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Advanced multilayer development for the water window spectral region

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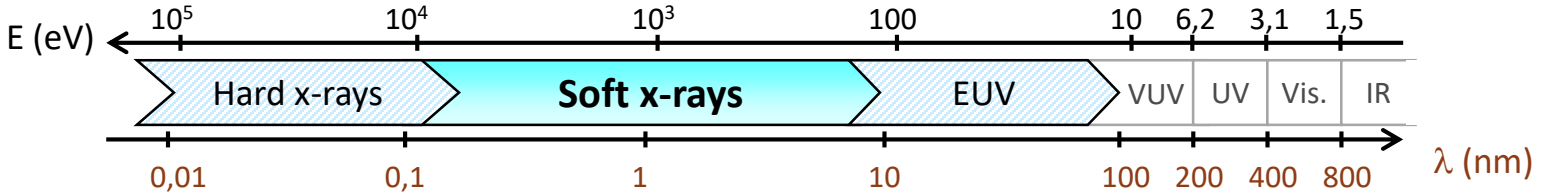
Multilayer interference coatings in the soft x-ray



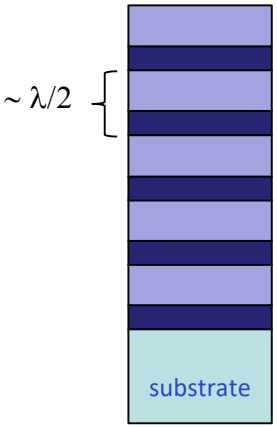
Complex refractive index

$\mathbf{n} = 1 - \delta + i\beta$

with $\delta < 10^{-2}$ and $\beta < 10^{-3}$

- **$\lambda < 10$ nm**
- low index contrast
- low absorption length

Short-wavelength challenges



For λ=6 nm :

$r_{vacuum/mat} \sim 10^{-2}$

$L_{absorption} \sim 20\ \lambda$

$\Rightarrow R_{max} \sim 30\%$

- ❑ Design optimization
- ❑ Refractive index not accurate
- ❑ Thickness control and reproducibility (**< 10 pm**)
- ❑ Ultra-smooth interfaces (**< 0.2 nm rms**)
- ❑ Surface oxidation or contamination
- ❑ Long-term stability

= more than 40 years of research in EUV/x-ray optics

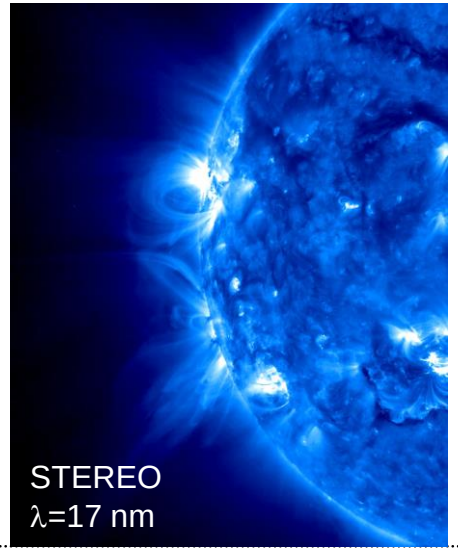
1980 : Nevot & Croce model for interfacial roughness, *Rev. Phys. Appl. 15, 761*

Space missions: SOHO/EIT (1995), STEREO/EUVI (2006)

Solar Physics

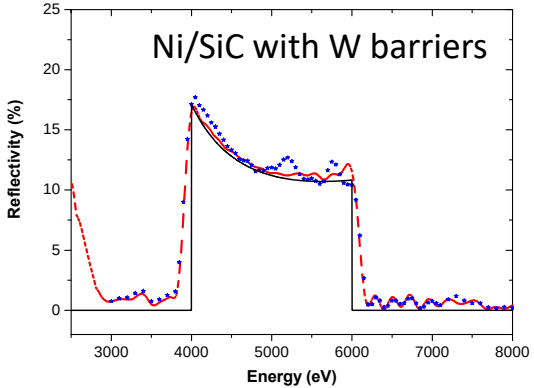
Solar Orbiter mission (2020)

