Optical properties of multilayers for operational wavelength between 6.x and 13.5 nm

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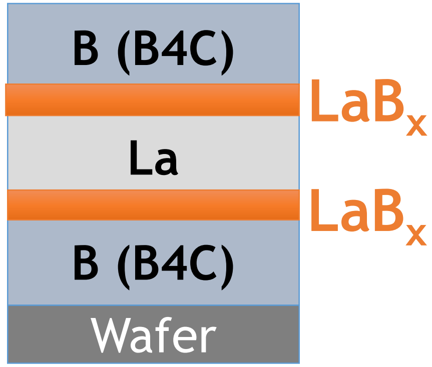
Outline

- Latest results on La/B-based multilayers for 6.x nm
  - Normal incidence
  - Grazing incidence

- Optical properties (spectral and angular bandwidth) of MLS in 6.7 – 13.5 nm
  - Calculations
  - Experimental verification

6.x nm: La/B based multilayers

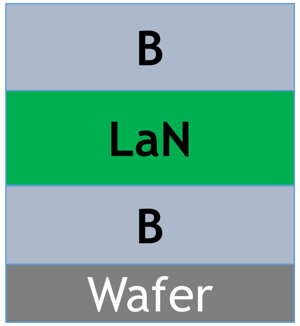


R (La/B4C) ≈ 45%

S.S. Andreev et.al., Nuclear Instruments and Methods in Physics Research Section A, Vol.603, Iss.1-2 (2009)

→ Broad interfaces formed (optically unfavorable)

