FOM-Institute for Plasma Physics Rijnhuizen

Designing of Multilayer Mirrors for Metrology of EUV Sources

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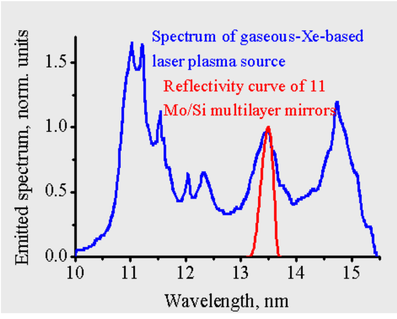
Motivation

Development of EUV lithography tools demands characterization and comparison of EUV sources with respect to the emitted radiation power

Emission spectrum of a EUV source is generally from several nm to several tens nm

The total throughput is determined by an optical system consisting of up to 11 Mo/Si mirrors

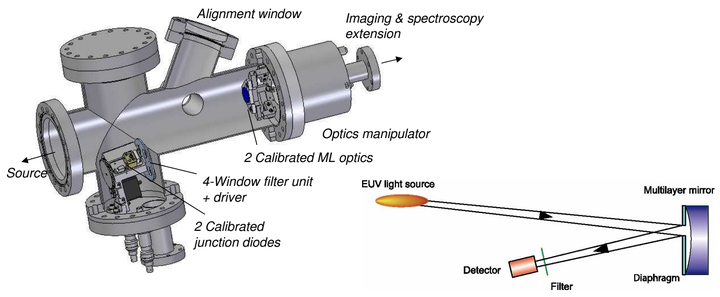
=> For metrology applications it is necessary to filter in-band radiation power out of the emission spectrum of the source



Question:
Is 'mimicking' of 11-mirror system possible with one depth-graded multilayer?

Requirements:
- *the same form of the reflectivity peak as after reflection from 11 periodic Mo/Si multilayer mirrors*
- *minimum reflectance outside the peak*

'Classic' FC2 diagnostics



- *Adaptive, universal concept*
  - *In-situ alignment & wavelength selection*
  - *Adjustable collimation*
  - *UHV compatible*
- *Analogous units installed at majority of source developers*
- *Measurement procedures widely disseminated*
  - R. Stuik, et al, Nuclear Instruments & Methods A **492** (1-2), pp. 305-316 (2002)
  - R. Stuik and F. Bijkerk, Nuclear Instruments & Methods A **489** (1-3), pp. 370-378 (2002)

Parameters used to characterize quality of the mirror

$$\chi_1 = \frac{\int_{out} \rho(\lambda)\,d\lambda}{\int_{peak} \rho(\lambda)\,d\lambda}\cdot 100\%\,; \quad \chi_2 = \max_{out} \rho(\lambda)\cdot 100\%\,; \quad \chi_3 = \left\{ \int_{peak} \left[\rho(\lambda) - \rho_{11}(\lambda)\right]^2 \frac{d\lambda}{\Delta\lambda} \right\}^{1/2} \cdot 100\%$$

$$\chi_4 = R_0 T_0 \cdot 100\%\,; \quad where \quad \rho(\lambda) \equiv \frac{R(\lambda)T(\lambda)}{R_0 T_0}\,; \quad \rho_{11}(\lambda) \equiv \frac{R^{11}_{per}(\lambda)}{R^{11}_{0\,per}}$$

$R(\lambda)$ – the reflectivity of a designed multilayer structure

$R^{11}_{per}(\lambda)$ – the total reflectivity of 11 periodic Mo/Si mirrors

$T(\lambda)$ – the transmittance of a free standing filter

$R_0, R^{11}_{0\,per}, T_0$ – the corresponding reflectance and transmittance at λ = 13.5 nm

Parameter χ_1: spectral purity of a reflected beam.
- mimicking 11 mirrors: χ_1 should be < 1%
NB: periodic mirror χ_1 > 20%.

Parameter χ_2: maximum amplitude of reflectivity oscillations outside the Bragg peak

Parameter χ_3: difference between the Bragg peak of a designed mirror and the peak after reflection from 11 periodic Mo/Si mirrors

Parameter χ_4: total transmittance of the mirror with the filter
(χ_4 = 10% desirable, χ_4 =3% still practical)

The merit function used under optimization

$$MF(l_1,\ldots,l_N) = \frac{1}{M_1}\sum_{\substack{j=1\\(peak)}}^{M_1}\left[\log\rho(\lambda_j) - \log\rho_{11}(\lambda_j)\right]^2 U(\lambda_j)$$

$$+\frac{1}{M_2}\sum_{\substack{j=1\\(out)}}^{M_2}\left[\log\rho(\lambda_j) - \log\rho_{\max}\right]^2 U(\lambda_j)V(\rho_j)\,; \quad V(\rho) = \begin{cases}1, & if \quad \rho > \rho_{\max}\\ 0, & if \quad \rho \le \rho_{\max}\end{cases}$$

The merit function is minimized with respect to the thickness of all layers.

