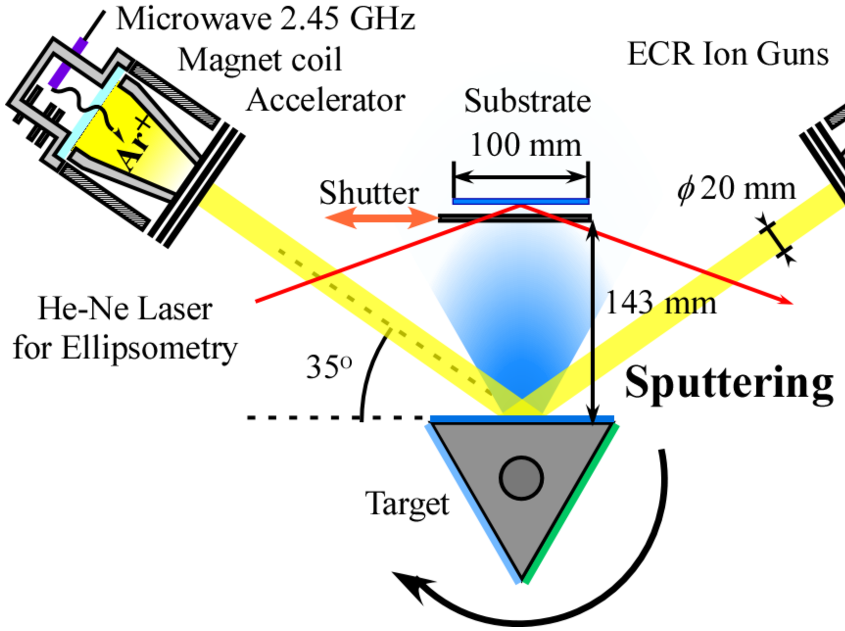

- **Reflectance: Design vs. Measurement**
  - Parameters are fixed for comparison.
  - Combinations of **B- and La-based**