Passivated La



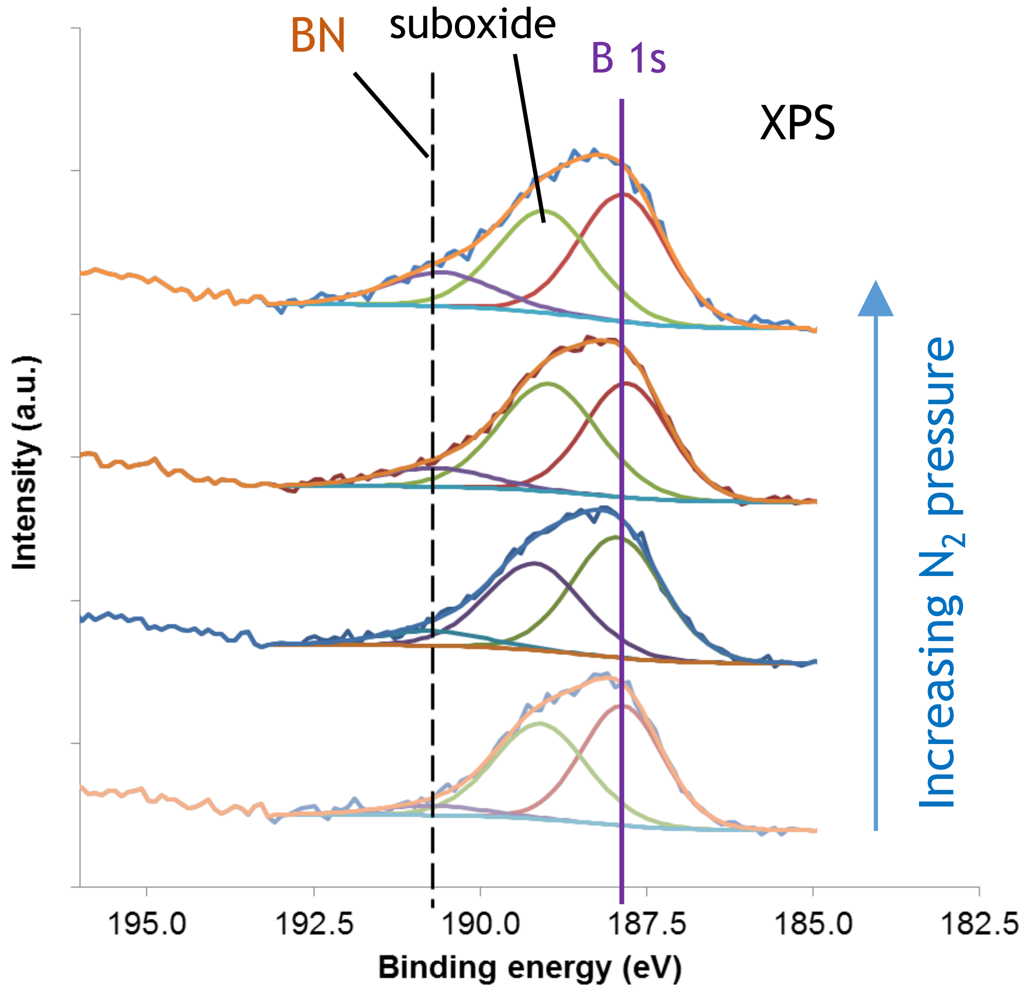
R (LaN/B) ≈ 57%

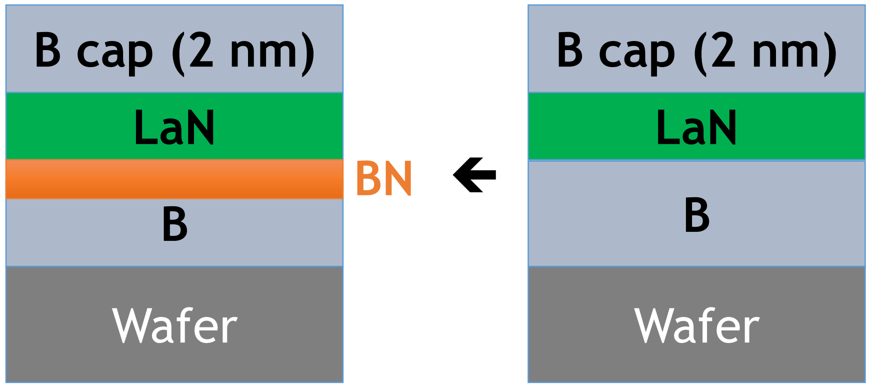
Technique for La passivation:
magnetron sputtering of La in N_2 environment

I.A. Makhotkin et.al., Optics Express, Vol.20, No.24 (2013)

XPS of test structures: BN formation

Nitrogen flow varied for LaN deposition in order to get fully-passivated LaN

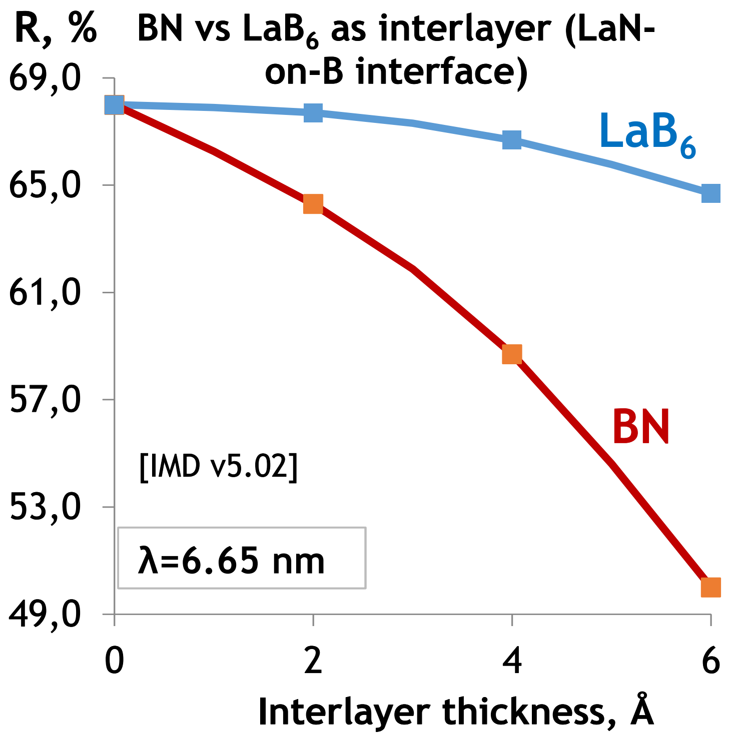




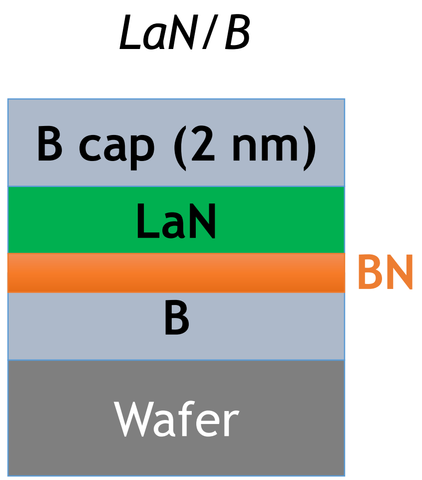
- XPS → BN formation during deposition ΔH(BN)≈ - 255 kJ/mol
- The higher the N2 pressure the more BN is formed

D.S. Kuznetsov et.al., Optics Letters, Vol.40, No.16 (2015)

