Reflective multilayer coatings, an enabling component of Extreme Ultraviolet Lithography and beyond.....

Eric Louis, Fred Bijkerk, Stephan Müllender

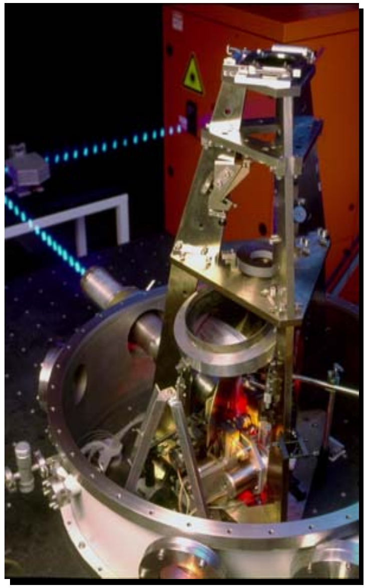
FOM Institute for Plasma Physics Rijnhuizen, The Netherlands
Carl Zeiss SMT GmbH, Germany

Outline

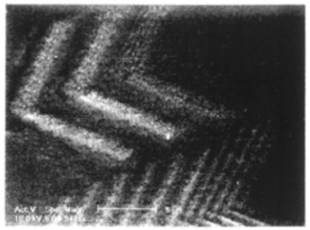
- Introduction
- Multilayer facilities at FOM and Carl Zeiss
- Multilayer development for EUV lithography
- Coatings on real optics
- Even shorter wavelength, Beyond EUV…… 6.x nm

EUVL: from basic research → *development labs*

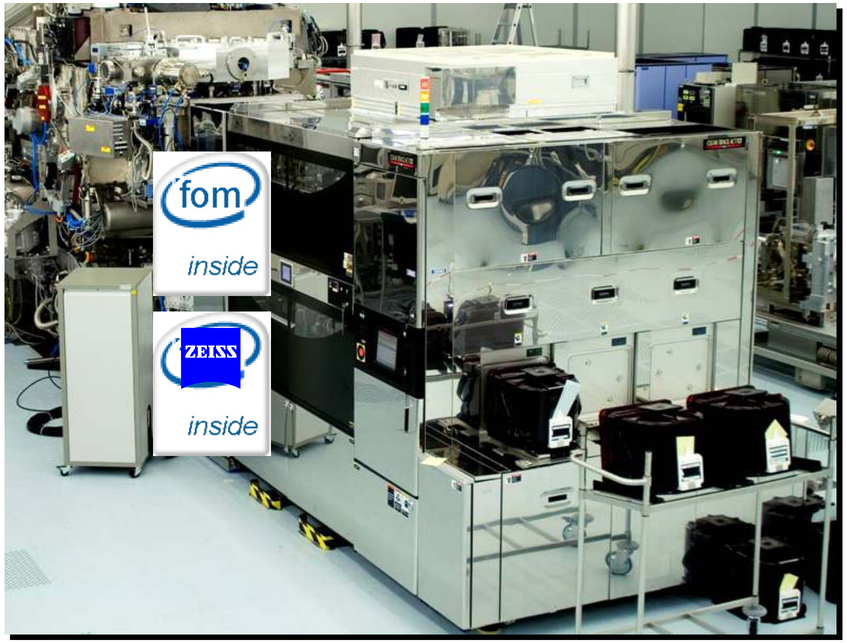
STW funded pilot research on lithographic imaging using 13.5 nm (1992)



13.5 nm exposures in resist



Two prototype 13.5 nm wafer scanners (Alpha Demo Tools, ADT) in full operation at IMEC & CNSE (2006)

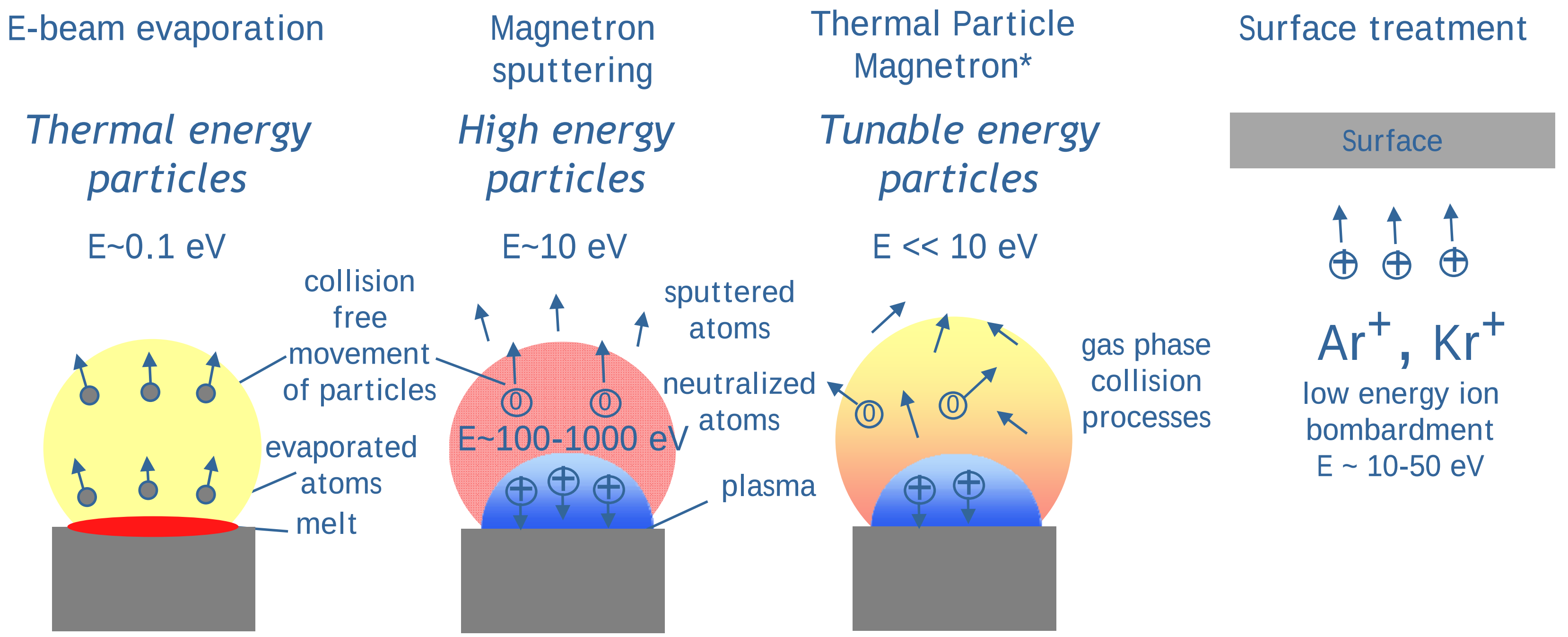


λ	*13.5 nm*
NA	*0.2*
# Multilayer optics	*10*
Max diameter	*45 cm*
Resolution	*~ diffraction limit*

Deposition processes

Energy of particles: main parameters responsible for balance between kinetics and thermodynamics in thin films

→ *Need different energies at different stages of ML growth*

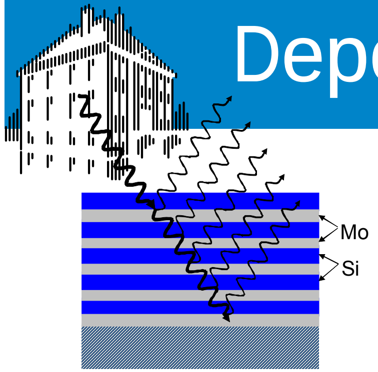


Thermal E particles: nucleate first monolayers

Higher energy particles: grow bulk layer

Ion bombardment: atom mobility, reconstruction, formation of compounds

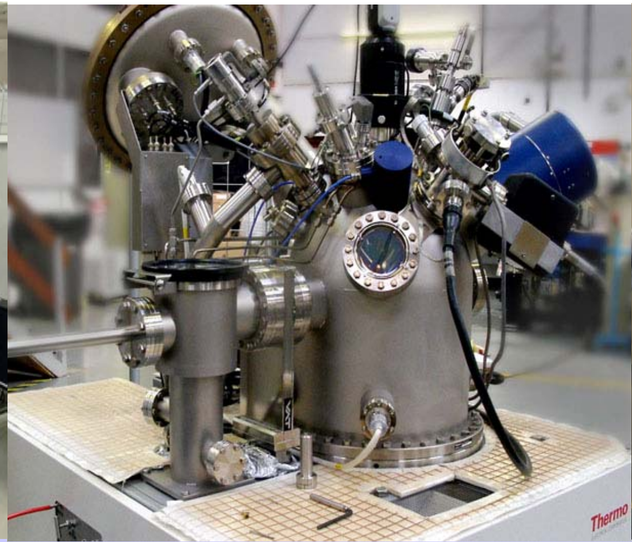
Deposition and analysis facilities @ FOM



- e-beam deposition
  - including ion beam polishing for layer smoothening
- magnetron sputtering (modified)

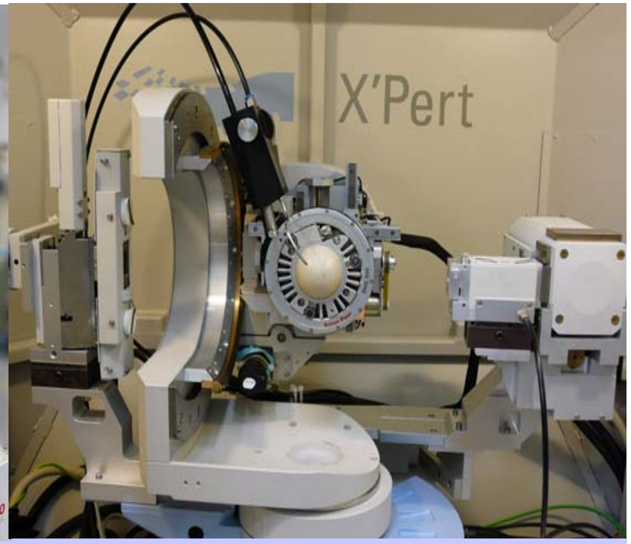
Coaters

- *E-beam, Magnetron Sputtering*



In-vacuo XPS, AES, STM

- *Morphology, Chemical analysis.*



Hard X-ray Diffractometer

- *Multilayer structure*
- *Crystalline structure*

…required for basic understanding of physics phenomena!

