Multilayer fabrication at FOM

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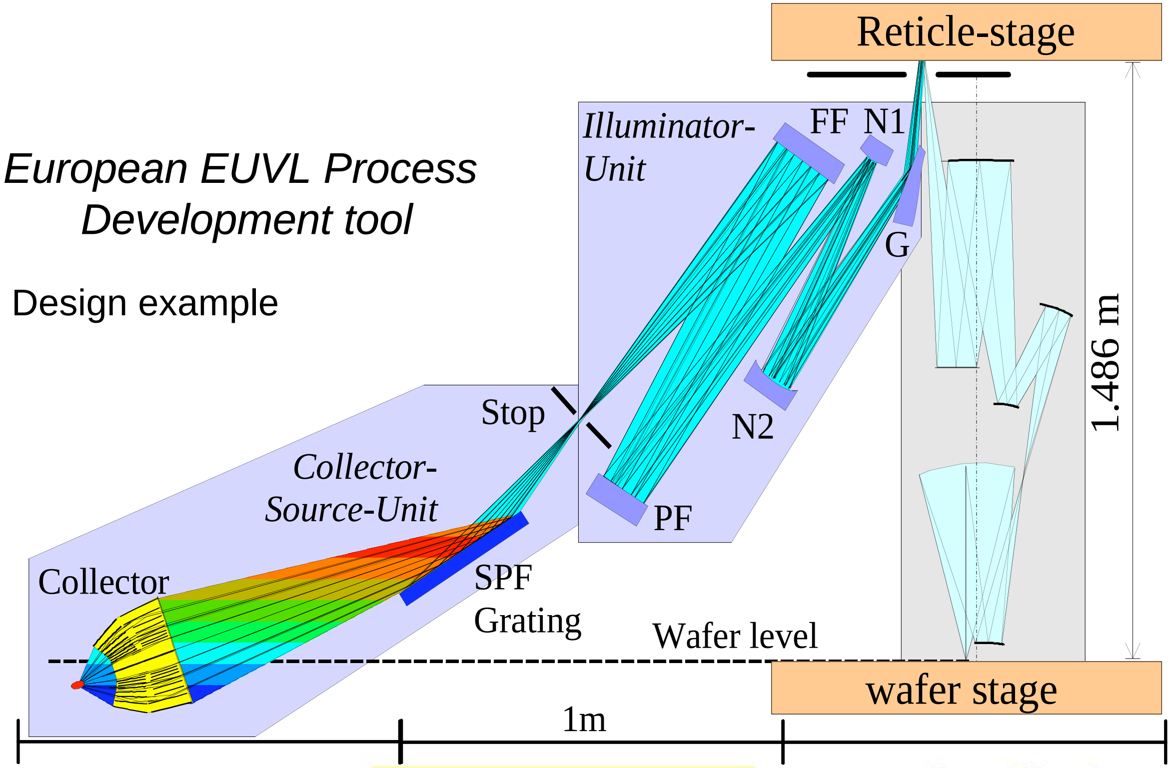
EUV lithography reqts on optics substrates

European EUVL Process Development tool

Design example



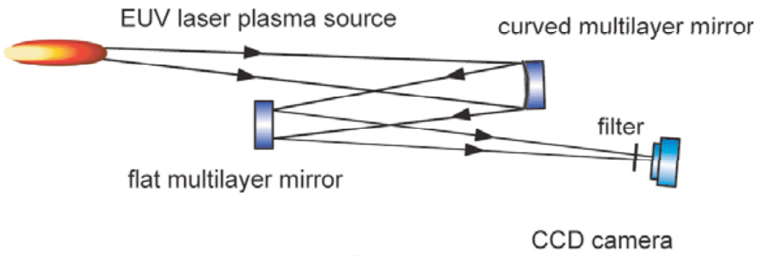
λ	**13.5 nm**
NA	**0.25**
Resolution	**50 nm**
field	**26x33 mm²**
Magnification	**4x**

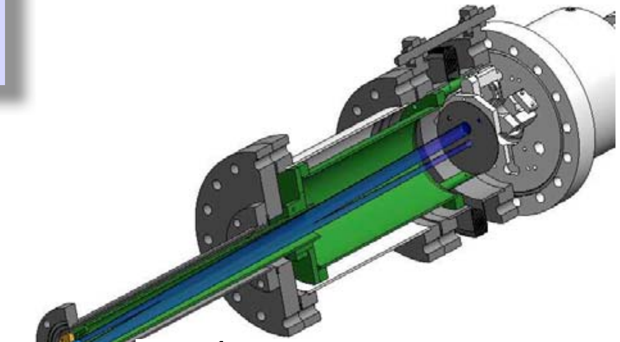
	Results	**Specifications**
Property	**M6**	alpha demo tool
figure [nm rms]	**0.10**	0.25*
MSFR [nm rms] /flare	**0.23**	0.25
HSFR [nm rms]	**0.28**	0.25

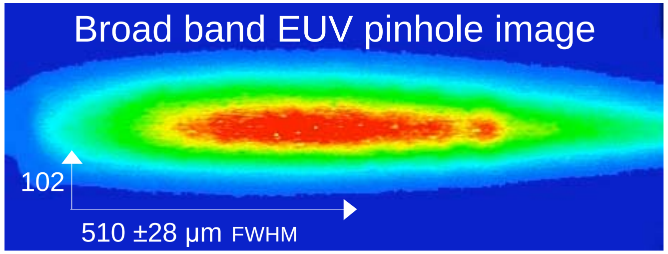
* incl coating

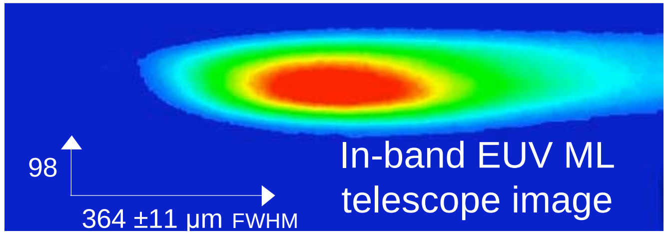
EUV imaging diagnostics

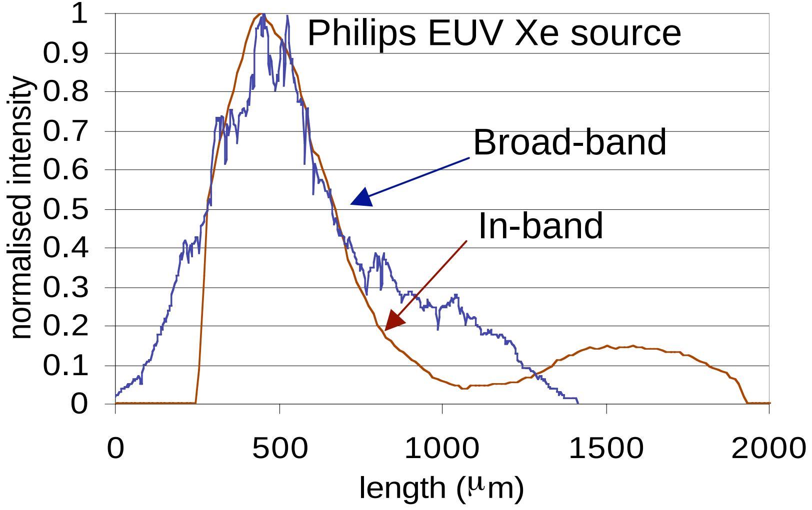
- *EUV telescope to measure narrow-band size of EUV sources*
- *EUV telescope images can differ considerably from results pinhole imaging*
  - EUV imaging: >40% smaller source size
  - Up to 20% EUV energy in source tail



