RECENT DEVELOPMENT OF XUV MULTILAYER COATINGS AT IOF

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FRAUNHOFER IOF

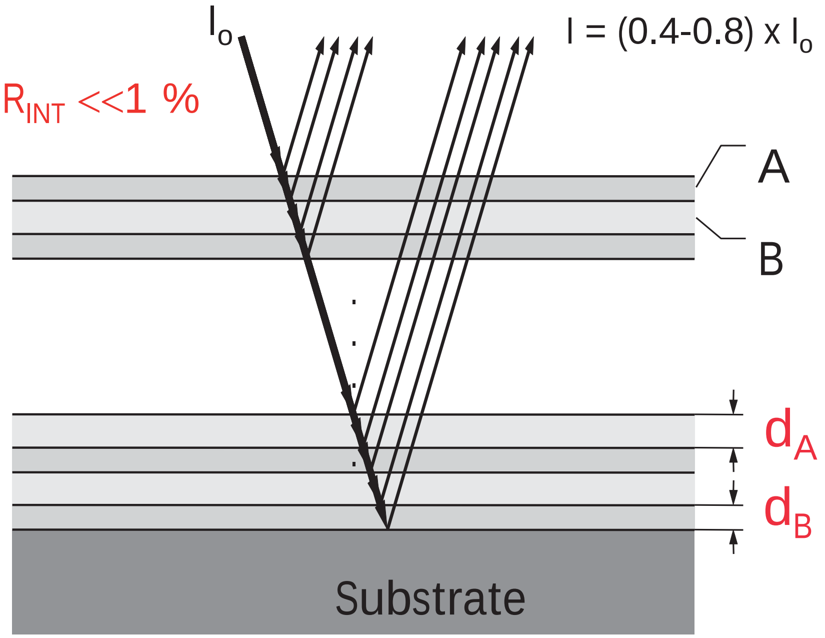
KEY FACTS

- 1992 founded
- 1999 first XUV mirror
- 2002 new building
- 2009-2011 extension
- 2017 Fibertechnology Center
- About 8,300 m² floor space
- 250 Employees + 80 Students

- Budget 2016: 26.8 million €
  (42 % industry projects)

DEVELOPMENT OF XUV MULTILAYER MIRRORS

PRINCIPLE OF CONSTRUCTIVE INTERFERENCE



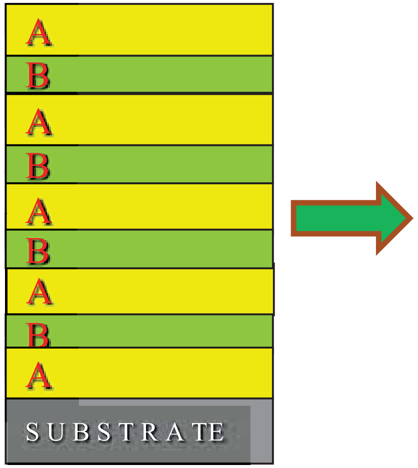
1972[1]	High R is possible in XUV
1986[2]	First mirror with R > 60%
1996[3]	C- diffusion barriers (stability)
2001[4]	B_4C- diffusion barriers (Reflectivity)

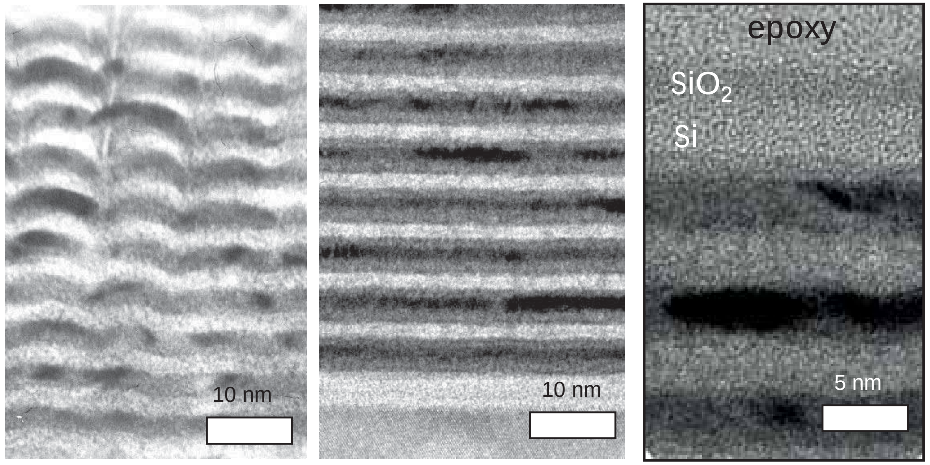
The trend towards shorter wavelengths requires a dramatic increase in the absolute accuracy at the same relative tolerances.

