# Adaptation of the reflectance of Bragg mirrors to wide source spectra

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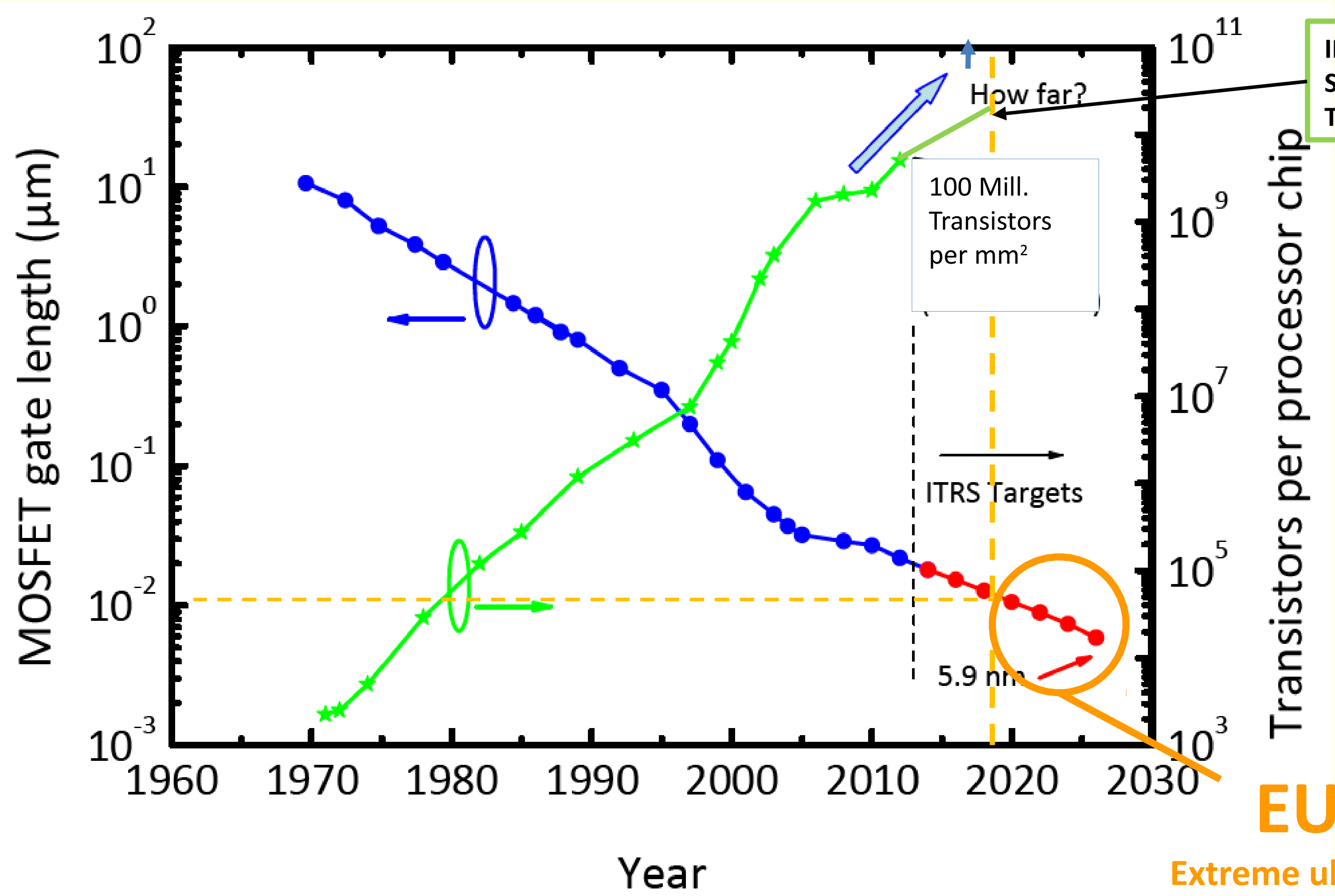
# Moore‘s Law

Number of transistors per chip doubles every 2 years



**INTEL: 10 nm**
**SAMSUNG, TSMC: 7 nm**

**EUV**

**Extreme ultraviolet**

## Why EUV (13.5 nm)?

13.5 nm: Higher resolution compared to 193 nm immersion lithography.