Parameter *V(ρ)* removes terms with small enough reflectance from the merit function. This results in facilitation of optimization process: there is no necessity to obtain the given form of the reflectivity curve outside the Bragg peak.

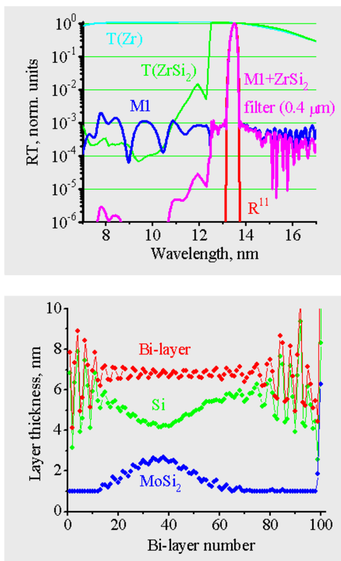
Parameter *U(λ)* is larger inside and nearby the Bragg peak to provide the necessary form of the peak and to damp oscillations of the reflectivity near the Bragg peak.

Parameter ρ_{max} characterizes the maximum value of the reflectivity outside the Bragg peak. Its value is decreased step-by-step during optimization down to 10^{-5} - 10^{-4}.

Why MoSi2/Si instead of Mo/Si?

- No control of interlayers in Mo/Si
  - no accurate knowledge on interlayers in Mo/Si
  $MoSi_2$ and Si do not interact (materials neighboring in the phase diagram)
- High thermal and radiation stability of $MoSi_2$/Si structure compared to Mo/Si (preferable for metrology of high-power sources)
- Reflectivity of $MoSi_2$/Si mirror is sufficiently high (50% at 13.5 nm).
- In MoSi2/Si more layers contribute to reflectance
  (additional freedom for the design)

Option M1: design without filter



$SiO_2/[Si/MoSi_2]^{100}/Si/Sub$

χ_1 = 2.47%
χ_2 = 0.20%
χ_3 = 2.3% R_0T_0 = 36.5%

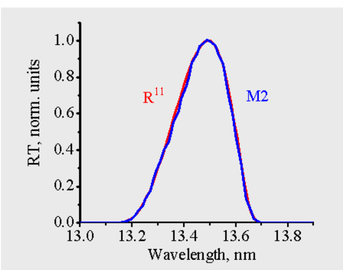
ZrSi2 filter added after design:

χ_1 = 0.69%
χ_2 = 0.13%
χ_3 = 2.4% R_0T_0 = 10.9%

Si-containing free-standing filter (e.g.MoSi2, ZrSi2):
- cuts efficiently radiation below 12.4 nm
- χ_1 decreases essentially

Option M1 designed without filter but operating with a filter is already quite acceptable for practical application

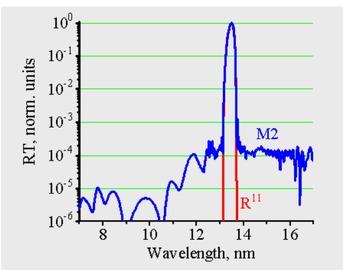
Option M2: design with MoSi2 filter, L = 0.26 μm

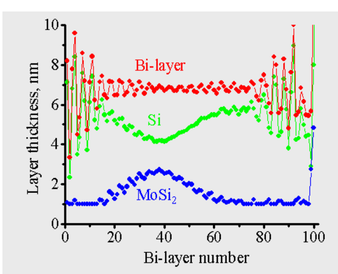


$SiO_2/[Si/MoSi_2]^{100}/Si/Sub$

Filter: $MoSi_2$ thickness L = 0.26 μm

χ_1 = 0.25%
χ_2 = 0.12% R_0 = 34.3%
χ_3 = 1.6% R_0T_0 = 10.5%





Optical parameters improved if filter is included in the design (because optimization performed in narrower spectral interval)

Option M3: three-component mirror

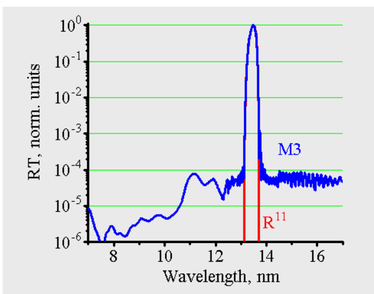
$SiO_2/[Si/SiC]^{12}/[Si/MoSi_2]^{58}/[Si/SiC]^{30}/Si/Sub$

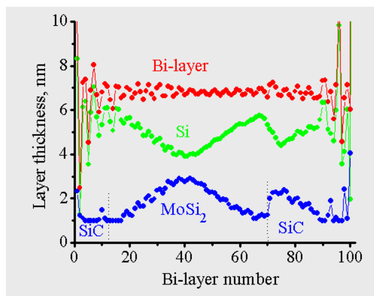
Filter: $MoSi_2$ thickness L = 0.26 μm

χ_1 = 0.15%
χ_2 = 0.055% R_0 = 32.3%
χ_3 = 2.3% R_0T_0 = 10.0%

Ultimate optical parameters of the option M2 are limited by restriction imposed on the minimum thickness of layers.