# **Task 3.** Identification of deposition-related issues

TOHOKU 大阪大学 K Program

1. Ion Sputtering System with Thickness Monitor and Control of Film Thickness Distribution

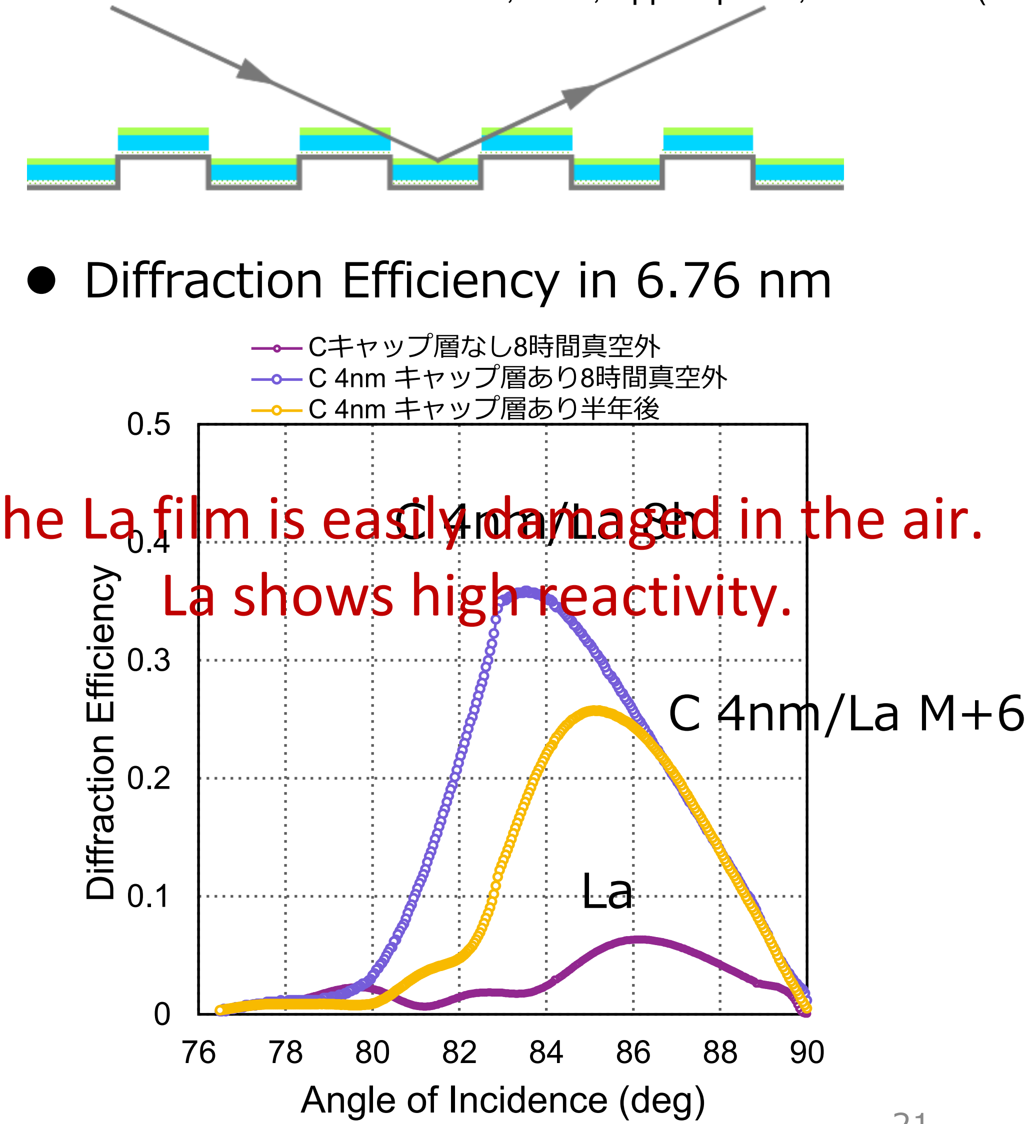



- Advantages of the Sputtering System:
  - Reducing the deposition pressure by two orders of magnitude
  - Reactive Sputtering
  - Precise Control of Film Thickness Distribution

➢ Previous our Research: Grating for 6.0〜9.5 nm

T. Hatano, et al., Appl. Opt. **60**, 4993-4999 (2021)

- Diffraction Efficiency in 6.76 nm




The La film is easily damaged in the air.

La shows high reactivity.

- Preliminary experiments motivated by La layer reactivity

**Prototype samples:**

- The La/$B_4C$ pair was selected. Sputtering targets of these materials are readily available.

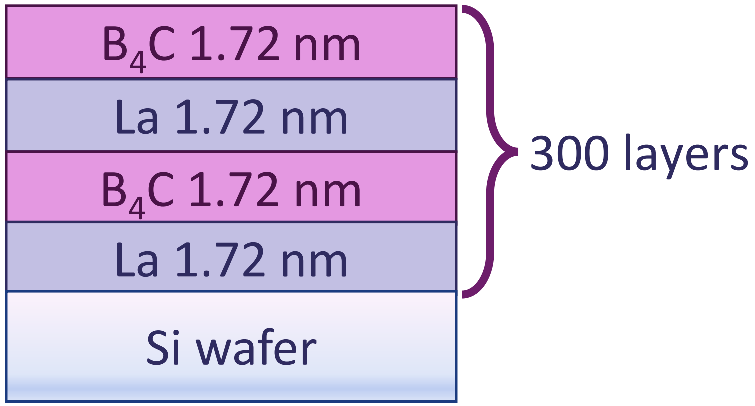
**Sample characteristics:**

- The ML surface will be protected by an inert $B_4C$ layer.
- The MLs will be fabricated with varying $Ar^+$ acceleration voltages to investigate deposition condition.
  - Acc. Vol. = 0.5kV, **1.0kV**, 1.5kV, 2.0kV.