1st dual-band coating for EUV telescope



High Energy Physics

Broadband coatings for x-ray diagnostics

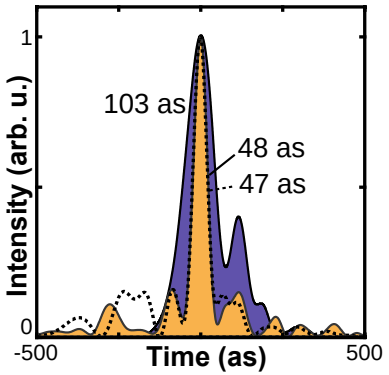


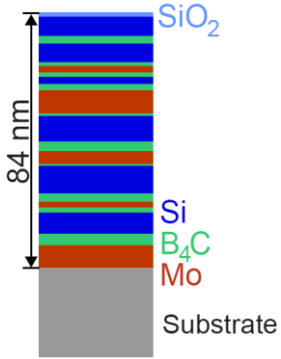
-> LLE (Rochester), LMJ (France)

F. Bridou et al., NIMA 2012
B. Emprin et al., OE 2014

Ultrafast science

- ✓ 1st attosecond pulse compression with ML mirror
- ✓ 1st measurement of ML spectral phase in the x-ray





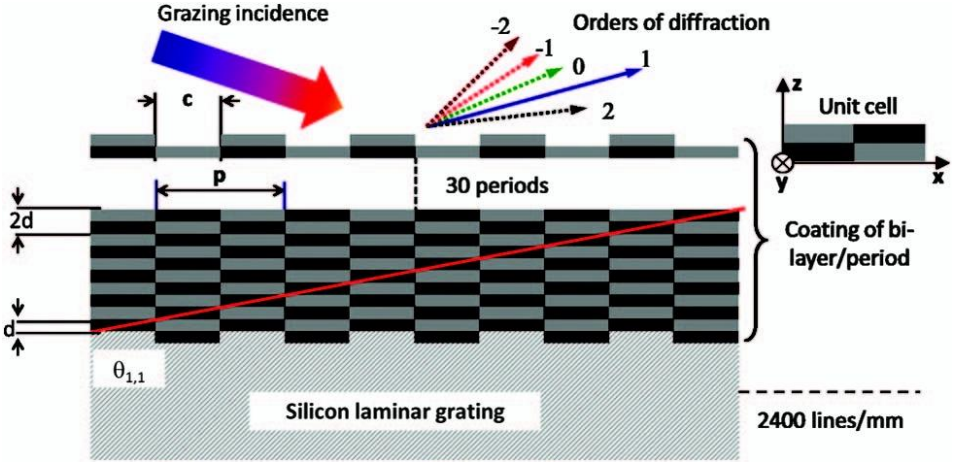
-> ATTOLAB beamlines (France)

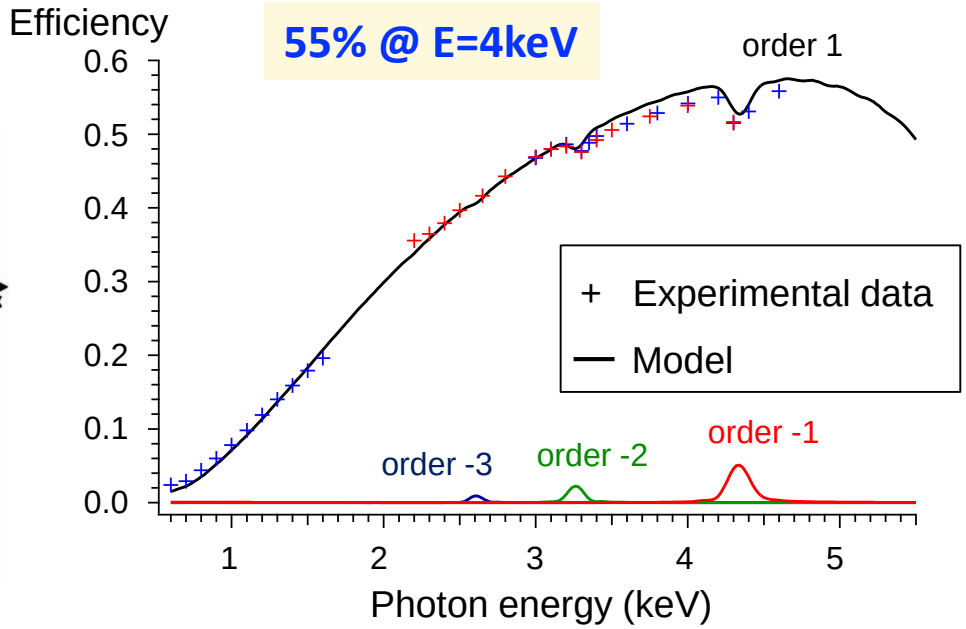
C. Bourassin-Bouchet et al., OE 2011
S. de Rossi et al., OL 2015