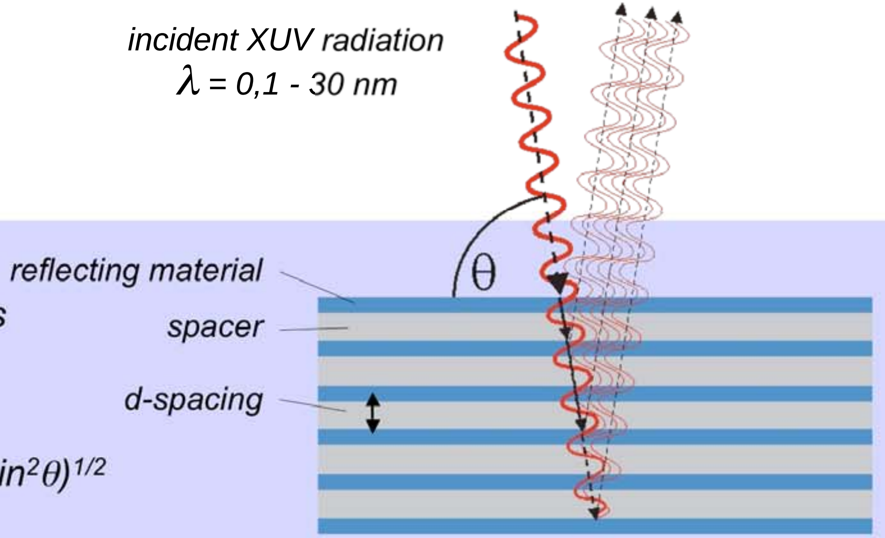








Multilayer reflection



Principle

- Bi-layer systems: reflecting & spacer layers
- Summation of in-phase partial reflections

Design/simulation/analysis

- Bragg condition: $n\,\lambda = 2d \sin\theta\,(1-\sin^2\theta_c/\sin^2\theta)^{1/2}$
- Fresnel equations + roughness models
- DW-factor: $R = R_0 \exp(-k(\sin\theta\,.\,\sigma)^2/\lambda)$
- Γ-ratio: $d_{reflecting} / (d_{reflecting} + d_{spacer})$
- Complex indices of refraction, atomic scattering factors f1, f2, density

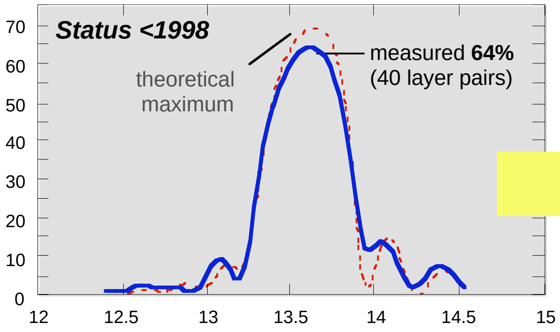
Deposition processes

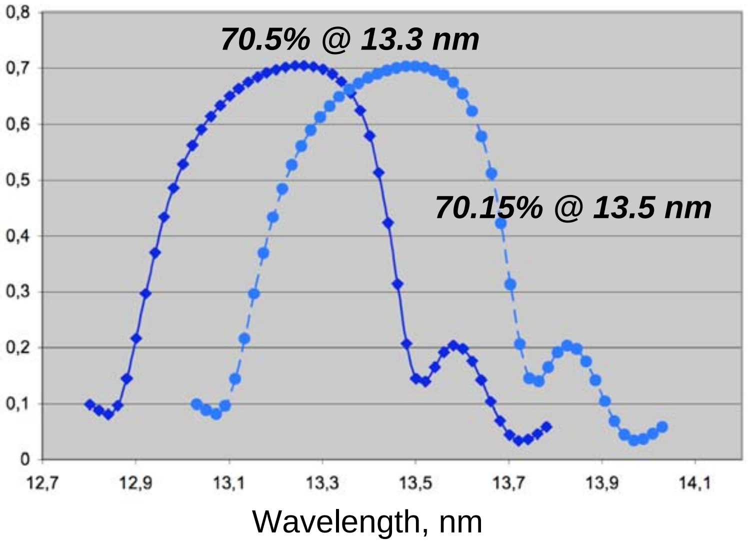
- Optimize combination materials + optical properties
- Thin film materials growth process
- Controlled low interface roughness & intermixing of layers
- Regular, reproducible stack without layer thickness errors

- Bragg: $n\,\lambda = 2d \sin\theta\,(1-\sin^2\theta_c/\sin^2\theta)^{1/2}$

Multilayer Reqts

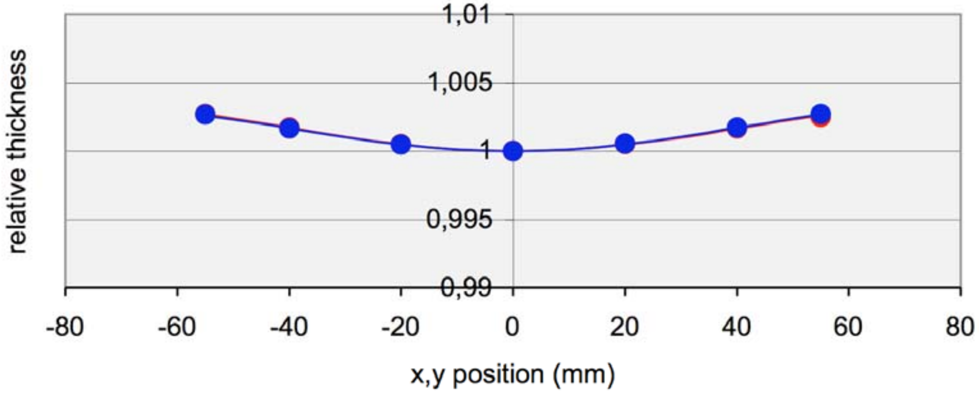
- Near-theoretical values of reflectivity
  - -13.5 nm @ normal incidence
- Lateral uniformity within ≤0.1%
  - -Gradients and flat profiles over ≤500 mm dia
- Unprecedented temporal/thermal stability
- Extreme radiation hardness: 3×10^4 h to ΔR/R 1%
  - -Moderate vacuum conditions
- Contamination: ≤1% over 3×10^4 h