Extension of Moore‘s law down to 5 and 3 nm.

Strong Sn plasma source.

## Why mirrors?

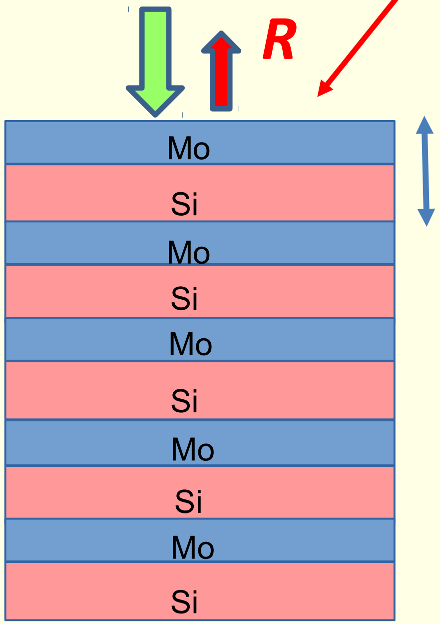
Refractive index  of “all“ materials is close to 1.

Constructive interference of waves reflected from interfaces.

Multilayer mirror → high reflectance.

Mo/Si mirror has peak reflectance at 13.5 nm.

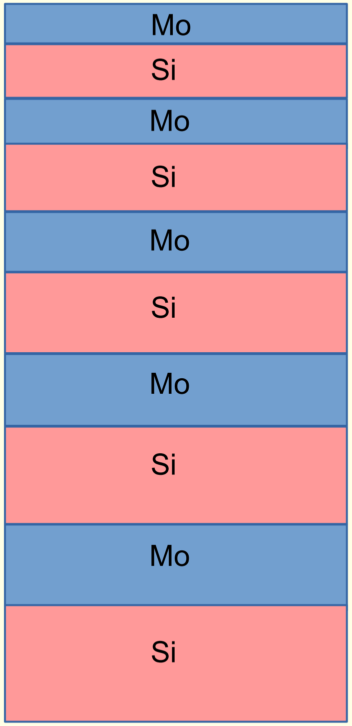
# The Standard Bragg-Mirror Structure and the Graded Structure for 13.5 nm



40 double layers

period: 6.9 nm
(≈13.5 nm/2),
Mo: 40%
→ Constructive interference

Index contrast ($n_r$):
**„high“**
0.999 (Si)
0.924 (Mo)



**Linear depth grading:**
e.g.: top double layer : 6.6 nm
bottom double layer: 9.24 nm
→ **grading factor 1.4**

**Purpose:** Exploiting more of the Sn spectrum by graded mirrors

**Standard EUV mirrors have narrow angular and spectral range of reflectance.**

**THIS WORK:**
**Extension of the ranges by modifications of the multilayer period (“grading“) of the mirrors.**

**Calculation of the reflectance *R*: multiple scattering method**
N. Stefanou et al., Comp. Phys. Comm. **113**, 49 (1998); **132**, 189 (2000). Modified for wavelength dependence of the complex *n* (R. Meisels)