2D nanometric multilayer structures

Cr/B_4C alternate multilayer grating for tender X-rays

F. Chouekani et al., OL 2014
F. Polack et al., PXRNMS 2018





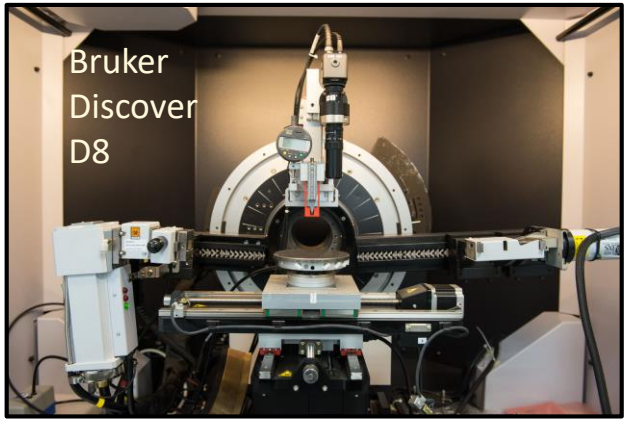
3 SOLEIL beamlines are now equipped with alternate multilayer gratings !

LCF Experimental Facility

EUV/x-ray coatings

2 Magnetron Sputtering (RF/DC, 4 targets)
1 Ion Beam Sputtering (4 targets)

Cu-Kα X-ray reflectometry

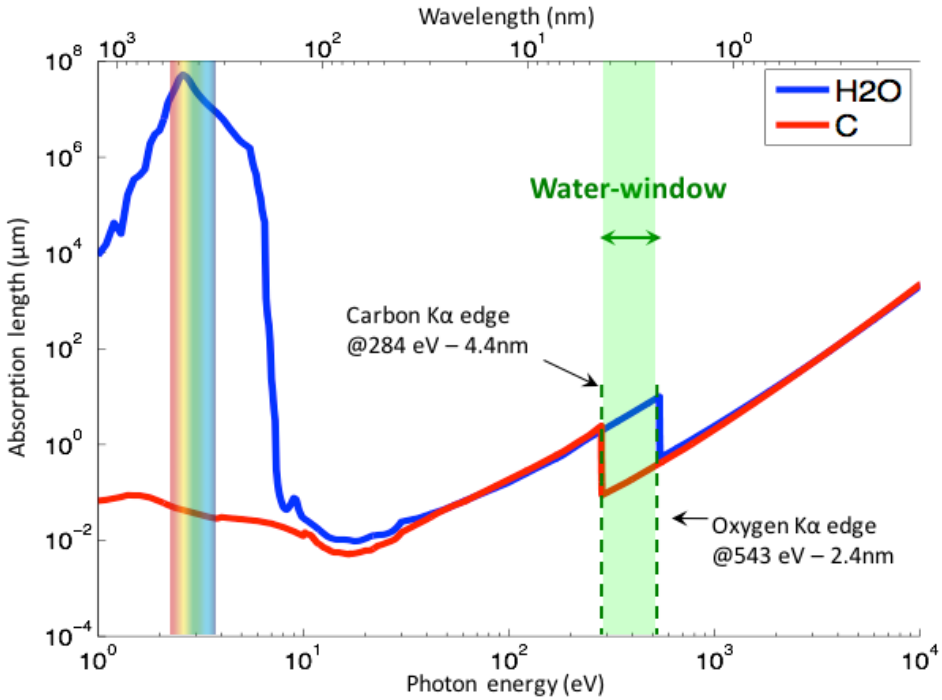


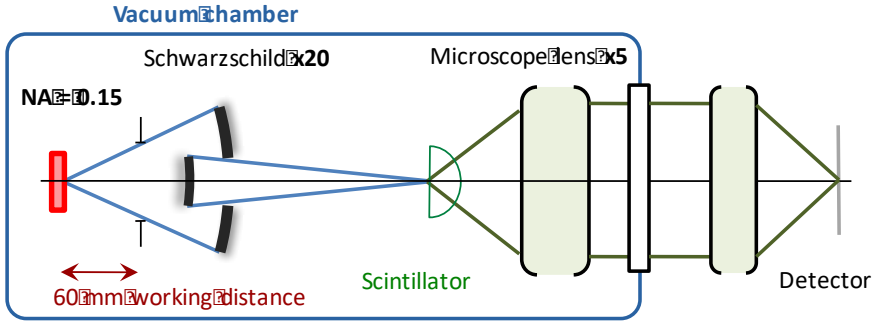
Soft x-ray reflectometry

SOLEIL SYNCHROTRON

Metrology beamline

X-ray microscopy in the water window (λ ≈ 3 nm)