Delayed La nitridation

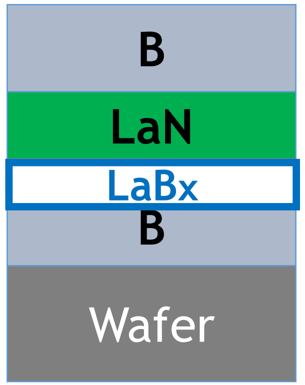


→ BN is optically unfavorable



→ LaN protecting upper interface but making lower interface worse

Delay in La passivation to avoid BN



Step 2: fully-passivated LaN

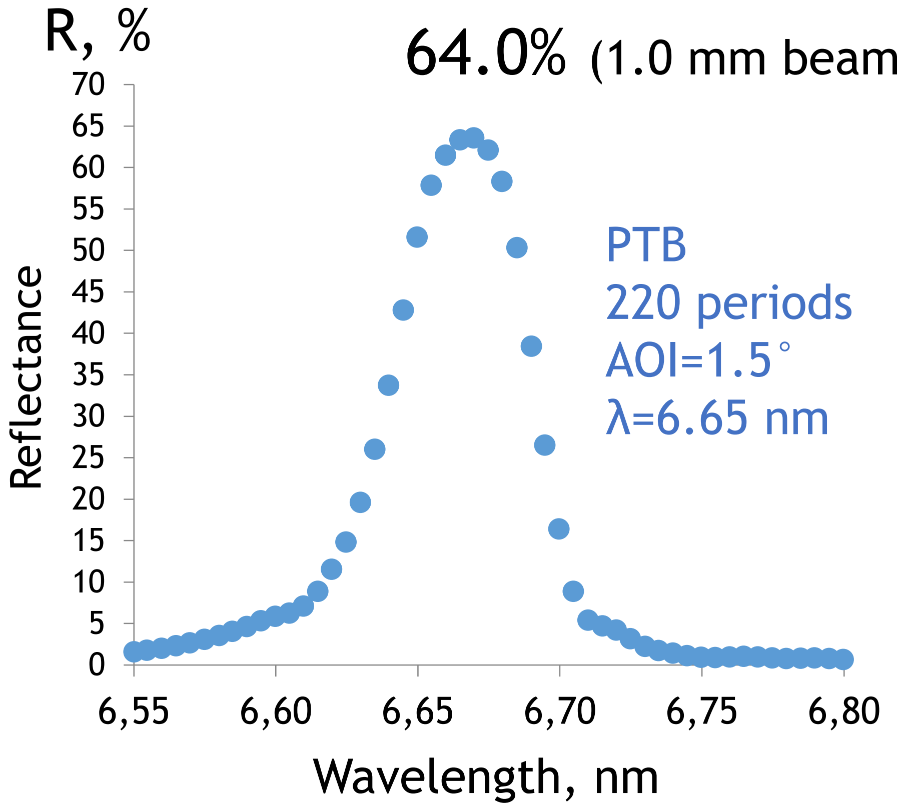
Step 1: thin non-passivated La

D.S. Kuznetsov et.al., Optics Letters, Vol.40, No.16 (2015)

LaN/La/B MLS reflectivity

66.5% (0.2 mm beam-spot)

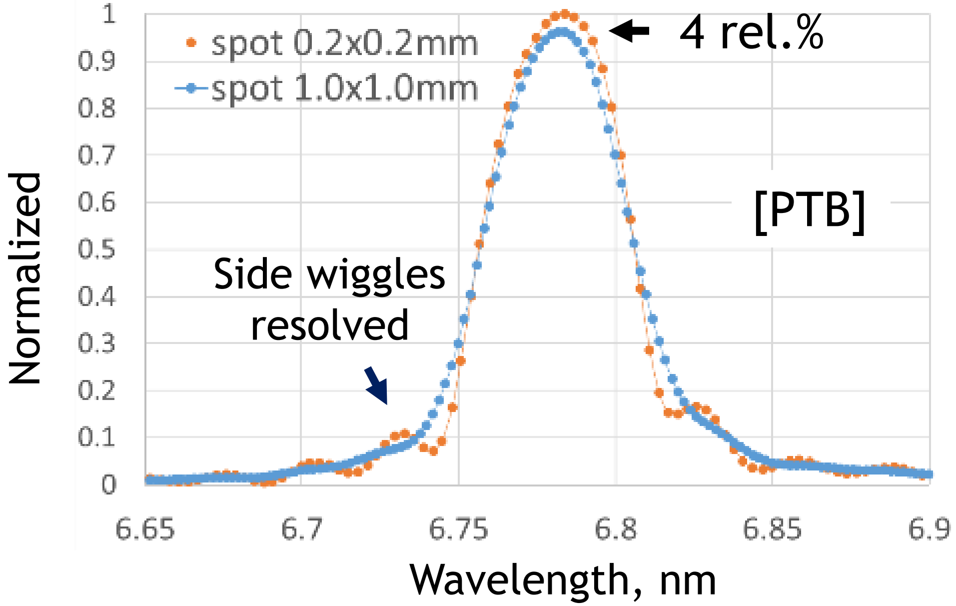
64.0% (1.0 mm beam-spot)

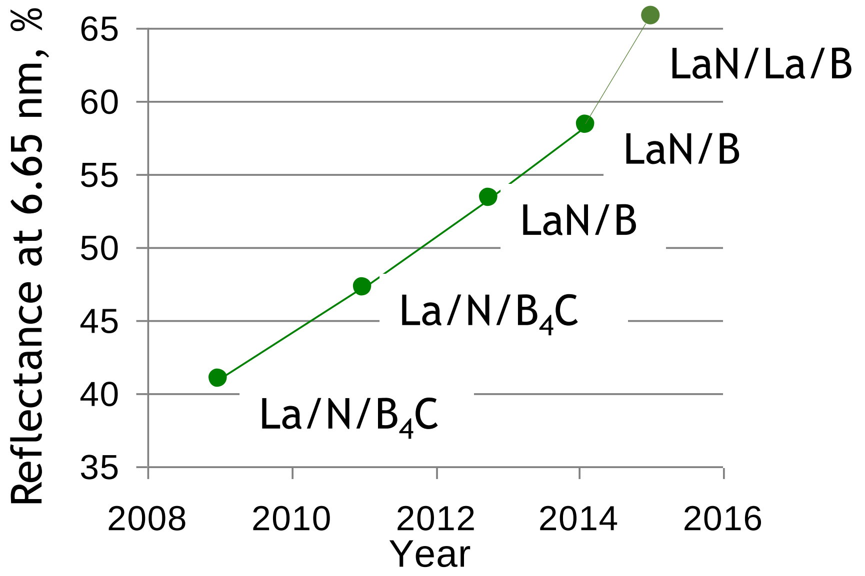


Sample with lateral period gradient of 0.23 Å/mm

D.S. Kuznetsov et.al., Optics Letters, Vol.40, No.16 (2015)

