Multilayer Optics, Past and Future

Eberhard Spiller

Imaging with light

Waves move by λ in 10^{-15} to 10^{-19} sec

Wave trains are 10^{-14} to 10^{-18} sec long

Each wavelet contains less than 1 photon

Eye responds in about 0.1 sec

- Everything is washed out !
- How can we see?

Solutions

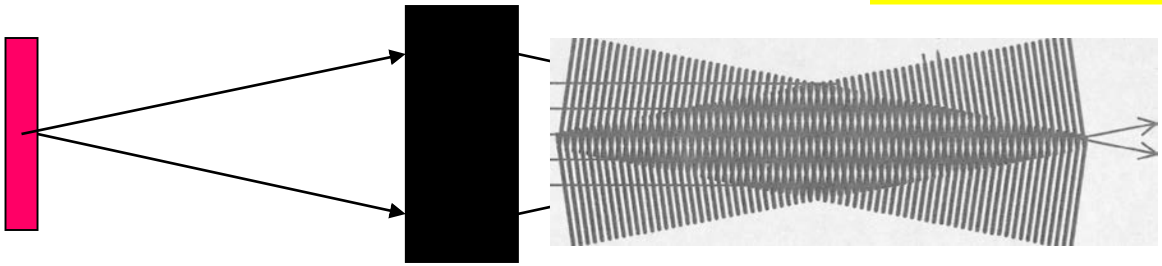
- 1) Use short observation time $<10^{-15}$ sec
  need intensity, computer power,
  sample is destroyed
- 2) Generate standing waves that last
  need mirrors, lenses, coherence

- 3) Use simple objects (crystals):
  enhanced diffraction peaks
  low information content
  simple reconstruction, resolve atoms

