Multilayer optics for next-generation EUVL systems

Regina Soufli

regina.soufli@llnl.gov

Lawrence Livermore National Laboratory

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Key Contributors

Eberhard Spiller
Russell Hudyma
Eric Gullikson (LBNL)
John S. Taylor
Gary Sommargren
Michael A. Johnson
Jim Folta
Don Sweeney
Chris Walton
Andy Aquila (LBNL)
Franklin Dollar (LBNL)
Jeff C. Robinson
Sherry Baker
Jay Ayers
Shannon Ayers
Susan Ratti
Mark Schmidt
Fred Grabner
Rick Levesque

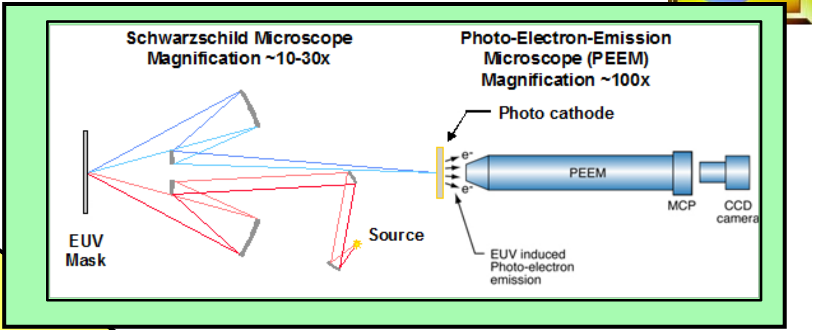
Presentation Outline

- General principles of EUVL optical substrates, multilayer coatings, roughness and scattering, precision surface metrology
- Example #1: 0.30-NA Micro-Exposure Tool (MET) (two-mirror micro-field system)
- Example #2: 0.1-NA Engineering Test Stand (ETS) (four-mirror scanning system)
- Example #3: EUVL collector substrates, polyimide smoothing
- EUV multilayer optics for solar physics
- Diffraction limited x-ray mirrors for free-electron lasers

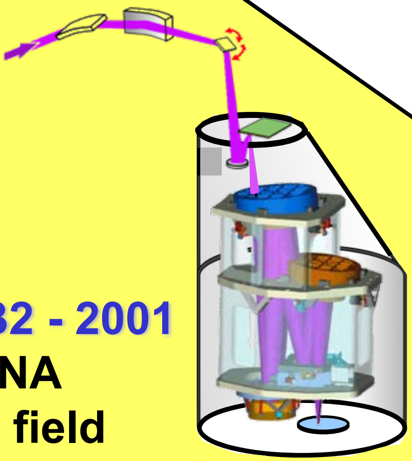
EUVL requires all-reflective optical systems

10x1 - 1996
10x2 - 1999
0.1 NA
“Microstepper”

ETS POB1 - 2000
0.1 NA
Full-field scanner

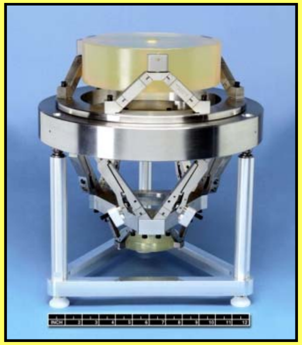


EUV AIMs Tool
Proposed 2001

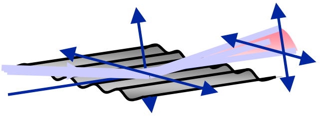


SES POB2 - 2001
0.1 NA
Static field

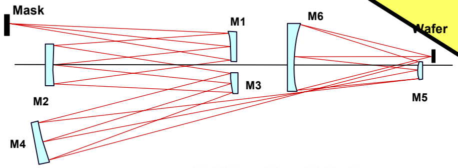
MET
2002-today
0.3 NA
μstepper



ETS Condenser

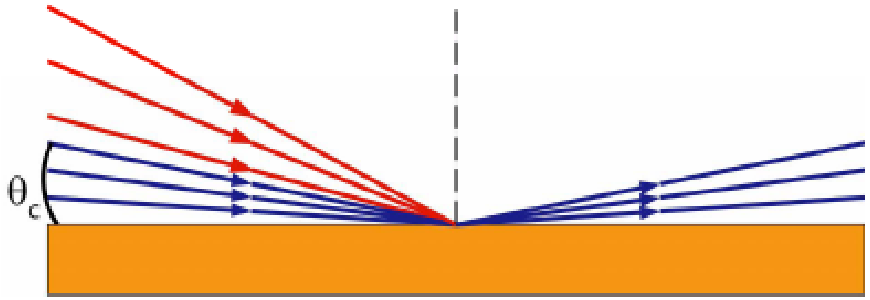


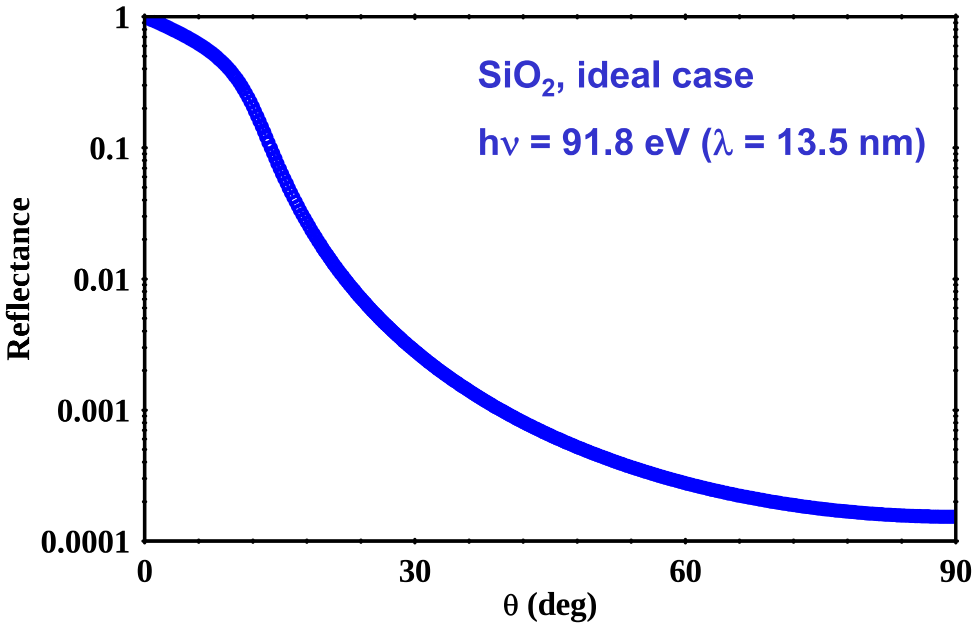
Ripple-Plate Condenser



High NA Projection System

In the EUV/x-ray range, the reflective performance of materials is governed by the effect of total external reflection



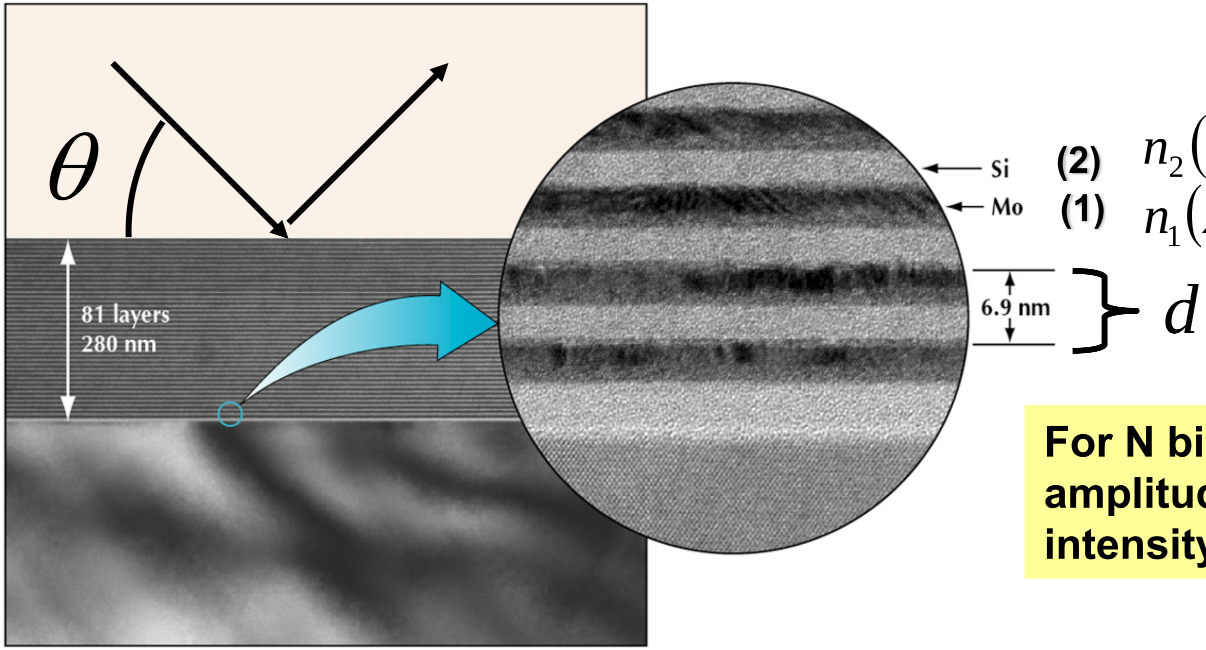


- EUV/x-ray region coincides with core electron binding energies → strong absorption. Refractive index n is expressed as a complex number: $n = 1-\delta + i\beta$, where $\delta, \beta \ll 1$
- For grazing incidence angles $\theta \leq \theta_c \approx \sqrt{2\delta}$, total external reflection occurs (similar to the "total internal reflection" effect at visible wavelengths, per Snell's law)
- $\theta_c \sim \lambda\sqrt{Z}$

D. T. Attwood, *Soft X-rays and Extreme Ultraviolet Radiation, Principles and Applications*, Cambridge University Press (1999).

E. Spiller, *Soft X-ray Optics*, SPIE Press, Bellingham, WA (1994).

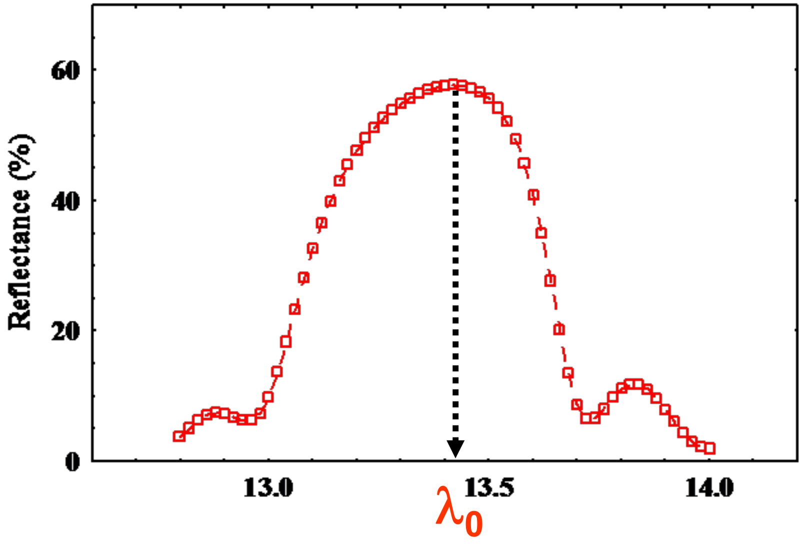
Multilayer interference coatings



(2) $n_2(\lambda)=1-\delta_2(\lambda)+i\beta_2(\lambda)$

(1) $n_1(\lambda)=1-\delta_1(\lambda)+i\beta_1(\lambda)$

For N bilayers: Electric field amplitude is increased by ~ N, intensity is increased by N^2



Bragg equation for multilayers:

$$m\lambda_0 = 2d\sin\theta\sqrt{1-\frac{2\overline{\delta}}{\sin^2\theta}}$$

$m=1, \theta \rightarrow 90^\circ$ **(near-normal incidence)**

$$\lambda_0 \approx 2d$$

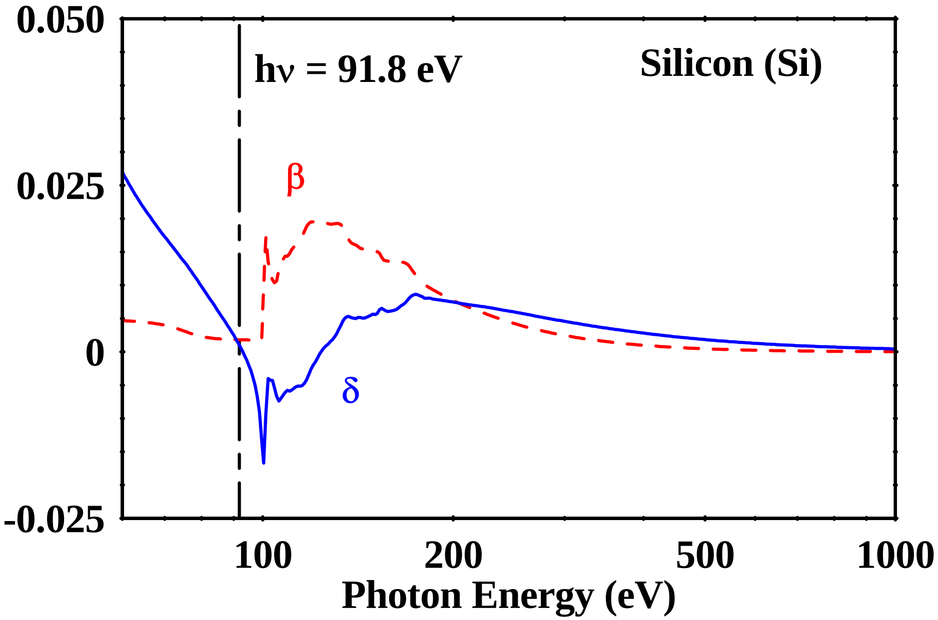
Multilayer materials selection is driven by optical properties

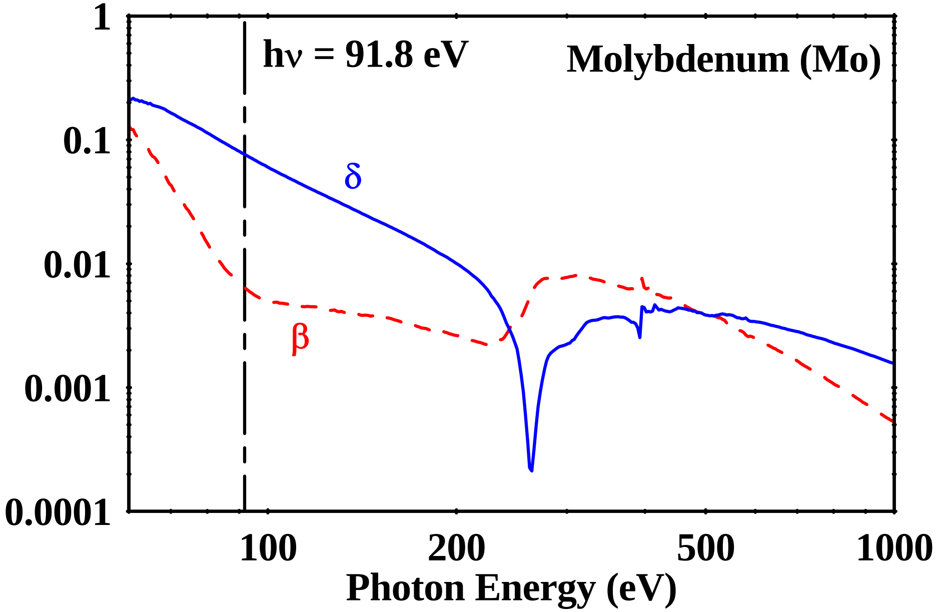
Multilayer materials need to:

✓ have good optical contrast in the desired energy region of operation

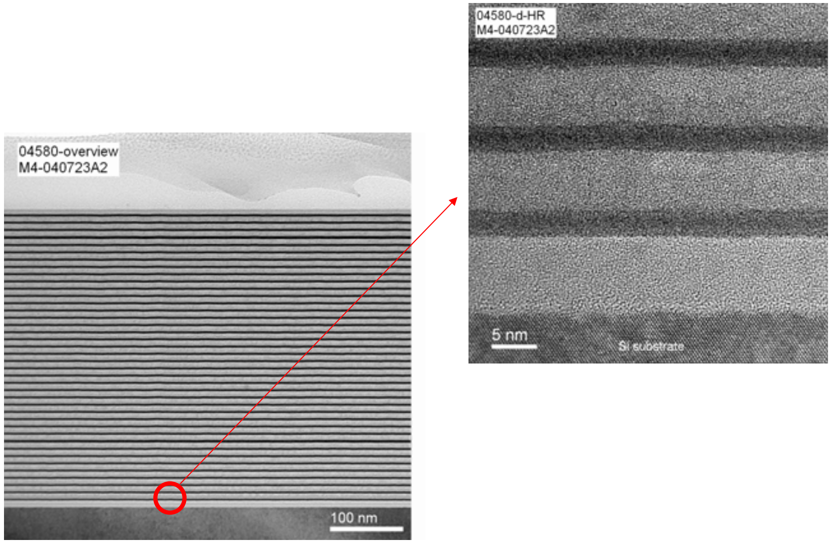
✓ be chemically compatible with each other

✓ form stable interfaces

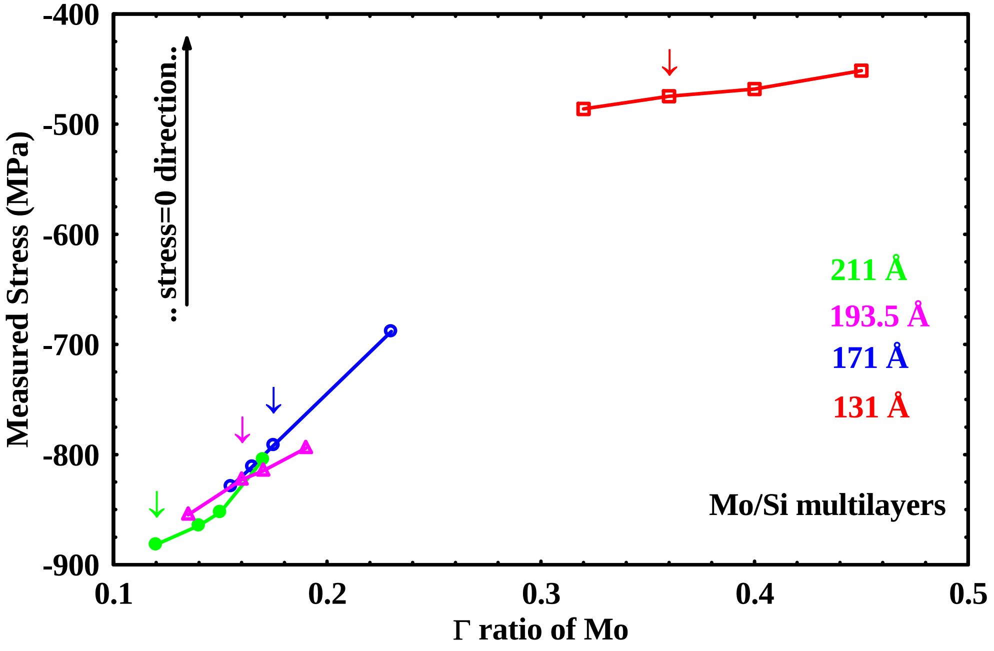




Multilayer microstructure and stress properties depend on deposition method, Γ-ratio and layer thicknesses



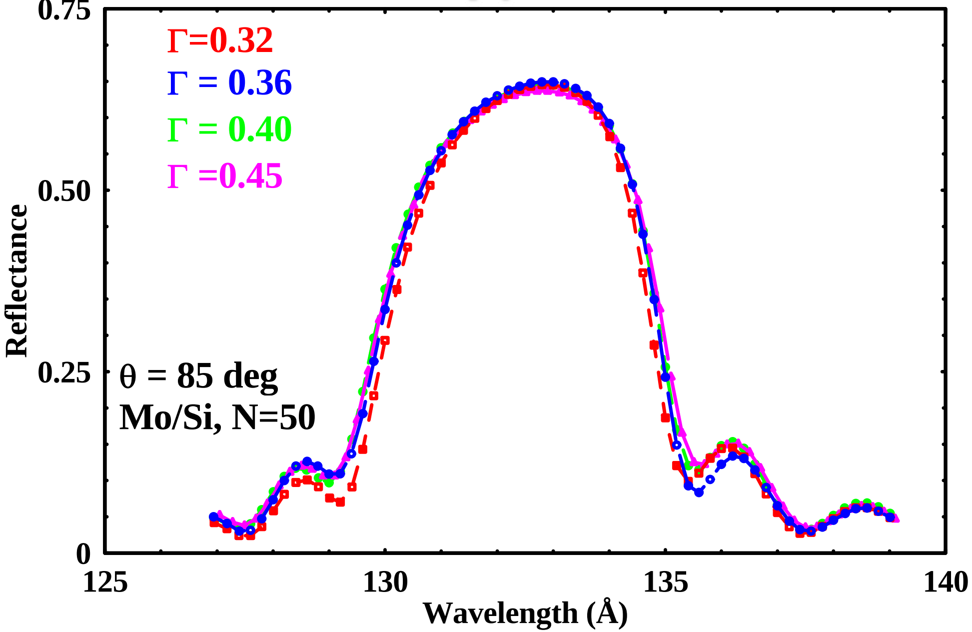
$\Gamma = d_{Mo} / d_{tot}$

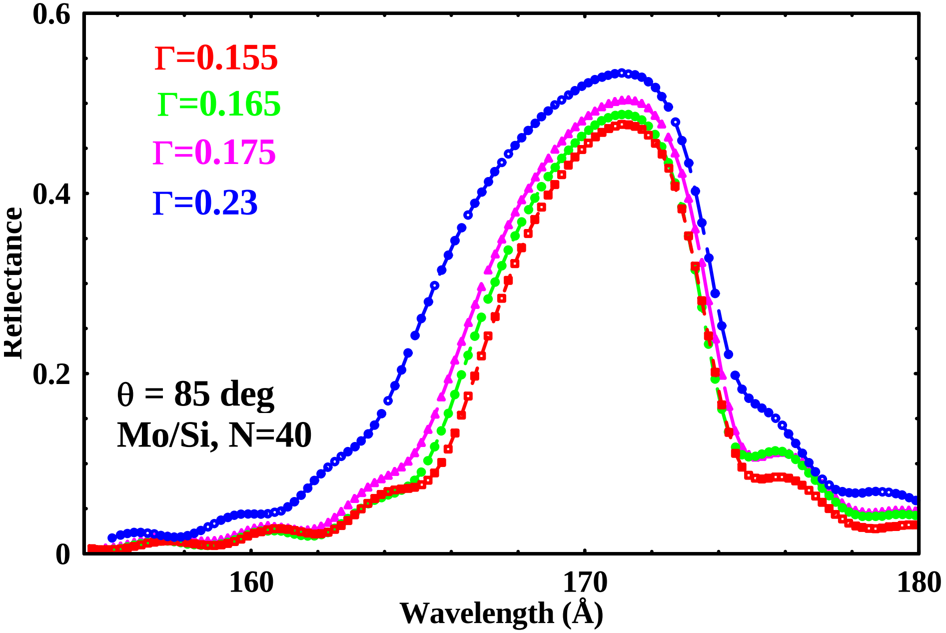


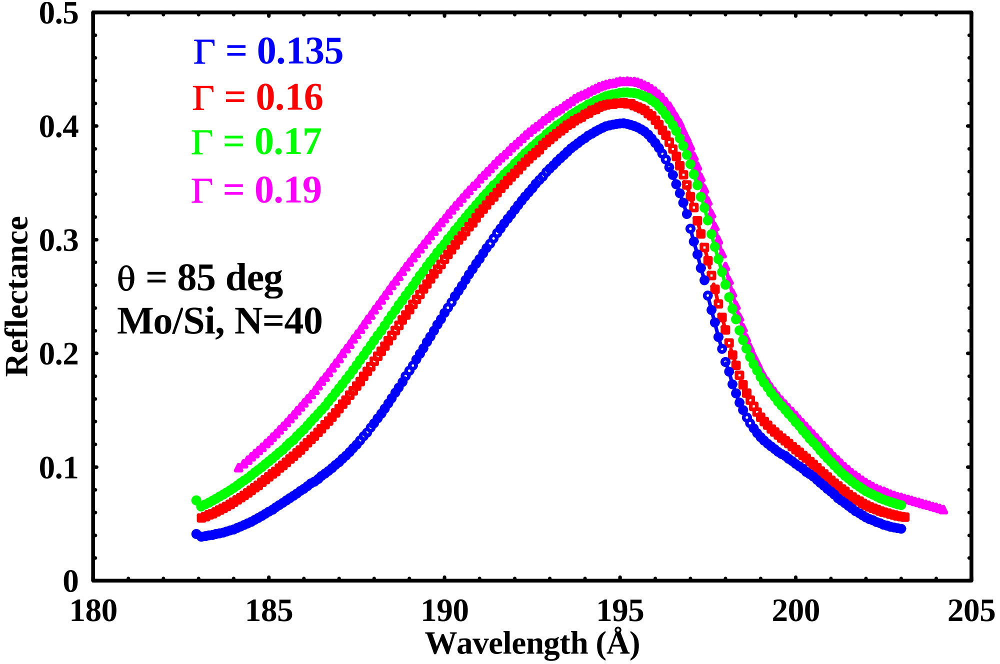
DC-magnetron sputtered Mo/Si multilayer with Γ=0.16 at 19.35 nm

R. Soufli, D. L. Windt, J. C. Robinson, et al, “Development and testing of EUV multilayer coatings for the atmospheric imaging assembly instrument aboard the Solar Dynamics Observatory”, Proc. SPIE 5901, 59010M (2005).

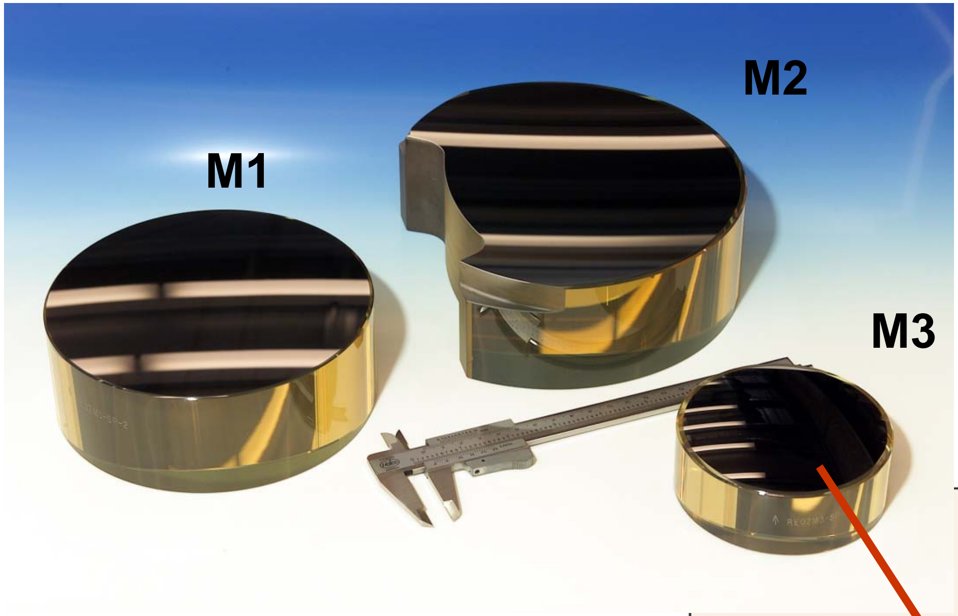
Γ-ratio also affects multilayer reflectivity, bandwidth and out-of-band suppression







Highly reflective and precise multilayer optics enable normal-incidence imaging at EUV wavelengths

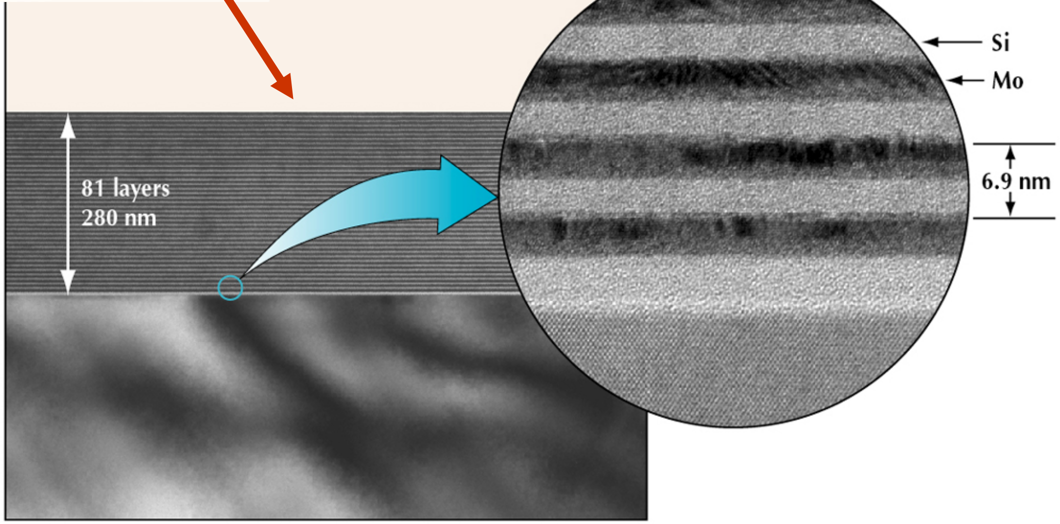


DC-magnetron sputtered Mo/Si projection optics for a 0.1-NA, 24 mm x1.5 mm ring field EUV step-and-scan system operating at 13. 35 nm (EUVL program)

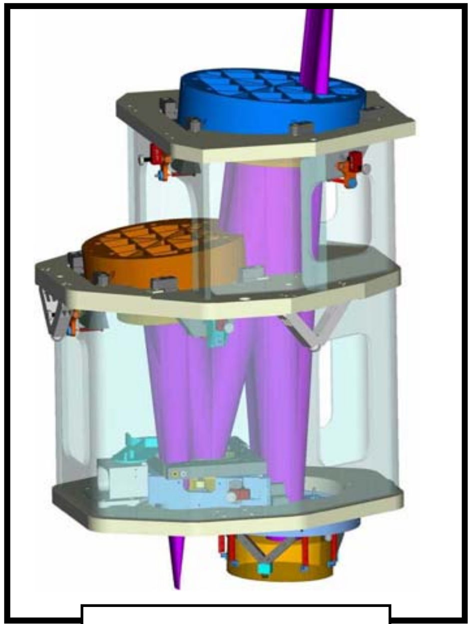
R. Soufli *et al*, SPIE Vol. 4343, p.51-59 (2001)