Deposition facilities @ Carl Zeiss

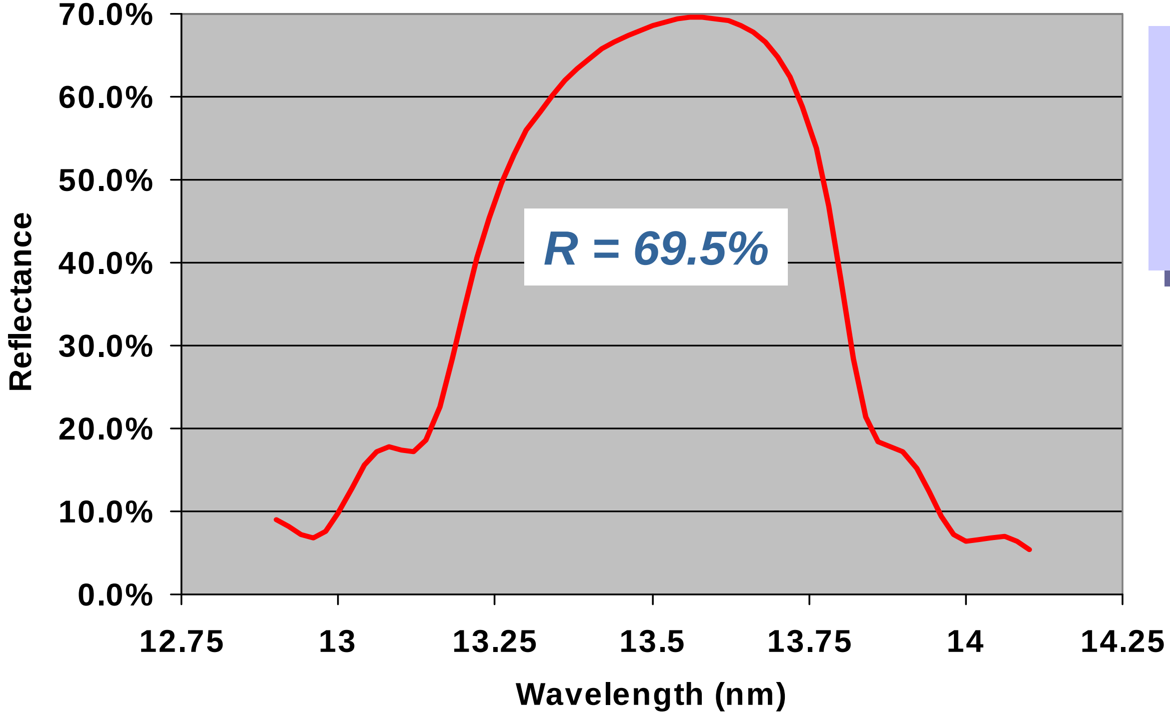
e-beam deposition
- including ion beam polishing for layer smoothening

magnetron sputtering

…required for industrial coatings on large > 0.5 m substrates

Normal incidence reflectance

EUV reflectometry at PTB, Berlin, Germany



50 periodes Mo/Si:

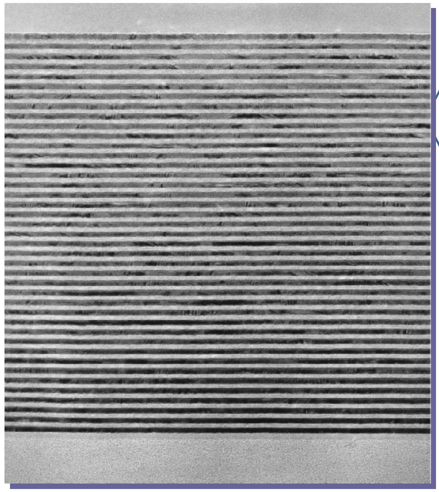
69.5 % @ 13.5 nm

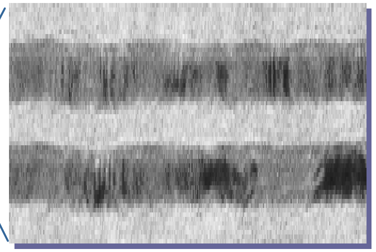
(1.5 º off normal, PTB)

→ *69.5 % highest possible value for Mo/Si, but still < theoretical 75 %*

Interface engineering

HRTEM



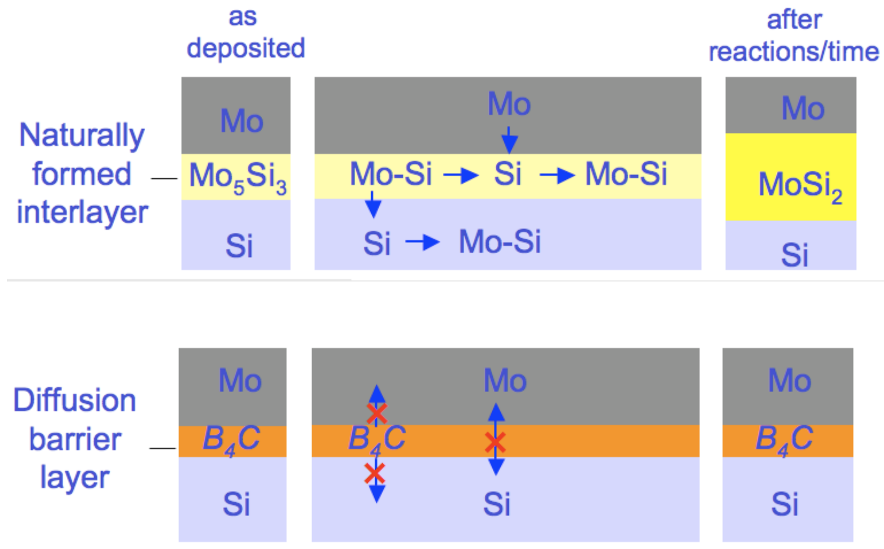


- Layer interdiffusion
- Compound formation
- Interface roughness
- Crystallization
- Density variations
- Void formations
- …