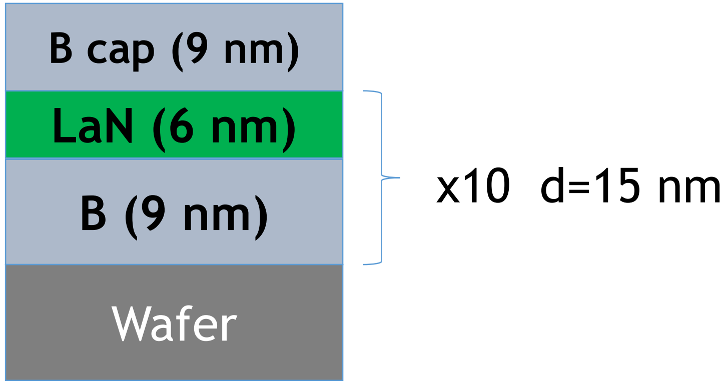
Influence of spot size on measured R



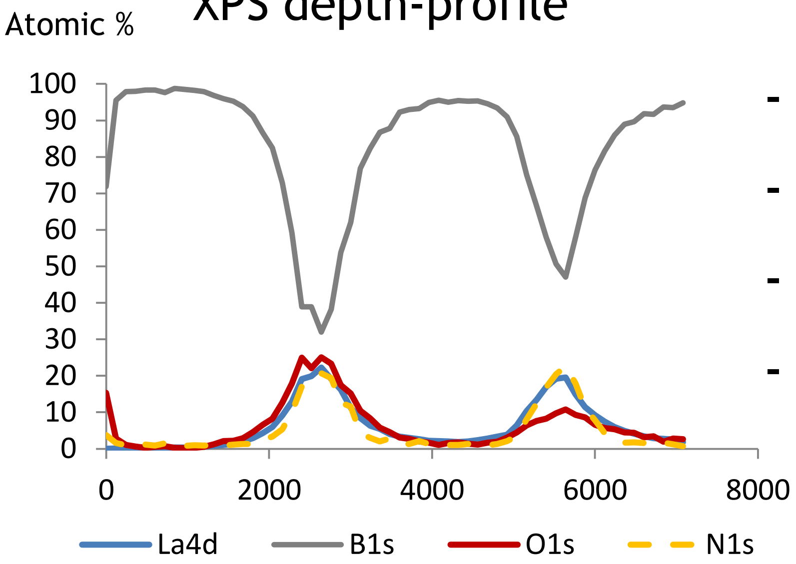


Grazing incidence LaN/B MLS

MLS designed for 77 degrees off normal

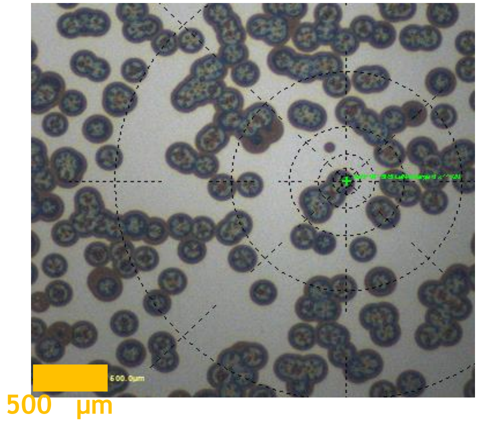


XPS depth-profile



- Linked to oxidation
- B layers intact
- O2 diffuses through B
- Oxidation of LaN, > 1 period

Two weeks after deposition



Optical microscopy: blister like defects

Puzzle: no deterioration in case of La without nitridation!

→ B protective properties against oxidation depend on substrate layer

D.S. Kuznetsov et.al., Journal of Nanoscience and Nanotechnology, Vol.19, 585-592 (2019)