Performance requirements for multilayer-coated EUVL optics

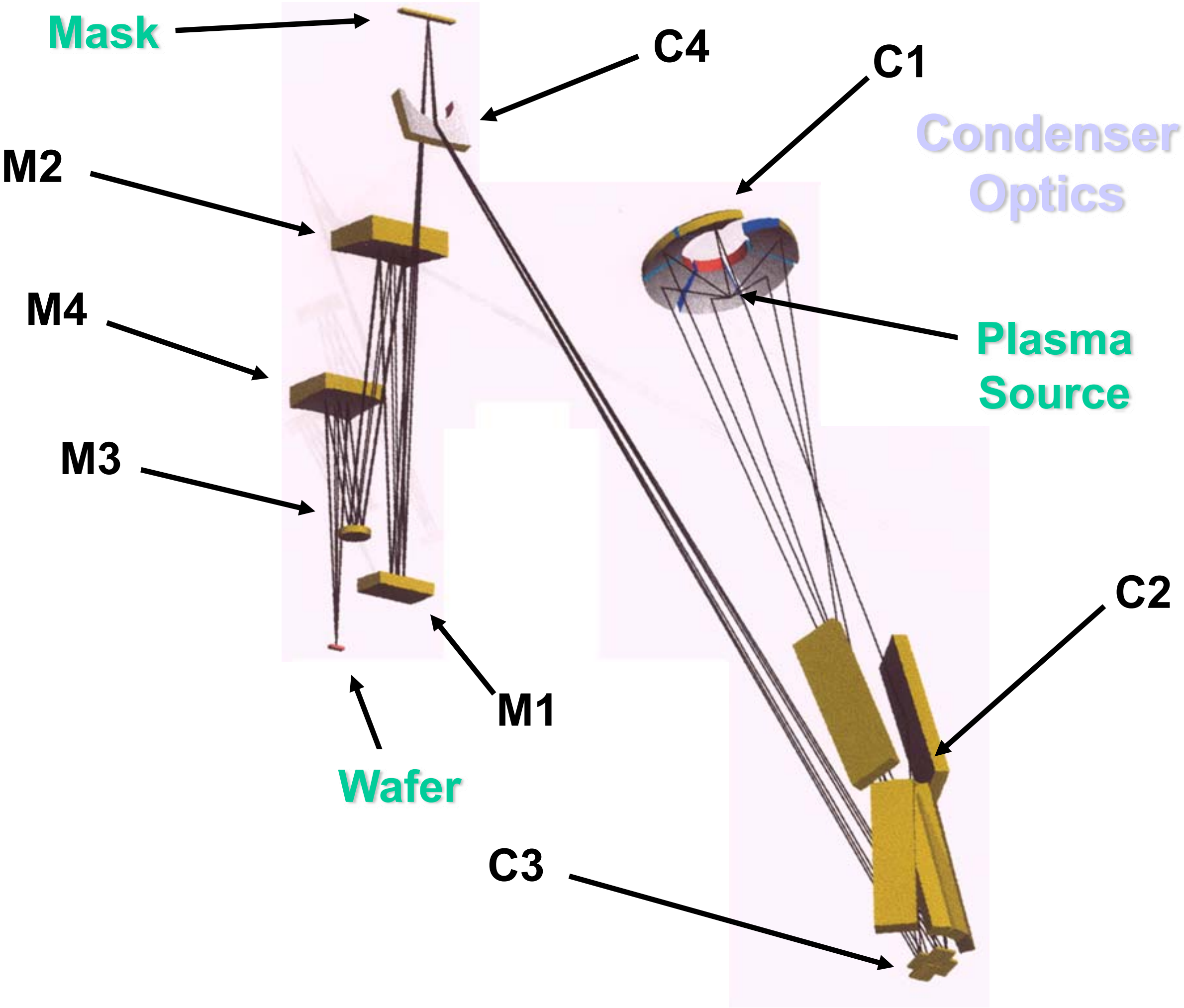
- **Wavefront control**
- **Spectral matching**
- **High + uniform reflectance**
- **Lifetime stability**



The Engineering Test Stand (ETS) employs a 0.1-NA ring-field imaging system for a 24-mm field of view

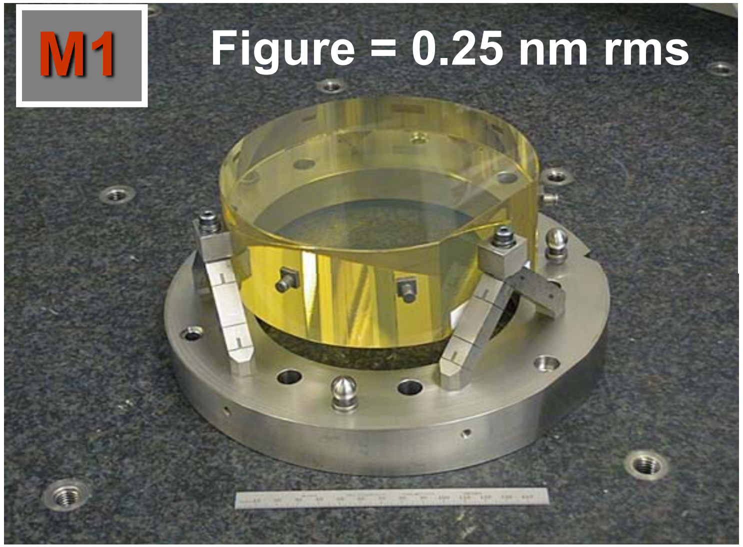


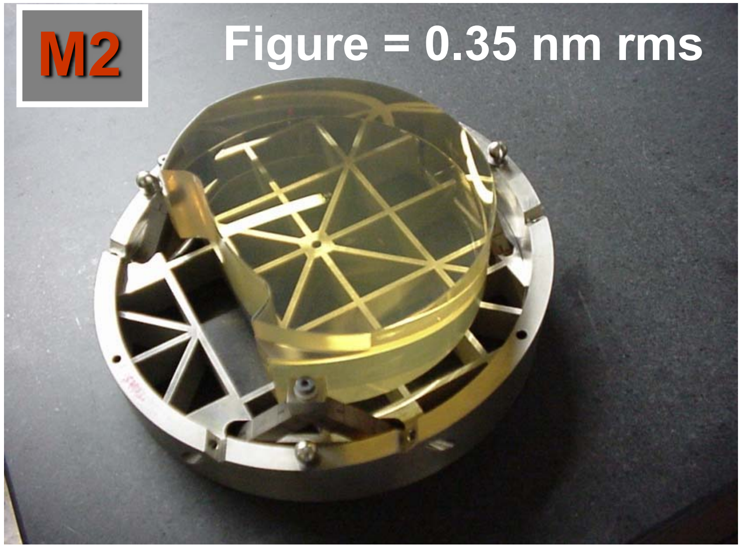
Assembled Camera

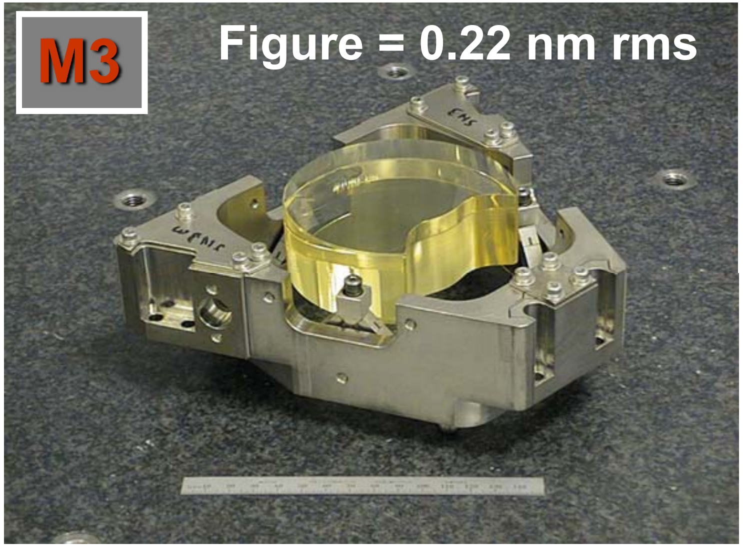


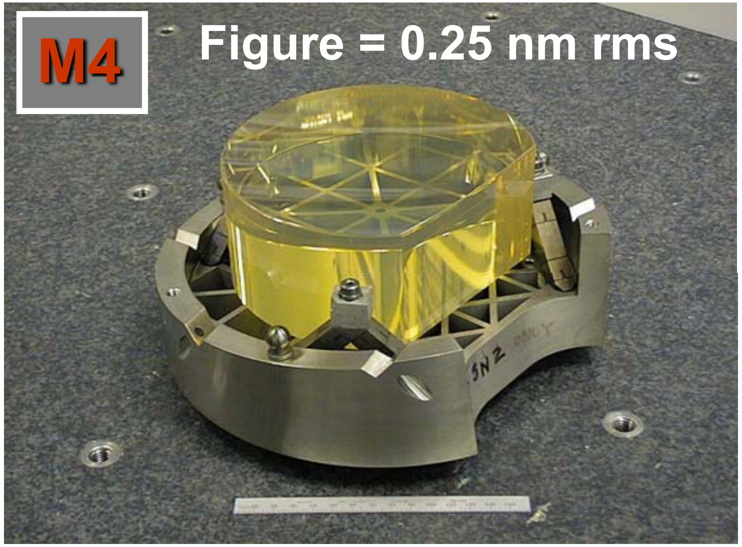
D. A. Tichenor et al., "System integration and performance of the EUV Engineering Test Stand," *Proc. SPIE* 4343, 19–37 (2001).

Four ETS Set 2 camera substrates on their mounting fixtures


M1
Figure = 0.25 nm rms

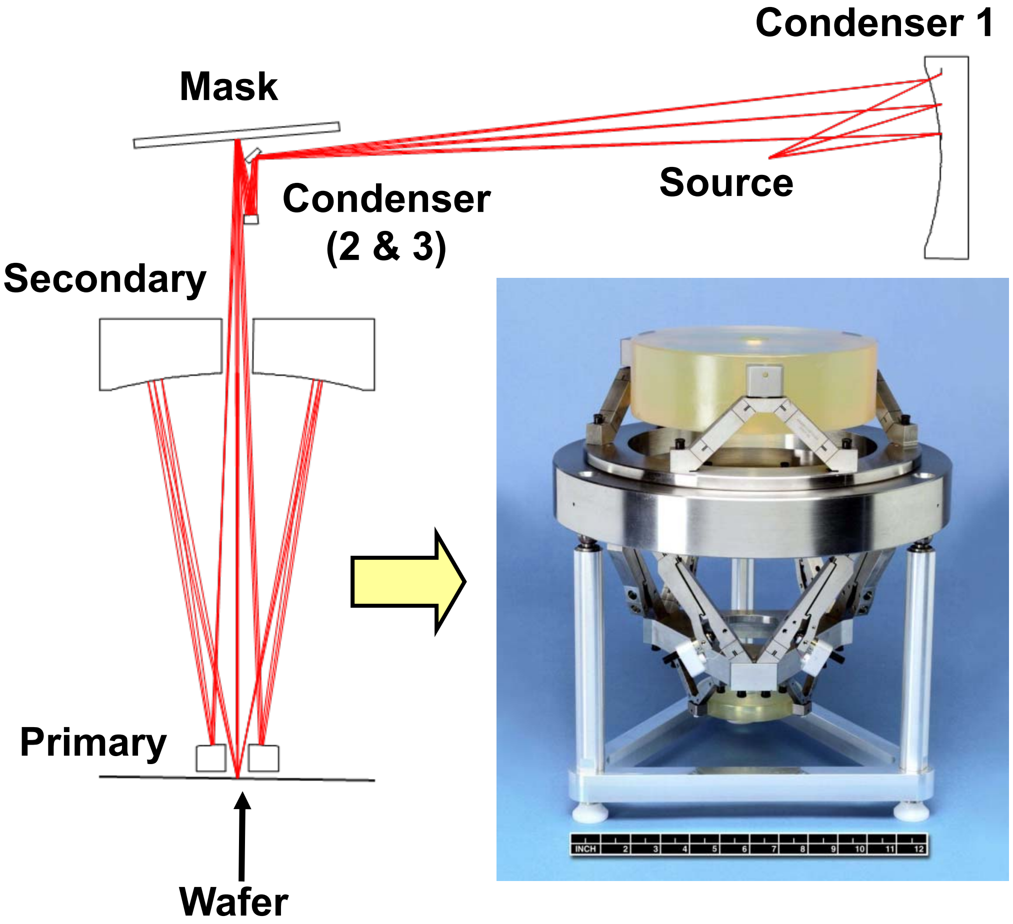

M2
Figure = 0.35 nm rms


M3
Figure = 0.22 nm rms


M4
Figure = 0.25 nm rms

ETS substrates made by Tinsley

The Micro-Exposure Tool (MET) provides early learning with a high-NA imaging system



Micro-Exposure Tool (MET) System Characteristics

- 5x reduction
- NA 0.30 (20 nm resolution)
- 600 µm x 200 µm field
- Residual WFE 0.42 nm rms
- Aspheric departure
  - M1: 3.8 µm
  - M2: 5.6 µm
- Obscuration: 10%

Carl Zeiss manufactured the MET camera substrates

Regina Soufli, 07/15/09

EUVL substrates need to satisfy stringent figure and finish specifications

	SET 1			SET 2		
	Figure	MSFR	HSFR	Figure	MSFR	HSFR
MET 1 (primary)	0.43	0.23	0.49	0.18	0.28	0.37
	0.43	0.33	0.54	0.22	0.25	0.38
MET 2 (secondary)	0.25	0.34	0.38	0.22	0.30	0.32
	—	0.46	0.38	—	0.28	0.37
Specification	0.33	0.30	0.50	0.25	0.20	0.40

— measured by Carl Zeiss
— measured by LLNL
All numbers given in nm rms

Figure errors lead to imaging aberrations –loss of resolution

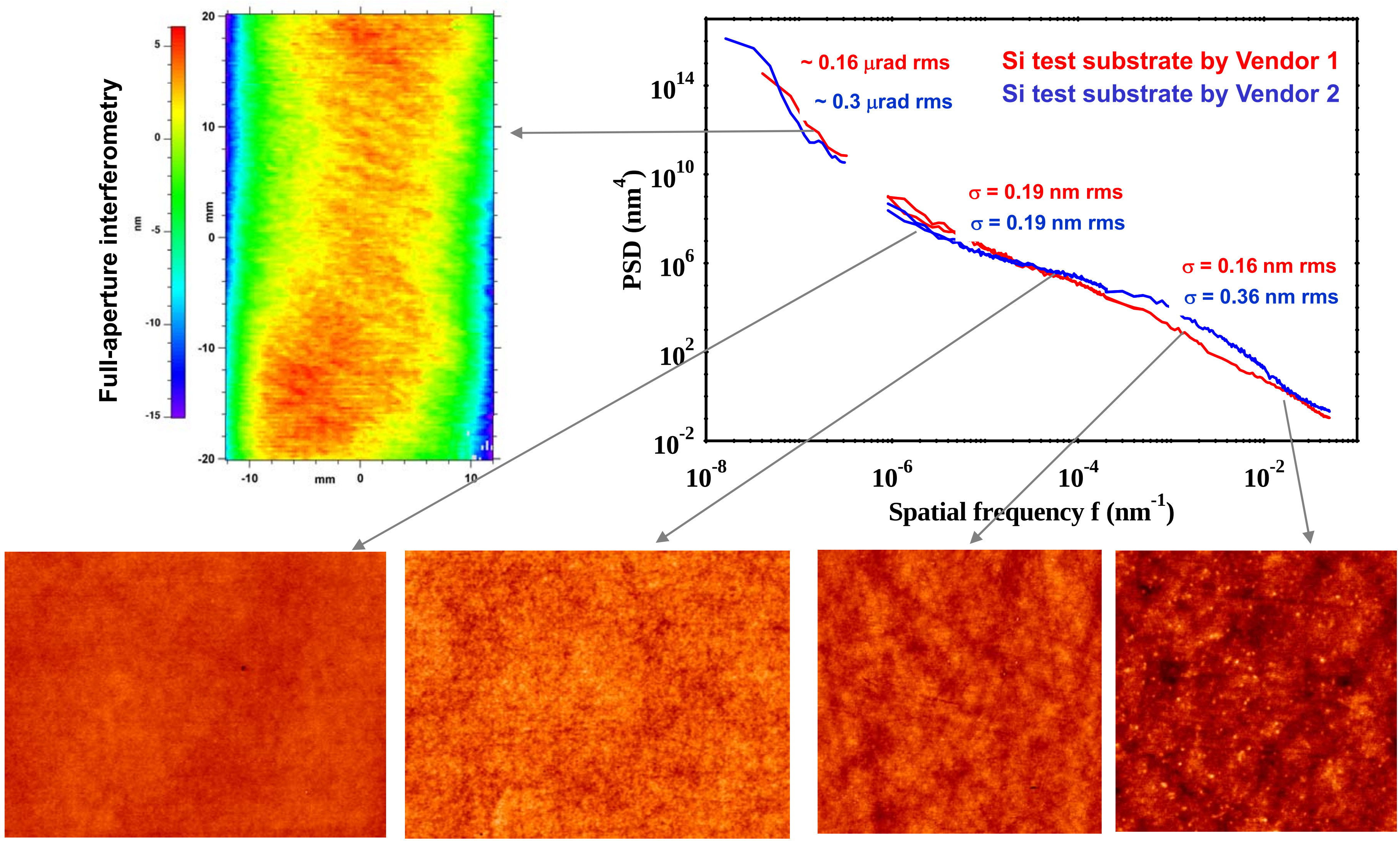
MSFR leads to flare, loss of contrast

HSFR leads to loss of reflectance (throughput)

U. Dinger, G. Seitz, S. Schulte, et al., “Fabrication and metrology of diffraction-limited soft x-ray optics for the EUV microlithography,” *Proc. SPIE* 5193, 18–28 (2004).