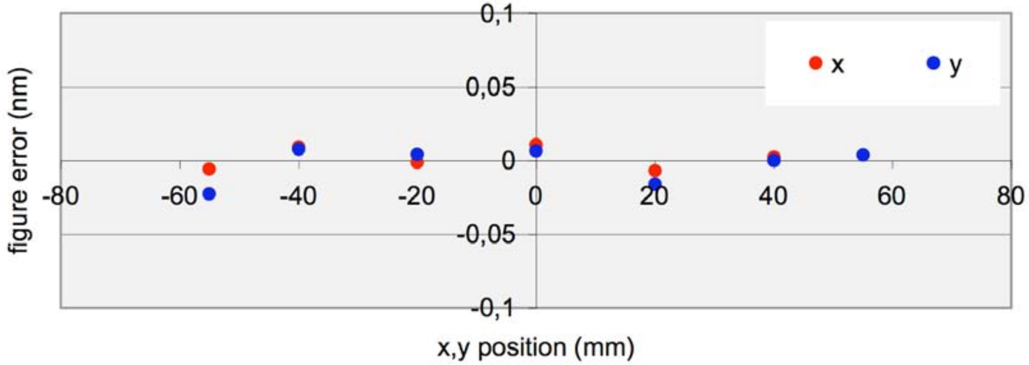




Progress in coating research ➔ twice higher total throughput of ten-mirror EUVL system

Control of lateral uniformity





- Total coating stack non correctable thickness error ≤15 pm rms, or 0.2 pm per period

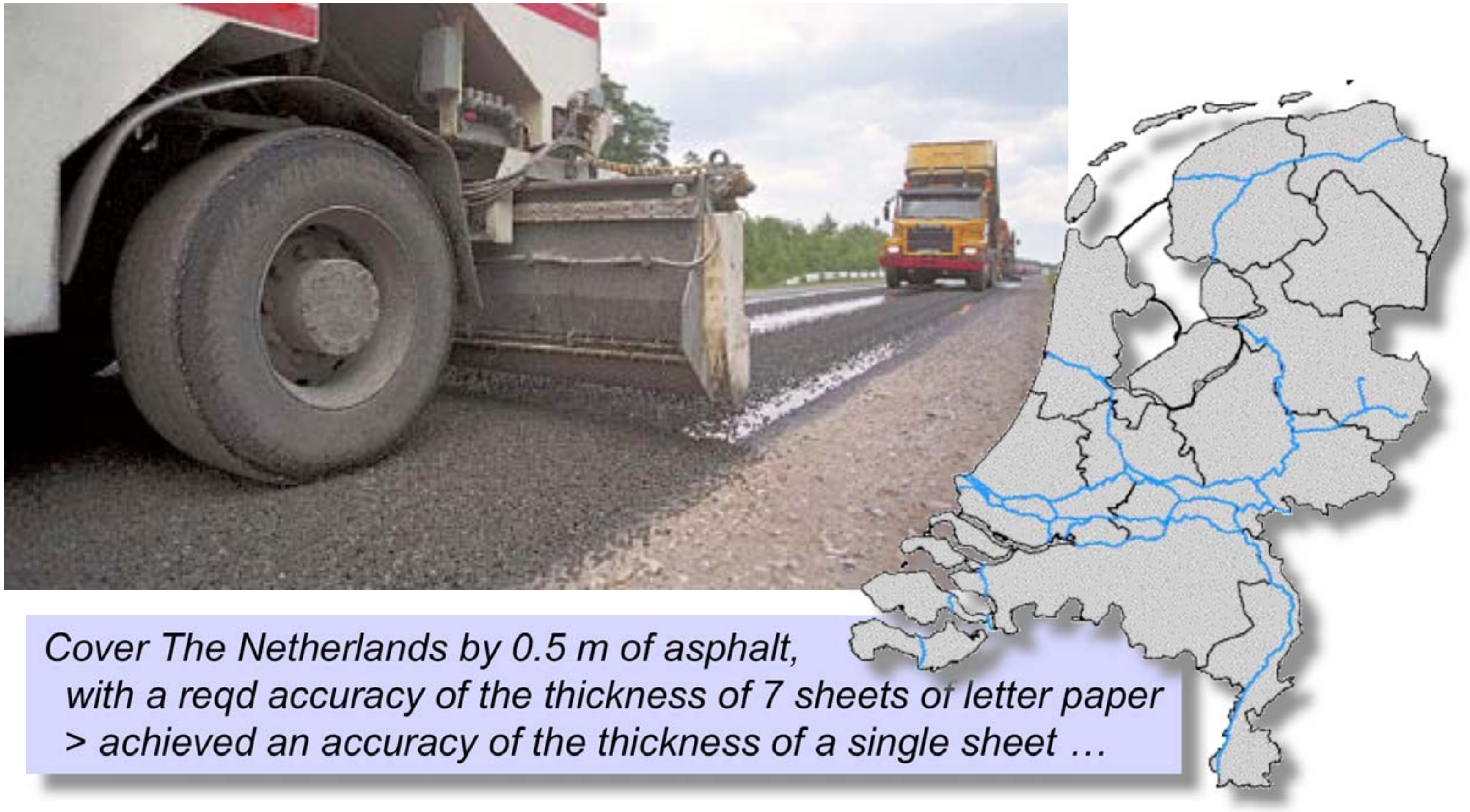
- *Factor 7 within spec*
- *Limited by resol. reflectometer*
- *3x better then competition*

'pm lateral coating accuracy'

Louis, Zoethout, van de Kruijs, et al, 3d Int EUVL Symp., www.sematech.org/docubase (2004)

‘Picometer coating accuracy’

on a macroscopic scale:



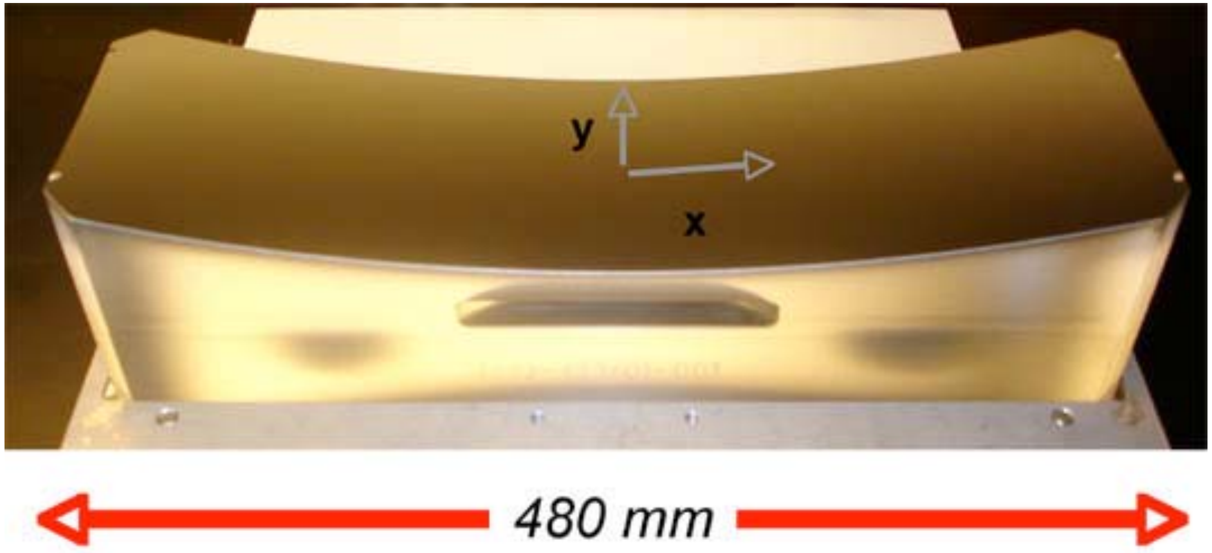
Cover The Netherlands by 0.5 m of asphalt,
with a reqd accuracy of the thickness of 7 sheets of letter paper
> achieved an accuracy of the thickness of a single sheet …