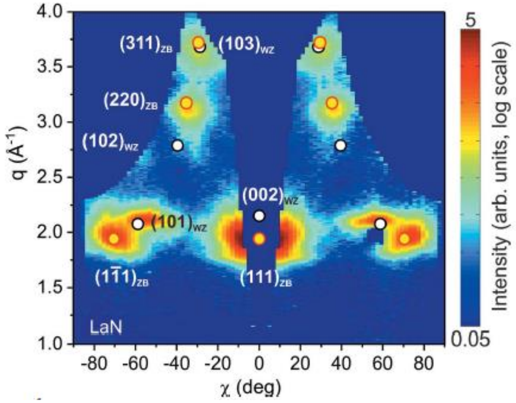
In situ studies of growth of La and LaN

MPI beamline Synchrotron Radiation Source ANKA, Karlsruhe

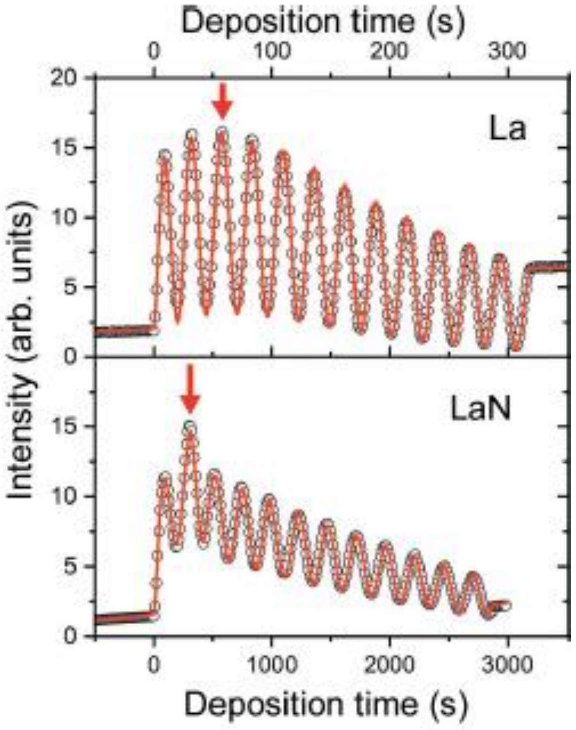
	La	LaN
Crystallization	At 2-3 nm	At 2-3 nm
Roughness	Slow increase from 5 nm of La	Sharp increase from 2-3 nm of LaN
Lattice	(111) FCC	(111) ZB* + (001) WZ*

- Mixed crystal structure of 2-3 nm LaN may be the reason for higher roughness
- Complex LaN structure could possibly affect top B layer structure

B.Krause et.al., Journal of Applied Crystallography, Vol.51, 1013-1020 (2018)