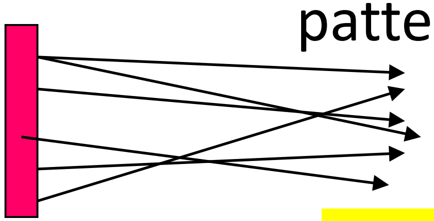
Standing waves
→ Image, hologram, ML

object

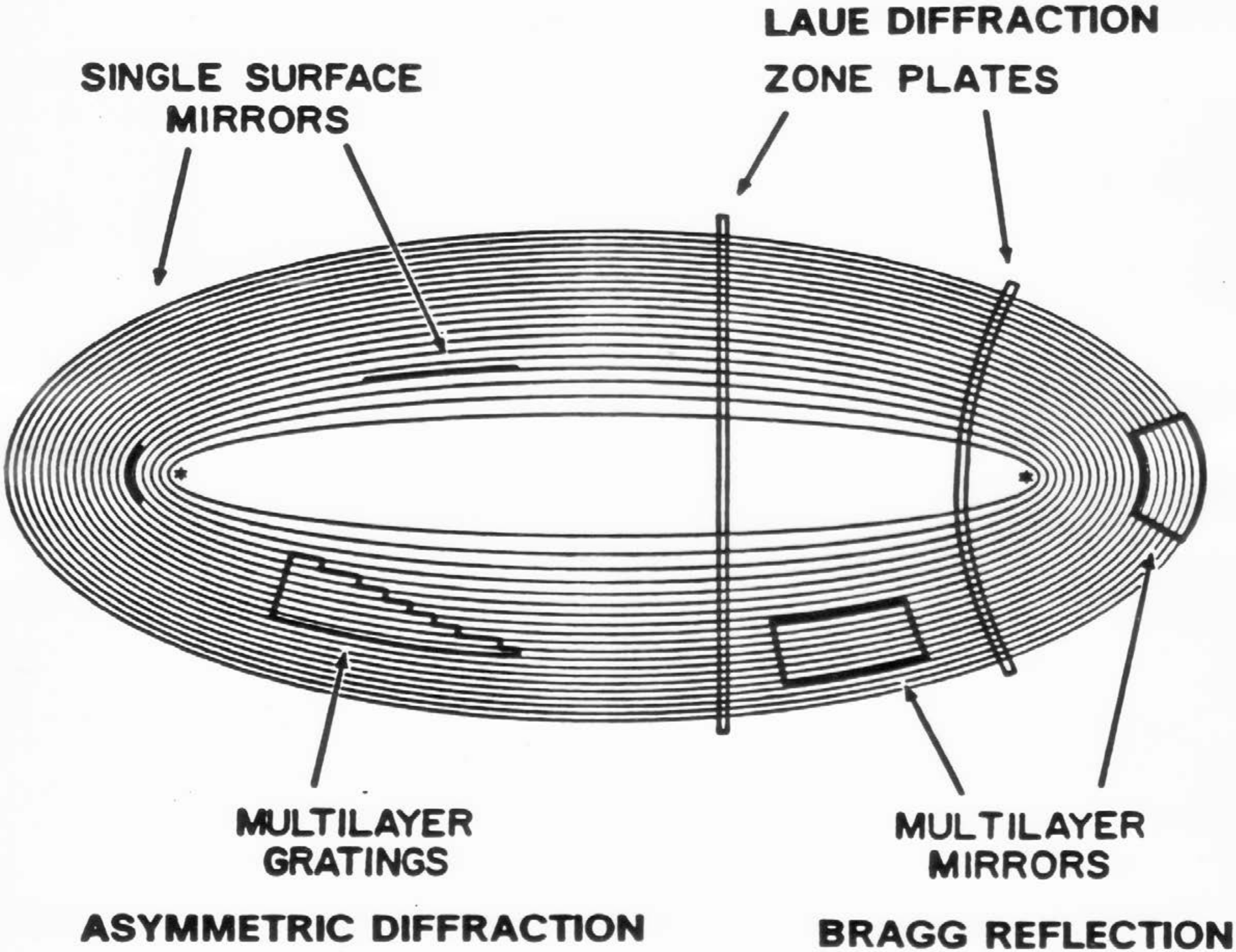
Optic



Moving
Diffraction
pattern



Fast detector → Computer → Image


LAUE DIFFRACTION
SINGLE SURFACE MIRRORS
ZONE PLATES
MULTILAYER GRATINGS
MULTILAYER MIRRORS
ASYMMETRIC DIFFRACTION
BRAGG REFLECTION

Multilayer Applications

Microscopes
Lithographic Cameras, EUV lithography, λ=13.5nm
Normal Incidence solar telescopes, λ= 6 – 80nm
Grazing incidence telescopes up to 100keV
Beam lines for synchrotrons, FEL
Spectrometers
New materials