50 periods Mo/Si

d = 6.9 nm, $\Gamma \approx 0.4$

Dr. F. Tichelaar, Delft University of Technology



➔ *Diffusion barrier layers reqd at sub-nm thickness*

➔ *Materials & growth determined*

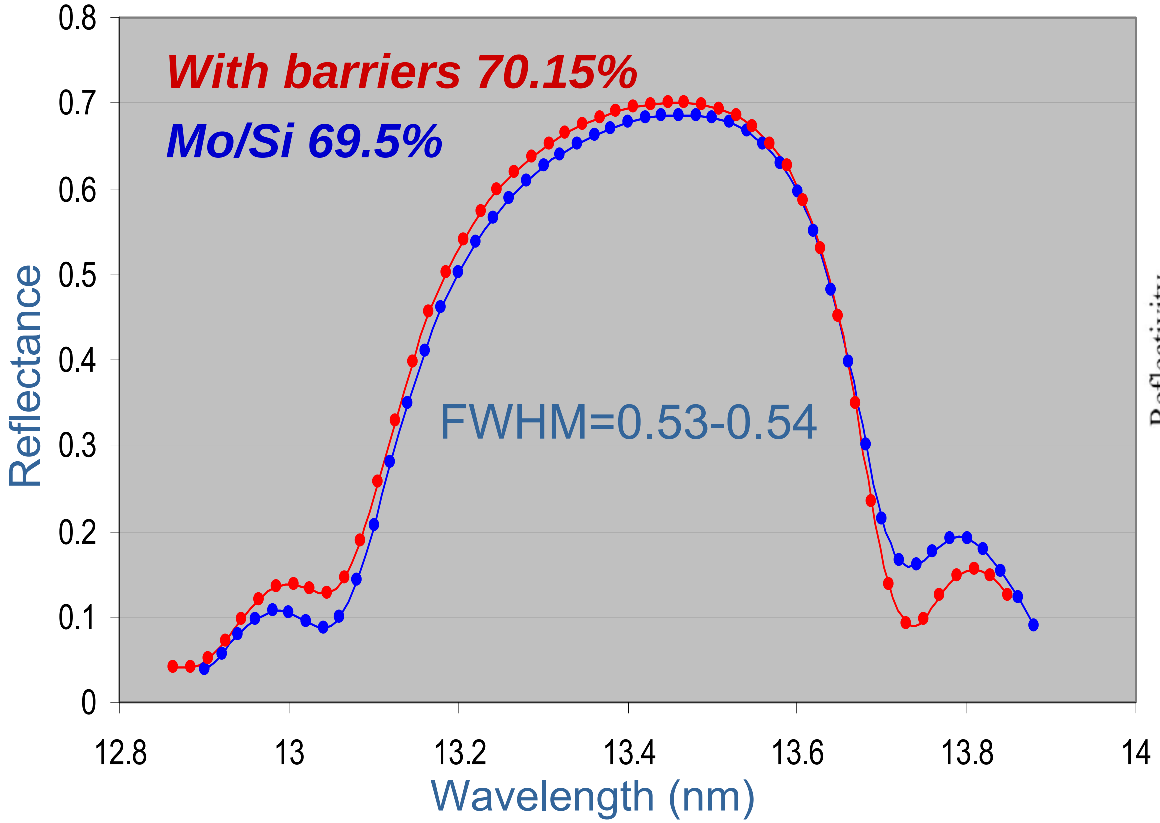
➔ ***'Interface engineering'***

Thin barriers: prevent diffusion & enhance reflectance

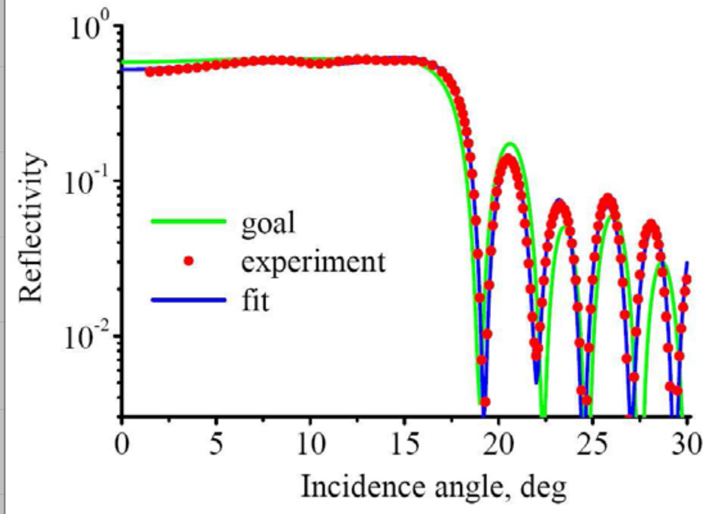
Thick barriers: prevent diffusion

Barriers: reflectance & bandwidth

Reflectance @ 1.5 º off-normal



Improved angular width: depth graded ML



A.E. Yakshin, R.W.E. van de Kruijs, et al, SPIE, Vol. 6517, 2007

A.E. Yakshin et al, Optics Express **18**, 6957-6971 (2010)

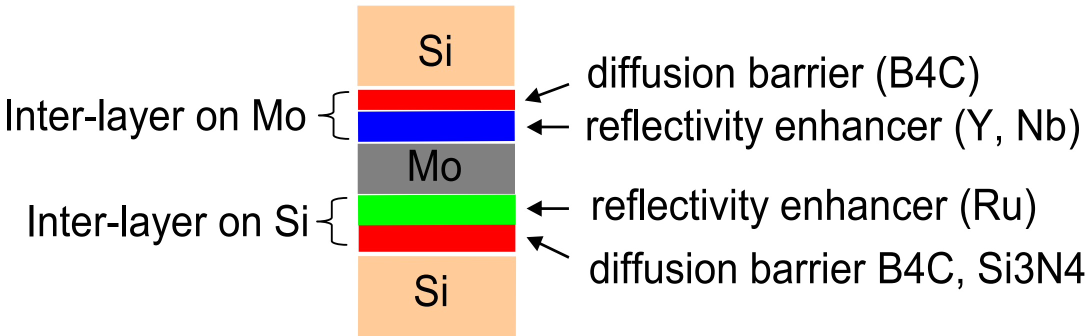
Thin barriers enable reflectance enhancement !

Compounded interlayer systems

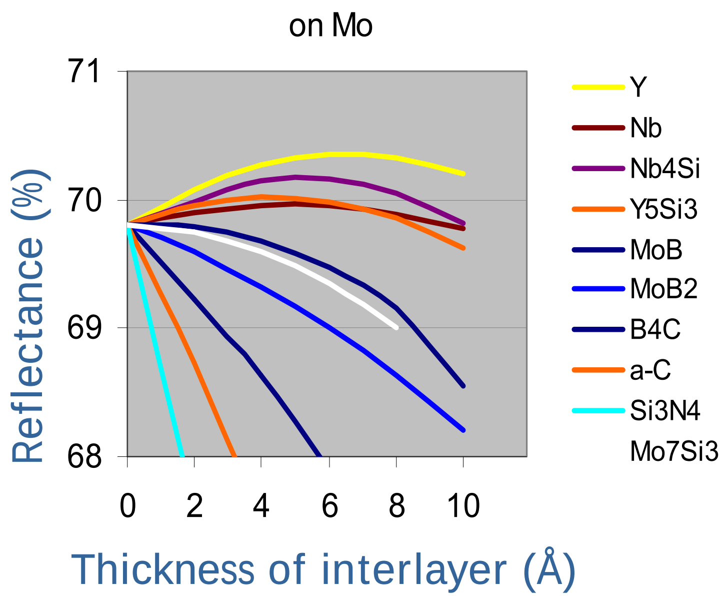
Traditionally one diffusion barrier with both favorable optical and diffusion reduction properties per interface.

Can it be functionally split: optical - diffusion ?

From bi-layer to six-layer design *



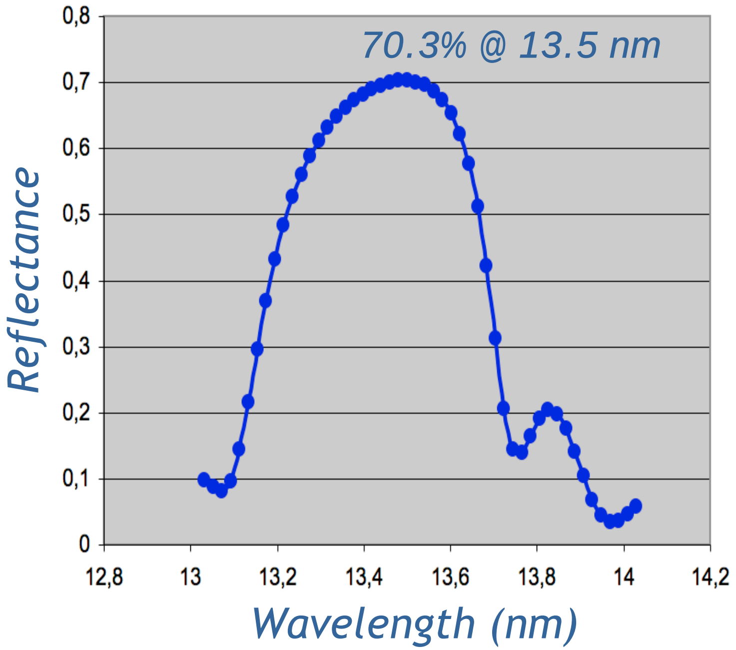
Calculated reflectance for candidate materials

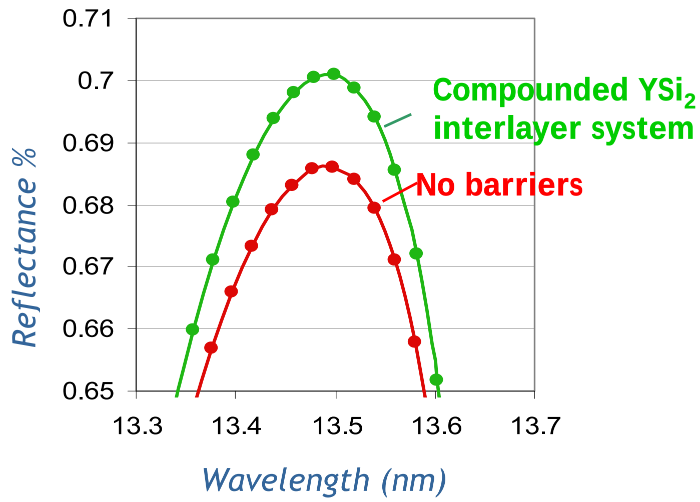


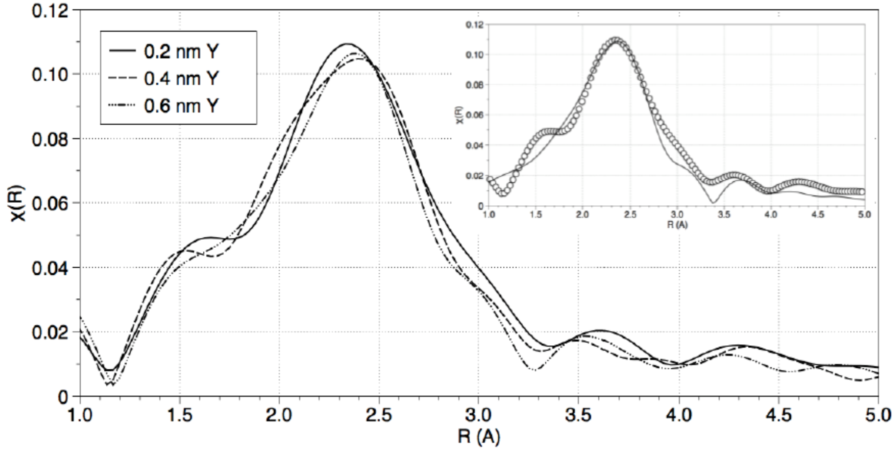
** A.E. Yakshin, et. al, Patent US 60/888,144, US, EU (2007)*

Compounded interlayer systems

Can these Å-scale structures be made?