**Evaluation methods:**

- The layers were evaluated using the methods:
  XRR, BEUV Ref., SEM & STEM, HAXPES, ARPES, and XPS

➢ Fabricated Multilayer (Nominal values)



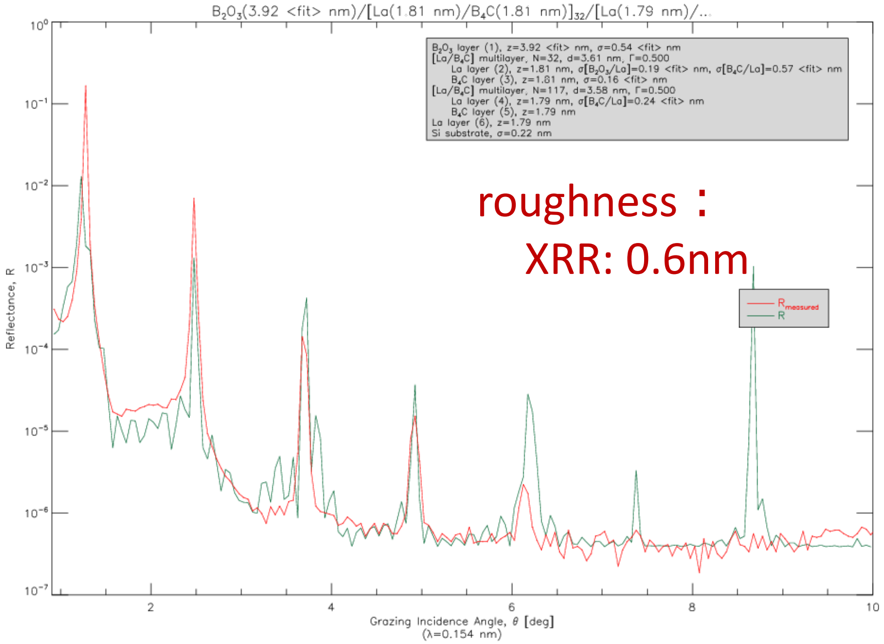
# **Task 3 & 4.** Measurement Results of XRR & BEUV Reflectance