R. Soufli, R. M. Hudyma, E. Spiller, et al., “Sub-diffraction-limited multilayer coatings for the 0.3 numerical aperture micro-exposure tool for extreme ultraviolet lithography,” *Appl. Opt*. 46, 3736–3746 (2007).

EUVL optics require state-of-the-art surface metrology for the figure, mid- and high spatial frequency ranges



2.95 mm
Zygo 2x

0.37 mm
Zygo 20x

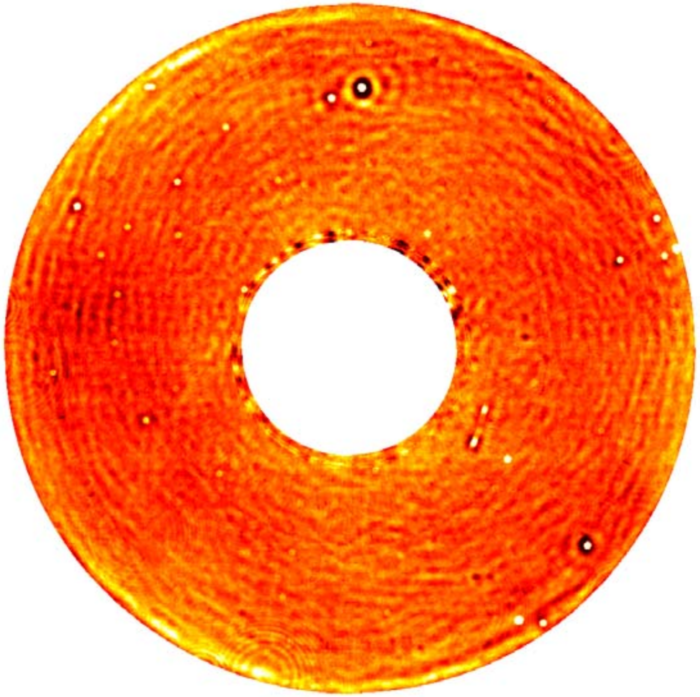
10 μm
AFM

2 μm
AFM

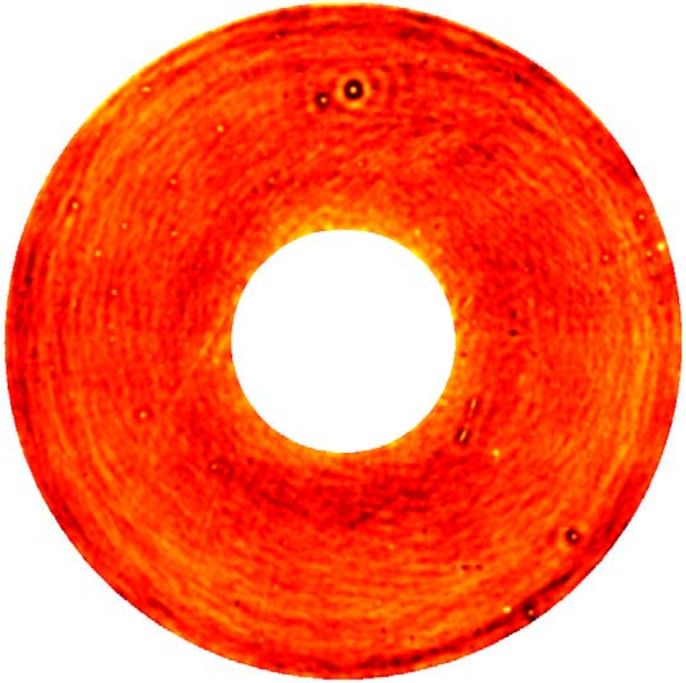
Regina Soufli, 07/15/09

Visible-light, phase-shifting diffraction interferometry was used at LLNL to measure EUVL camera optics

Zeiss measurement (MET M1)
flipped and rotated to register
0.22 nm rms when clipped and binned



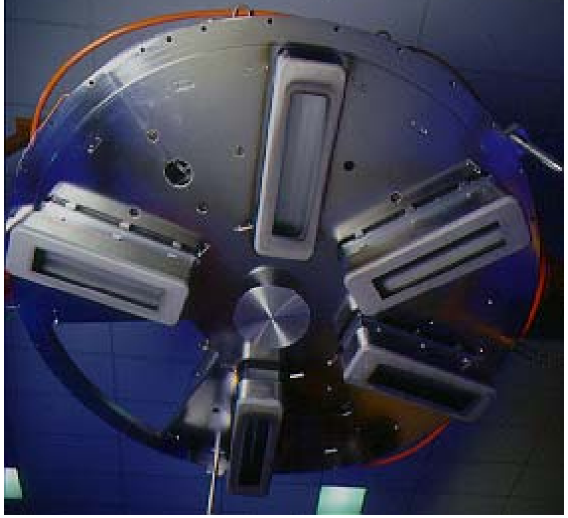
LLNL measurement (MET M1) by Phase Shifting Diffraction Interferometry (PSDI)
magnification adjusted fractionally by 1.7×10^{-5}
0.29 nm rms when clipped and binned



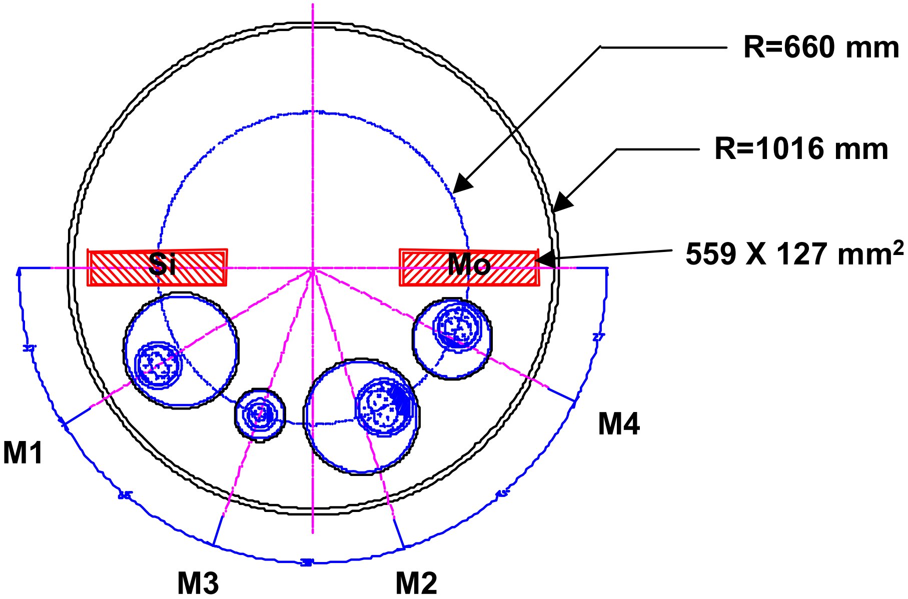
Sommargren, G.E., "Phase shifting diffraction interferometry for measuring extreme ultraviolet optics," OSA Trends in Optics and Photonics Vol. 4, *Extreme Ultraviolet Lithography*, Kubiak and Kania, eds. (Optical Society of America, Washington, DC 1996), pp. 108-112.

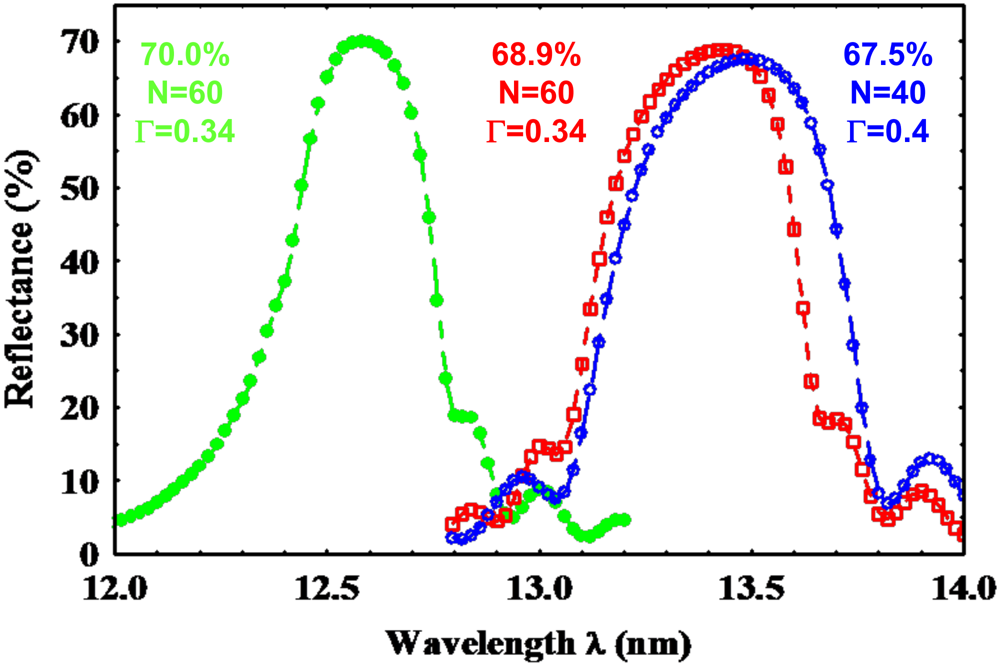
G. E. Sommargren, D. W. Phillion, M. A. Johnson, N. Q. Nguyen, A. Barty, F. J. Snell, D. R. Dillon, L. S. Bradsher, "100-picometer interferometry for EUVL", Proc. SPIE 4688 316-328 (2002).

DC-magnetron sputtering is a proven deposition technique for the multilayer-coating of EUVL camera and collector optics



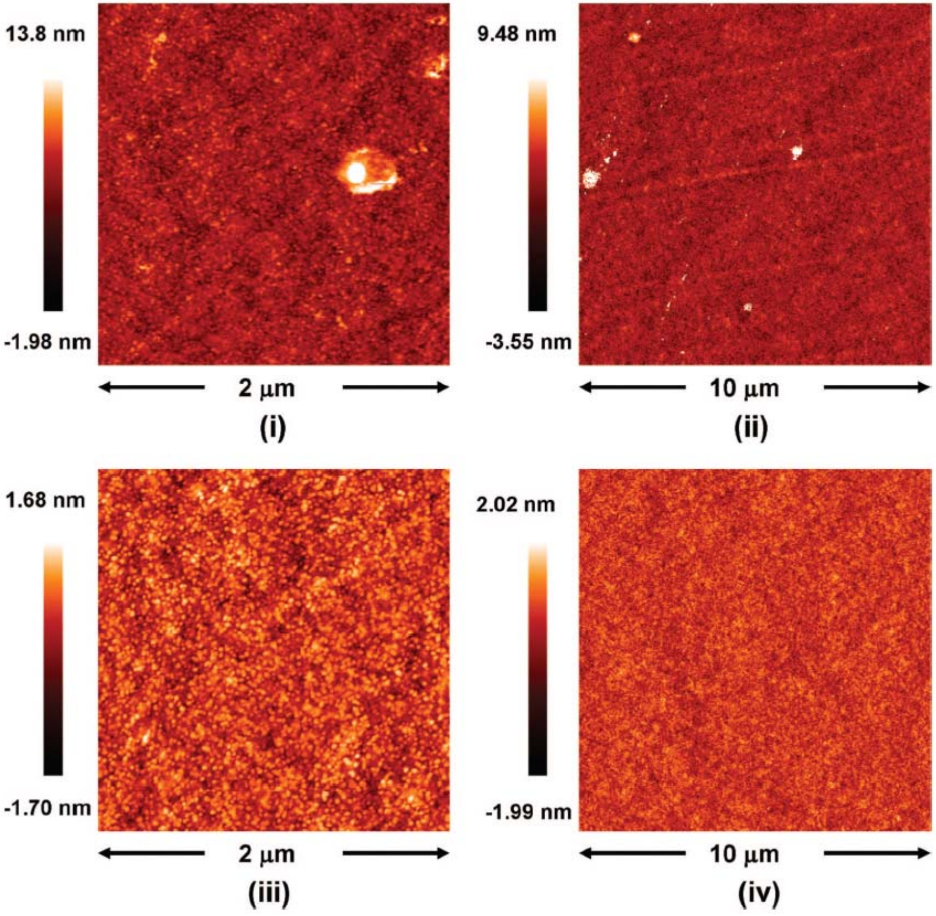
Underneath view of LLNL chamber lid with 5 sputtering targets





LLNL cleaning facility for optical substrates

Custom-developed process includes: rinsing in a water-based solution, followed by drying in N_2 environment using semiconductor-grade system (*YieldUp*™, pictured). Located next to multilayer deposition system.