# Reflectance *R* as a function of wavelength and angle

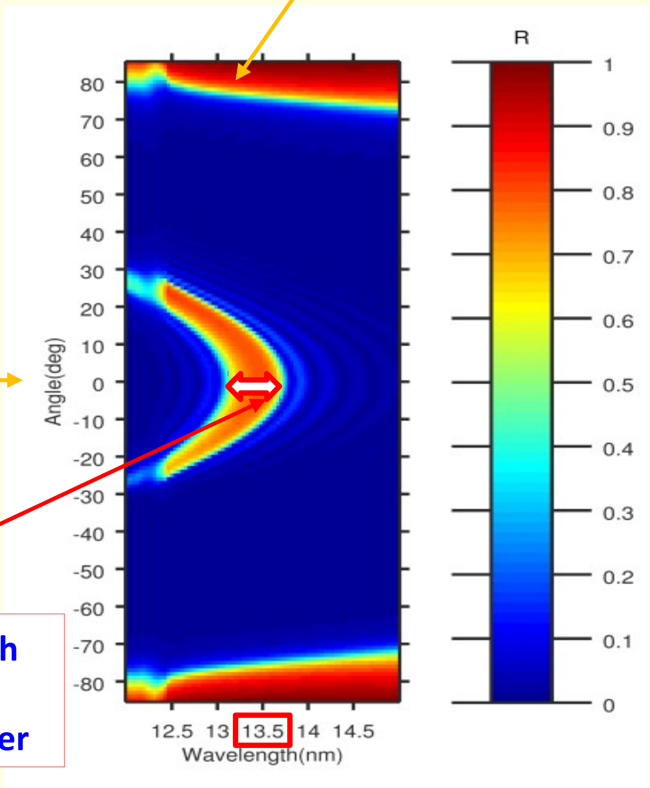
Standard and graded Mo/Si mirror near 13.5 nm

**standard mirror: no grading**

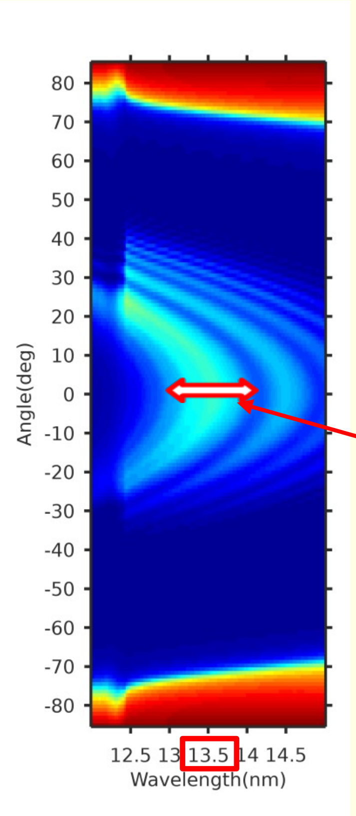
**graded mirror**

Total reflection

Normal incidence



Narrower than the width of the Sn spectrum
→ loss of radiation power

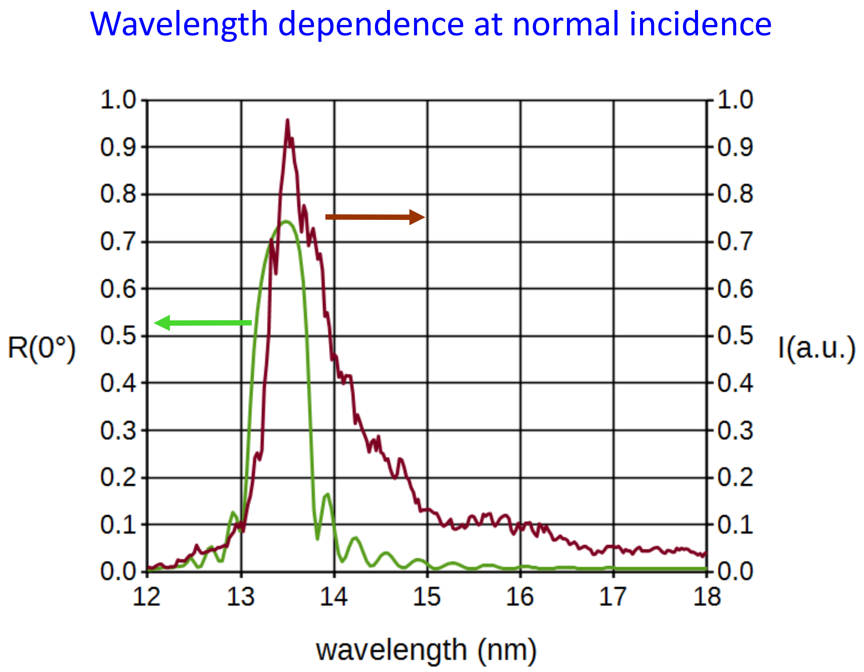


Widened range of reflectance, but peak value reduced

Positive (negative) angle: s (p) polarization
Unpolarised radiation: $(R_s+R_p)/2$