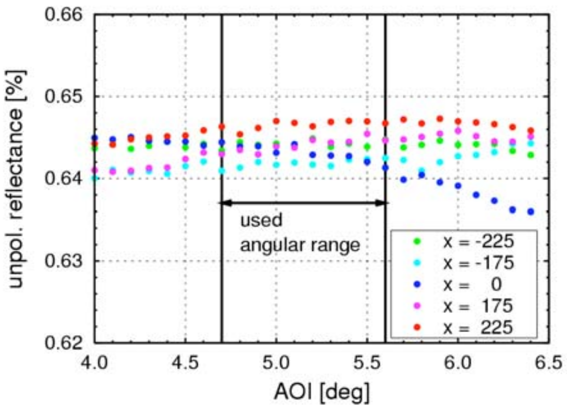
Scaling coating technology

largest EUVL optical element

Reqt. reflectivity @ used AOI +/-< 1% of target value

➔ 0.3% d-spacing budget



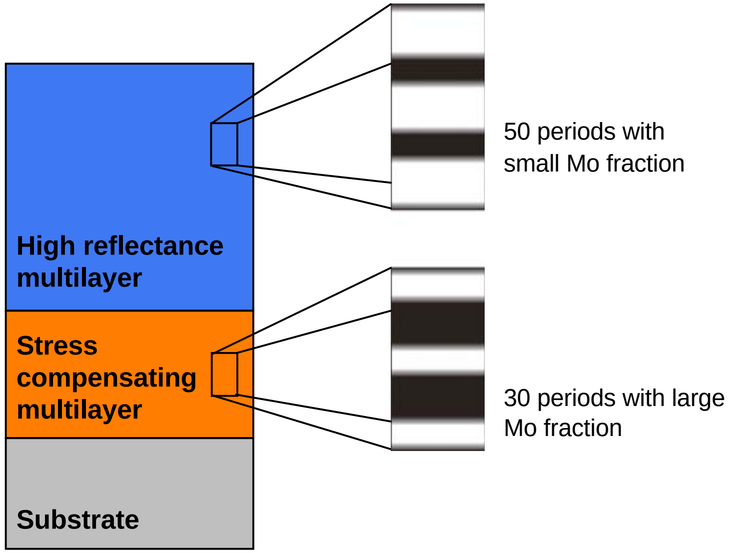


Largest EUV ML optic to date successfully coated

- *First real EUV optic from new large area EUV coating facility @ SMT*
- *Several new coating technologies successfully incorporated*
- *Lateral uniformity < 0.2%*
- *Reflectivity 64.5% and uniform uniformity +/- 0.25%*

Compensating ML-induced stress

Compounded multilayer system



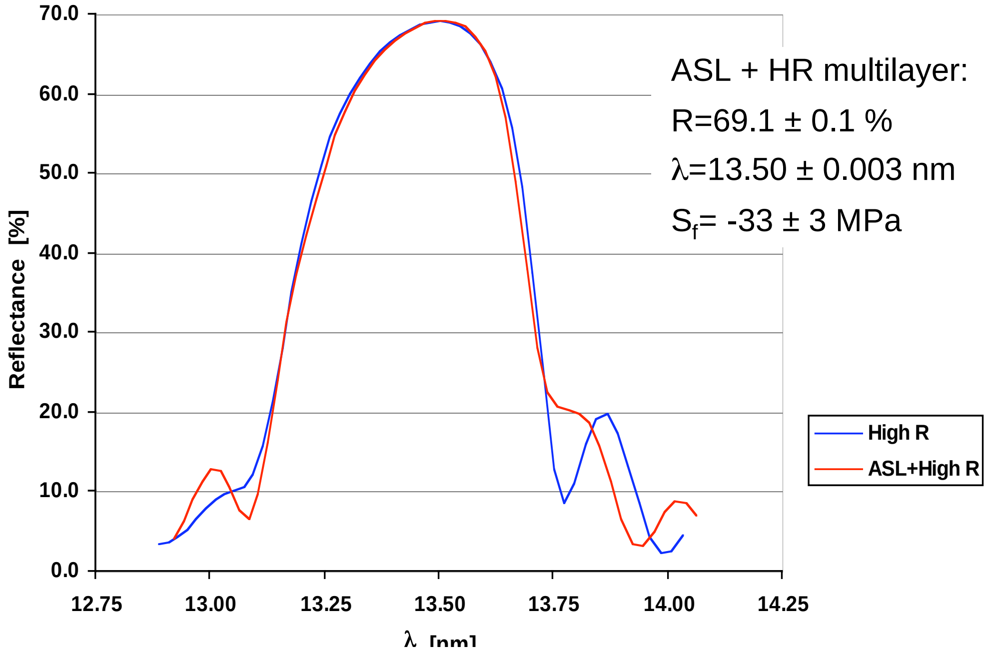
High reflectance multilayer

Stress compensating multilayer

Substrate

50 periods with small Mo fraction

30 periods with large Mo fraction



ASL + HR multilayer:

R=69.1 ± 0.1 %

λ=13.50 ± 0.003 nm

S_f= -33 ± 3 MPa

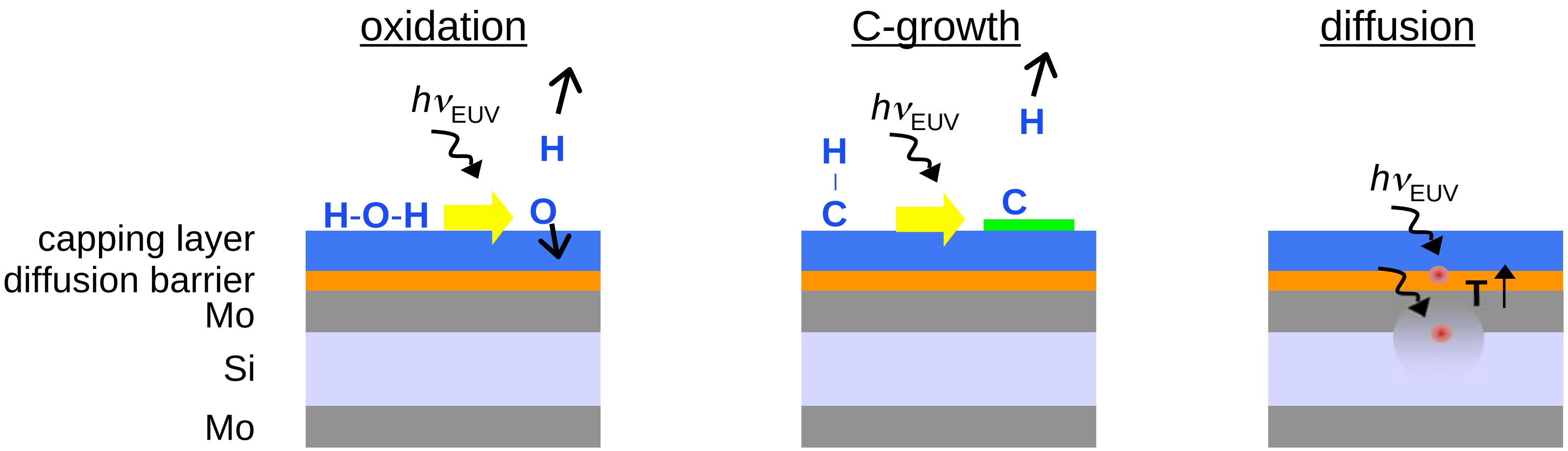
- *Full stress compensation feasible without sacrificing EUV optical performance*
  - ✓ *-33 MPa demonstrated*
  - ✓ *>69% reflectance*