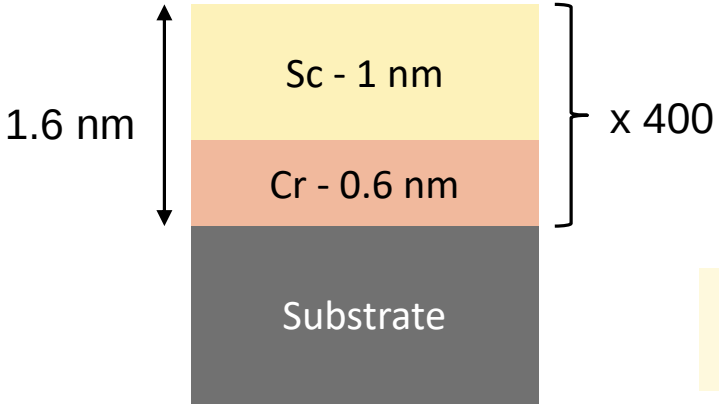


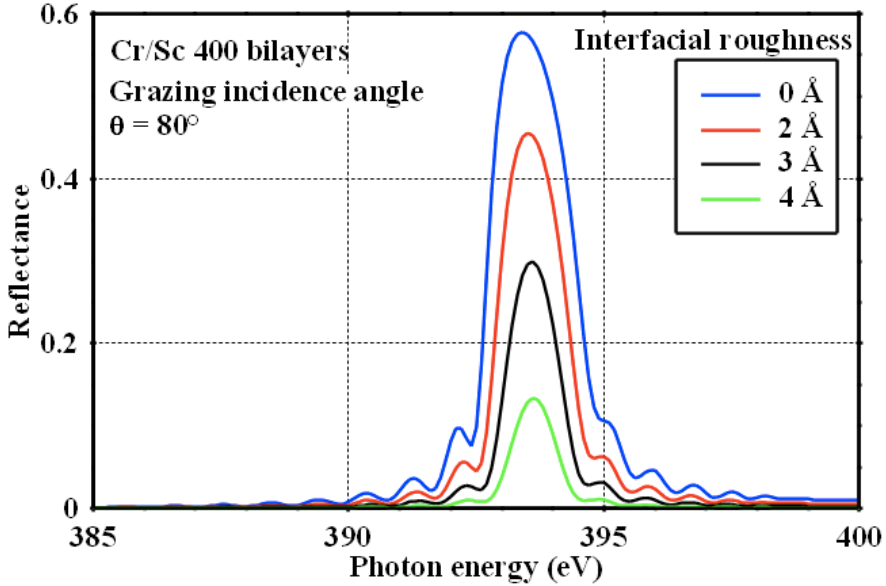
Primary and secondary mirrors have to be efficient at 3 nm wavelength

Cr/Sc reflectance is dominated by interfacial effects

Near-normal incidence interference coating

Best material pair = Cr/Sc (Salashchenko 1994)
Period thickness ≈ 1.6 nm
Theoretical peak reflectance > 55%