T. Ejima, R. Nakamura, & T. Hatano, Photon Factory Activity Report 2024 #42 (2025)

TOHOKU UNIVERSITY 大阪大学 K Program

- XRR result of $B_4C$/La ML Film

Nominal value: [$B_4C$ 1.72nm/La 1.72nm]*150



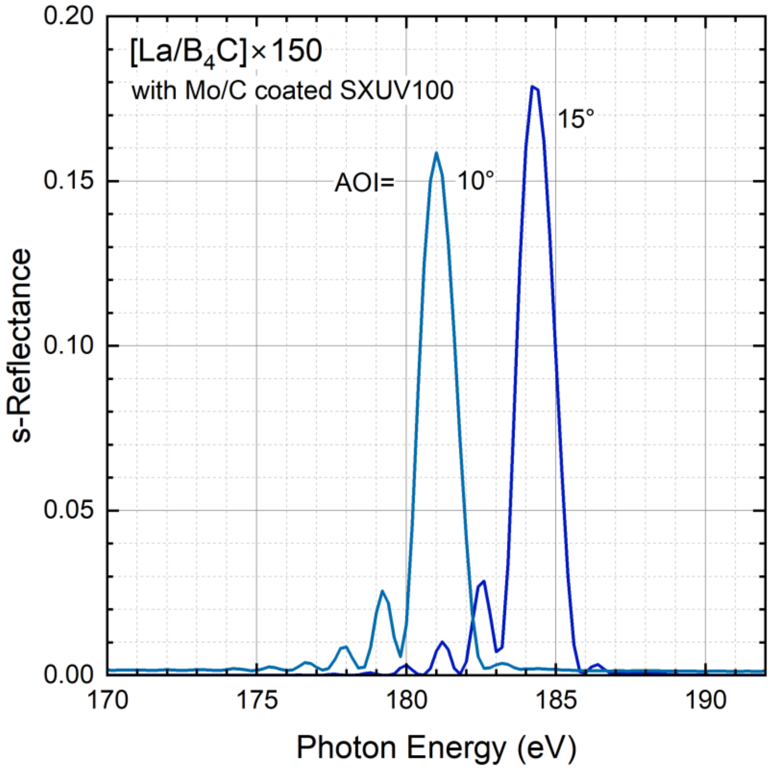


Evaluated value：

[La 1.81nm/$B_4C$ 1.81nm]*32

+ [La 1.79nm/$B_4C$ 1.79nm]*117

- BEUV Reflectance of $B_4C$/La ML Film

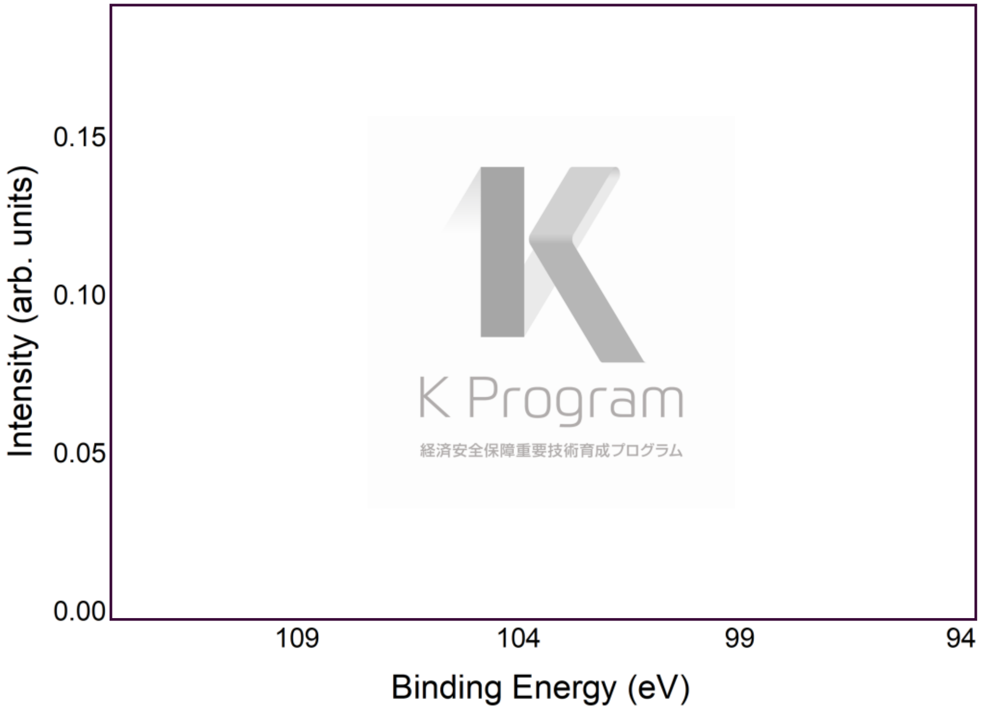



- The MLs maintains the same reflectance for 4 months after the deposition.
- Low reflectance

→ The reason of low ref. ?