Zoethout et al, SPIE 5037, Sta Clara, pp. 872-877 (2003)

EUV optics key research & development

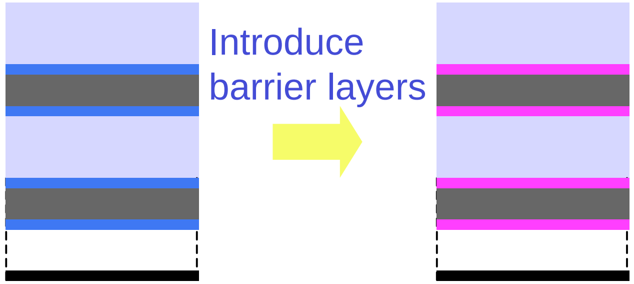
Physics & engineering for 2nd generation of EUV multilayers

- *surface photo-chemistry at EUV photon energies*
- *chemical and diffusion barriers & interaction with incident radiation*
- *plasma processing and deposition processes*

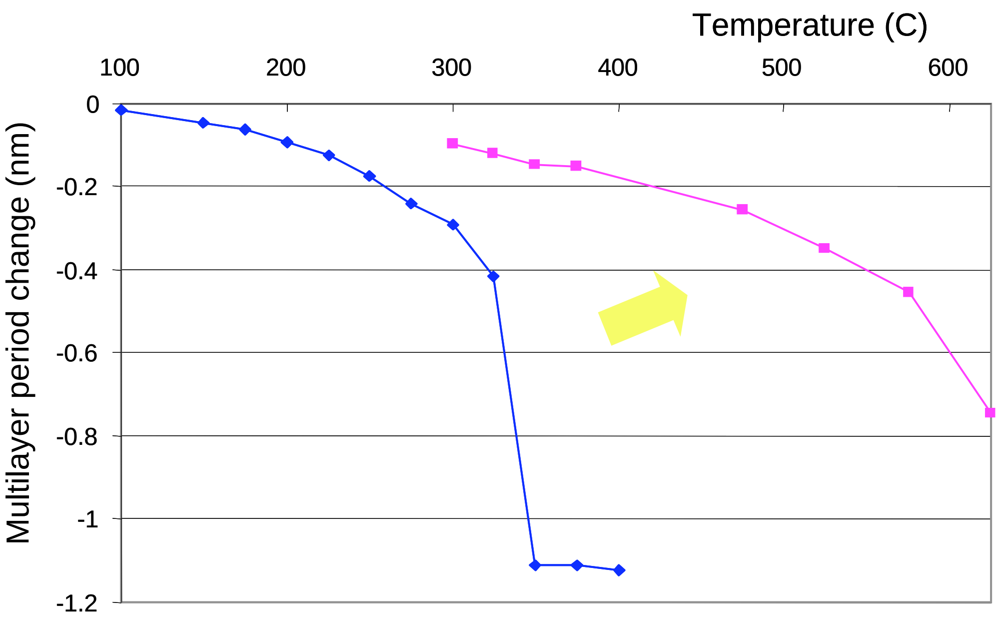


While meeting Zeiss-ASML road map ...

Diffusion barrier layers

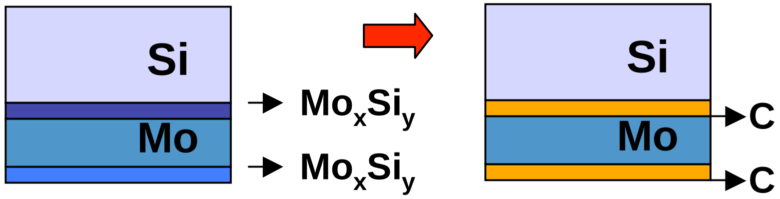

Introduce barrier layers

13.5 nm multilayers for exposure to kW EUV plasma light sources



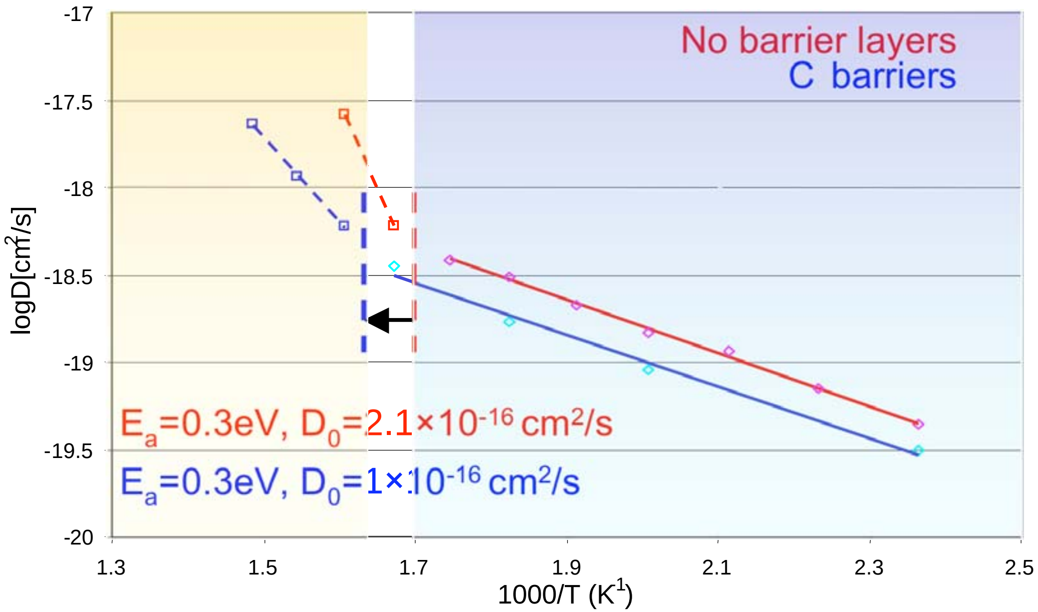
Barrier layers
➔ reduce diffusion, postpone phase-transformation

Barrier layers: diffusion reduction



Arrhenius:

$$D=D_0\exp(-E_a/kT)$$



-First stage :	C-barrier results in reduced growth of 1 monolayer No change in activation energy
-Second stage :	C-barrier results in delayed full interdiffusion of the multilayer $\Delta T_{\mathbf{delay}}$ = 25°C