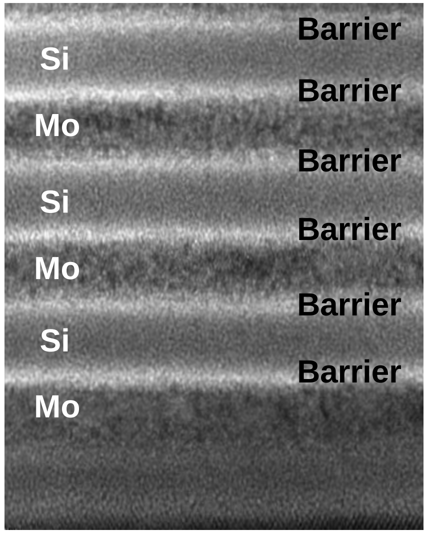


➔ *Sub nm interlayers can improve refractive index distribution*

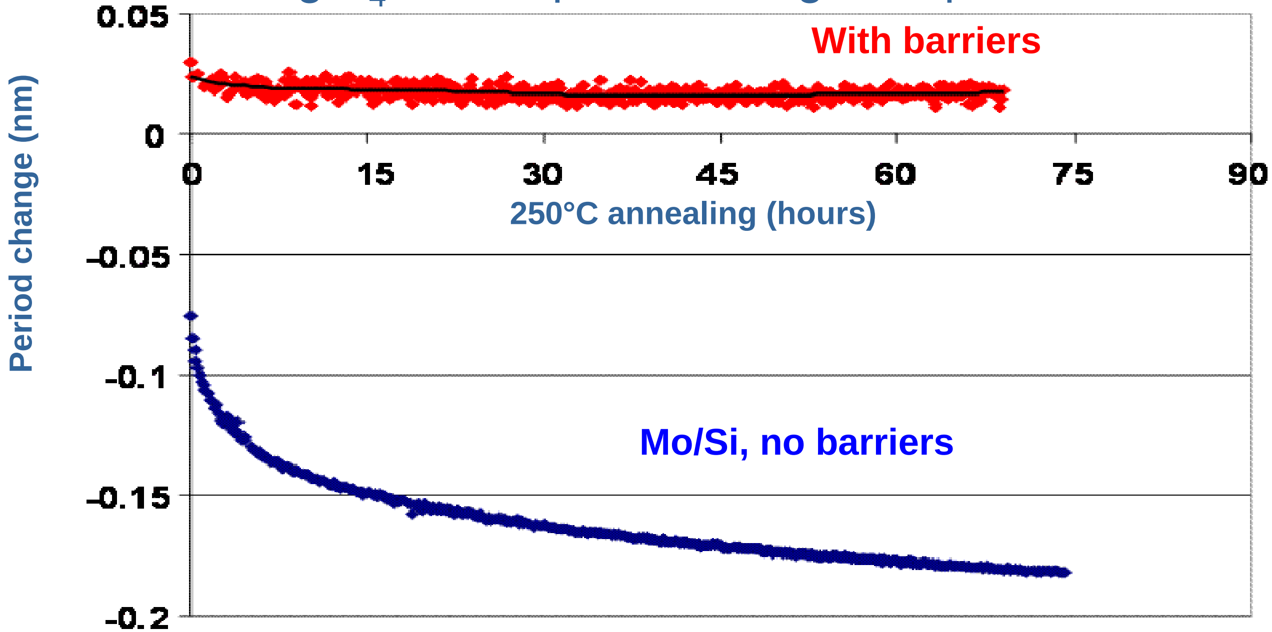
Yakshin, et al, SPIE 6517-17 (2007)
Bosgra, et al, to be submitted

Diffusion barriers for thermal stability

- 30 % radiation absorbed
  - improve thermal resistance

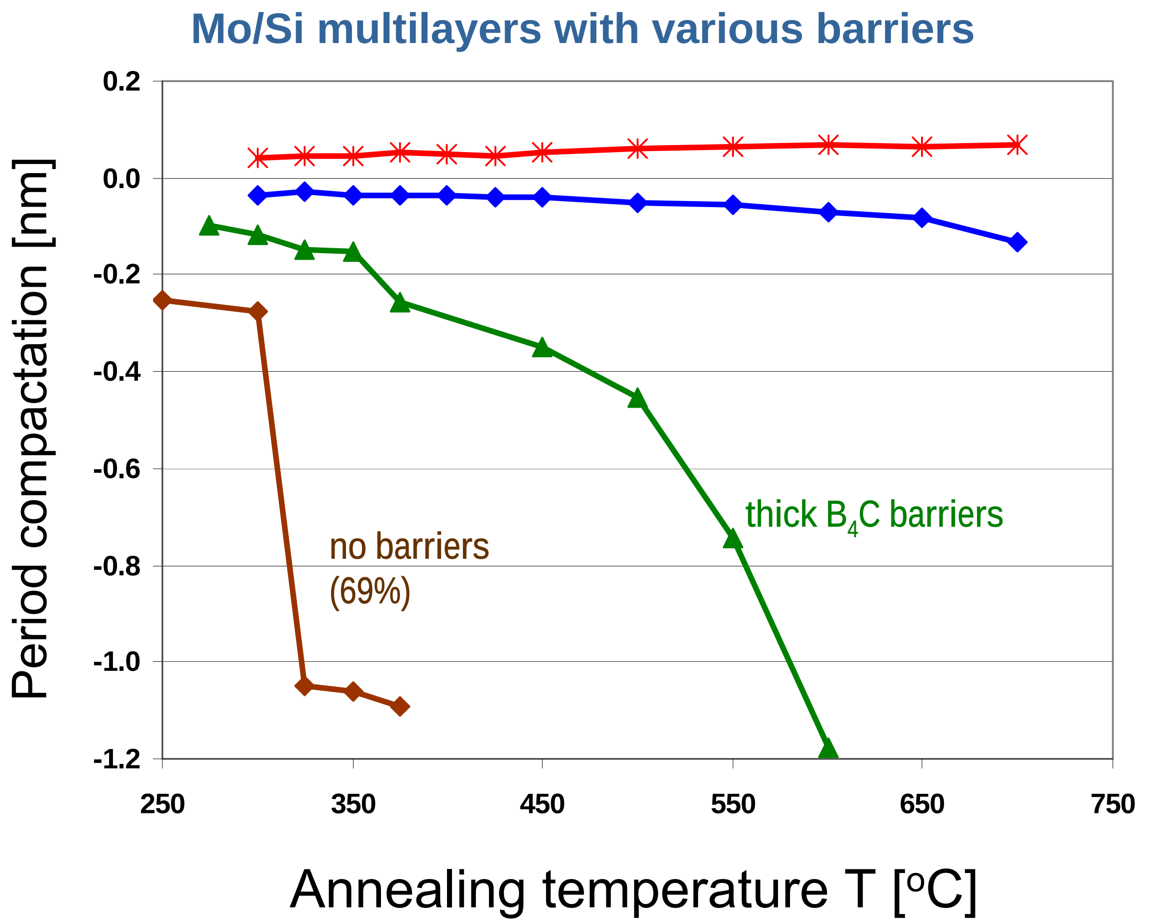


Using B_4C : compound with good optical contrast



- Clear improvement, but what is actually formed?