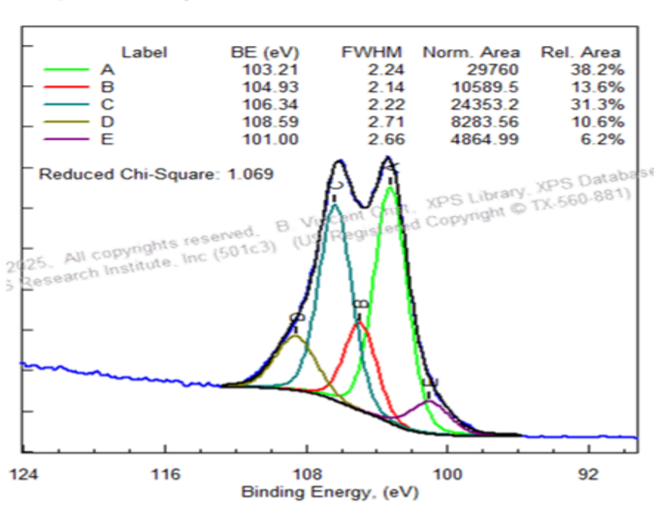
# Task 3 & 4. Characterization of La/$B_4C$ multilayers using HAXPES

- HAXPES spectrum in La4d region




- The spectral shape reproduced well by the peak fitting using the reference values of $LaB_6$ [1].

The measured La4d spectrum closely resembles the previous reports of $LaB_6$.



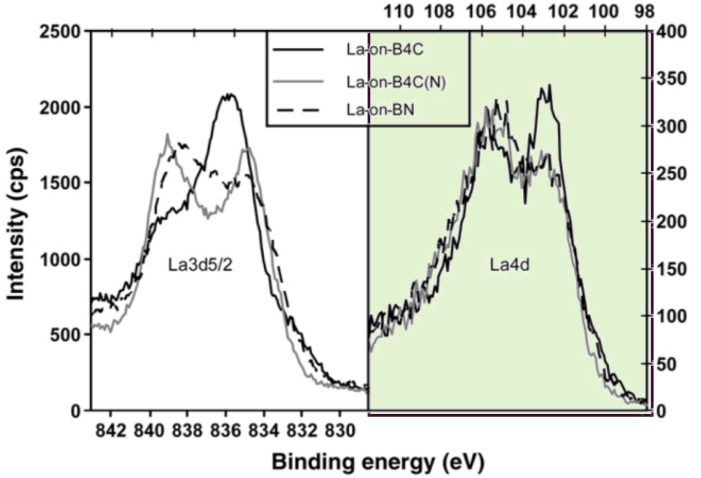




**Fig. 1.** The $La3d_{5/2}$ and La4d peaks of the three discussed bilayers. For the La-on-$B_4C$(N) interface, the $B_4C$ substrate layer was post N-treated, for the La-on-BN interface, it was grown by NIBAD.

[1] https://xpsdatabase.net/lanthanum-spectra-lab6-lanthanum-hexa-boride/

[2] T. Tsarfati, R.W.E. van de Kruijs, E. Zoethout, E. Louis, F. Bijkerk, "Nitridation and contrast of B4C/La interfaces and X-ray multilayer optics", , Thin Solid Films **518** (2010) 7249–7252.

# Summary of Task 3 & 4

**Evaluation of Results for Prototype La/$B_4C$ MLs:**

- **XRR:** periodic structure
- **BEUV R:** $R_s$ = 0.23 @ AOI = 15°
- **TEM & STEM:** La and B exhibit clear periodic structure.
- **HAXPES@La4d:** La layer predominantly consists of $LaB_6$.
- **ARXPS@C1s:** $B_4C$ is disrupted at the La–$B_4C$ interface, forming La–B bonds and converting the La layer into $LaB_6$.
- **XPS@La4p+B1s:** Coexistence of $LaB_6$ and $B_4C$ concerning with HAXPES result.

→ The results suggest that the La layer reacts with B and changes to $LB_6$.

**Issue from the Experimental Results:**

- Reactivity of La layer

# Summary

- Overview of our project in K Program

- Specific Research Objective and present status
  - The ion sputtering system is operating in non-reactive mode.
  - The QE monitor provides sub-nanometer sensitivity, and the SHEL shift varies depending on the number of layers.
  - The La layer reacts strongly with B.
    - How to get a steep interface between La- and B- compounds ?

*Thank you for your attention!*