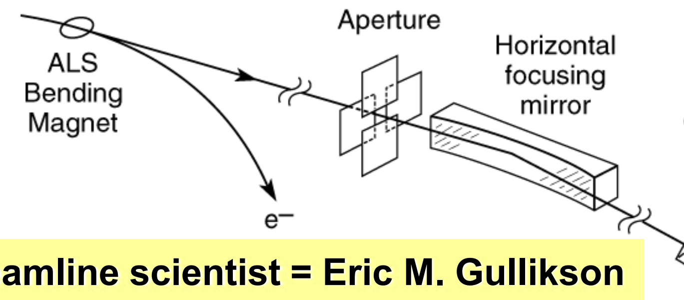


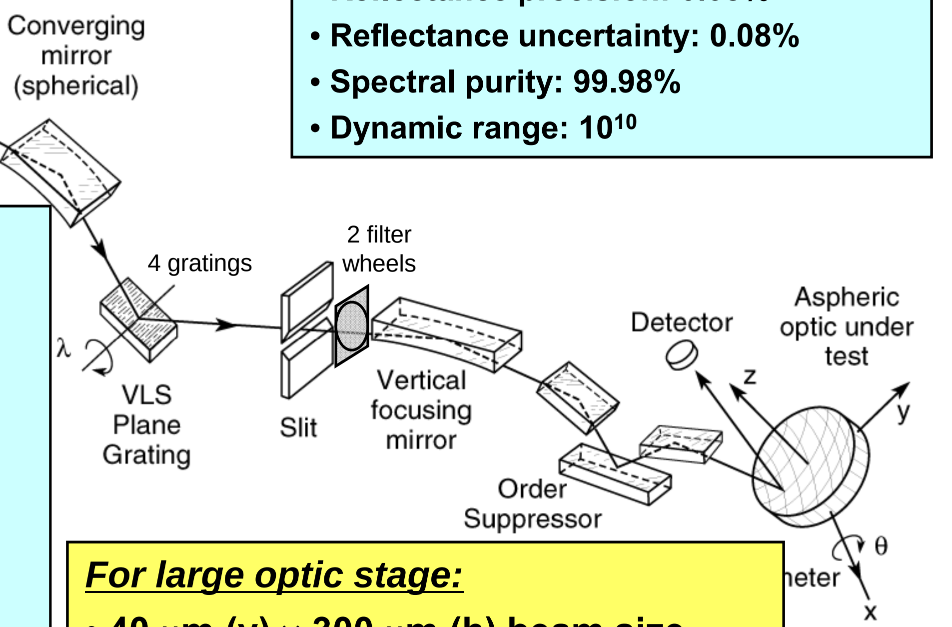
LLNL AFM images on a Zerodur AIA flight substrate: (i), (ii) as-received and (iii), (iv) after cleaning.

R. Soufli, S. L. Baker, *et. al*, Appl. Opt. 46, 3156-3163 (2007).

The reflectometry and scattering beamline 6.3.2 at the ALS synchrotron (LBNL) is used for at-wavelength characterization of EUV/x-ray optics

1-50 nm wavelength range

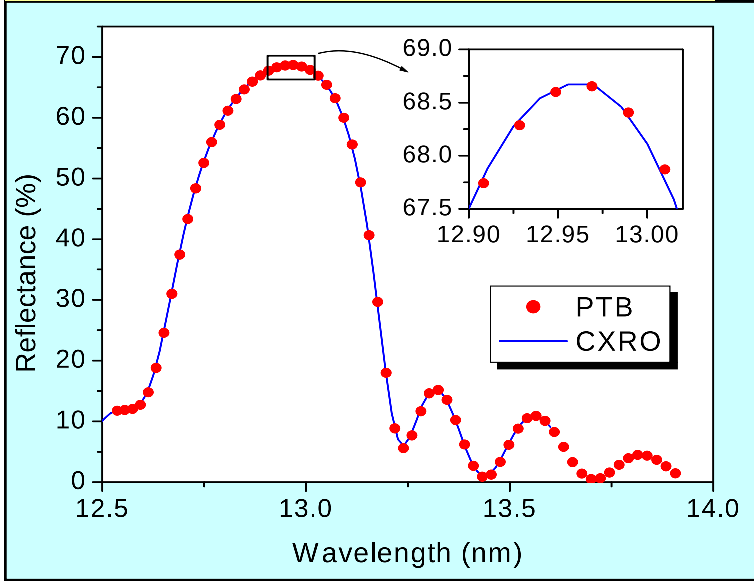




Beamline Specifications

- **Wavelength precision: 0.007%**
- **Wavelength uncertainty: 0.013%**
- **Reflectance precision: 0.08%**
- **Reflectance uncertainty: 0.08%**
- **Spectral purity: 99.98%**
- **Dynamic range: 10^{10}**

Beamline scientist = Eric M. Gullikson



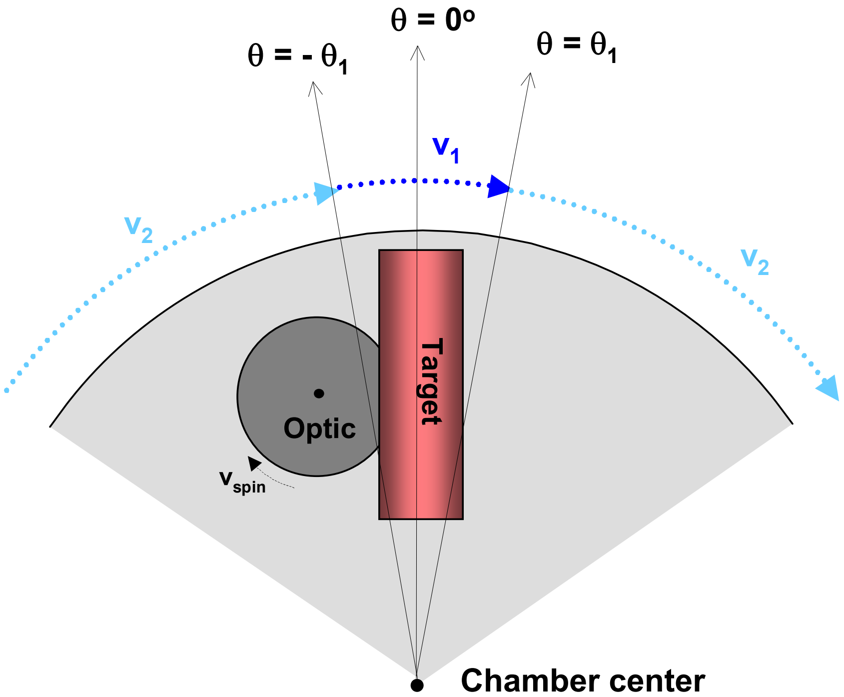
Cross-calibration results are shown between beamline 6.3.2 (CXRO) and PTB, BESSY synchrotron (Berlin, Germany)

For large optic stage:

- **40 μm (v) × 300 μm (h) beam size**
- **100 μm positioning precision (x,y,z)**
- **0.05 deg θ-precision**
- **0.5 deg φ-precision**
- **Photodiode acceptance = 2.4 deg**

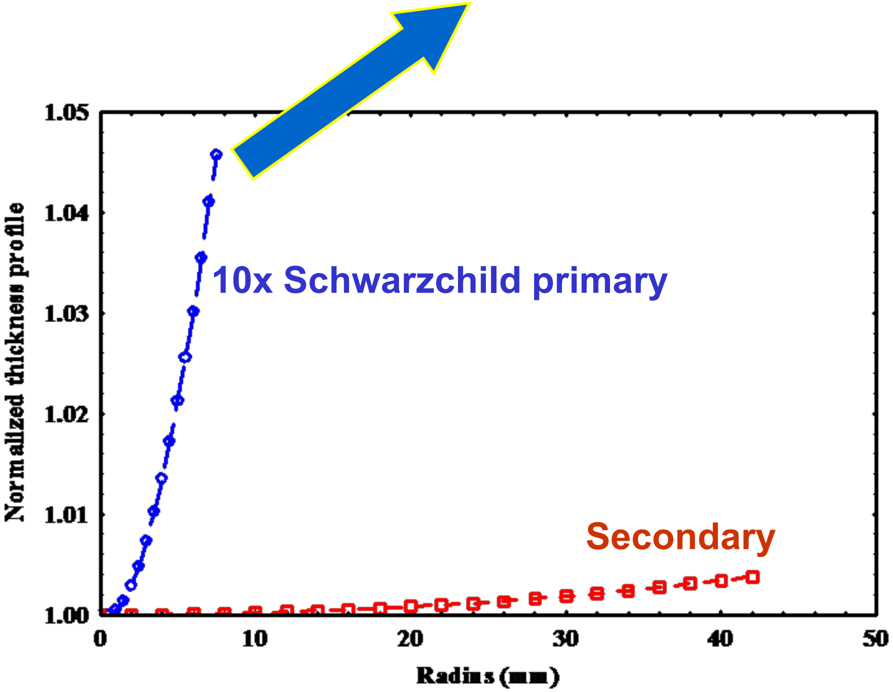
LG156

Velocity modulation is a rapidly converging method used for ultra-precise multilayer film thickness control

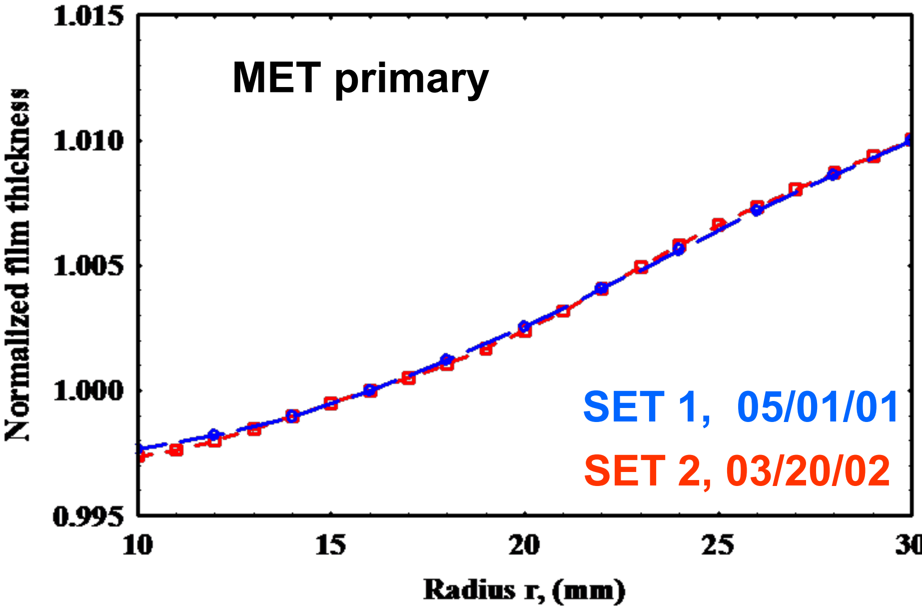


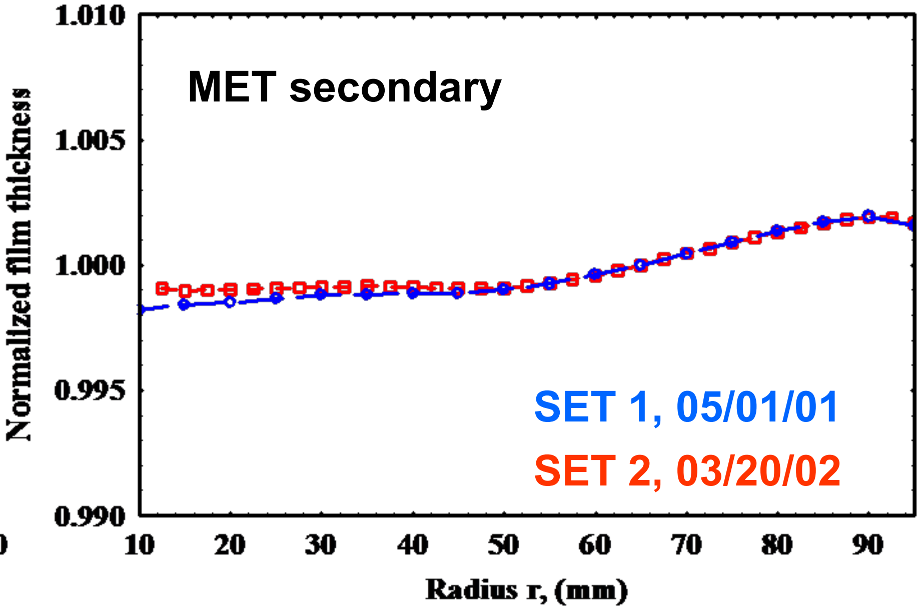
1. Simulate deposition process
2. Select optimum (v_2/v_1, θ_1), to achieve desired thickness profile
3. Measure results on test optic and iterate

Achieved using velocity modulation. Until recently, such steep thickness gradients were believed to be possible only by positioning hardware masks over the optical substrate



DC-magnetron sputtered coatings using velocity modulation demonstrate excellent process stability

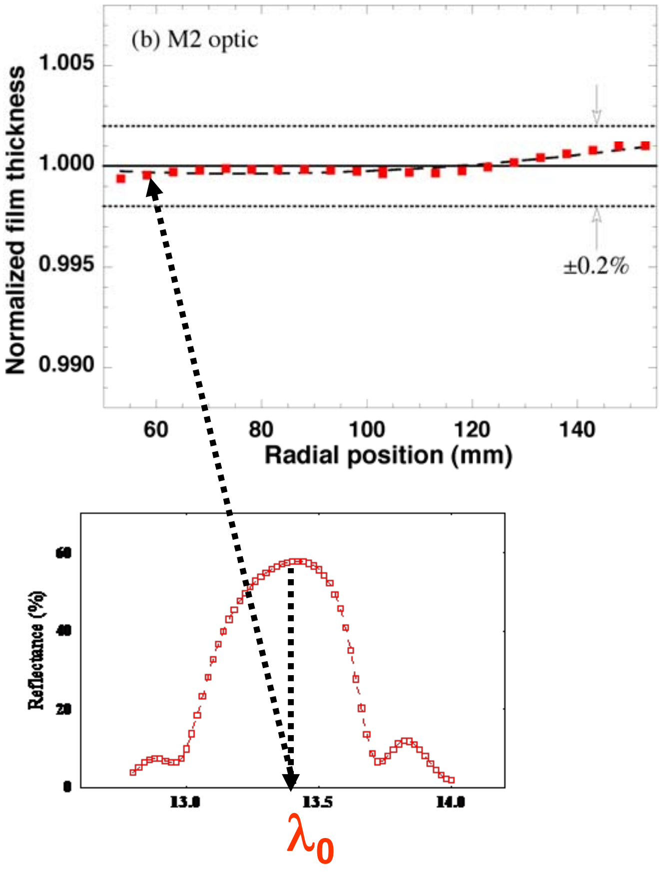




Multilayer thickness profiles deposited over a period of 11 months using identical coating recipes

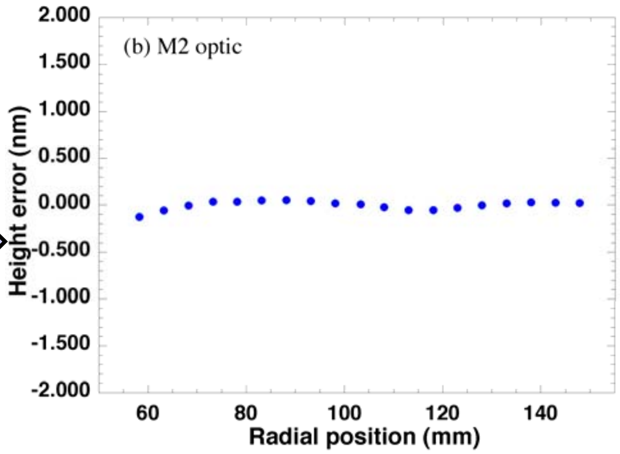
Coating profile for EUVL camera optics is optimized for lowest added figure error, rather than peak-to-valley thickness variation

Normalized film thickness as determined by EUV reflectance measurements



subtract best-fit spherical term, compensable during alignment

Non-compensable multilayer-added figure error

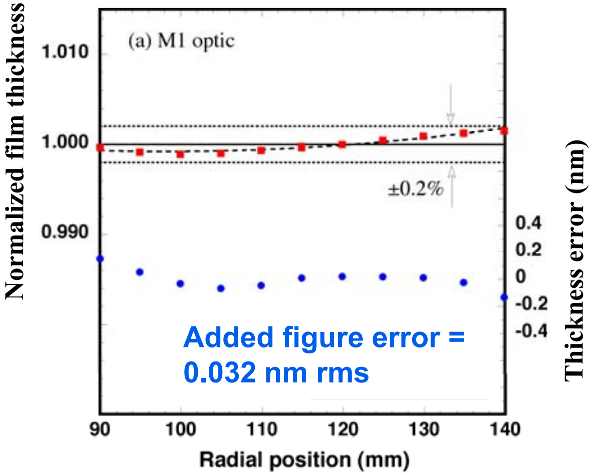


RMS of the figure error, weighting the data by illuminated area

Added figure error = 0.037 nm rms

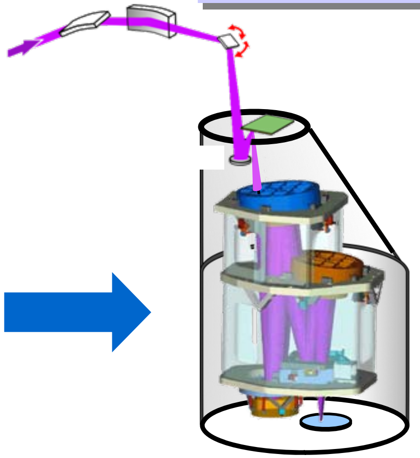
We have developed projection optics with sub-diffraction-limited performance during the EUVL program