Thermal resistance various barriers

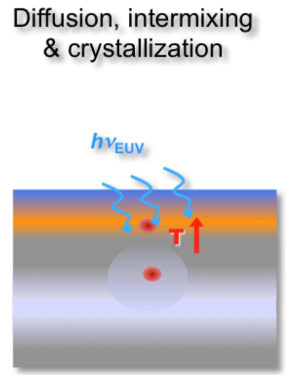


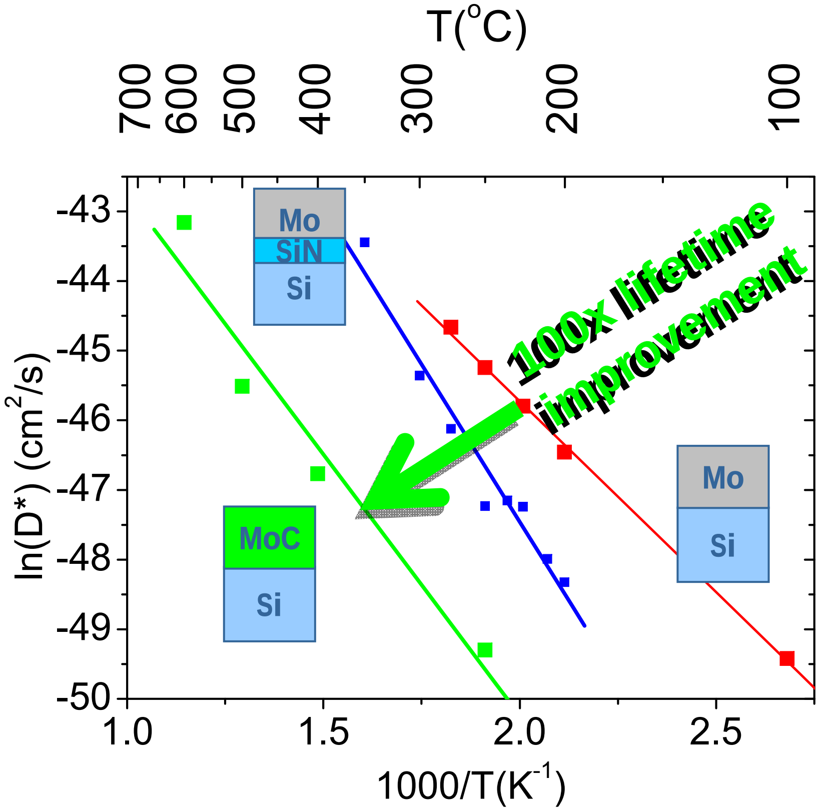
- Very good thermal stability achievable, but at the expense of reflectance

'Diffusion scaling laws'

Passivated systems and systems with diffusion barriers

Goal: study diffusion at initial stage





Arrhenius plots provide method for scaling of diffusion.

Activation energies provide information about fundamental diffusion processes.

$$D = D_0 \exp \frac{E_a}{kT}$$

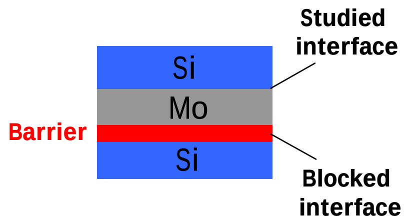
Y-value D_0

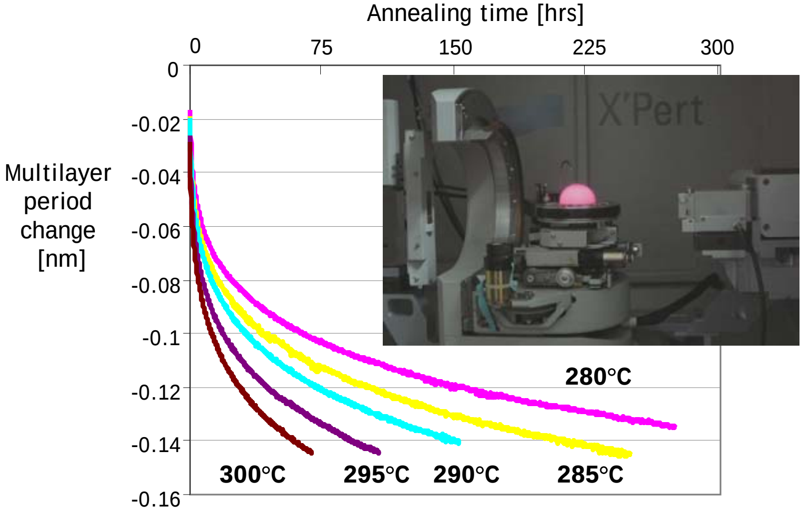
Slope: E_a

Tsarfati, et al, JAP 105 (2009)
Bruin, et al, ASS, 10-02316R1 (2010)

Activation energy atomic scale interdiffusion

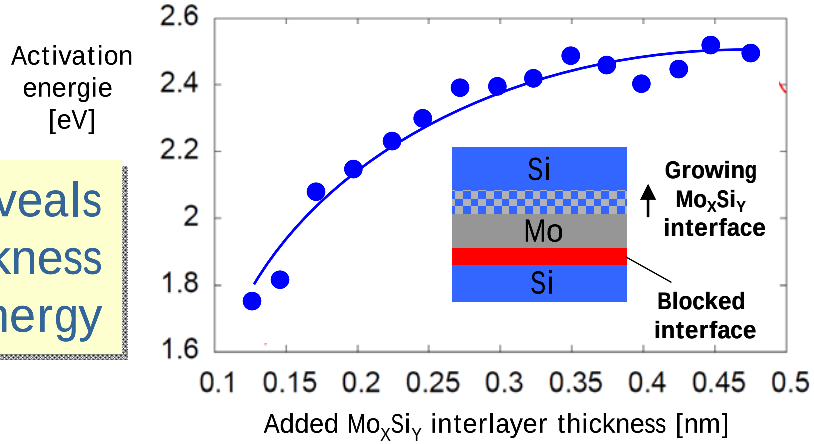
Selective analysis of interface diffusion by use of diffusion barriers





In-situ structure investigation shows temperature dependent change with sub-pm accuracy

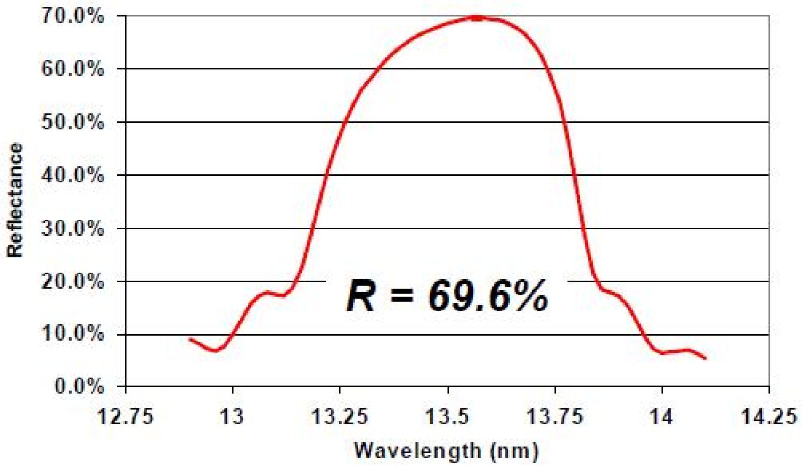
➔ Diffusion kinetics modeling reveals interdiffusion layer thickness dependent activation energy



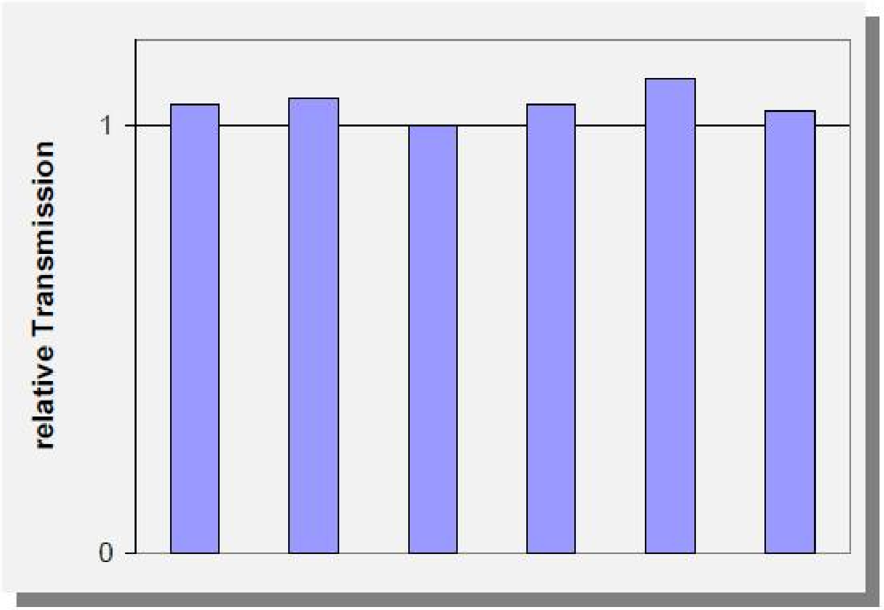
Jeroen Bosgra, Robbert vd Kruijs, Andrey Yakshin

Courtesy of Dr. Peter Kürz, Carl Zeiss SMT GmbH (EUVL symp. Kobe, 2010)

NXE:3100 – Coating reflectivity significantly increased compared to ADT



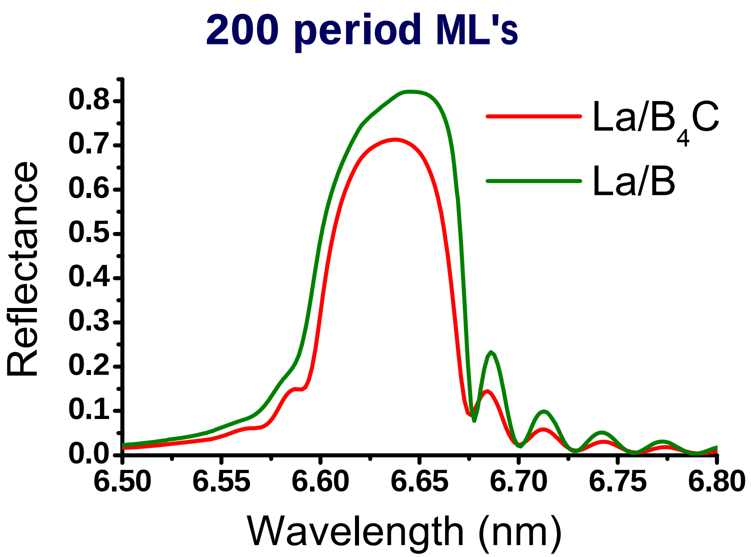
Coated at FOM, measured at PTB
ADT: ~ 64% (typical achievements)