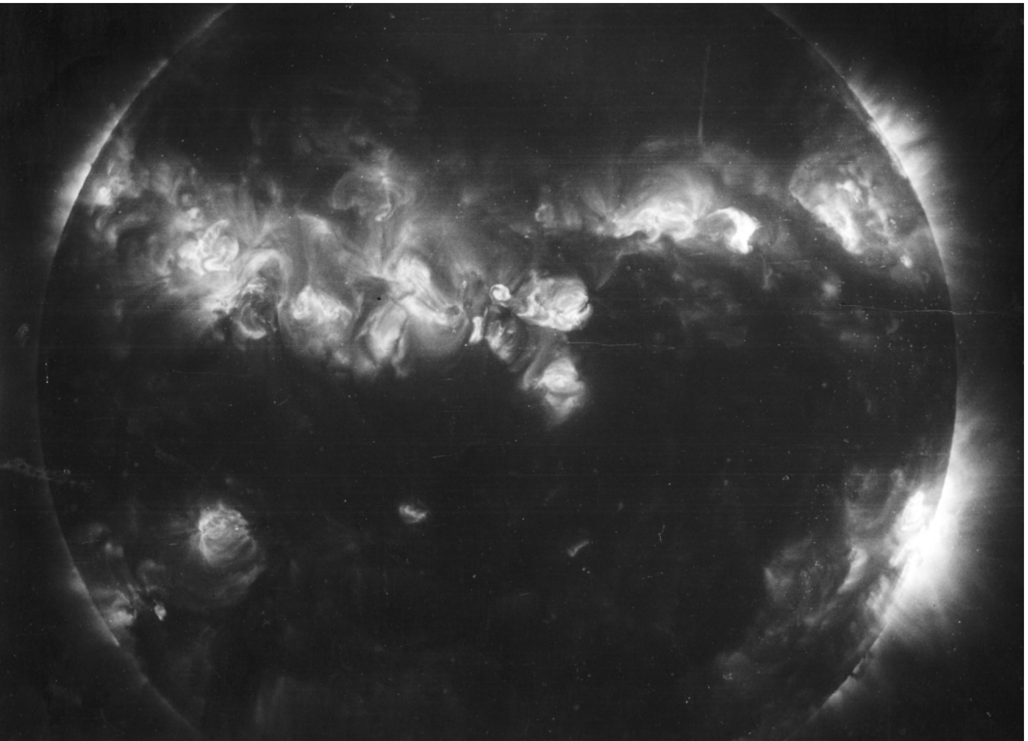
Best λ for EUV lithography

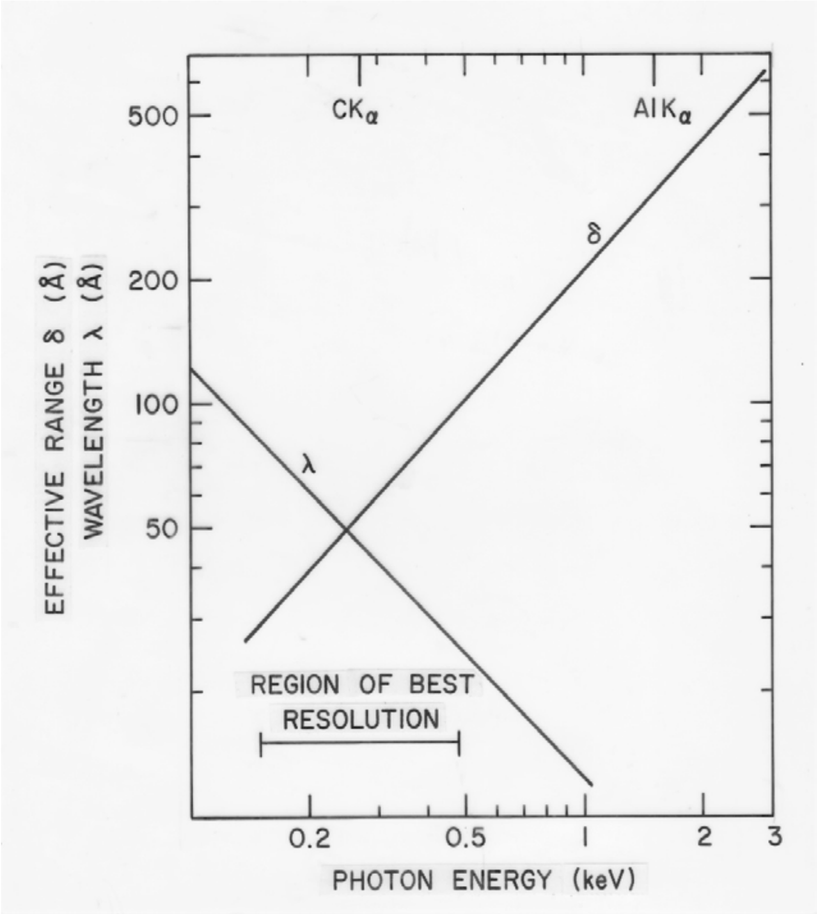
Resolution: Wavelength and range of secondary electrons: λ=5nm
Problems: Higher exposure. Exp increase with $1/\lambda^3$