# Comparison of Reflectance Spectrum, R(0°) and Sn Source Spectrum I

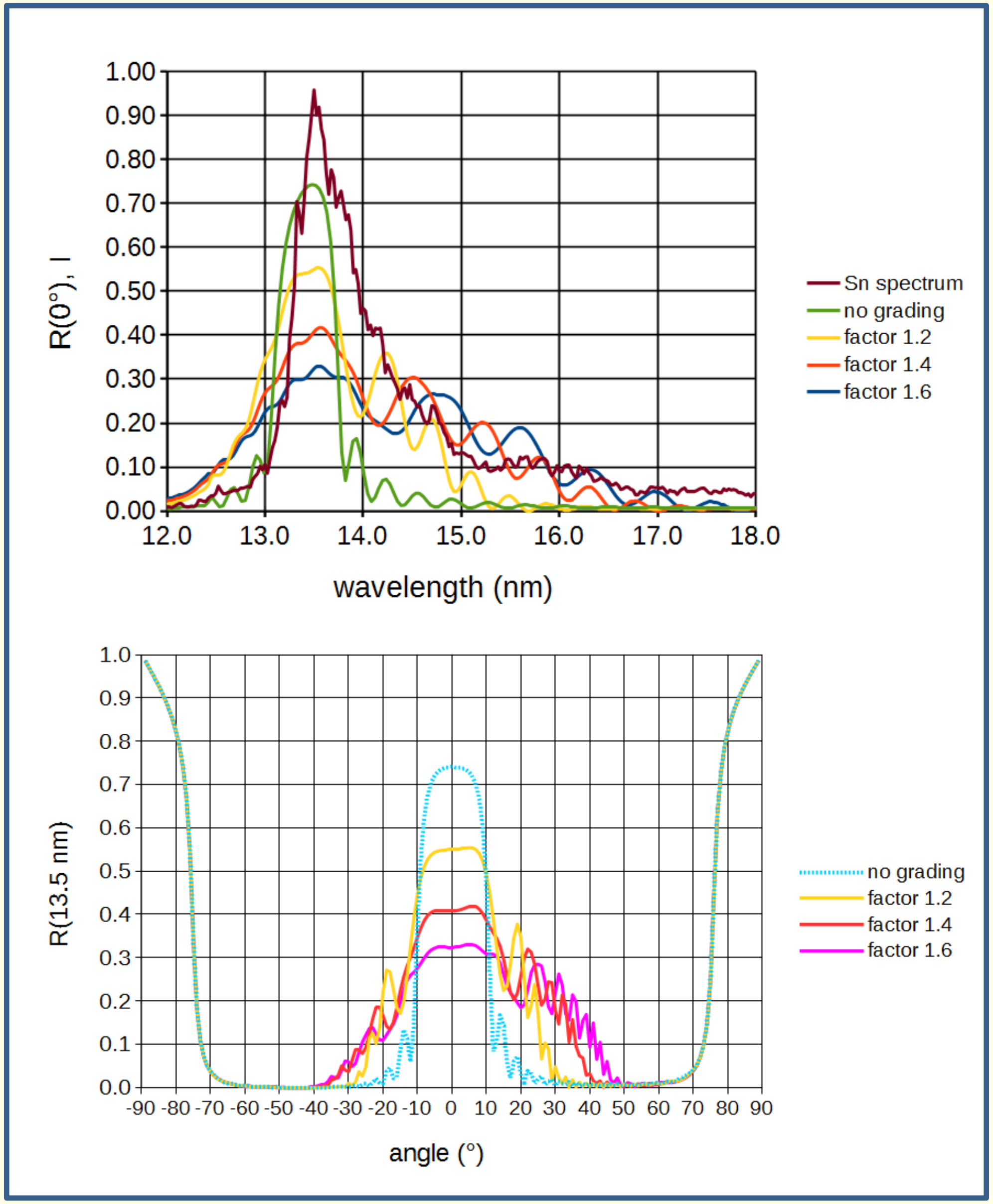
no grading



Wavelength dependence at normal incidence

Data of Sn source spectrum from:
A. Endo, "CO2 Laser Produced Tin Plasma Light Source as the Solution for EUV Lithography," ch.9, *in* M. 393 Wang, ed., *Lithography*, ISBN 978-953-307-064-3 (2010).