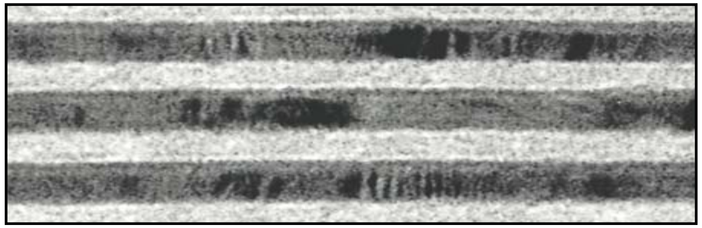


about 50% more transmission of 3100 projection optics

Downscaling λ to 'beyond EUV': 6.x nm

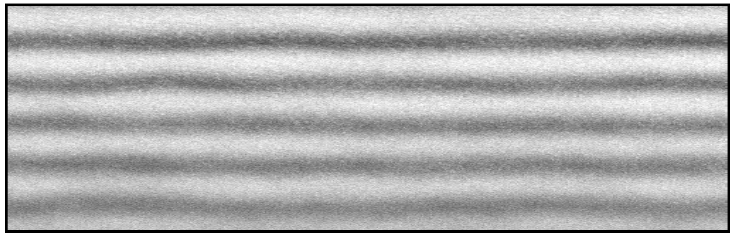
Materials choice determined by optical constants
- low absorption, high contrast





Mo/Si

La/B_4C



From 13.5 to 6.x nm:

- *"Just switch material and reduce layer thicknesses", but …………*
  - *Individual layers ≈ 1 nm*
  - *Effect of roughness & interdiffusion become dominant*

→ Degree of difficulty increases enormously!

Development beyond EUV coatings

New approaches to be pursued:

- *Film nucleation and layer growth*
  - *Dependence of layer growth on ad-atom energy*
  - *Kinetic Growth Manipulation (KGM)*
- *Interface control by layer passivation*
- *Multilayer analysis by He-ion microscopy*
  - *sub-nm depth resolution*

Thermodynamics @ La/B_4C interfaces

At interfaces: 7 La + 6 B_4C → 4 LaB_6 + 3 LaC_2 (ΔH = - 305.4 kJ/mole)

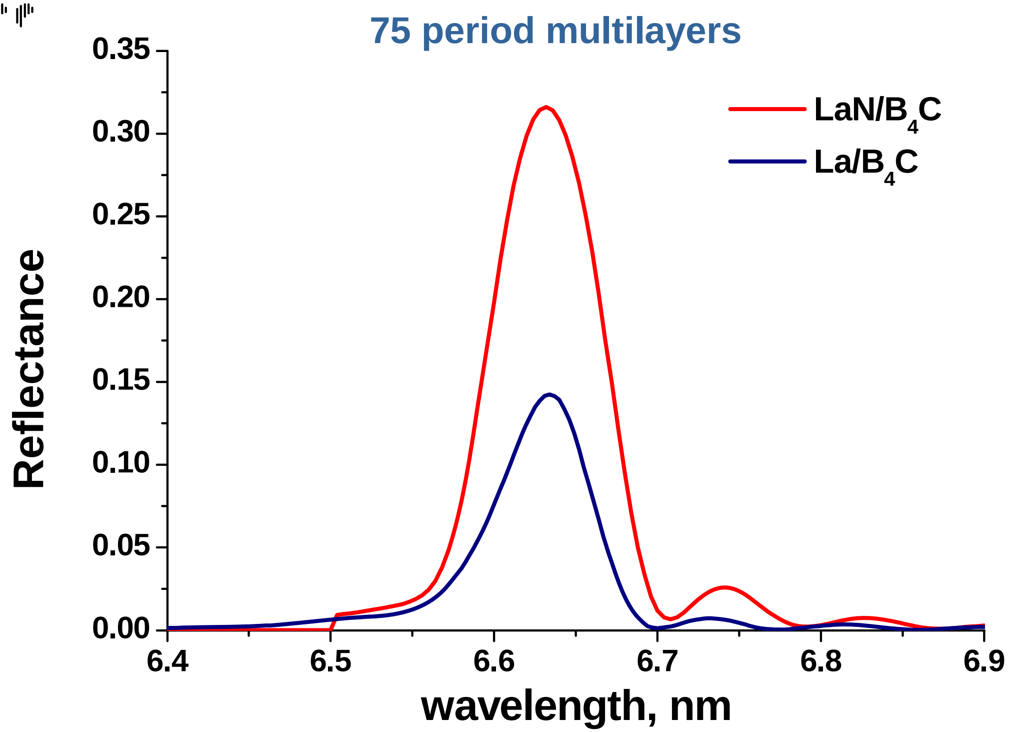
Compound	LaN	BN	LaB_6	LaC_2	B_4C	La
ΔH^{for} (kJ/mol)	-303	-255	-130	-89	-71	0
n	0.981	0.995	0.992	0.986	0.999	0.984
β (10^{-3})	1.420	0.894	0.853	0.996	0.528	1.075

→ *Introduce stable nitrides by N^+-ion treatment:*

- *Nitride formation can prevent LaB_6 and LaC_2 formation*
- *LaN can enhance optical contrast [1,2,3]*

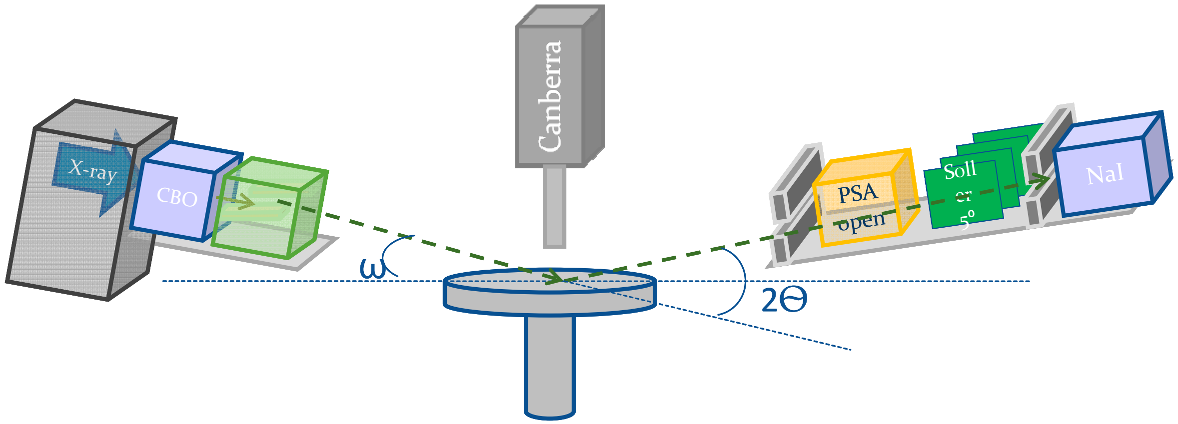
[1]T. Tsarfati et al., "Reflective multilayer optics for 6.7 nm wavelength radiation sources and next generation lithography", Thin Solid Films 518, 5, 1365-1368 (2009)
[2]T. Tsarfati et al., "Nitridation and contrast of B4C/La interfaces and multilayers" Thin Solid Films 518, 24, 7249-7252 (2010)
[3]Patent: T. Tsarfati et al., P16795DE US 61/079307 (US), DE102008040265 (Germany), priority date 16 September 2008

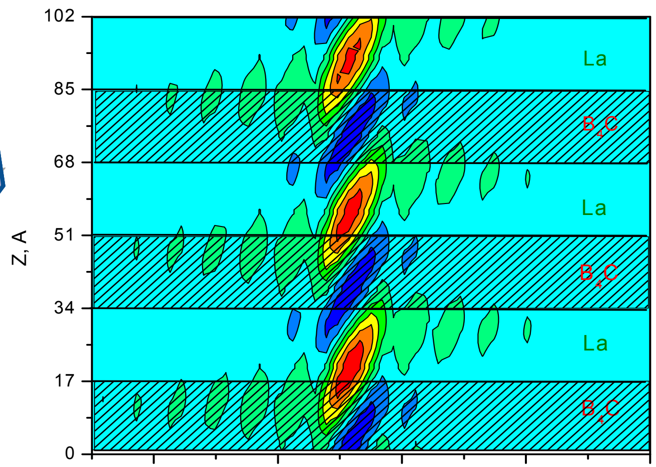
How does LaN perform in reflectance?