[1] *E. Spiller: Appl. Phys. Lett. 20, pp. 365-367, 1972*
[2] *T. W. Barbee: Opt. Eng. 25, pp. 893-915, 1986*
[3] *H. Takenaka: J. Elec. Spec. & Rel. Phenom 80, p. 381, 1996*
[4] *S. Bajt: Proc. SPIE 4506, p.65, 2001*

IMPERFECTIONS IN XUV MULTILAYER MIRRORS

FROM “IDEAL” TO REAL MIRROR:





Interface roughness **Interdiffusion** **Surface oxidation**

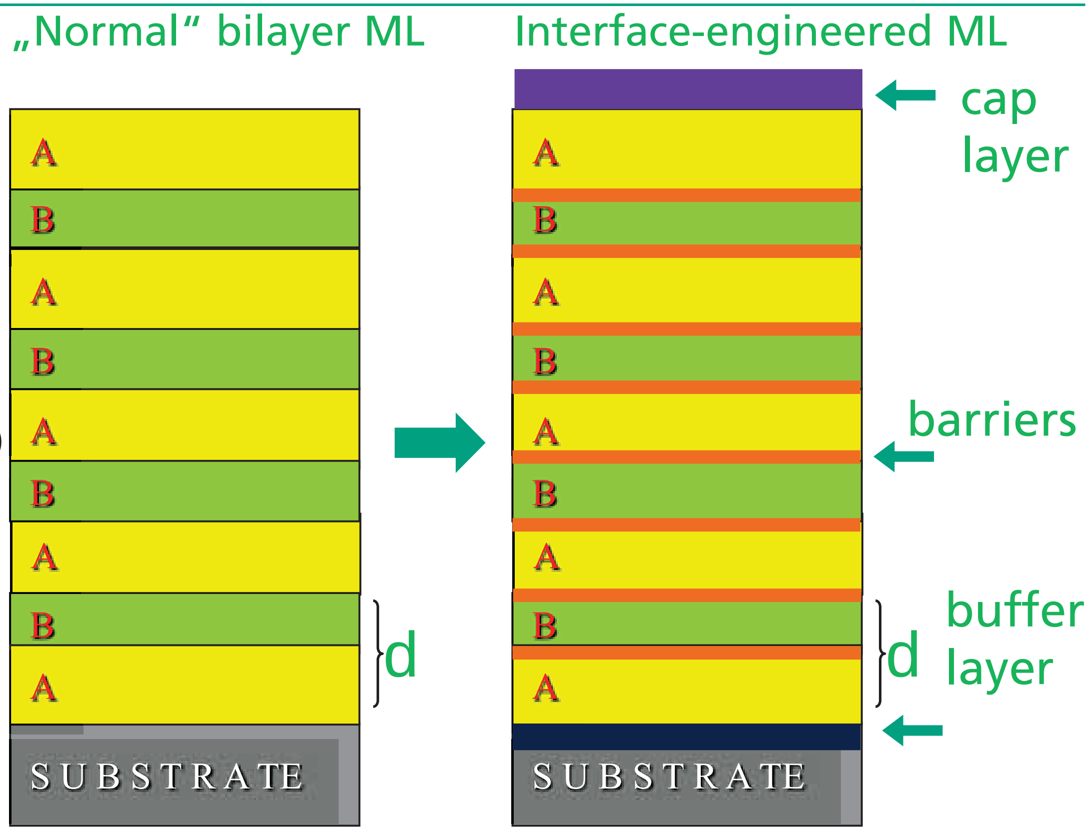
Mo/Si **Mo/Si** **Mo/Si**

To enhance the optical performance of XUV mirrors interface and surface imperfections have to be mitigated!