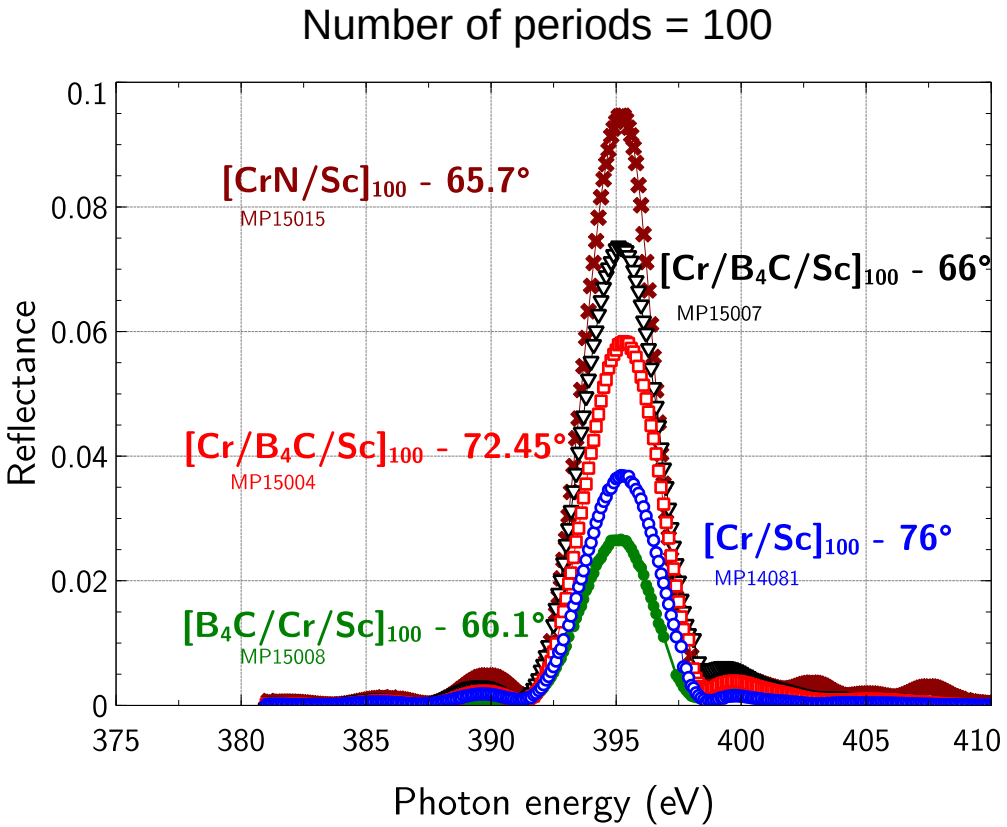


Experimental peak reflectance is severely reduced by interfacial roughness and/or interdiffusion

17.3% - Magnetron sputtered Cr/Sc – F. Shaefers et al., 2003
20.7% - ion-assisted deposition - F. Eriksson et al., 2008
32.1% - B_4C barrier layers - E. Gullikson et al., 2008 *unpublished*

Optimization of Cr/Sc aims at improving the interfaces

- ✓ Optimization of deposition parameters
  A. Hardouin et al., J. Vac. Sci. Tech. A 2008
- ✓ Study of interfaces
  M. Wu et al., Opt. Eng. 2017
- ✓ Effect of Cr/Sc nitridation
  A. Hardouin, PhD thesis 2007
  C. Burcklen et al., Opt. Lett. 2017
- ✓ Effect of B_4C barrier layer
  C. Burcklen et al., Opt. Lett. 2017

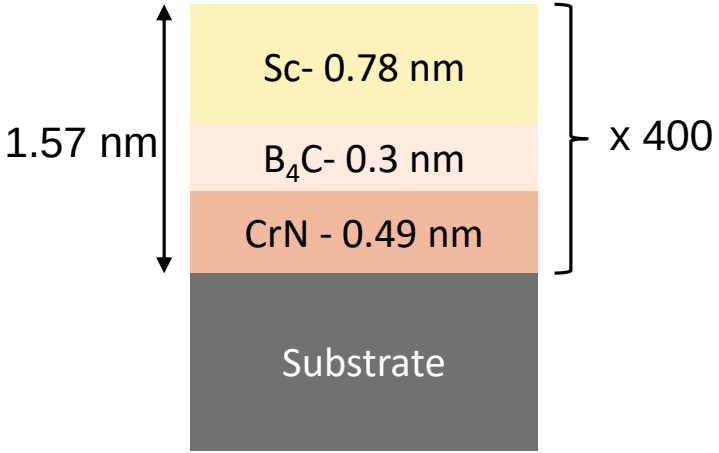


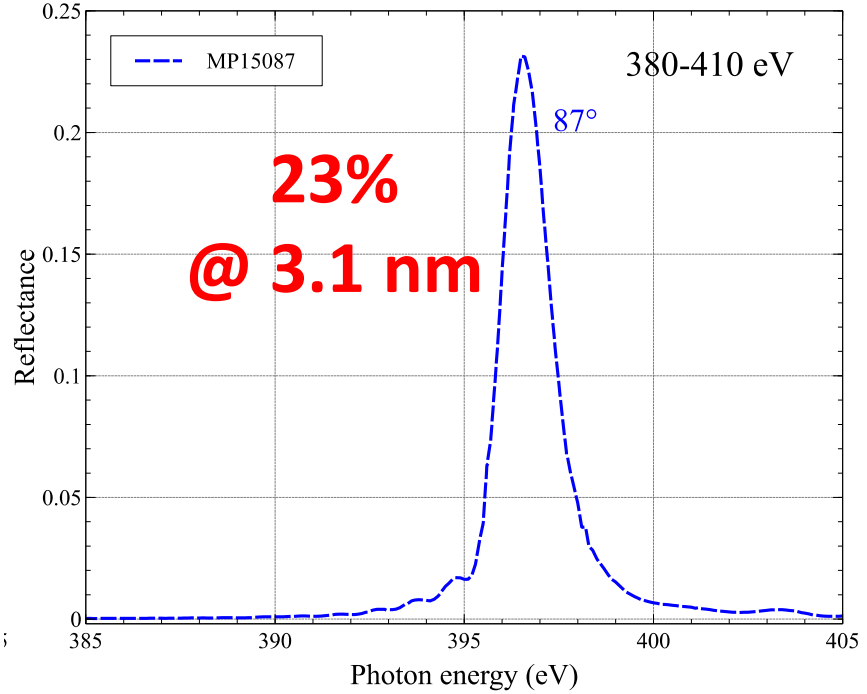
Enhanced reflectance with Cr nitridation and B_4C barrier layer