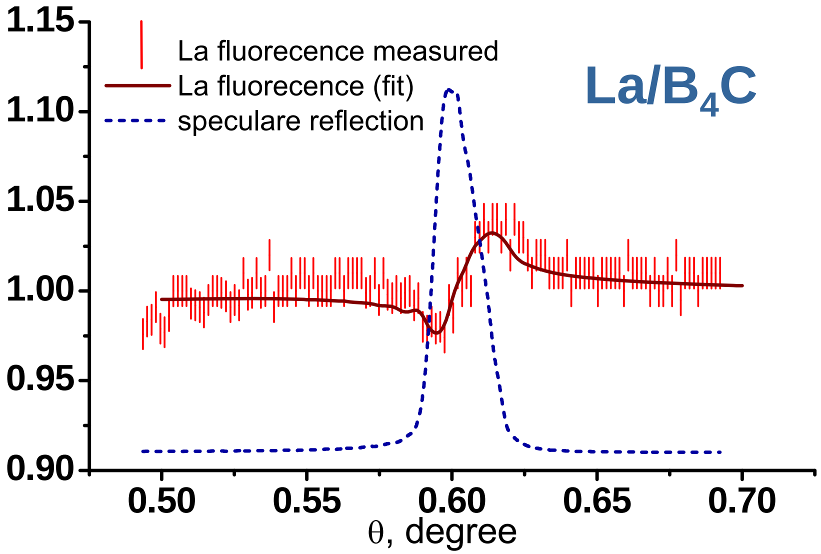


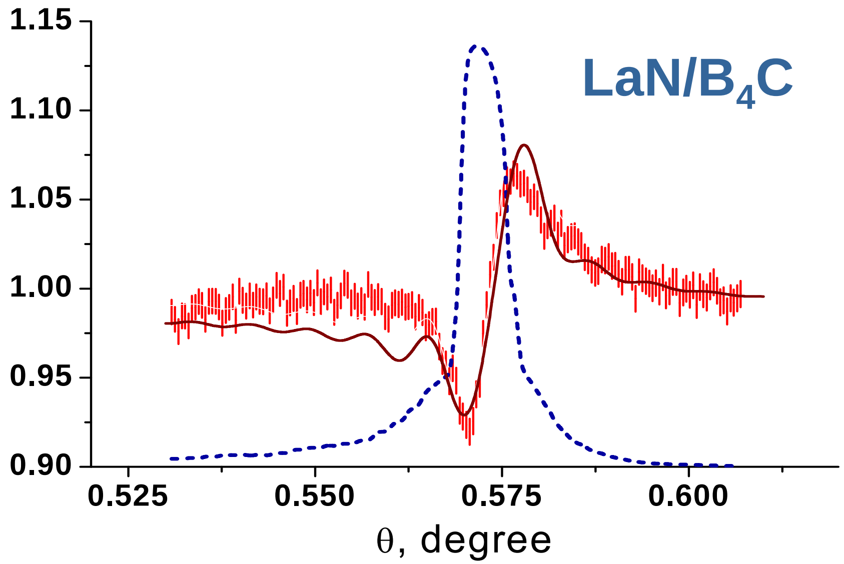
- Only 75 period multilayers
- Dramatic difference in maximum reflectance:
- → Better optical contrast? Better localization of materials?