STRATEGY FOR IMPROVEMENT OF MULTILAYER COATINGS

Interface-engineering:

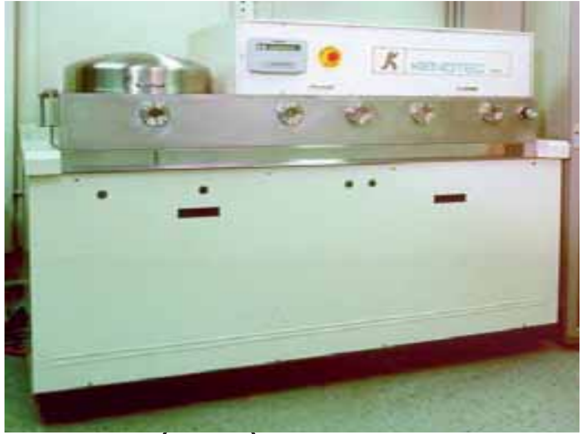
- diffusion barriers
  (B_4C, C, Cr, …)
- capping layer
  (C, Ru, TiO_2, Nb_2O_5…)
- buffer layer
  (Cr/Sc, ZrN,….)



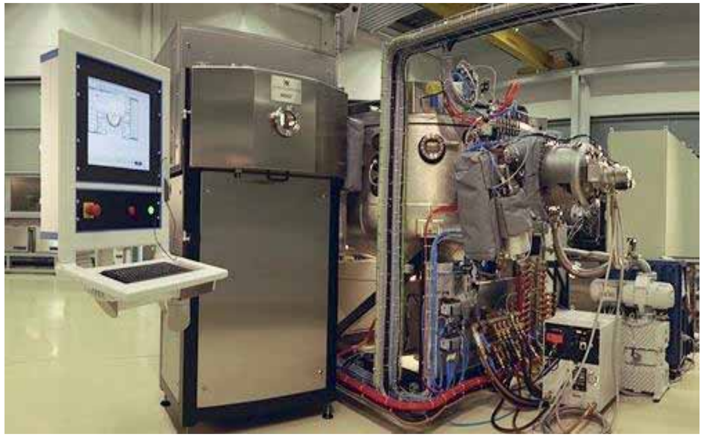
Today an interface-engineered design (> 5 materials) is a powerful method to mitigate the level of structural imperfections in XUV multilayer mirrors