Soft X-ray Reflectometry at SOLEIL

$CrN/B_4C/Sc$, d = 1.567 nm, 400 periods

Highest published value of reflectance in the water window



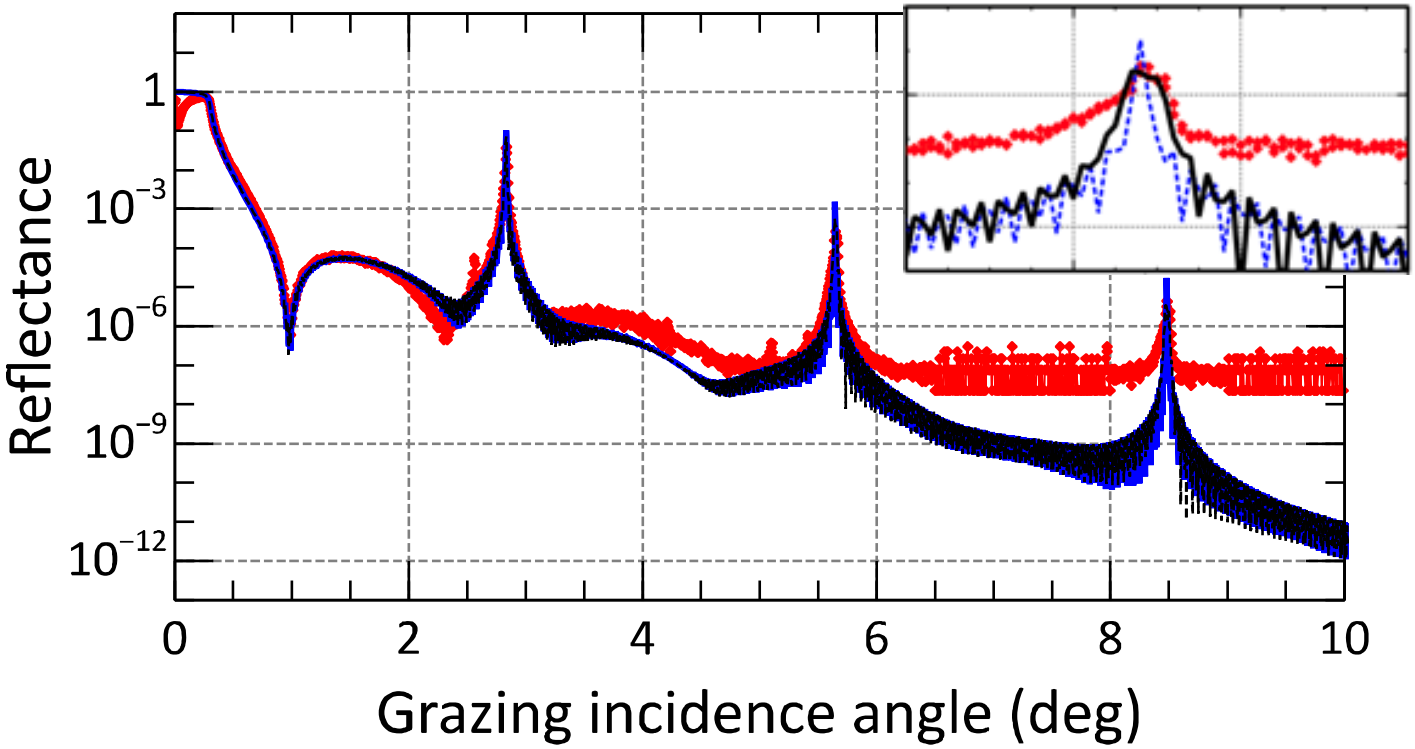