Angular Bandwidth of ML is reduced (field)
Damage to all components

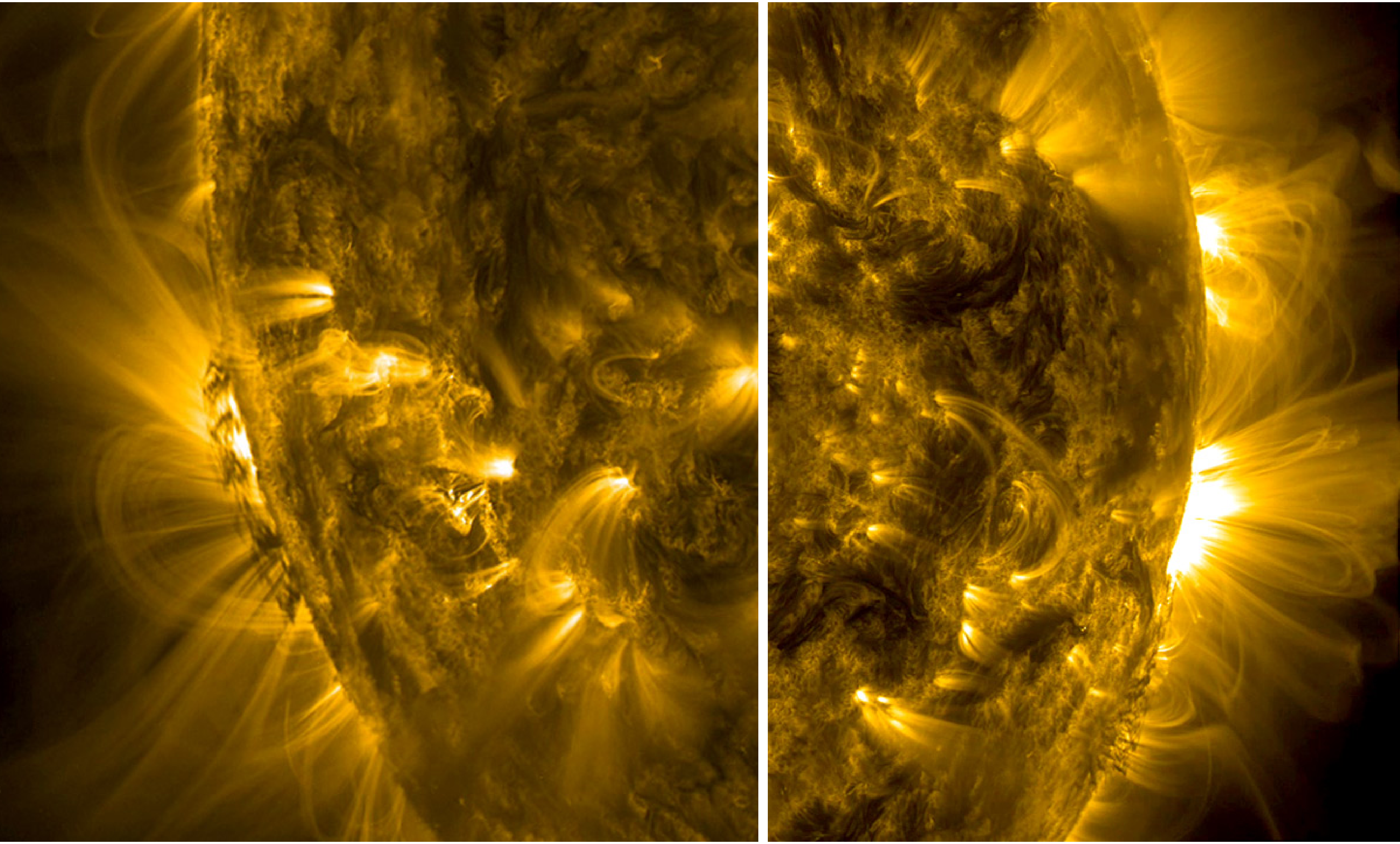
My Guess: Stay with λ=13.5nm

NIXT telescope at 6.35nm (1986)



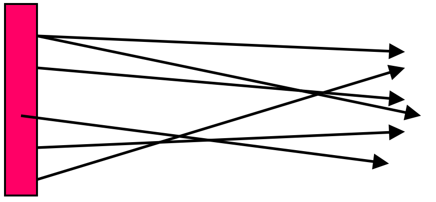


SDO, launch 2011, http://sdo.gsfc.nasa.gov/



Direct Reconstruction

Simple?



Needed:

Coherent source (FEL)