Example of XRD map for LaN



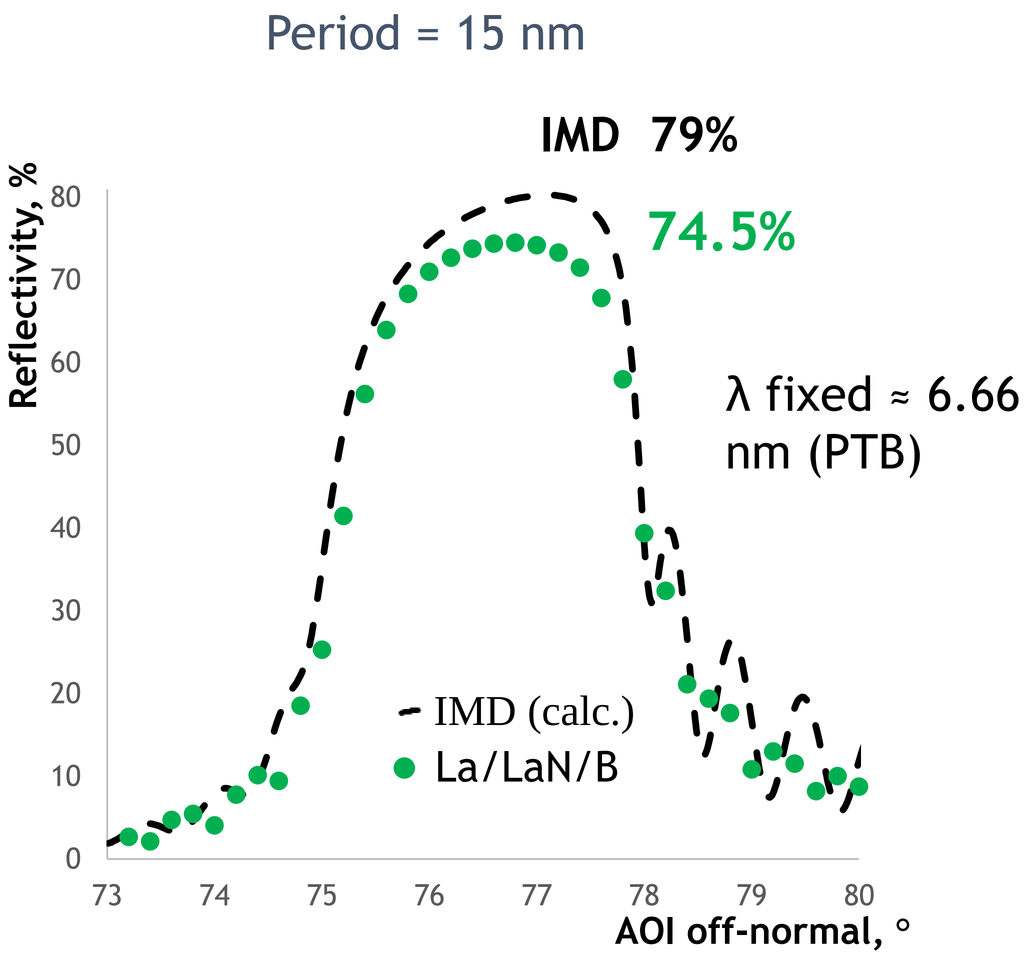
In situ XRR at 10 keV at 1.5

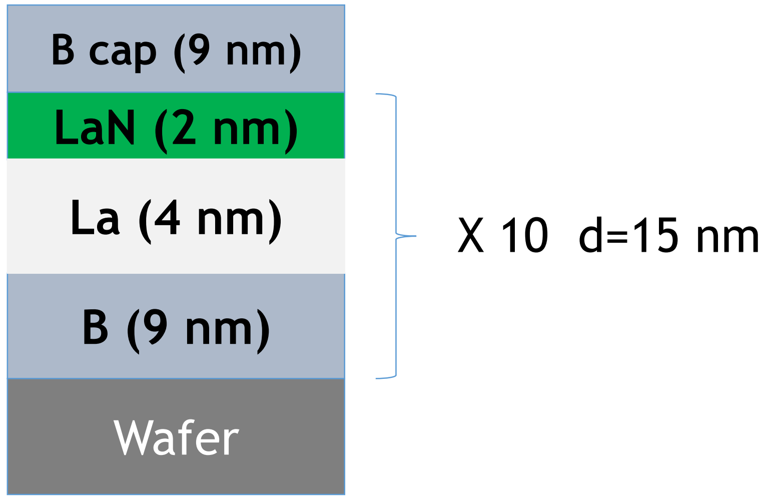
* Phases identified:

Wurtzite (WZ)

Zincblende (ZB)

Multilayer reflectivity at 6.7 nm





- Stability to storage in air > 2 years
- R=74.5% vs theoretical 79%

D.S. Kuznetsov et.al., Journal of Nanoscience and Nanotechnology, Vol.19, 585-592 (2019)

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Promising canidates for 6.7 - 13.5 nm

Pair	d nm	λ max, nm	R max@ λ max	Experimental R	AOI off-normal	Ref.
Mo/Si	6.4	**13.5**	73.8	**>70% @13.5 nm**	1.5°	
Mo/Be/Si		**12.9**	76.0	**72.8%@12.9 nm**	21.3°	V.N.Polkovnikov et.al., PXRNMS, Paris, 2018
Pd/Sr	5.8	**11.4**	80.9	No data		
Ru/Be	5.6	**11.2**	79.0	**63.7@11.4 nm**	5°	S. Bajt et al., Colorado, July 19-23 (1999)
Mo/Be	5.6	**11.2**	76.7	**70.3%@11.3 nm**	6°	Svechnikov M.V. et. al., Optics Express 26, 33718–31 (2018)
Ag/BP	4.7	**9.3**	78.5	No data		Idea: V.V.Medvedev et.al., Optical Materials Express, Vol. 5, Issue 6, (2015)
LaN/B	3.3	**6.7**	79.3	**66.5%@6.7 nm**	1.5°	D.S.Kuznetsov et.al., Optics Letters, Vol.40, No.16 (2015) + this presentation

- Reflectivities above 66.5% achieved below 13.5 nm and further progress is possible

→ Should also consider <u>angular</u> bandwidth for shorter period multilayers

Angular bandwidth dependence

- Angular bandwidth directly affects numerical aperture → resolution
  - $NA \propto \sin\theta$
  - feature size $\propto \frac{\lambda}{NA}$

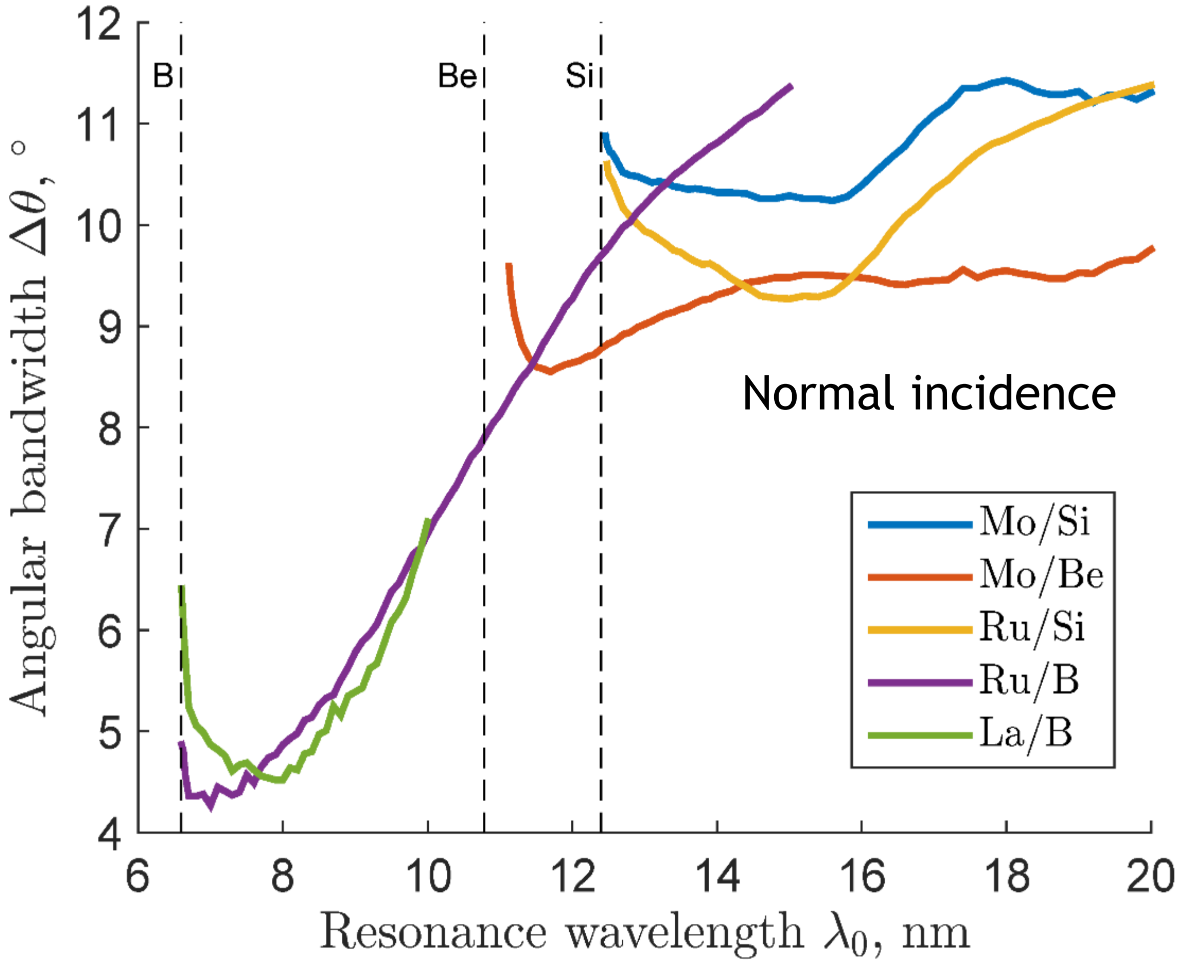
Generally $\Delta\theta$ will decrease with λ