M1 mirror, PO Box 2



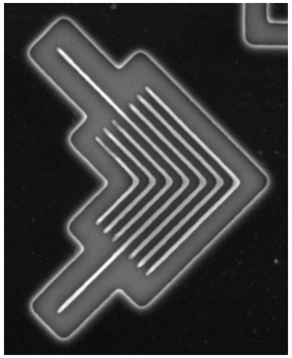
Added figure error = 0.032 nm rms

SES at ALS

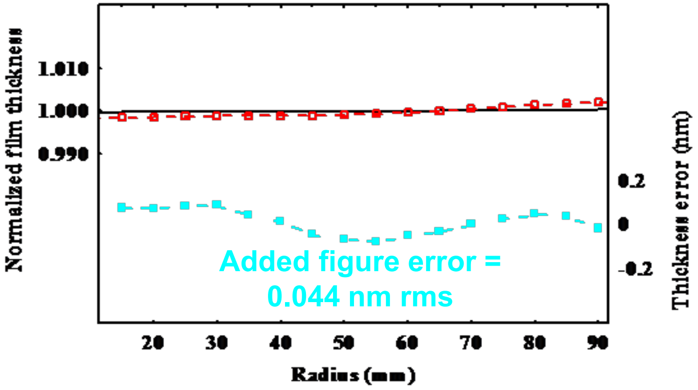


R. Soufli *et al*., *Proc. SPIE* 4343, 51-59 (2001)

39-nm, 3:1 elbows *(Patrick Naulleau, LBNL)*

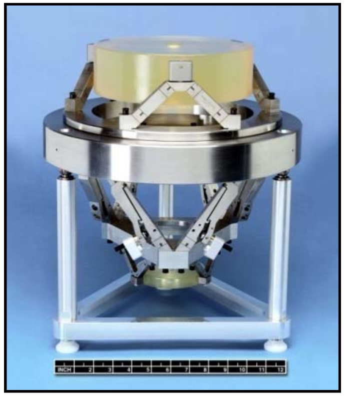


M2 mirror, MET Set 1



Added figure error = 0.044 nm rms

MET camera



R. Soufli *et al*., *Appl. Opt.* 46, 3736-3746 (2007)

Measured wavefront = 0.55 nm rms

K. A. Goldberg et al, J. Vac. Sci. Technol. B 22(6), 2956-2961 (2005)

Printed 20 nm equal-line, and 21 nm isolated-line features

P. P. Naulleau et al

Substrate roughness “propagates” through the multilayer stack and causes flare and loss in mirror reflectance due to scattering in non-specular directions

J. Appl. Phys., Vol. 84, No. 2, 15 July 1998

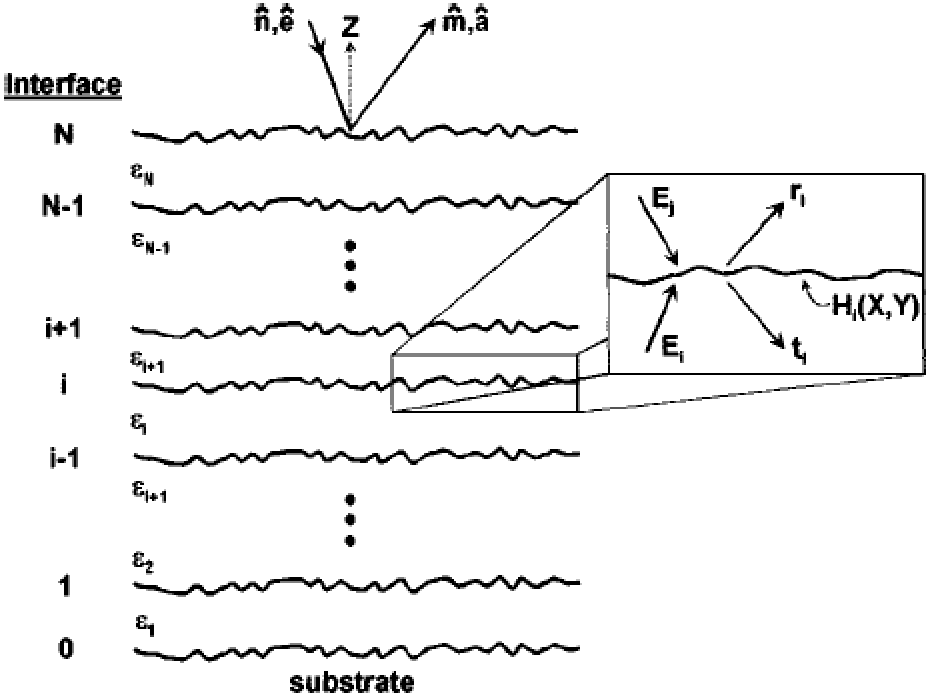


FIG. 6. Schematic diagram of a multilayer film having rough and diffuse interfaces. The inset shows the scattering process at the ith interface. The specular fields E_i and E_j are incident on either side of the interface. The nonspecular scattering into mode $(\hat{m},\hat{a})$ consists of two parts, the field r_i that is scattered towards the top of the film and the field t_i that is scattered towards the substrate.

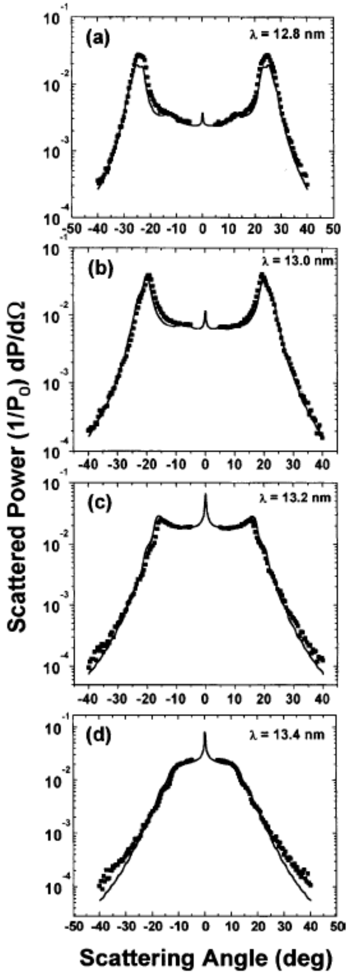
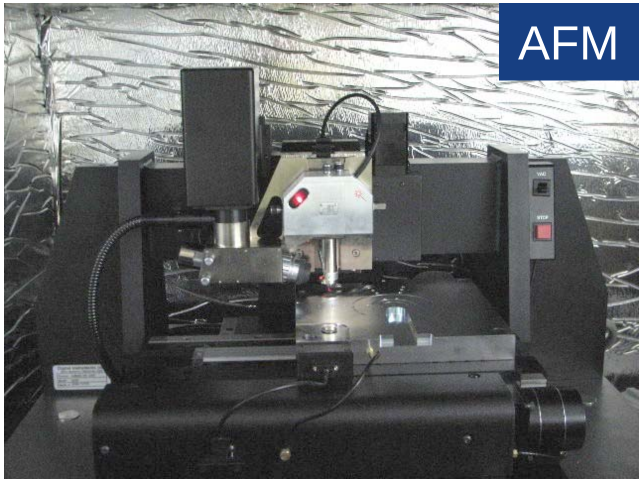


FIG. 11. Nonspecular scattering measured from the canonical Mo–Si multilayer film at normal incidence and for several different wavelengths. Data within four degrees of the specular direction is obscured by the wings of the specularly reflected beam. The solid lines are the scattering distributions predicted by the theory, based on the measured roughness of the multilayer film.

D.G. Stearns, D. P. Gaines, D. W. Sweeney and E. M. Gullikson, “Non-specular x-ray scattering in a multilayer-coated imaging system”, J. App. Phys. 84, 1003-1028 (1998).

LLNL precision surface metrology lab

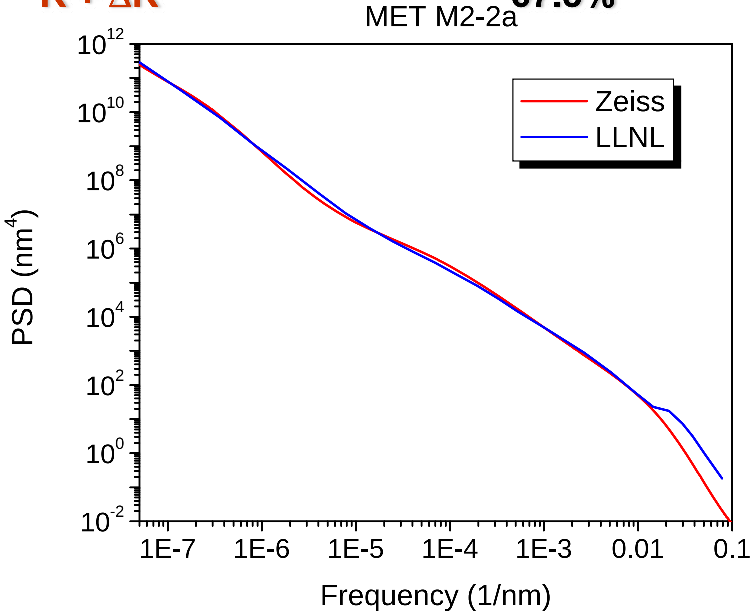
- *Digital Instruments Dimension 5000*™ Atomic Force Microscope (AFM) includes acoustic hood and vibration isolation. Noise level = 0.03 nm rms
- *Zygo NewView*™ Optical Profiling Microscope
- *LEO 1560* ™ Scanning Electron Microscope (SEM)



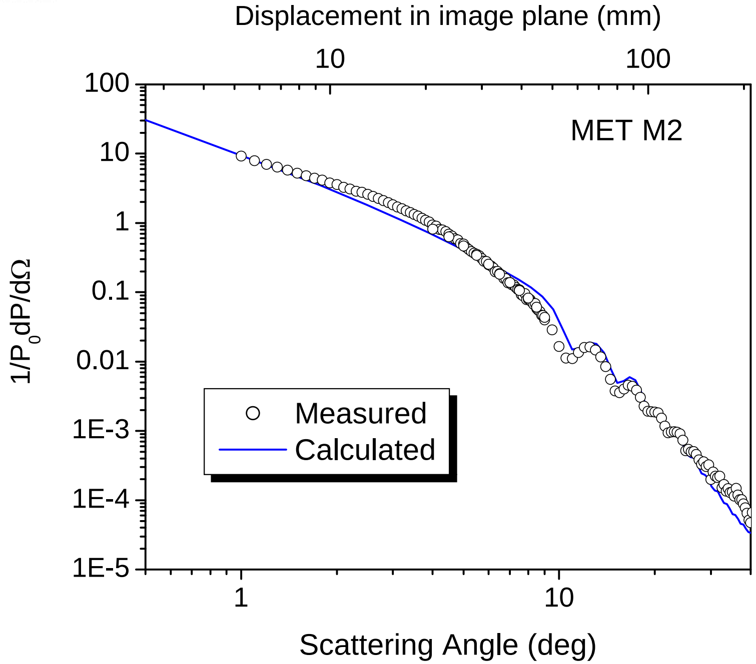
Regina Soufli, 07/15/09

Detailed models have been developed and validated experimentally for the scattering from multilayer-coated EUV optics

	MET 1 (primary)	MET 2 (secondary)
Substrate HSFR	0.37 nm rms	0.32 nm rms
Expected loss ΔR	6.1%	5.2%
Measured R	61.2%	62.4%
R + ΔR	67.3%	67.6%



LLNL / Zeiss metrology validation

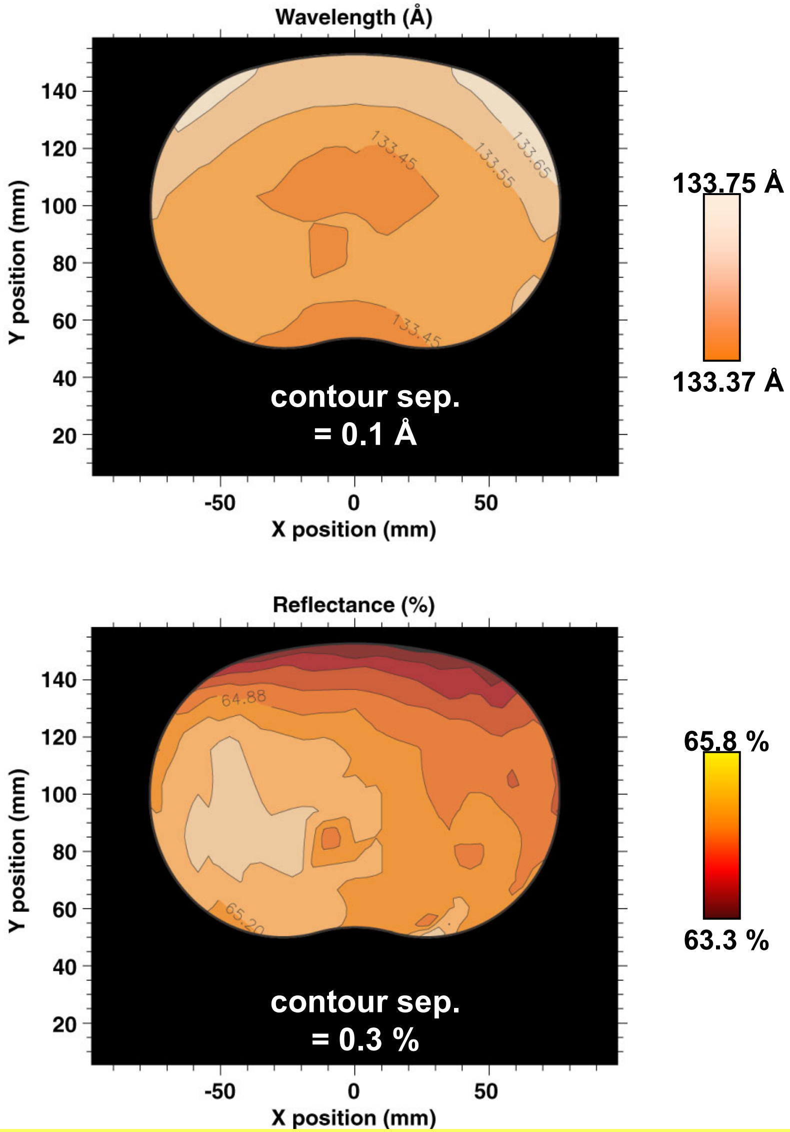


LLNL metrology / scattering model / ALS scattering measurements validation

R. Soufli *et al.*, *Appl. Opt.* 46, 3736-3746 (2007)

D. G. Stearns, "Stochastic model for thin film growth and erosion," Appl. Phys. Lett. 62, 1745-7 (1993).
E. M. Gullikson, "Scattering from normal incidence EUV optics", Proc. SPIE 3331, 72-80 (1998).
D.G. Stearns *et al*, "Non-specular x-ray scattering in a multilayer-coated imaging system", J. App. Phys. 84, 1003-1028 (1998).