# Effect of grading

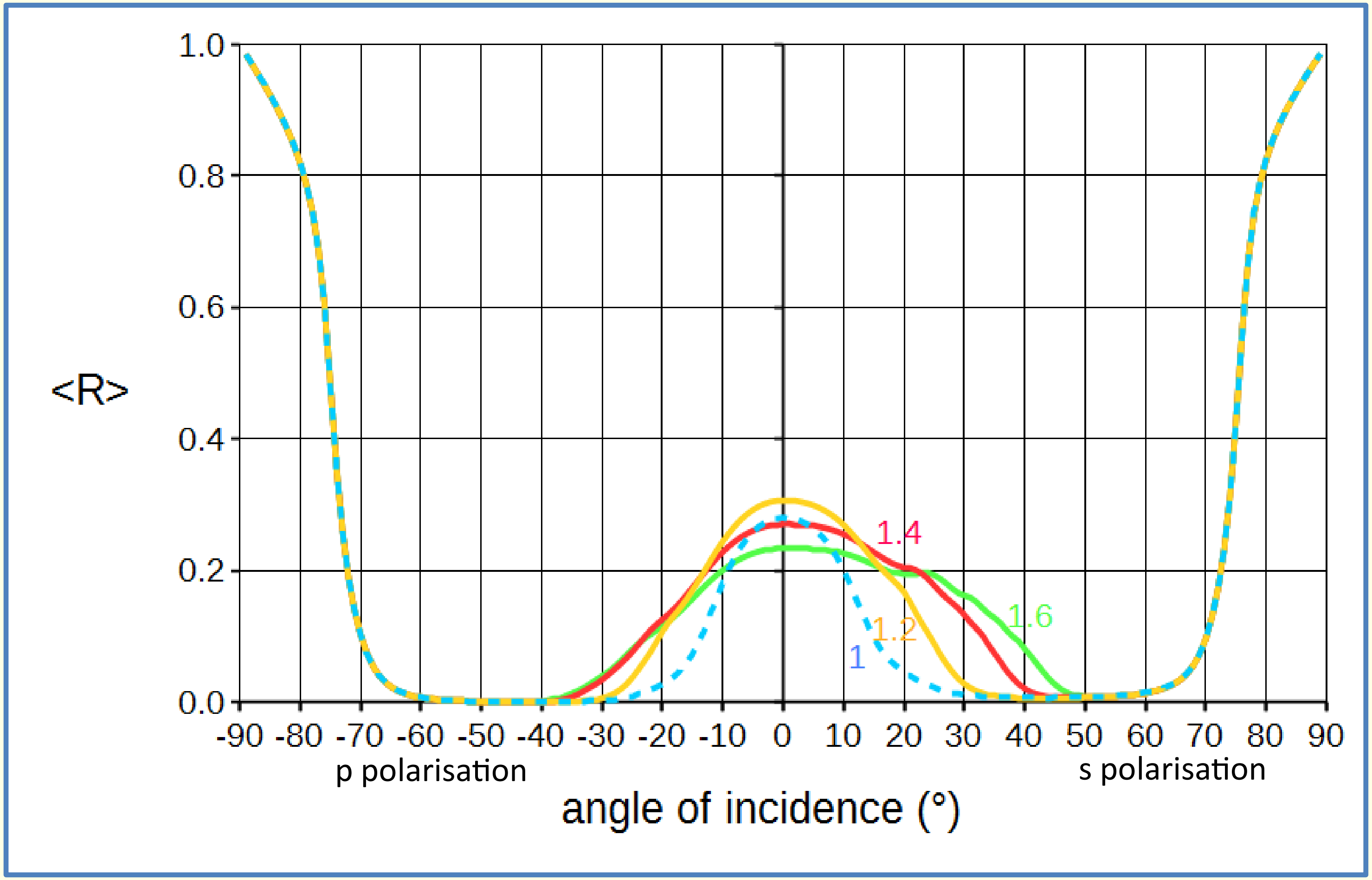


Adapting the reflectance spectrum to the Sn spectrum by proper grading:
Grading factor 1.2 (yellow) adapts the width of R without to much loss in peak reflectance

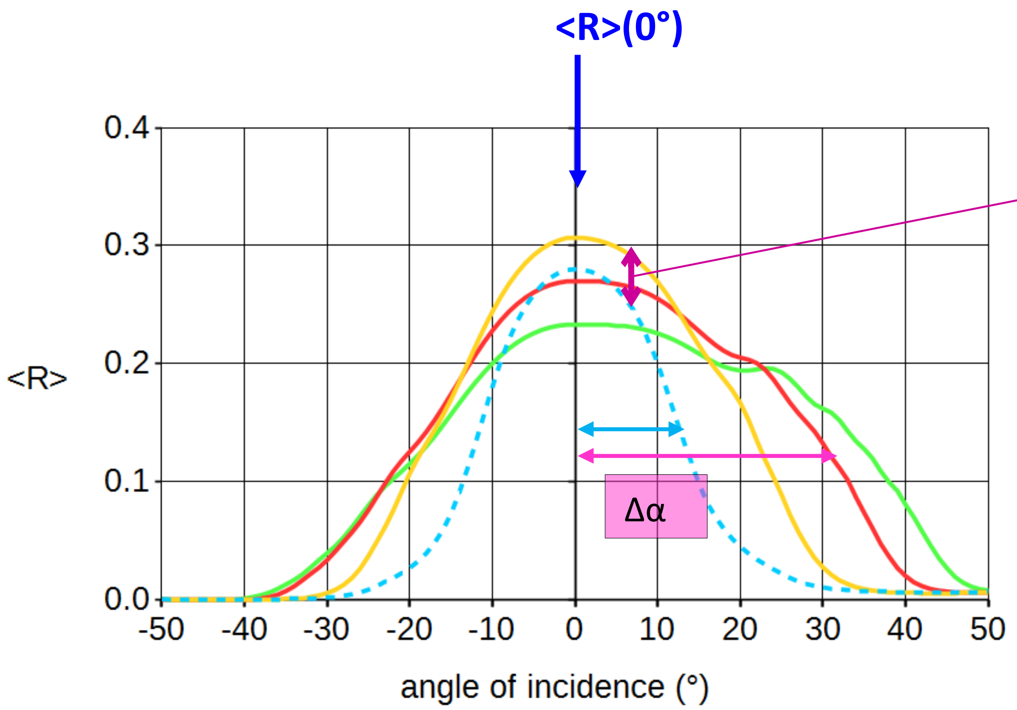
Effect on the angle dependence of R at 13.5 nm:
Wider angular range with increased grading

# Weighting the reflectance with the Sn spectrum <R> → exploiting more EUV power with graded mirrors despite the reduced peak value of R

$$\langle R\rangle(\varphi) = \frac{\int I(\lambda)R(\lambda,\varphi)}{\int I(\lambda)}$$



# Analysis of the weighted reflectance <R>



More intensity with grading factor 1.2 than without grading at all angles.