XSW: Fluorescence yield analysis

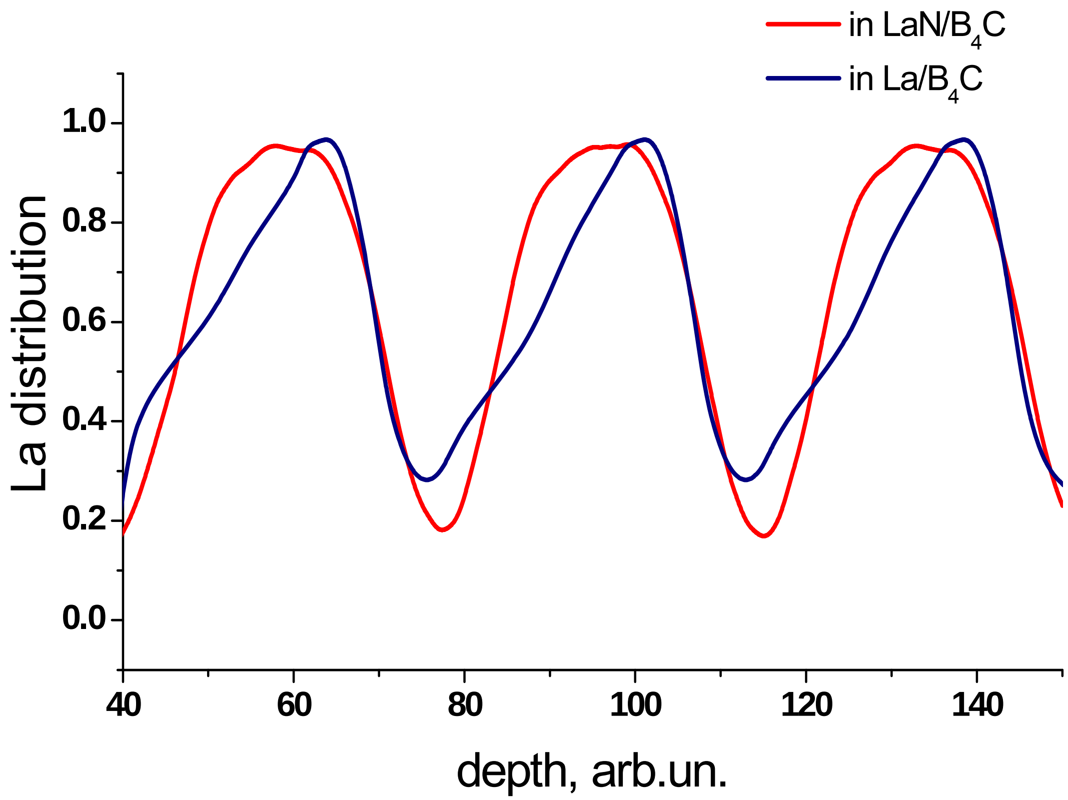








La-profile in multilayer

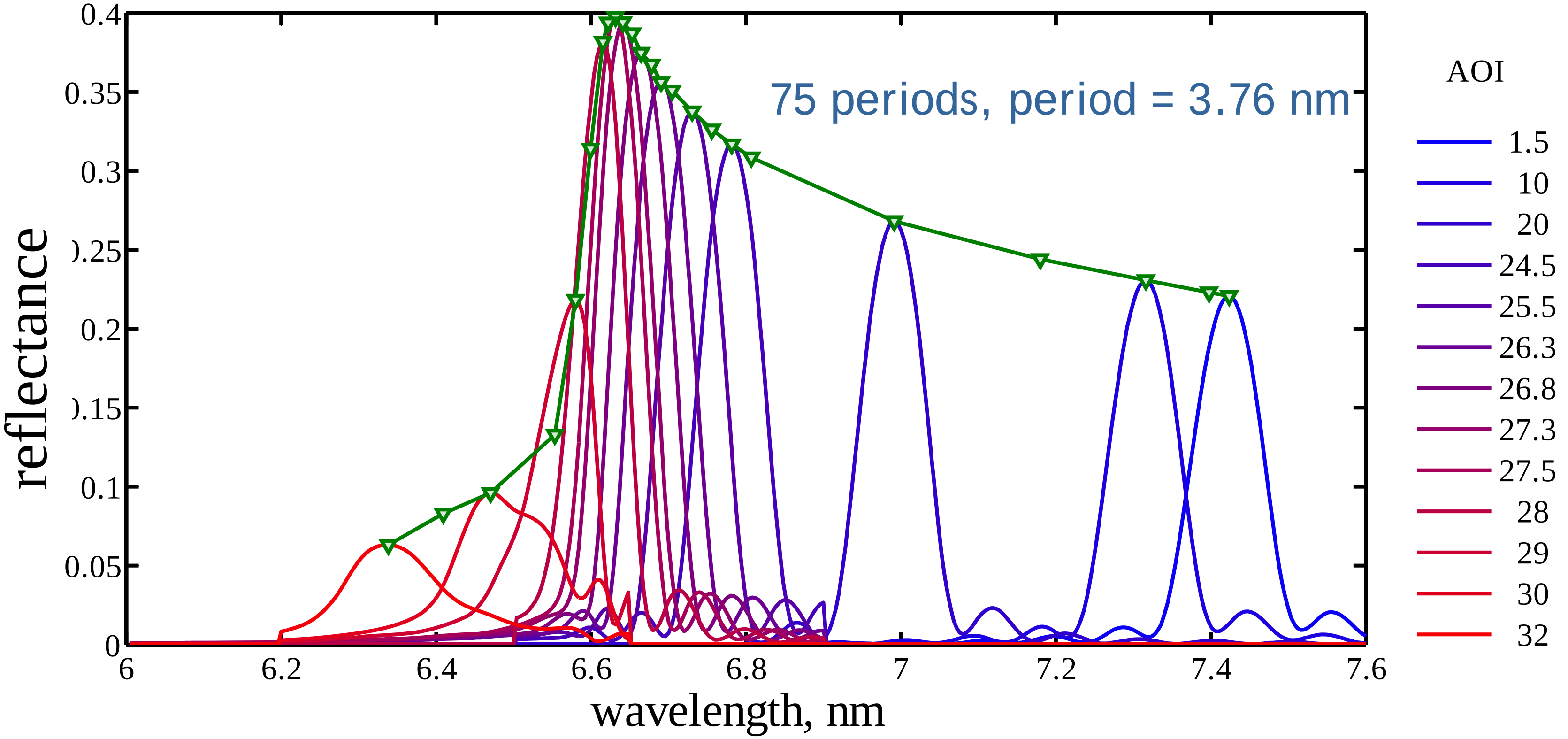


Collaboration with
Sergei Yakunin
Kurchatov Institute,
Moscow, Russia

Much better localization of La in LaN/B_4C

→ improved optical contrast

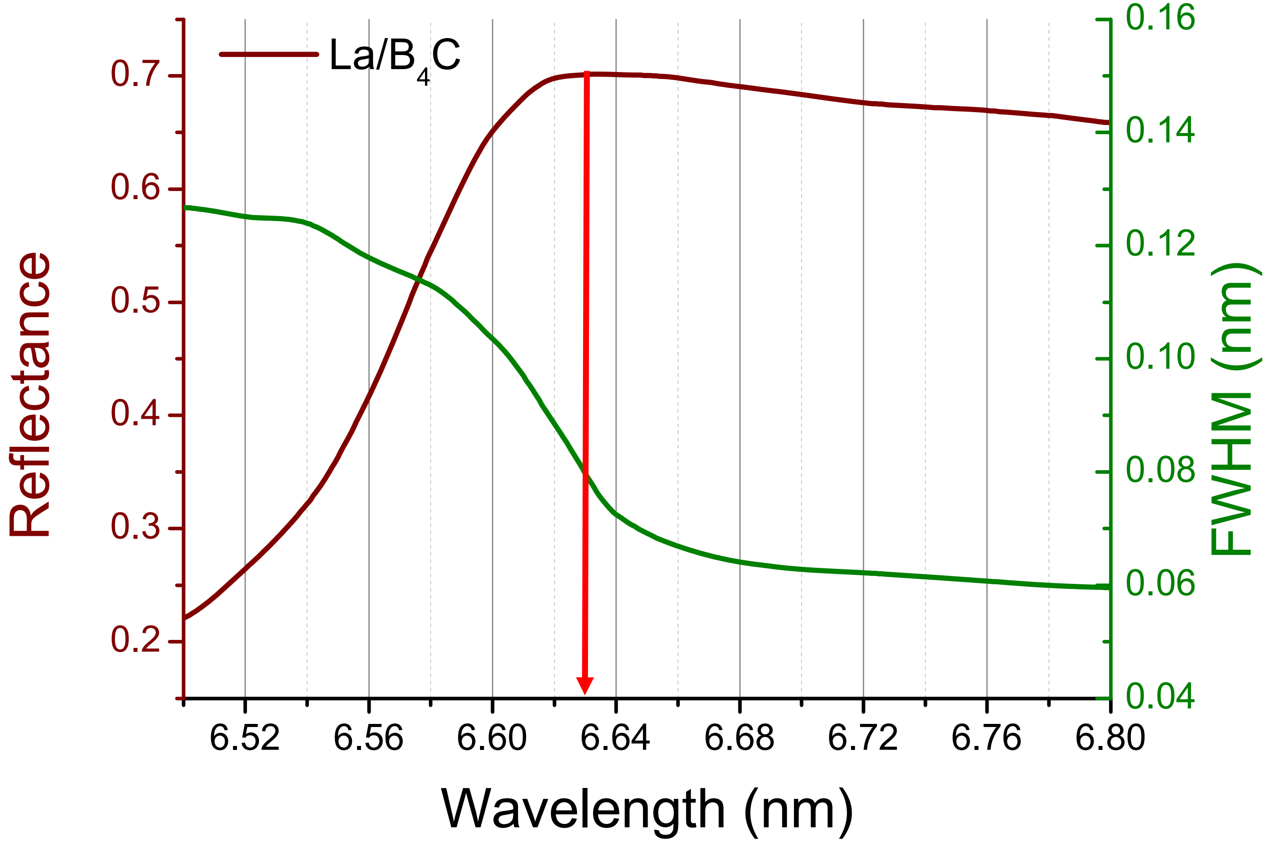
Approaching the B-edge….



- La/B_4C ML reflectivity increases near B absorption edge
- Effect enhanced by s-polarised measurements
- Good fit obtained using experimental B optical constants (Regina Soufli and Monica Fernandez)

Approaching the B-edge….

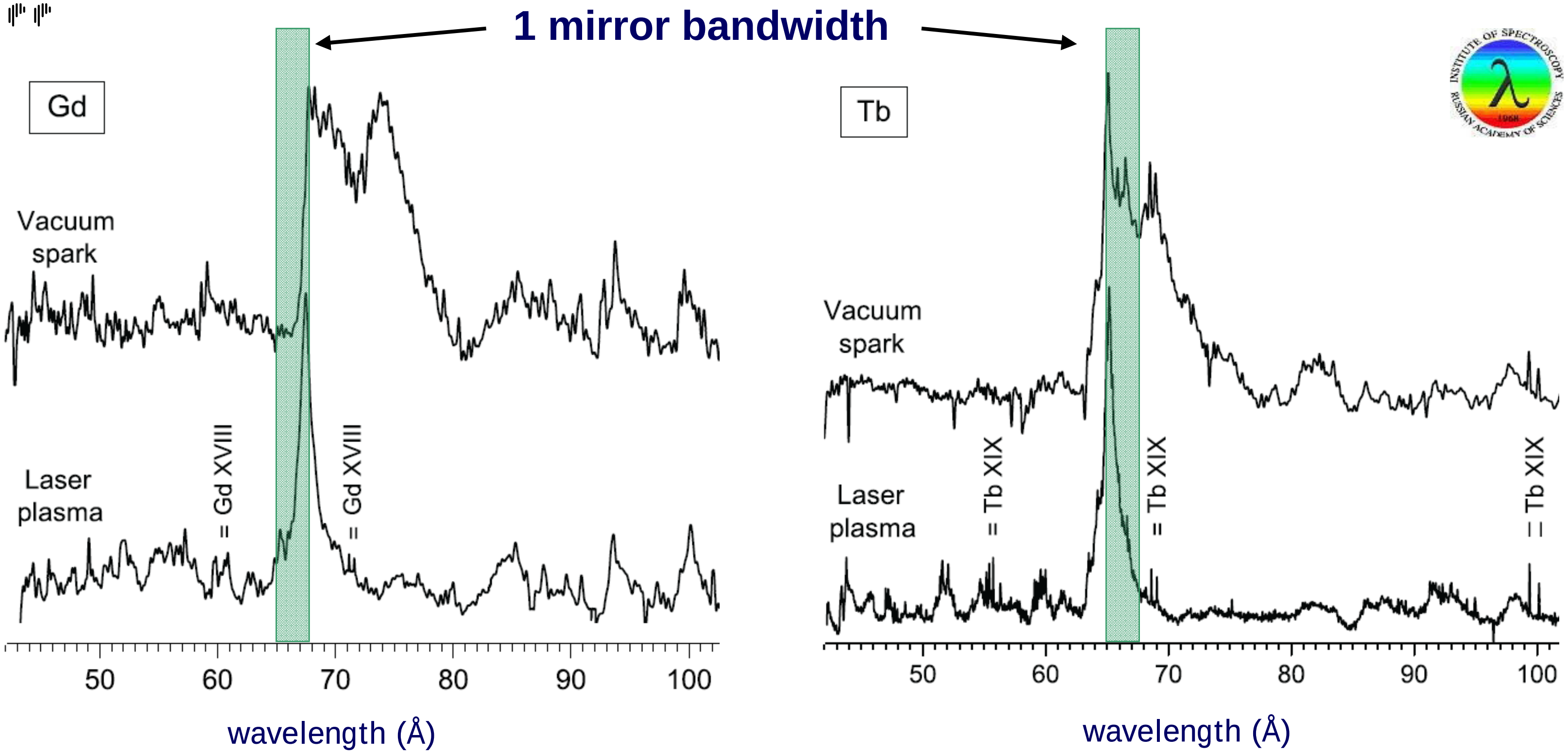
Calculated normal incidence reflectance and band width[1,2]



1. R. Soufli et. al., Appl. Opt., Vol. 47, 25, 2008
2. M. Fernandez-Perea et. al., J. Opt. Soc. Am. A, Vol. 24, 12, 2007

→ *Optimum normal incidence reflectance and enhanced band width at 6.63 nm*

Gd and Tb emission spectra



S.S. Churilov et al., Phys. Scr. 80 (2009) 045303

→ *Operational wavelength 6.x nm lithography:*

- *simultaneous optimization of source and multilayer performance*
- *together with optical design*

Summary

Multilayer performance EUV

- Reflectance 69.5 % for Mo/Si, 70.15-70.30 % with barriers
- B_4C barriers enhance thermal stability
- ML's can be stable up to 700 º C
- 69.6% achieved on real optics, profile within spec

Beyond EUV or 6.x nm

- Passivation of interfaces → improved optical contrast
- Focus research on LaN/B_4C
- Enhanced ML performance near B-edge
- Optimum wavelength depends on multilayer, source and optical design

Acknowledgements

Coworkers at FOM and ZEISS and ASML

The team at PTB Berlin for reflectometry

Thank you!

Research programs: XMO, CP3E, ACHIEVE, EXEPT