C. Burcklen et al., Opt. Lett. (2017)

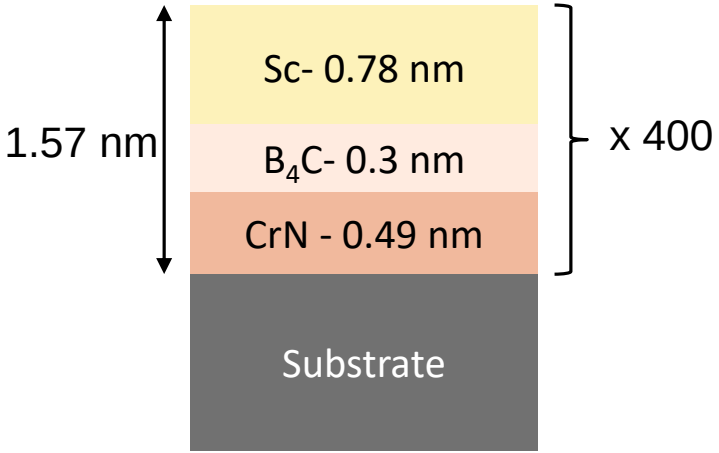
Drift during deposition is about 0.025 pm/period

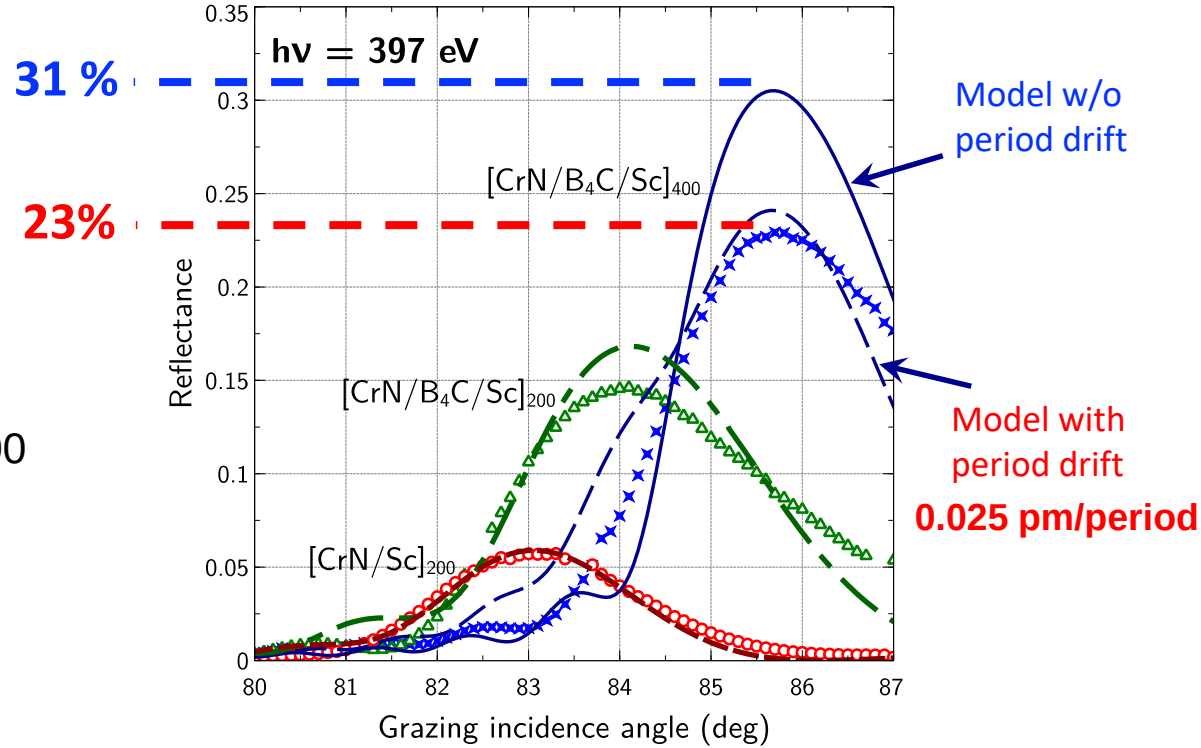
Grazing incidence X-ray Reflectometry at 0.154 nm