**Grading factor:**
blue: 1 (no grading)
yellow: 1.2
red: 1.4
green: 1.6

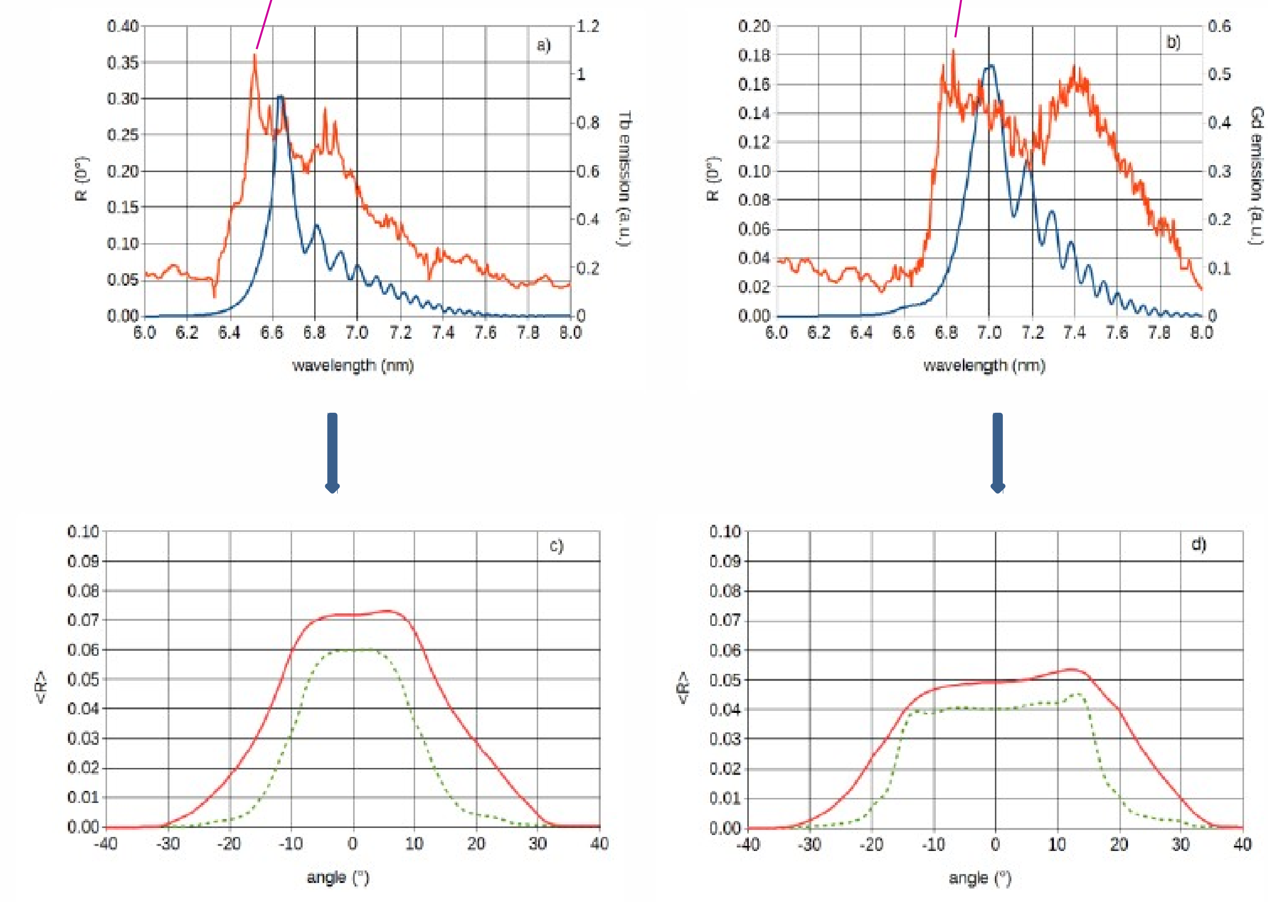
**Area below <R> curves**

| Grading | <R> (0°) | Δα | optical throughput | | |
|---|---|---|---|---|---|
| | | | -50° to +50° | (±)2°-10°<br>CRAO= 6° | (±)2°-22°<br>CRAO= 12° |
| 1 | 0.287 | 13.7 | 1 | 1 | 1 |
| 1.2 | 0.307 | 21.2 | 1.38 | 1.10 | 1.36 |
| 1.4 | 0.272 | 29.4 | 1.56 | 1.00 | 1.34 |
| 1.6 | 0.235 | 35.5 | 1.55 | 0.87 | 1.20 |