- Spectral bandwidth $\sqrt{\frac{\Delta\lambda}{\lambda_0}}$ decreases with wavelength λ
- Analytical approximation *

$$\Delta\theta = 2\sqrt{\frac{\Delta\lambda}{\lambda_0}};\ \theta_0 = 90°;\ \text{atomic scattering factors } f_1, f_2 = const$$

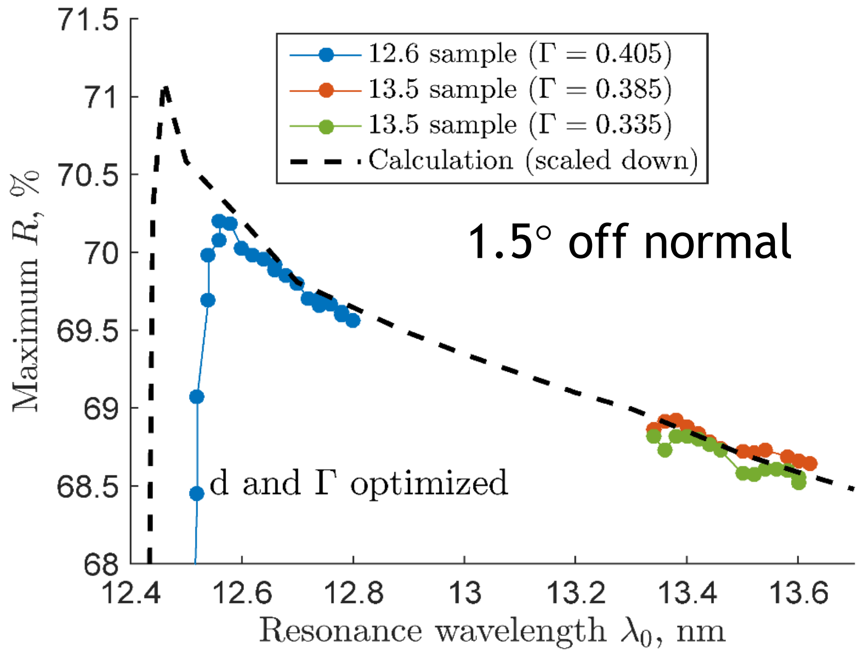
* I. V. Kozhevnikov and A. V. Vinogradov, Multilayer X-ray Mirrors (1995)

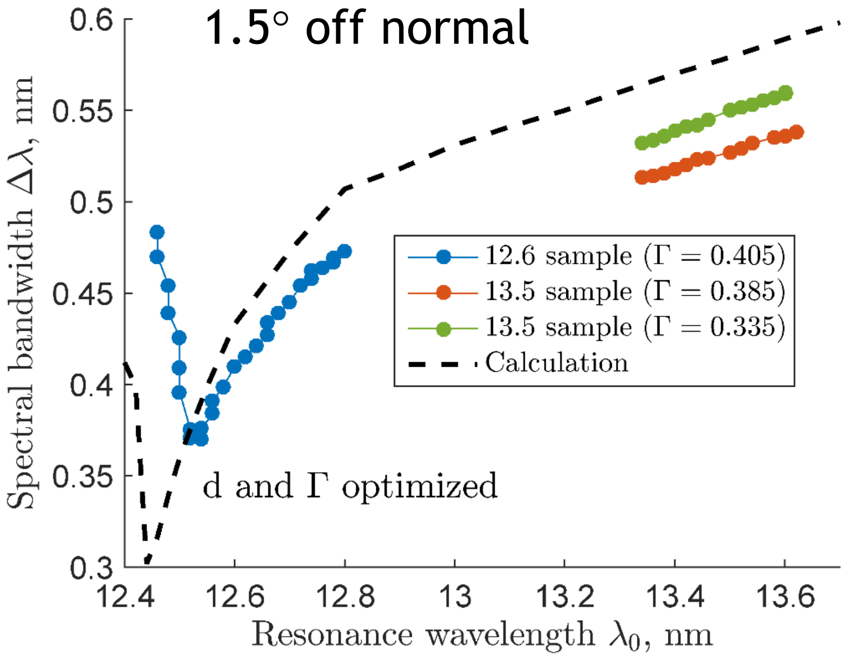
Angular vs wavelength and spectral bandwidth