SPUTTERING SYSTEM AT THE IOF

2 X MRC (1998): R&D system



NESSY 1 (2003): 3 x ∅ 300mm

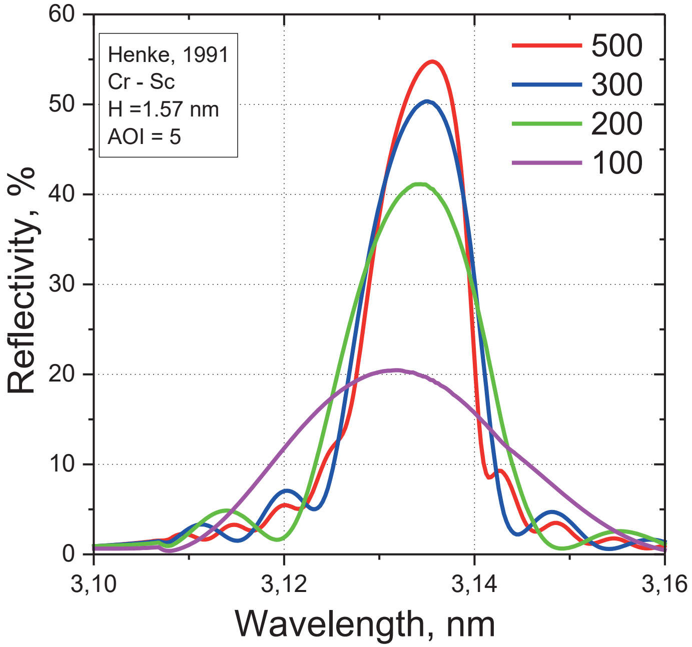


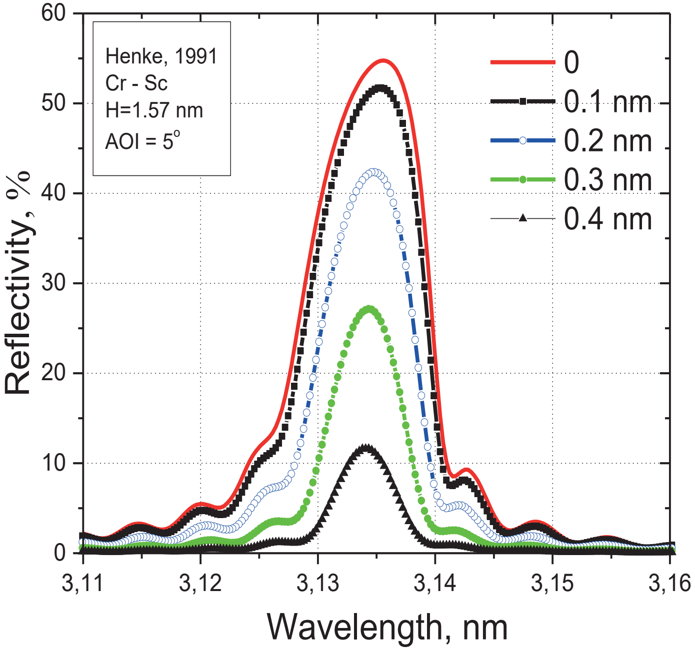
NESSY 2 (2010): up to ∅ 650mm

NESSY 3 (2013): R&D system

MULTILAYER MIRRORS FOR MICROSCOPY (λ = 2.4 - 4.4 NM)

Theory:





- R > 30 % @ 3.1 nm:
  - N = 500
  - < 0.3 nm

$$R = R_0 \exp\left[-\left(\frac{2\pi m\sigma}{H}\right)^2\right]$$

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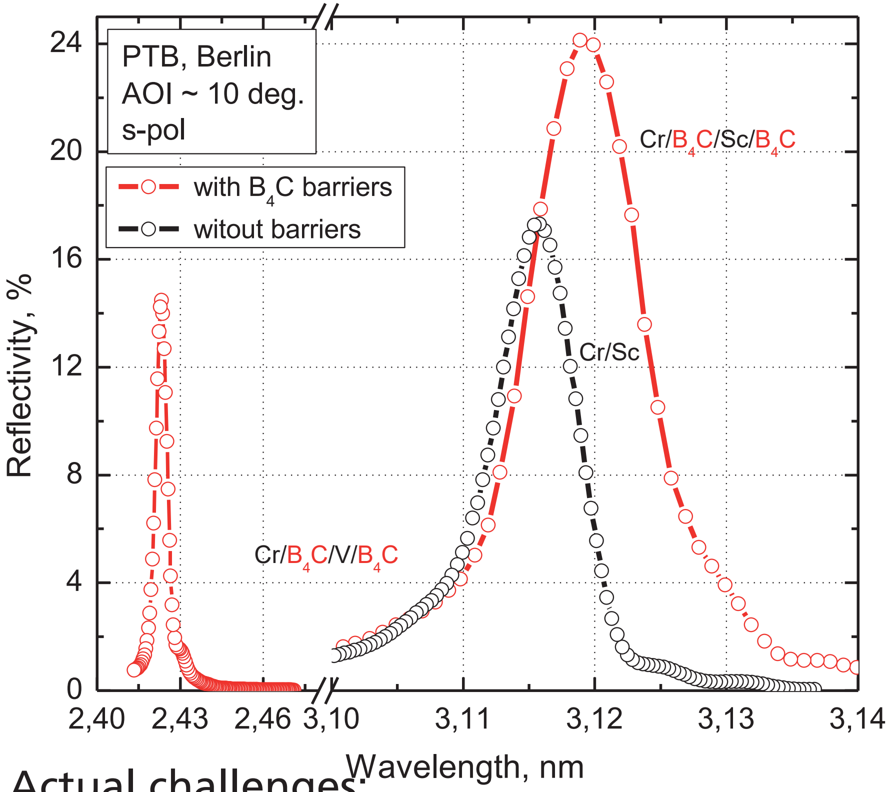
MULTILAYER MIRRORS FOR MICROSCOPY (λ = 2.4 - 4.4 NM)



Without barriers:

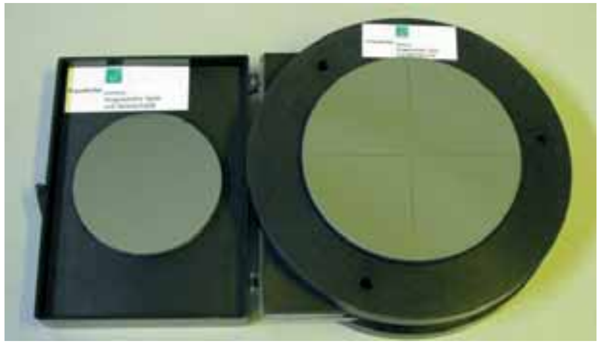
- R = 0.2% @ 2.42 nm
- R = 17.2% @ 3.12 nm

With B_4C-barriers:

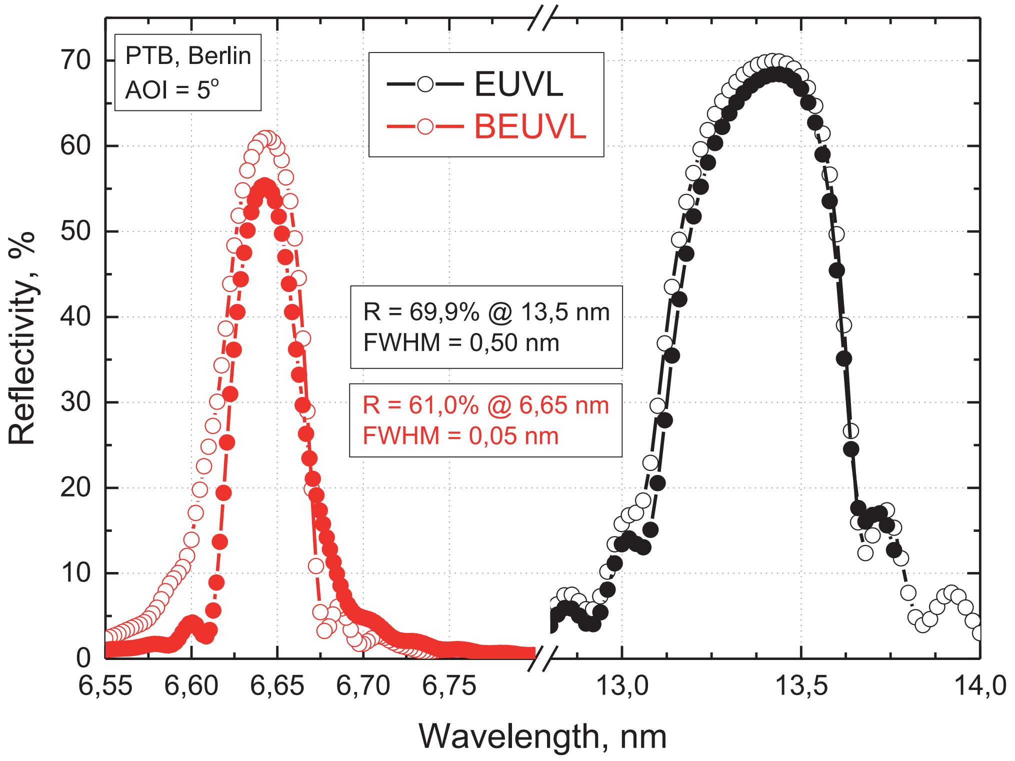
- R = 14.2% @ 2.42 nm (+ 14.0%)
- R = 24.2% @ 3.12 nm (+ 7.0%)

Actual challenges:

- R > 30% @ 3.1 nm
- FWHM > 0.1 nm



HIGH-REFLECTIVE MULTILAYER MIRRORS FOR EUV-LITHOGRAPHY



Without barriers:

- R = 68.5% @ 13.5 nm
- R = 56.0% @ 6.7 nm

With C- barriers:

- R = 69.9% @ 13.5 nm (+ 1.5%)
- R = 61.0% @ 6.7 nm (+ 5.0 %)

Challenges:

- R > 70% @ 6.7 nm & FWHM > 0.1 nm

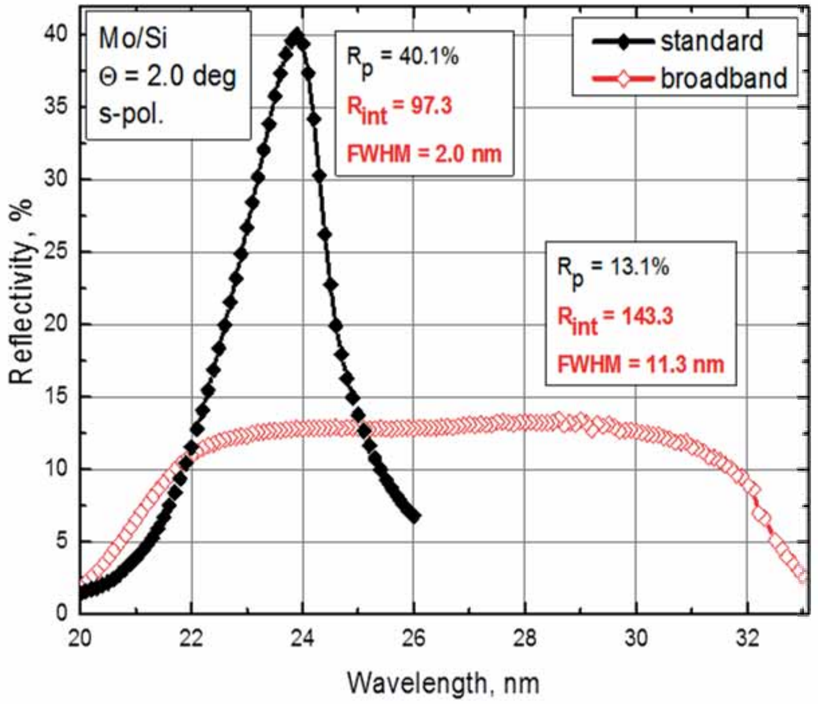
LPP COLLECTOR COATING FOR EUV-LITHOGRAPHY

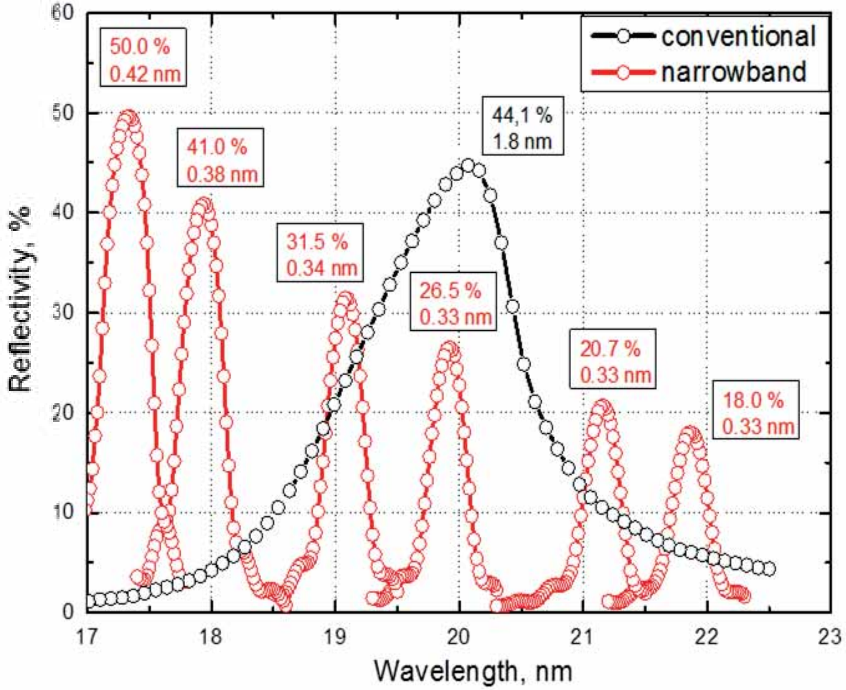
- Rs > 65 %
- $\lambda = (13.5 \pm 0.03)$ nm