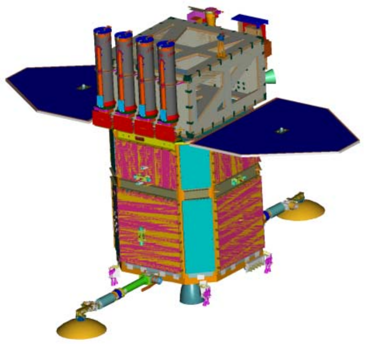
HSFR non-uniformity leads to EUV reflectance variations on the multilayer-coated optic



2D EUV reflectance maps serve as an additional method for verifying substrate finish uniformity

2D contour maps of ETS optic M2 obtained at ALS beamline 6.3.2

We have developed EUV multilayer optics and precision metrologies for next-generation EUV solar physics and space weather satellites

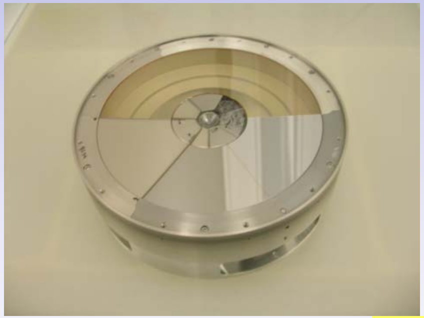


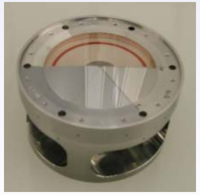
Multilayer-coated flight mirrors for NASA's Solar Dynamics Observatory (SDO). Launch date: November 2009

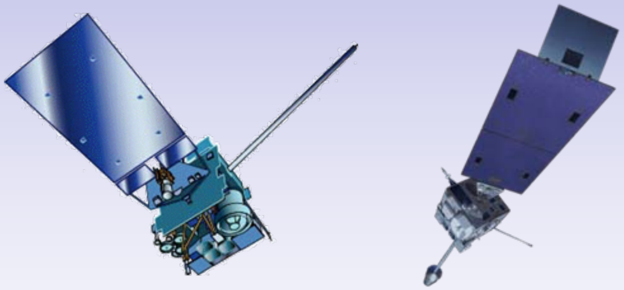
R. Soufli, *et al*, Appl. Opt. 46, 3156-3163 (2007).

R. Soufli, *et al*, Proc. SPIE 5901, 59010M (2005).

7 EUV wavelengths (9.4 nm to 33.5 nm)







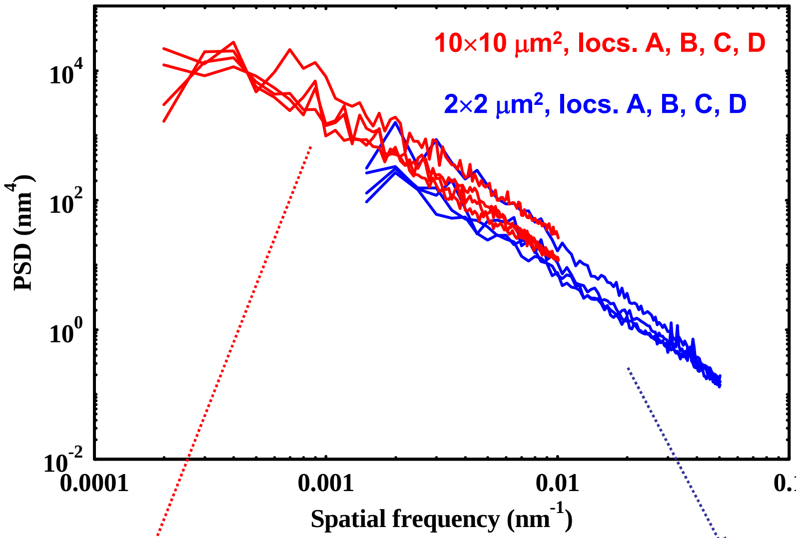
Multilayer-coated test mirrors for NASA/NOAA's GOES-R space weather satellite. 6 EUV wavelengths , 9.4 nm to 30.4 nm. Launch date: 2014

Regina Soufli, 07/15/09

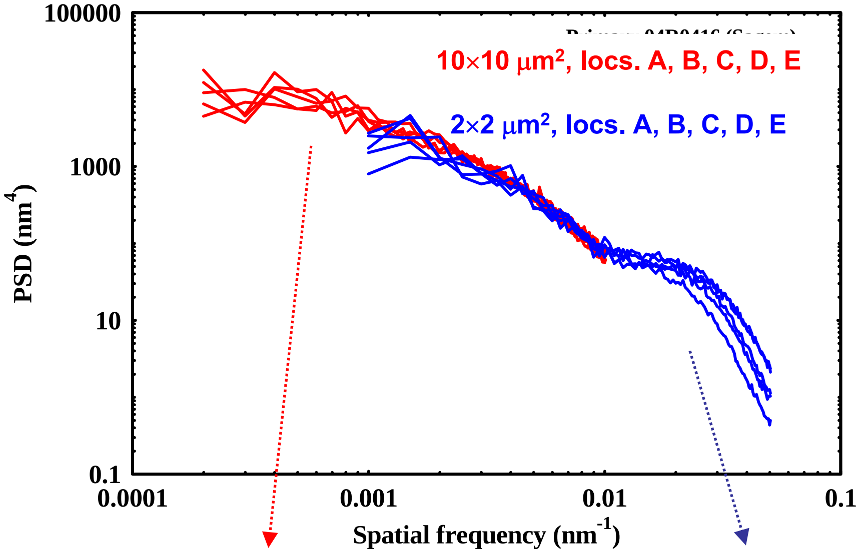
LLNL AFM measurements on NASA flight substrates reveal surface morphology related to specific polishing techniques

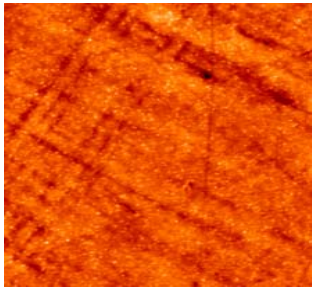
Atmospheric Imaging Assembly (AIA) instrument, Solar Dynamics Observatory (SDO)

Vendor 1, Zerodur™ substrate

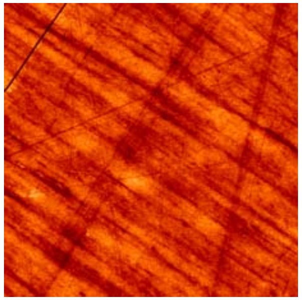


Vendor 2, Zerodur™ substrate

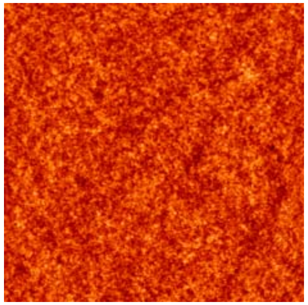




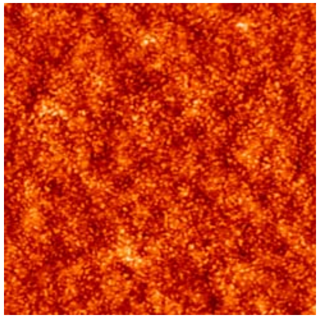
10×10 μm², loc. B



2×2 μm², loc. B
σ = 0.14 nm rms



10×10 μm², loc. E



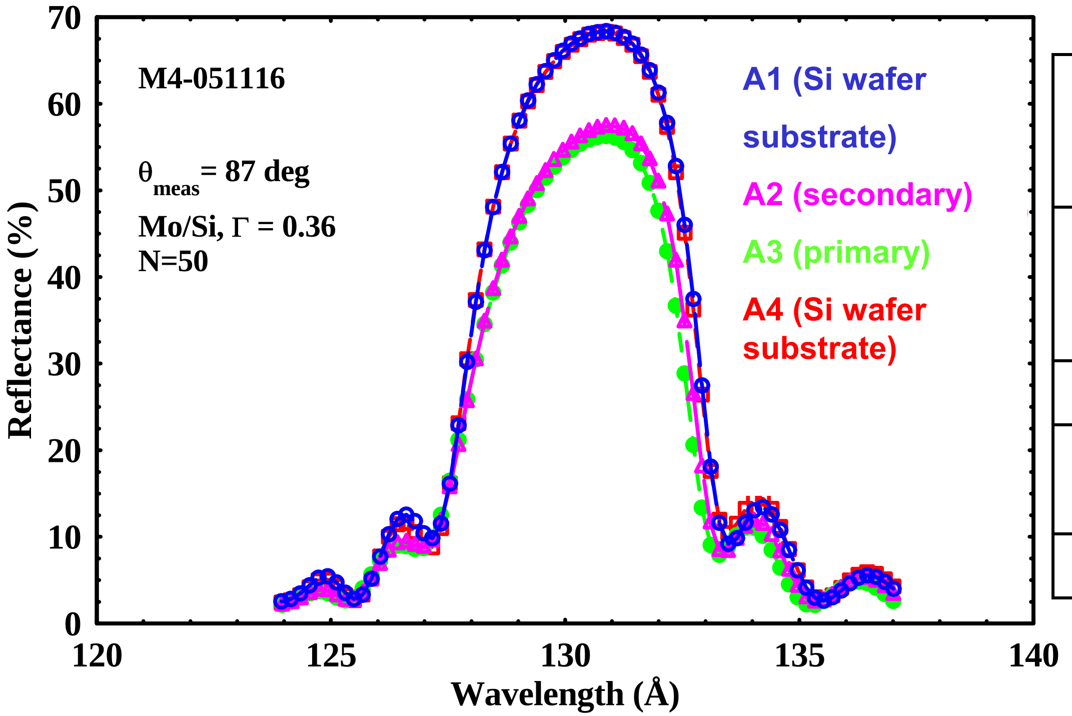
2×2 μm², loc. E
σ = 0.51 nm rms

$$\sigma^2=\int_{f_1}^{f_2} 2\pi f S(f)\,df$$

where $S(f) \equiv$ PSD (nm⁴), $f_1 = 10^{-3}$ nm⁻¹, $f_2 = 5\times10^{-2}$ nm⁻¹

R. Soufli, S. L. Baker, D. L. Windt, E. M. Gullikson, J. C. Robinson, W. A. Podgorski, L. Golub, Appl. Opt. 46, 3156-3163 (2007)

Measured EUV reflectance of multilayer-coated NASA mirrors is consistent with substrate roughness measured by AFM at LLNL

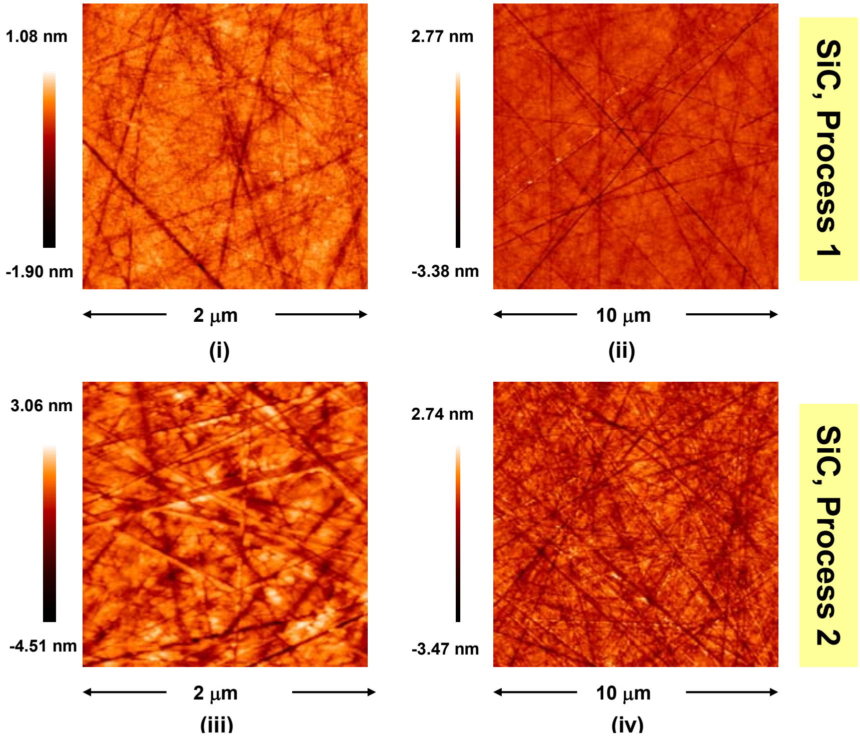


Flight mirror	Primary (A3)	Secondary (A2)
Substrate roughness (Å rms)	5.0	5.2
R_{peak} (%)	56.2	58.8
ΔR* (%, absolute)	8.5	8.4
$R_{peak} + \Delta R$	64.7	67.2

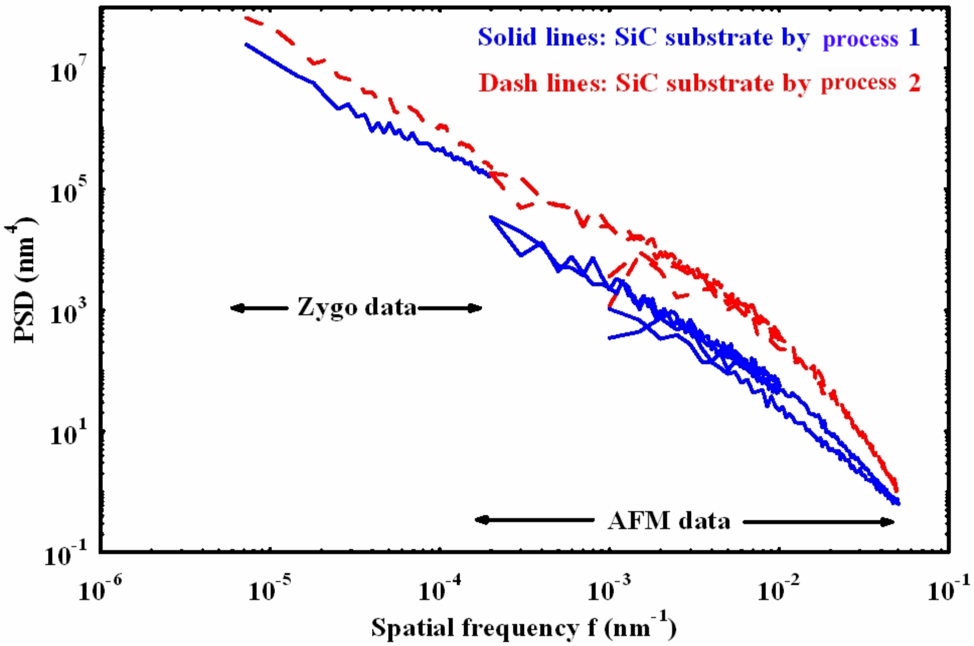
*ΔR = predicted reflectance loss due to high-spatial frequency roughness, based on AFM measurements of the substrate and on a multilayer growth model. Calculation performed by E. M. Gullikson, LBNL.

Regina Soufli, 07/15/09

EUVL collector optics require special substrate materials and polishing techniques



(i) (ii) (iii) (iv)



	HSFR 0.05 μm < Λ < 2 μm
Process 1	0.30 nm rms
Process 2	0.84 nm rms

D. S. Martínez-Galarce, P. Boerner, R. Soufli, B. De Pontieu, N. Katz, A. Title, E. M. Gullikson, J. C. Robinson, S. L. Baker, “The high-resolution lightweight telescope for the EUV (HiLiTE)”, Proc. SPIE 7011 , 70113K (2008).