- In general angular bandwidth decreases with wavelength
- Angular BW for La/B drops x2 compared to Mo/Si, which counterbalances benefit of wavelength reduction
- Close to absorption edges: opposite dependence – for all systems
- Interesting potential for Mo/Si in case of tunable narrow-band source

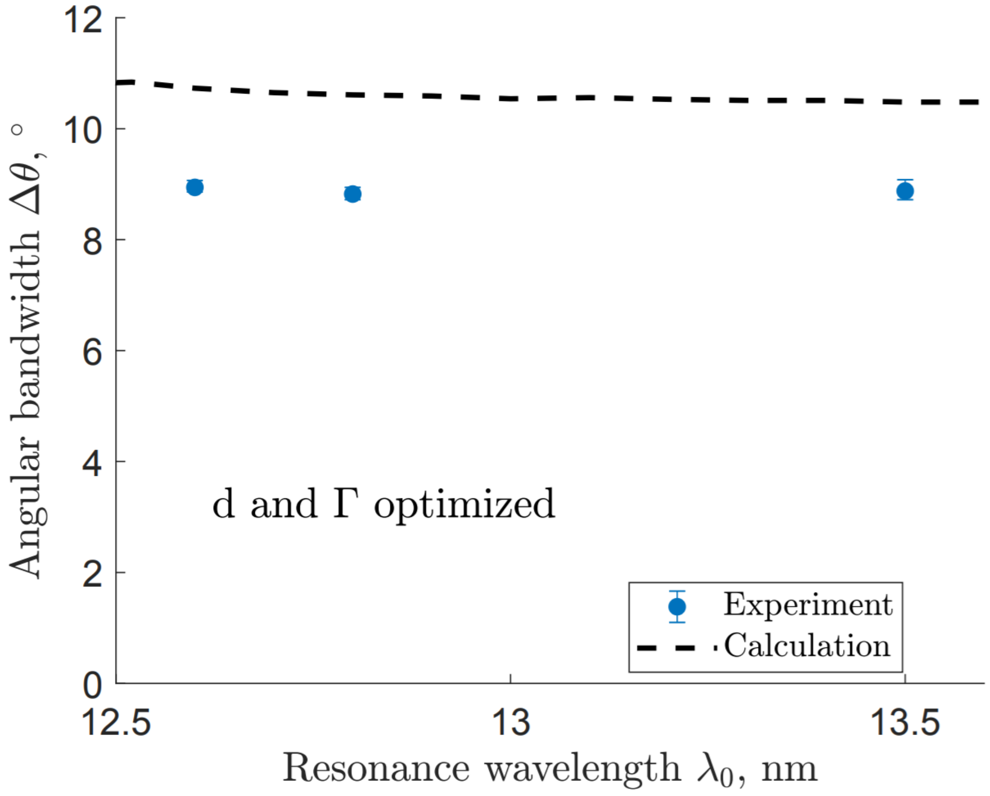
R and spectral bandwidth - experimental





- → **General trends in agreement with calculations**
  - ❑ R increasing by about **1.5%** close to edge
  - ❑ Spectral bandwidth reduces closer to edge
- → **Strong discrepancy in Si edge position (~1A or ~0.9eV)**
  - ❑ Cannot be explained by silicide interlayer formation
  - ❑ Calls for more accurate measurements of optical indices (CXRO data used)

Angular bandwidth - experimental



Angular bandwidth determined from wavelength scans at different angles

→ General trend of angular bandwidth in agreement with calculations

→ Angular bandwidth does not decrease when moving from 13.5 to 12.5 nm

→ Some discrepancy of the absolute angular bandwidth value calls for further research

Conclusions

- 6.7 nm wavelength
  - R=66.5% achieved experimentally at 1.5 degrees
  - R=74.5% achieved experimentally at 77 degrees
  - Further progress in R is possible
  - Smaller angular bandwidth at 6.7 nm needs solutions

- Angular bandwidth does not reduce with wavelength near absorption edges, which is beneficial for high NA systems
- For tunable narrowband source (FEL) → switching from 13.5 nm to 12.6 nm has advantages
  - Shorter wavelength
  - Higher reflectance (at least +1.5%) → lower absorption
  - Same angular bandwidth → no negative effect on NA

  → Mo/Si ML @ 12.6 nm is a good choice

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PTB

ZEISS