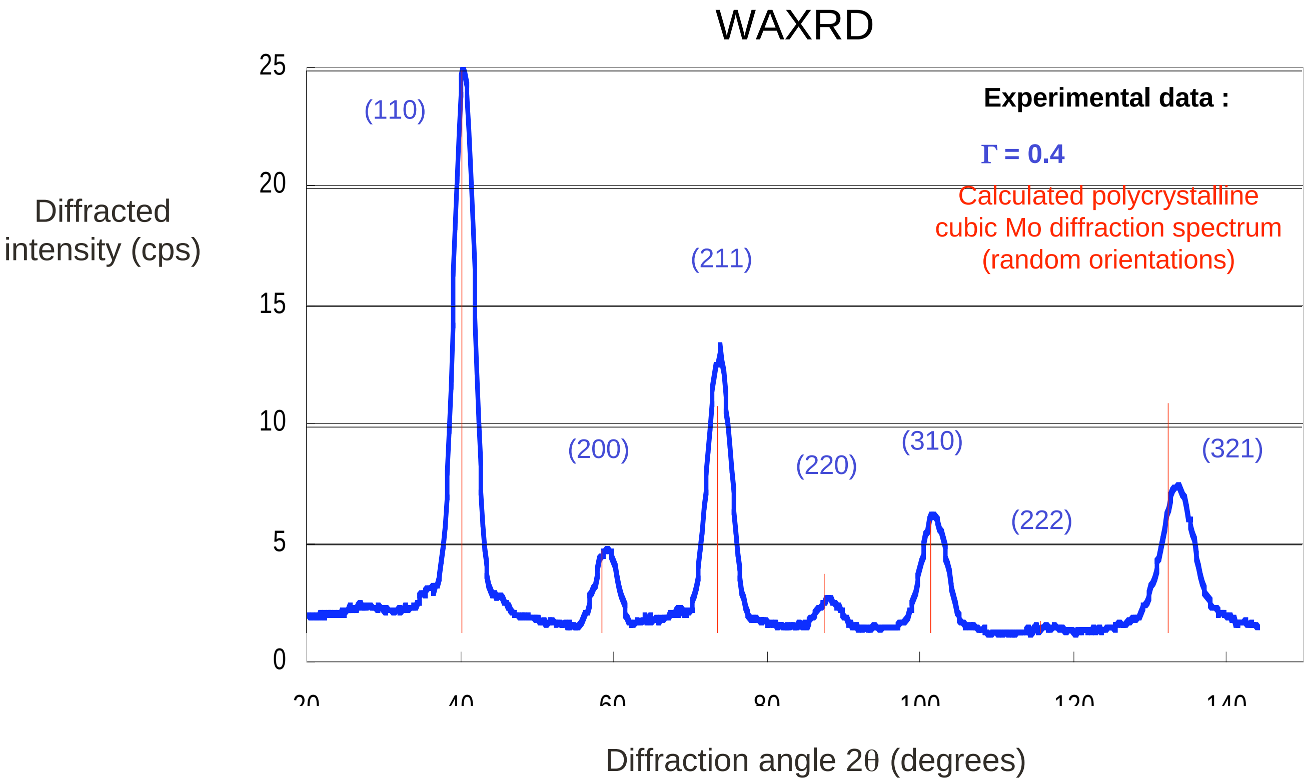
L.G.A.M. Alink, R.W.E. van de Kruijs, E. Louis et al., Thin Solid Films (accepted)
I. Nedelcu, R.W.E. van de Kruijs, E. Zoethout et al., (accepted).

Nano-crystallite growth

Scherrer's equation: $$L = \frac{0.94\lambda}{W\cos\theta}$$

λ : x-ray wavelength.

θ, W : diffraction angle and width.



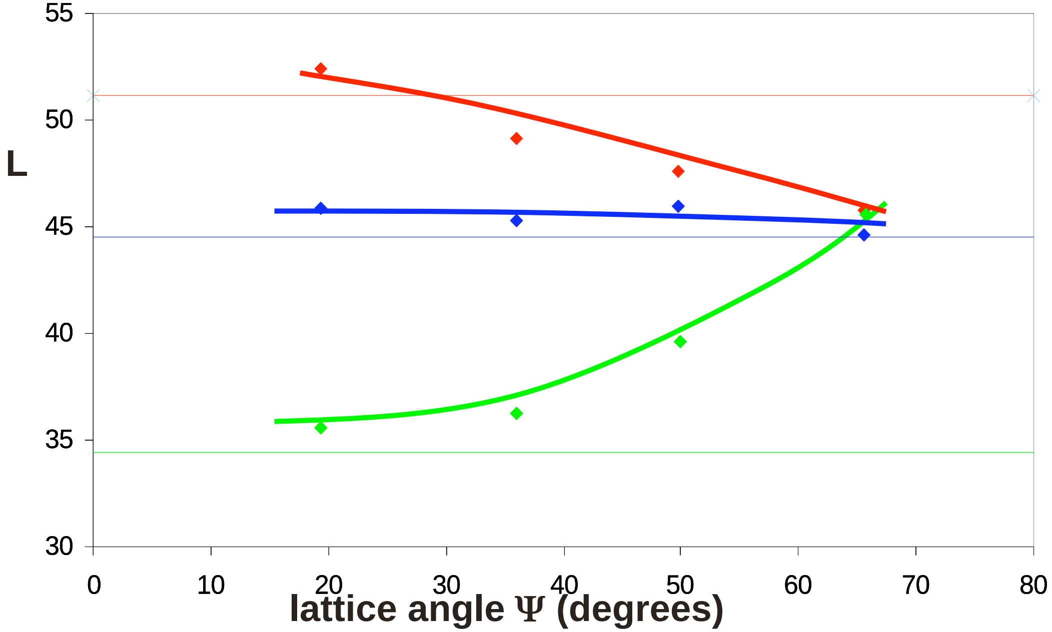
Peak positions :
Lattice structure, lattice strain

Absolute intensities :
Diffracting volumes

Relative intensities :
Crystallite orientations

Peak widths :
Crystallite sizes, strain fields

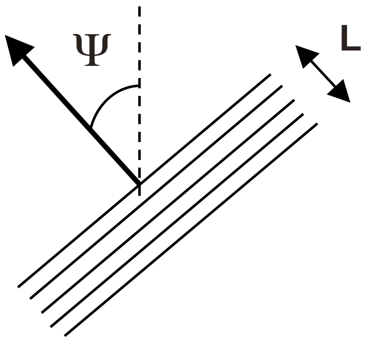
Nano-crystallite growth

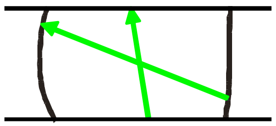


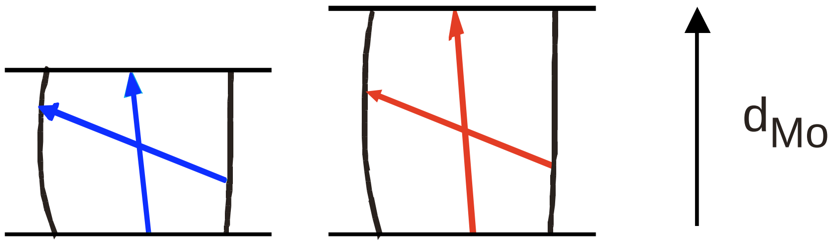
d_{Mo}

Mo nucleates on silicide layer:
structure of the silicide determines
structure of Mo

d increases
Γ increases
} d_{Mo} increases.