$CrN/B_4C/Sc$, d = 1.567 nm, 400 periods



Effect of period drift on the peak reflectance

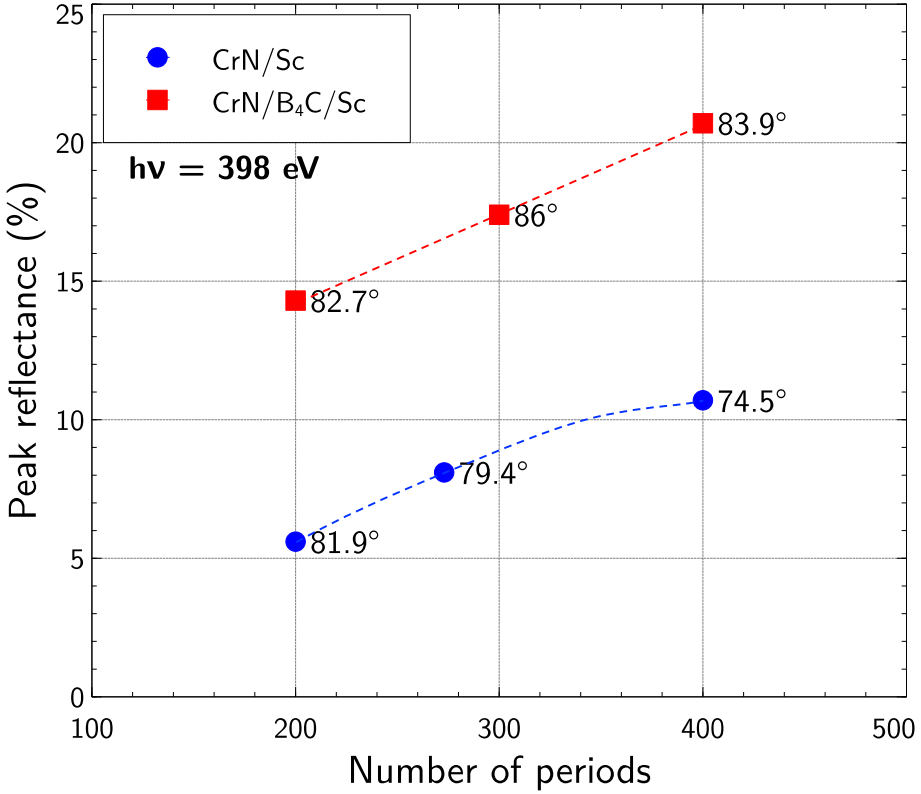




C. Burcklen et al., Opt. Lett. (2017)

Can we reach higher reflectance ?

- ❑ Decrease the period drift < 0.01 pm/period
- ❑ Increase the number of periods
- ❑ Optimize CrN, B_4C and Sc thicknesses



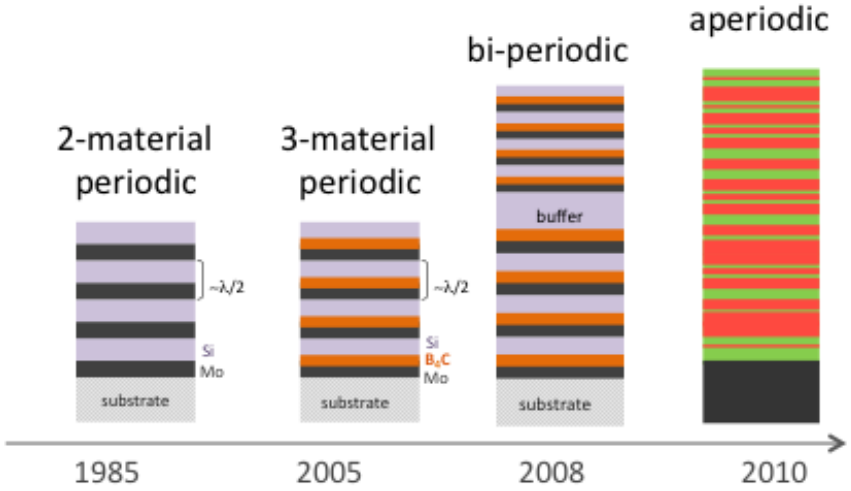
What we need ?

- ❑ Accurate (= experimental) values for CrN refractive index
- ❑ Analysis techniques with sub-nanometer resolution -> interface properties, N_2 profile

Challenges & opportunities for short-wavelength ML coatings

- ✓ Optimization of **deposition process** for new material combinations
- ✓ Physico-chemical properties of **sub-nanometric layers and interfaces**
- ✓ Accurate knowledge of thin film material **optical constants**

Historical evolution of EUV/x-ray ML structures



- ✓ **2D multilayer structures**
- ✓ **ultra-short period multilayers**
- ✓ **Narrowband mirrors**
- ✓ Mirrors with enhanced spectral purity
- ✓ Broadband mirrors
- ✓ Broadband mirrors with control of the spectral phase