EUVL collector optics have more relaxed figure specs compared to camera optics and could be fabricated using low-cost techniques

- Aspherical mirrors made by conventional figuring / finishing are very expensive
- Diamond-turned (metal) or ground (ceramic) mirrors are much cheaper and meet EUVL collector figure specs but have insufficient high-spatial frequency roughness (HSFR)

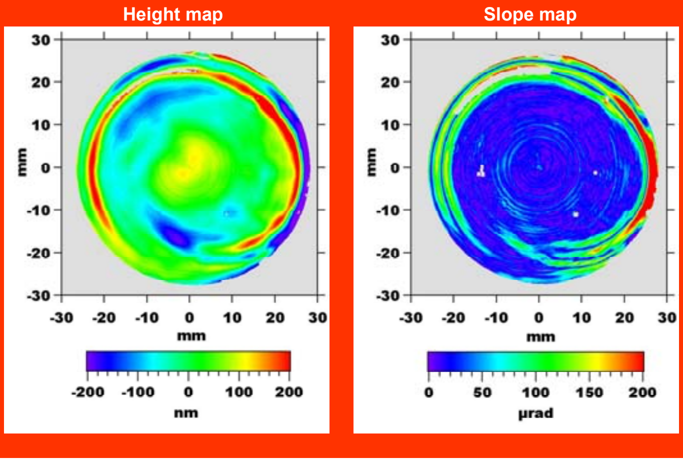
<u>**Proposed solution:**</u>

- Fabricate diamond-turned metal (e.g. Al) or ground ceramic (e.g. SiC) mirrors
- Reduce HSFR with smoothing film
- Follow with appropriate coating (single-layer or multilayer) for EUV reflectance

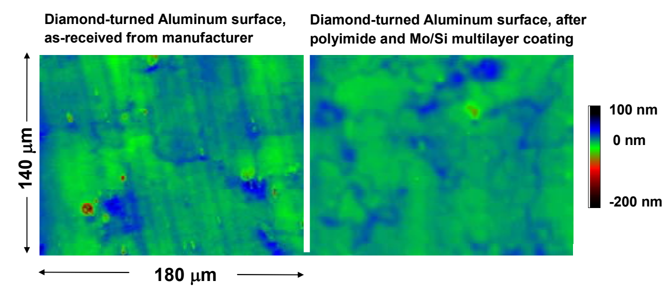
J. A. Folta, C. Montcalm, J. S. Taylor, E. A. Spiller, "Low-cost method for producing extreme ultraviolet lithography optics", U.S. Patent No. 6,634,760.

Polyimide-smoothing of diamond-turned EUVL collector substrates dramatically improves HSFR while maintaining figure

Visible light interferometry results from multilayer-coated, diamond-turned condenser mirror

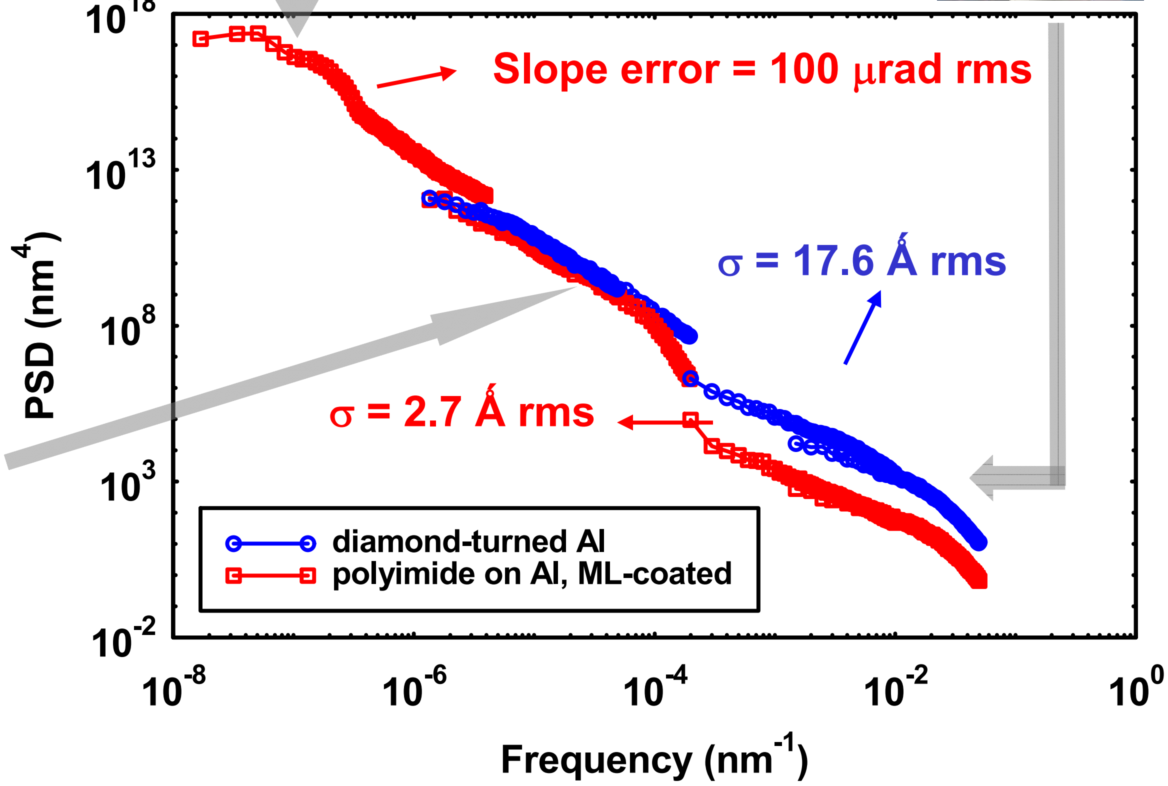


Polyimide smoothes high spatial frequency roughness, including 10 µm-range diamond turning marks



Measurements obtained with a Zygo New View™ optical profiling microscope operated at 40× objective lens magnification

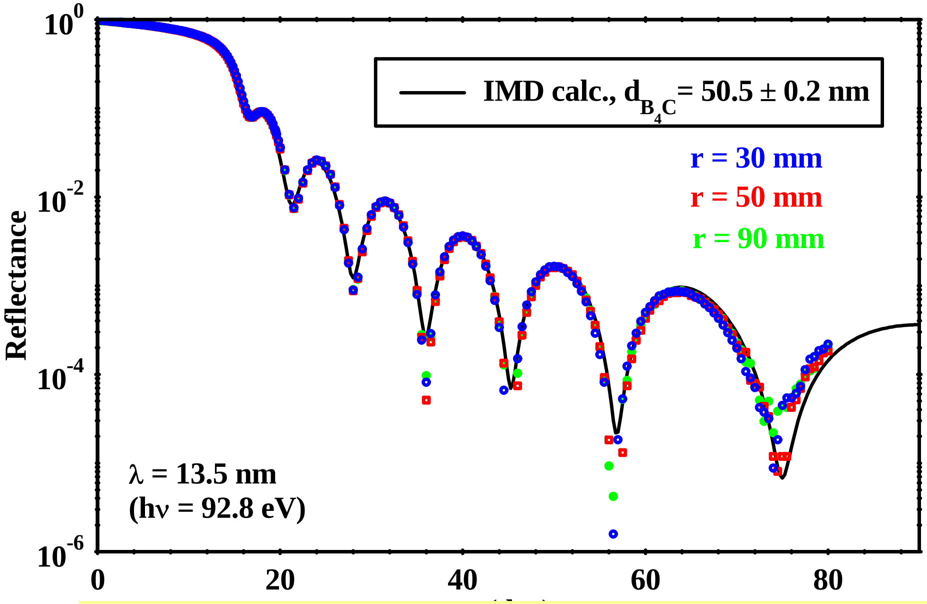
R. Soufli, E. Spiller, M. A. Schmidt, J. C. Robinson, S. L. Baker, S. Ratti, M. A. Johnson, E. M. Gullikson, Opt. Eng. 43(12), 3089-3095 (2004).



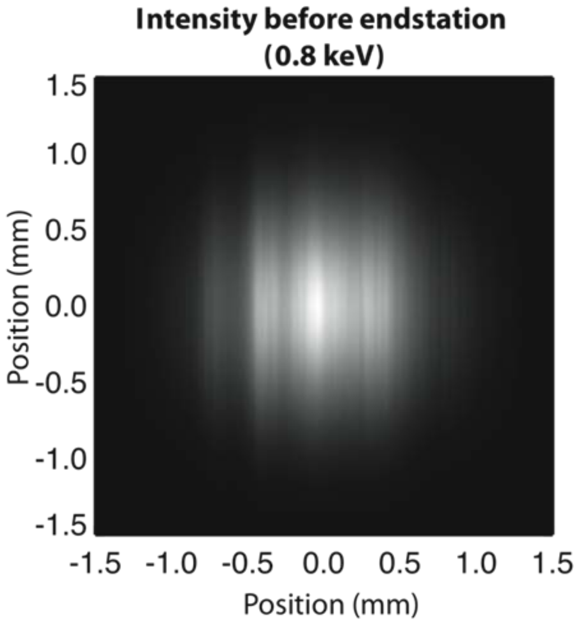
Acknowledgement: TOPO software by D. L. Windt

Regina Soufli, 07/15/09

We have developed diffraction-limited, damage-resistant x-ray mirror coatings for the LCLS free-electron laser



50.5 nm-thick B_4C on Si substrate. Coating variation = 0.14 nm rms (spec = 1 nm rms) across 175 mm CA



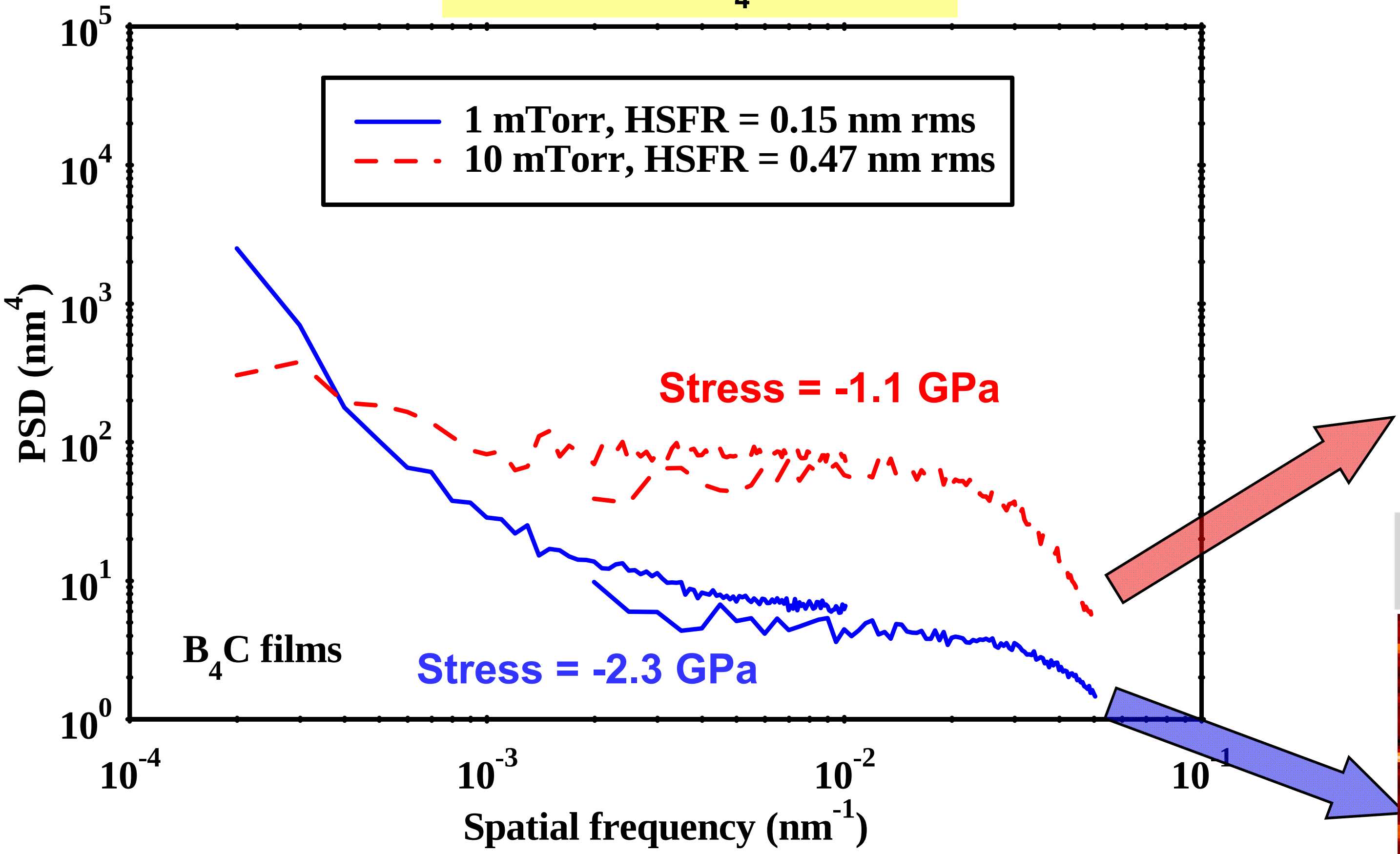
R. Soufli, at al, Proc. SPIE 7077, 707716 (2008).
A. Barty et al, Optics Express (2009).

450 mm

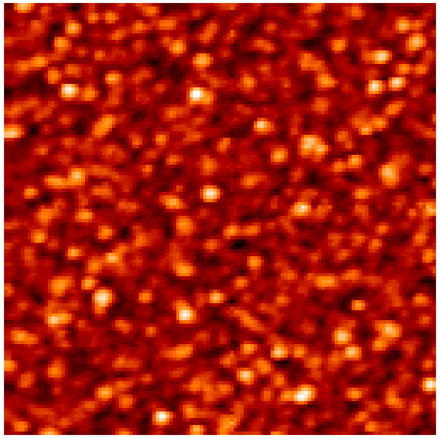
50 nm-thick SiC on Si substrate. Coating variation = 0.34 nm rms (spec = 1 nm rms) across 385 mm CA

B_4C thin film deposition parameters were especially modified to reduce coating stress

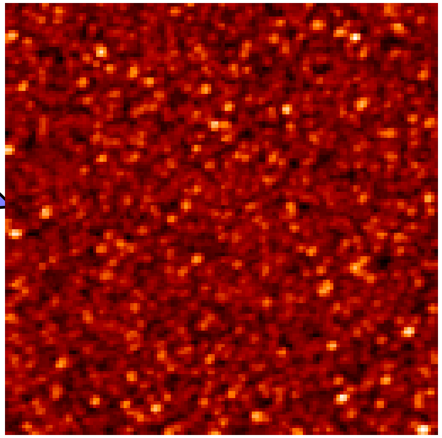
50 nm-thick B_4C films



500×500 nm² detail from 2x2 µm² AFM scan



500×500 nm² detail from 2x2 µm² AFM scan



$$\sigma^2 = 2\pi\int_{f_1}^{f_2} f\,S(f)\,df$$

where $S(f) \equiv$ PSD (nm^4), $f_1 = 5\times10^{-4}$ nm^{-1}
$f_2 = 5\times10^{-2}$ nm^{-1}

Acknowledgements

- The EUVL results in this presentation have been obtained through collaboration between researchers at Lawrence Livermore, Lawrence Berkeley and Sandia National Laboratories. Funding was provided by the EUV LLC (through a Cooperative Research and Development Agreement) and by Sematech
- Funding for the AIA / SDO EUV multilayer optics was provided by the Smithsonian Astrophysical Observatory
- Funding for the SUVI / GOES-R EUV multilayer optics was provided by Lockheed Martin Corporation
- LCLS work was funded by DOE Contract DE-AC02-76SF00515. This work was performed in support of the LCLS project at SLAC.
- This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.