# Extension to BEUV: La/B4C mirrors at 6.X nm

## Weighting with:

**Tb spectrum** **Gd spectrum**



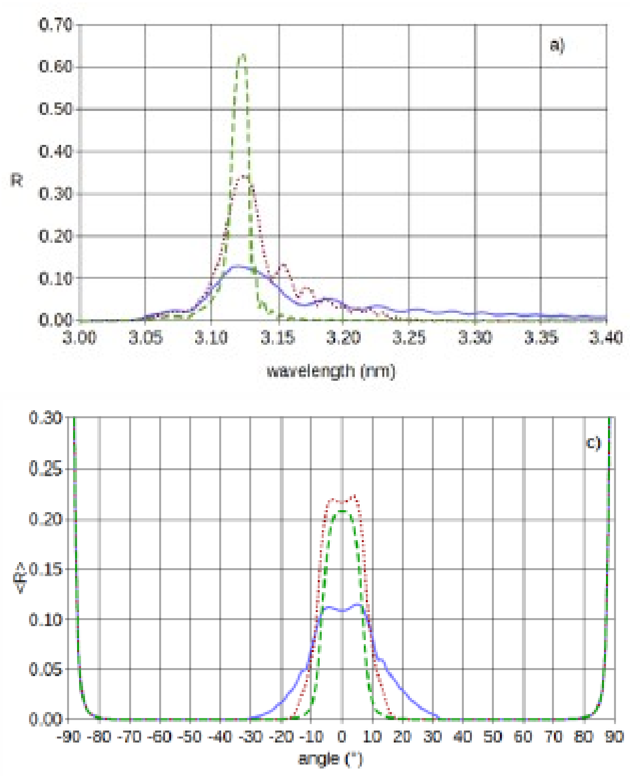
dashed:
no grading

full:
grading
factor 1.2

Weighting of the reflectance by source spectra [14]. a): Tb spectrum and La/$B_4$C reflectance (curve with peak at 6.64 nm). b): Gd spectrum and La/$B_4$C reflectance (curve with peak at 7 nm). c) and d): Weighted reflectance <R> for Tb and Gd spectrum, respectively. Dashed curves: not graded, full curves: graded with factor 1.2.

[14] S. S. Churilov et al., "EUV spectra of Gd and Tb ions excited by laser-produced and vacuum spark 398 plasmas," Phys. Scr. **80**, 045303 (2009).

# Cr/Sc mirror near 3.12 nm
## weighting by Bi spectrum



dashed:
no grading

dotted:
grading factor 1.05
(improvement at all angles below 15°)

full:
grading factor 1.2

Reflectance of standard and graded Cr/Sc mirrors: a) R at normal incidence at wavelengths near 3.12 nm. c) Weighted reflectance <R> for a Bi spectrum [15]. Total number of bi-layers: 400 (≈ semi-infinite case). Bilayer thicknesses: 1.56 nm (standard, dashed curves), 1.55 – 1.628 nm (grading factor 1.05, dotted curves), 1.54 – 1.848 nm (grading factor 1.2, full curves). Cr/Sc thickness ratio: 0.43.

[15] T. Higashiguchi et al., “Efficient “water window” soft x-ray high-Z plasma source,” J. Phys.: Conf. Ser. 463, 012024 (2013).

# Conclusions
# Depth-Graded mirrors

**Broader reflectance exploits more of a broad spectrum:**

- **13.5 nm, Mo/Si mirror - Sn source:**
- Optics with high numerical aperture:
  grading 1.2: allows to use larger angles (with
  larger angular aperture) and higher throughput
- <R> improvement up to ≈ 60% (-50° -- +50°),
  10 – 36% (CRAO= 6° -- 12°)

**Extension to "Beyond EUV":**

- **6.X nm: La/$B_4$C mirror - Tb source:**
  <R> improvement at all angles up to 40° (s and p pol.)
  for grading factor 1.2
- **3.12 nm: Cr/Sc mirror - Bi source:**
  <R> improvement at all angles up to 40° (s and p pol.)
  for grading factor 1.05