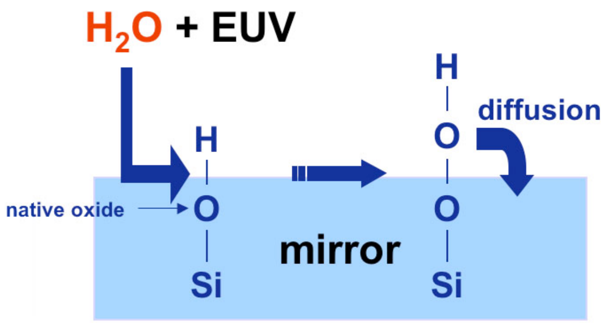


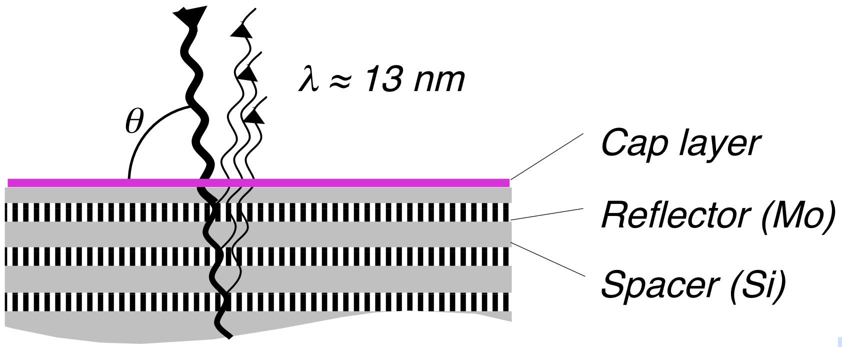


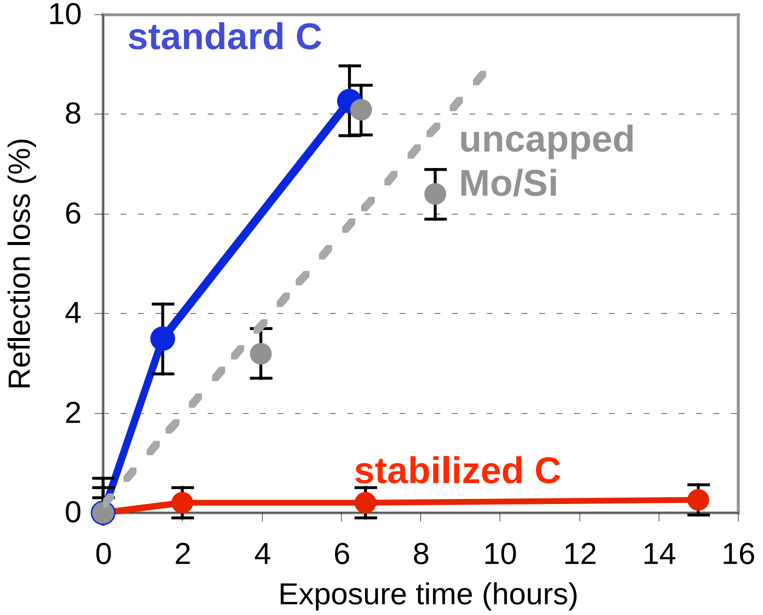


Columnar crystallite growth.
Transversal size determined by Mo layer thickness.

Protective capping layers







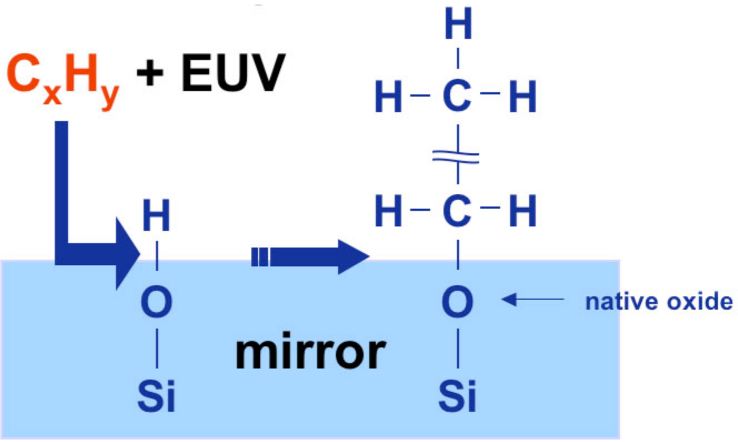
- Exposure of multilayer to high EUV flux
    - P = 10 mW/mm^2
- At (U)HV background gases
    - H_2O ~ 10^{-6} mbar
    - C_xH_y < 10^{-10} mbar

- *Stable C capping layer provides effective protection*
    - *Constant reflectivity over 15 hr continued exposure*
- *C properties critically depend on deposition & EUV stabilization*

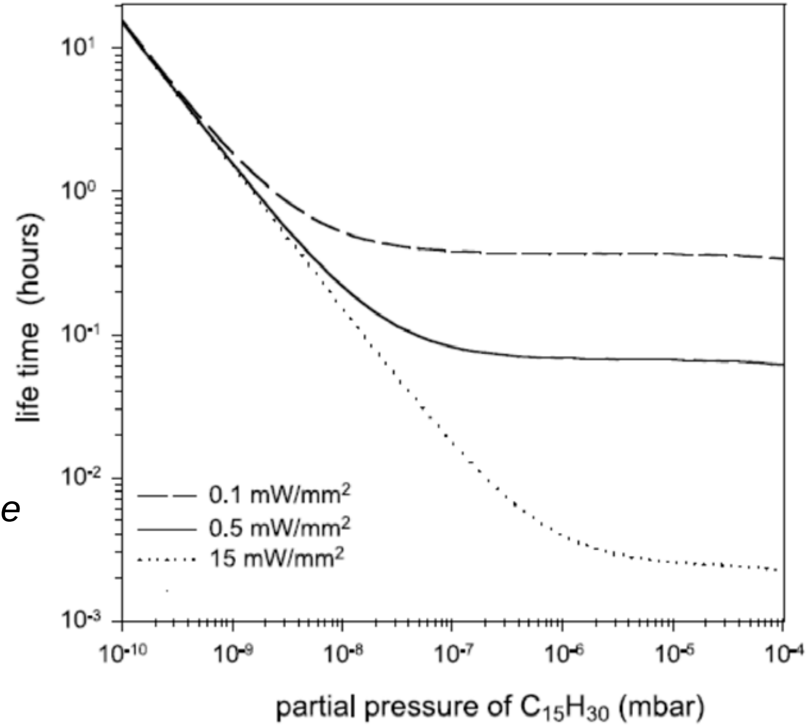
Oestreich, Louis, et al; SPIE 4146-07, 2000

Yakshin, Bijkerk,et al, Aset/Sematech Proc. www.sematech.org/docubase, pp. P6-6 (2001)