- → $\Delta d = 0.015$ nm = 15 pm

- Diameter: > 660 mm
- Lens sag: > 150 mm
- Tilt: > 45 deg
- Weight: > 40 kg

BROAD- AND NARROWBAND MULTILAYER FOR HIGH-ORDER HARMONIC GENERATION

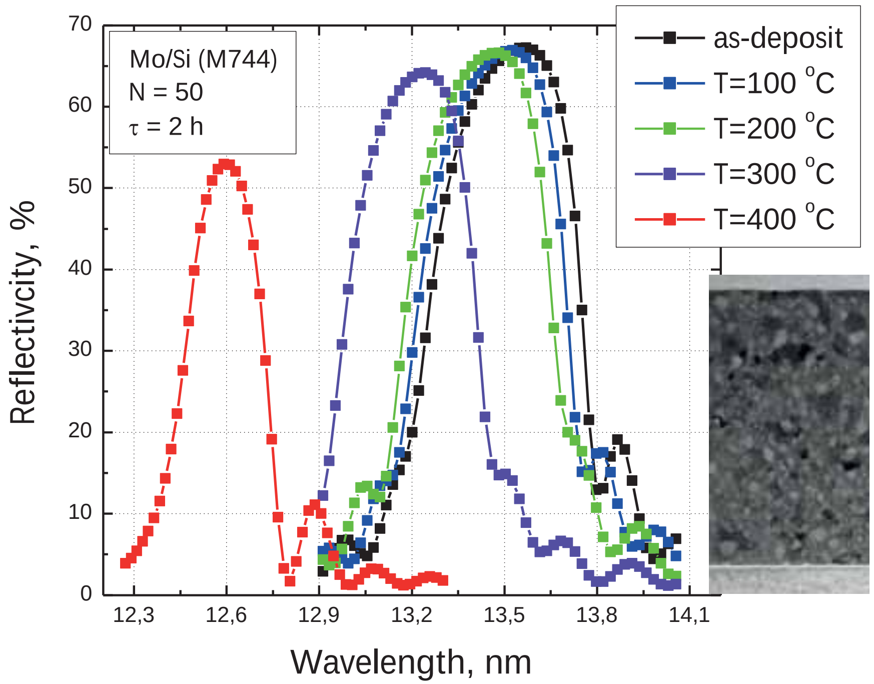




- Design: 5 materials / apperiodic
- Reflection: > 12% @ 22…31 nm
- Fluctuation: ± 0.5% @ 22…31 nm

- Design: 3 materials / periodic
- Reflection: > 20% @ 17…22 nm
- $\lambda/\Delta\lambda$: ~ 70 @ 17…22 nm

THERMAL STABILITY OF CONVENTIONAL MO/SI MULTILAYER MIRRORS



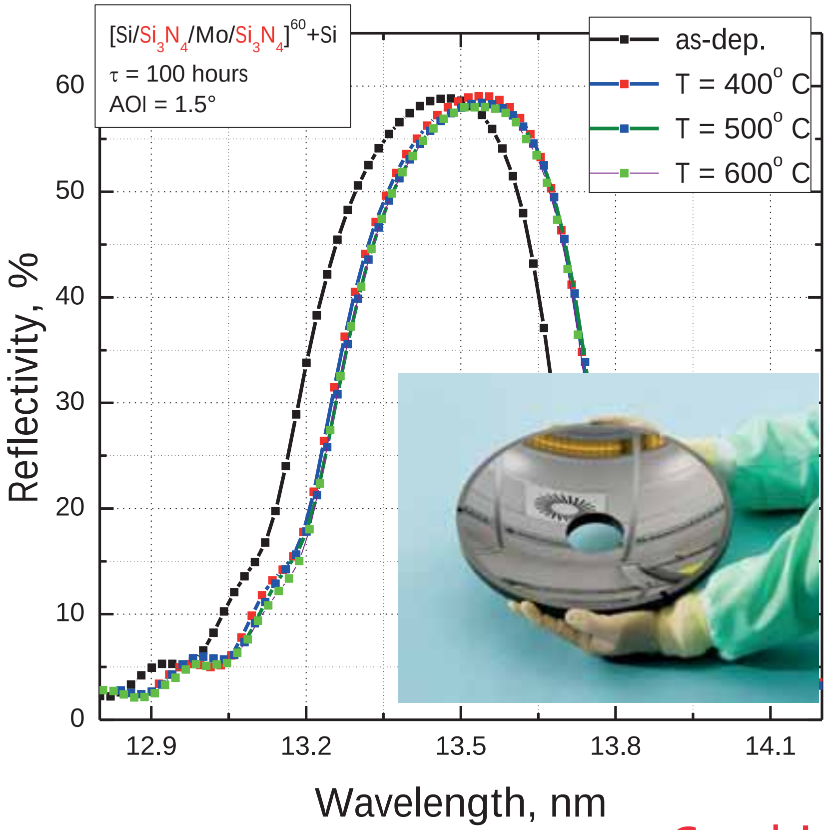
Mo/Si multilayer mirrors:

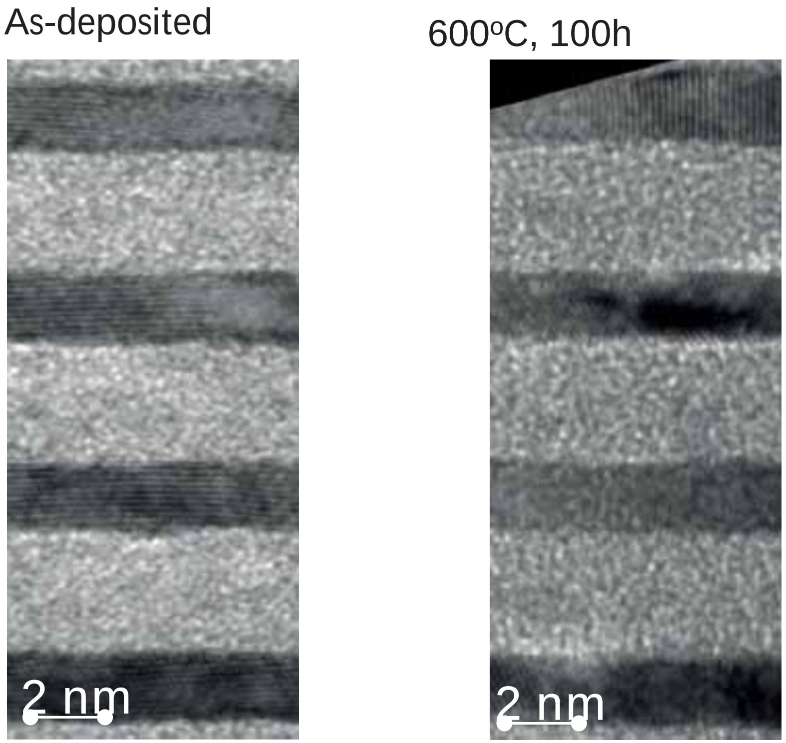
Max. reflectivity:	~ 68.5%
Max. temperature:	~ 100°C
Structure damage:	~ 700°C

A serious problem with XUV multilayers is the structural instability of their interfaces under high heat loads, which leads to a significant degradation of their optical performance.

MO/SI MULTILAYERS WITH ENHANCED THERMAL STABILITY

Optics with two requirements: T ≤ 600ºC and R ≥ 60% @ 13.5 nm




As-deposited

600ºC, 100h

Combination: R ≥ 60.0% @ 13.5 nm & T ≤ 600ºC

CURRENT STATE OF HIGH-TEMPERATURE MULTILAYERS FOR EUV-LITHOGRAPHY

Experimental reflectivity & thermal stability of Si-based multilayers:

System	T_{max}, °C	R $_{EXP}$, %	FWHM, nm
Mo/Si	< 100	69	0.51
Mo_2C/Si	≤ 350	67	0.48
Mo/C/Si/C	≤ 400	60	0.50
$MoSi_2$/Si	≤ 600	42	0.26
Mo/Si_3N_4/Si/Si_3N_4	≤ 600	60	0.47

Our limits:

- Development of HT- multilayers with T_{max} > 600°C is limited by temperature of crystallization of Si-layers (T ~ 650°C)

SUMMARY AND OUTLOOK

Remarkable progress has been made in the field of XUV multilayer coatings

Interface-engineered multilayer coatings with improved optical performance and enhanced stability were successfully developed for:

Microscopy:	Cr/V/B_4C	R = 14.2 % @ λ = 2.42 nm
	Cr/Sc/B_4C	R = 24.2 % @ λ = 3.12 nm
Lithography:	LaN/C/B	R = 61.0 % @ λ = 6.7 nm
	Mo/Si/C	R = 69.9 % @ λ = 13.5 nm
	Mo/Si_3N_4/Si/Si_3N_4	R = 60.0% @ λ = 13.5 nm & T $\leq$ 600 °C
HGG-optics:	BB-mirrors	R > 12% @ 22 ... 31 nm
	NN-mirrors	R > 20...50% @ 17... 22 nm / $\lambda/\Delta\lambda$ = 70

Thanks for your attention !