Three-components M3 with the reduced reflectance from upper and lower bi-layers is a solution to this problem.





Factors to enhance efficiency of filtering

1. Si-containing free-standing filter ($MoSi_2$ or $ZrSi_2$) cutting effectively short-wavelength radiation at λ < 12.4 nm.

2. Multilayer structure with the reduced reflectance from upper and lower bi-layers.

3. Free-standing filter thickness

$MoSi_2$ filter	L = 0	⇒	χ_1 = 2.47%,	R_0T_0 = 36.5%
N = 100	L = 0.26 μm	⇒	χ_1 = 0.25%,	R_0T_0 = 10.5%
	L = 0.5 μm	⇒	χ_1 = 0.09%,	R_0T_0 = 3.3%

4. Number of bi-layers constituent the multilayer

$MoSi_2$ filter	N = 75	⇒	χ_1 = 0.74%,	R_0T_0 = 8.1%
L = 0.26 μm	N = 100	⇒	χ_1 = 0.25%,	R_0T_0 = 10.5%
	N = 125	⇒	χ_1 = 0.16%,	R_0T_0 = 10.5%

Summary

1. The possibility to design the EUV multilayer 'mimicking' 11-mirror system of the EUVL tool has been theoretically demonstrated.
2. Multilayers with stable interfaces (e.g. MoSi2/Si, etc) should be used for real implementation.
3. For real implementation, depth-distribution curve of the layer thicknesses will be determined by the trade-off between optical properties and control of layer thicknesses during fabrication.
4. The critical factor resulting in the deformation of the reflectivity curve is random layer fluctuations, which should be less than 0.02 nm.

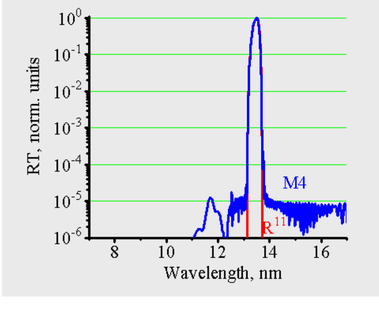
Option M4: combining all factors for enhanced spectral purity

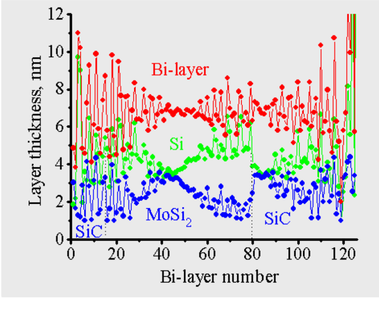
$SiO_2/[Si/SiC]^{15}/[Si/MoSi_2]^{60}/[Si/SiC]^{45}/Si/Sub$

Filter: $MoSi_2$, L = 0.47 μm

χ_1 = **0.017%**
χ_2 = 0.027% R_0 = 26.1%
χ_3 = 1.7% R_0T_0 = 3.1%

Very high spectral purity but depth-distribution of layer thickness is complicated for fabrication





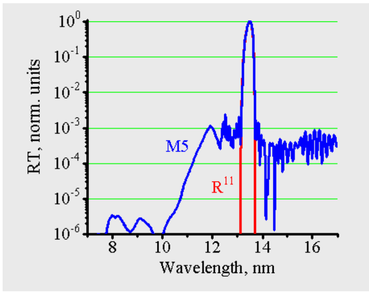
Option M5: design to obtain 'smooth' depth-distribution

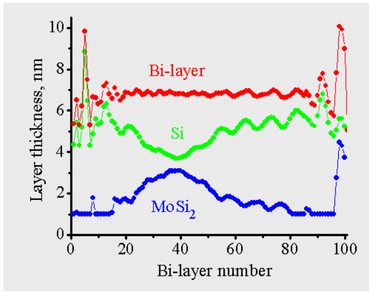
$SiO_2/[Si/MoSi_2]^{100}/Si/Sub$

Filter: $MoSi_2$, L = 0.26 μm

χ_1 = 1.0%
χ_2 = 0.24% R_0 = 38.7%
χ_3 = 1.9% R_0T_0 = 11.9%

'Smooth' depth-distribution of layer thickness is possible at the expense of optical properties





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