Protective capping layers, C deposition



C-contamination model Jonkers and Bisschops



Without EUV: physisorption of CH at mirror surface
EUV: cracking of molecular bonds, chemisorption

Lifetime criterion: 1 nm C (~1% abs)

S. Oestreich et al; SPIE 4146-07, 2000

Control of surface oxidation

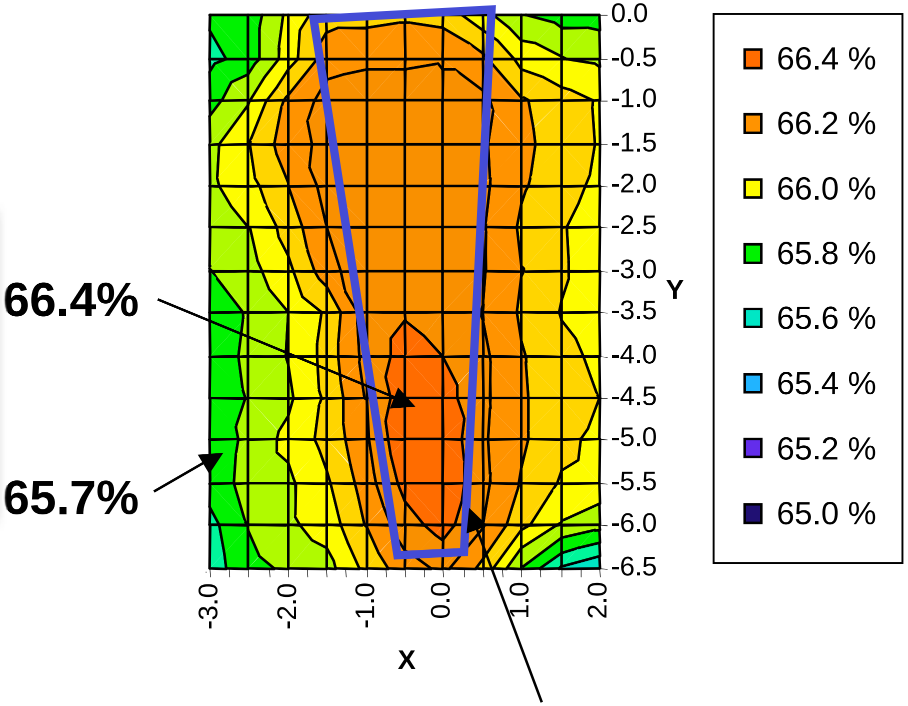
Life time expt: 230 h EUV exposure @ PTB

Background: C_xH_y, H_2O, O_2
Intensities: ≤ 30 mW/mm²

Mo/Si + capping layer:

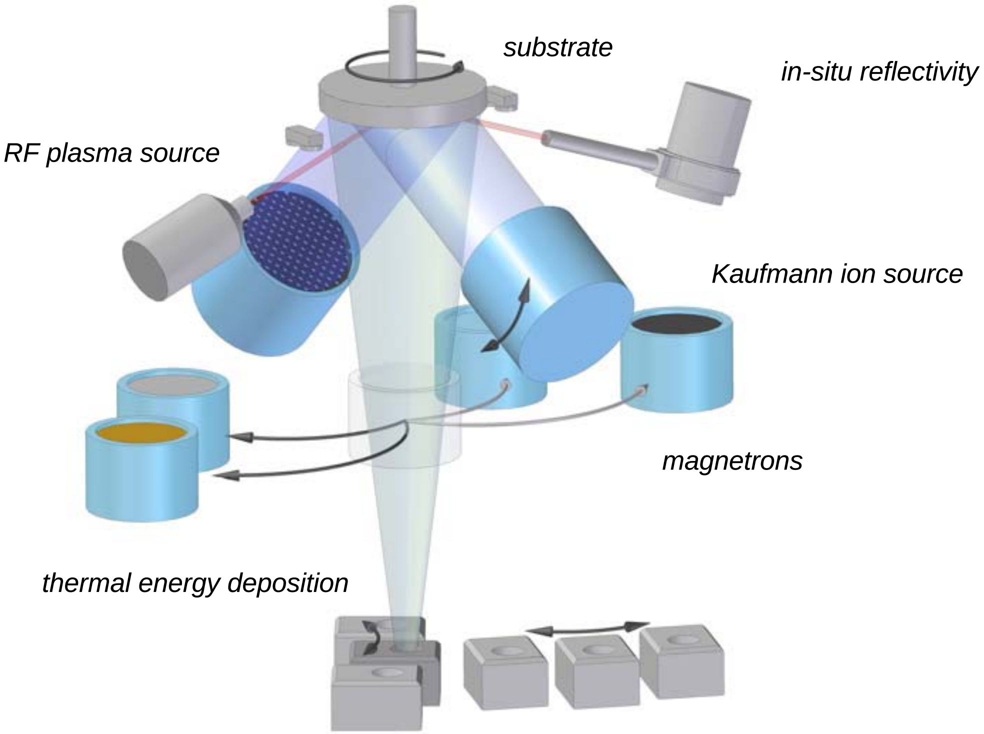
- No loss of reflectivity
- Surface analysis shows no oxidation or other damage
- Extrapolation: ≥1000 hrs lifetime (1% ΔR)

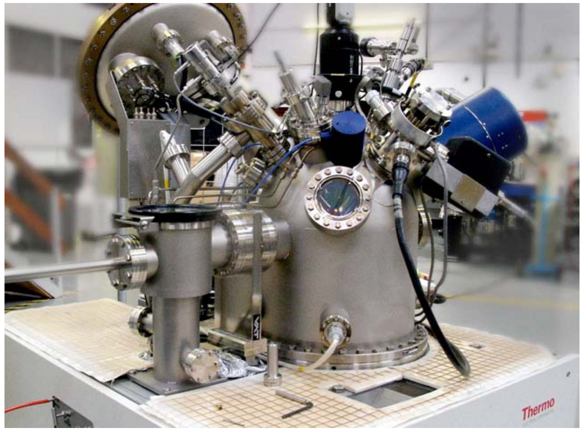
Initial reflectance 66.4%



estimated position of EUV spot

Coating infrastructure





Advanced Development Coater

- thermal, medium energy deposition
- plasma & ion surface treatment

Analysis Advanced Development Coater

- XPS, AES, SEM
- Ion-beam surface analysis
- GI- XRR, XRD

Summary & outlook

1. **Existing ML know-how available to VUV/XFEL ML applications**
    - *Bi-layer systems with high, inherent thermal stability*
    - *Barrier layered systems with enhanced reflectivity + thermal stability*
    - *Capped systems with stabilized surfaces*
    - *Technology to uniformly coat large, GI optical surfaces*
2. **Synergy from running, lithography motivated research programmes**
    - *Inert MLs with high radiation hardness*
    - *High thermal stability*
    - *Studies on atomic/molecular deposition processes*
3. **ML-VUV/XFEL case?**
    - *Thermal issue by average power on ML ‘managable’*
    - *Peak power levels show physics materials limits, but not likely ML specific*
    - *Deposition & layer hardening process essential*

➔ Opportunity for exploring the ML VUV/XFEL limit