Many diffraction patterns for 3-D

Object is destroyed at each exposure

Inject identical particles, different orientation

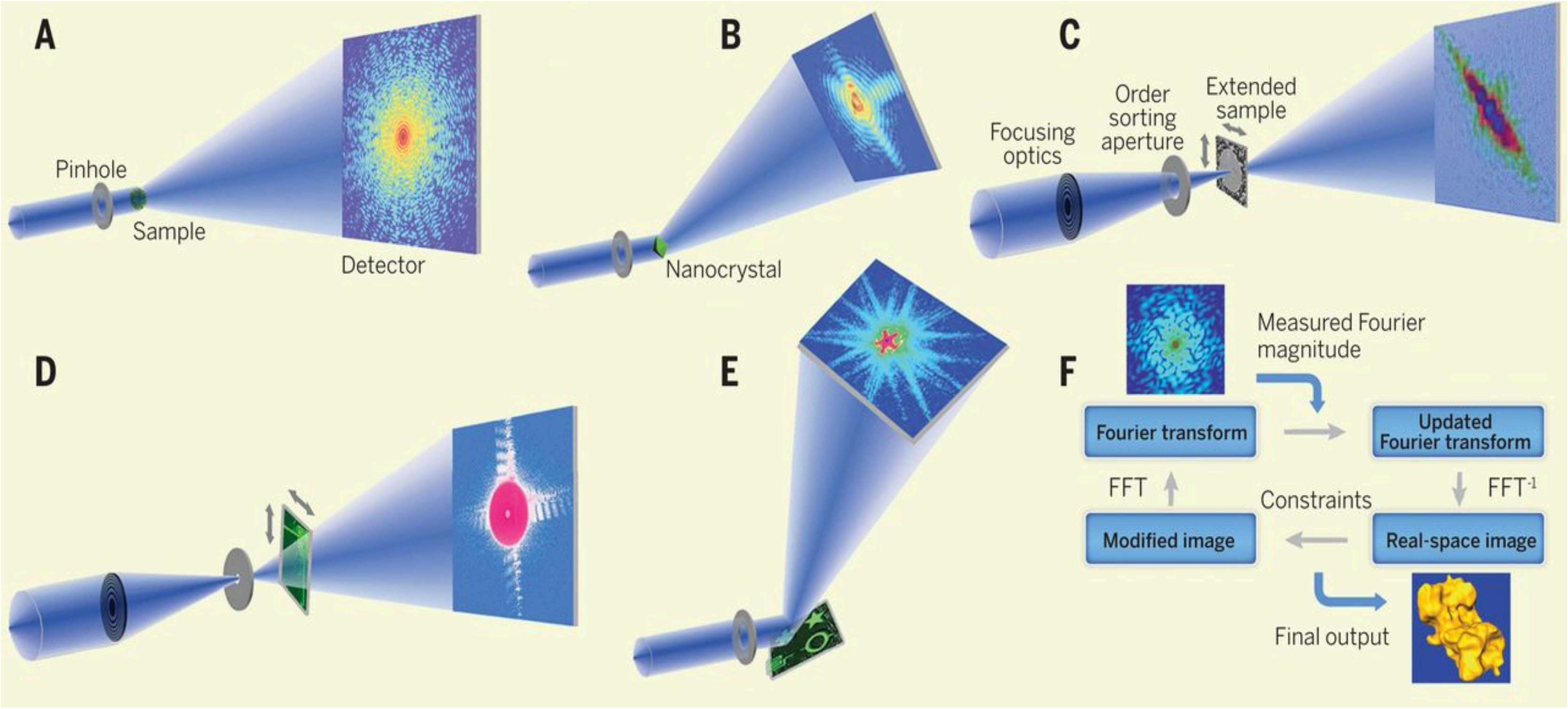
Many diffraction patterns, pick good ones

Get the phases

Reconstruct 3-D image

Computer power and algorithms

J. Miao et al. Science 2015



History of X-Ray Optics   bias: high resolution images

Röntgen, 1895	Shadow graphs, No lenses or mirrors
Laue, 1912	X-ray-diffraction
Bragg, 1914	Atomic resolution for crystals
Ewald, 1916	Dynamical Theory
Compton, 1923	Grazing incidence mirror, capillaries (1931)
Kiessig, 1931	Thin film interference with x-rays
Langmuir- Blodgett	crystals or multilayers, Λ=3-8 nm. (Nobel 19332)
DuMond&Youtz, 1935	X-ray peaks from multilayers, diffusion const.
Bormann, 1941	Standing wave in crystal reduces absorption
Kirkpatrik-Baez, 1948	Imaging with 2 cylinder-mirrors, zone plates
Wolter, 1952	Imaging with 2 conic sections

Recent History

Möllenstedt,1966	**Zoneplates by electron-beam**
Schmahl, 1969	**Zoneplates by holography**
Spiller, 1972	**Multilayers for XUV near normal incidence telescopes, microscopes, cameras, polarizers**
Spears, 1972	**X-ray lithography (shadowgraphs)**
Walker, Golub,	**1988 XUV telescopes for sun's corona SOHO, TRACE**
Hawryluk, Kinoshita,Vinogradow , 1988	**EUV projection lithography**
Snigirev 1996	**Multi-lenses**
Tinsley, 1998	**Figure, finish of mirrors in 1 Å range**
EUVL LLC, 2001	**EUVL cameras within diffraction limit**
FEL for x rays, 2009	**Reconstruction in 3-D from diffraction patterns**
Future Challenge:	**Phase contrast for medical x-rays**

Deposition Methods

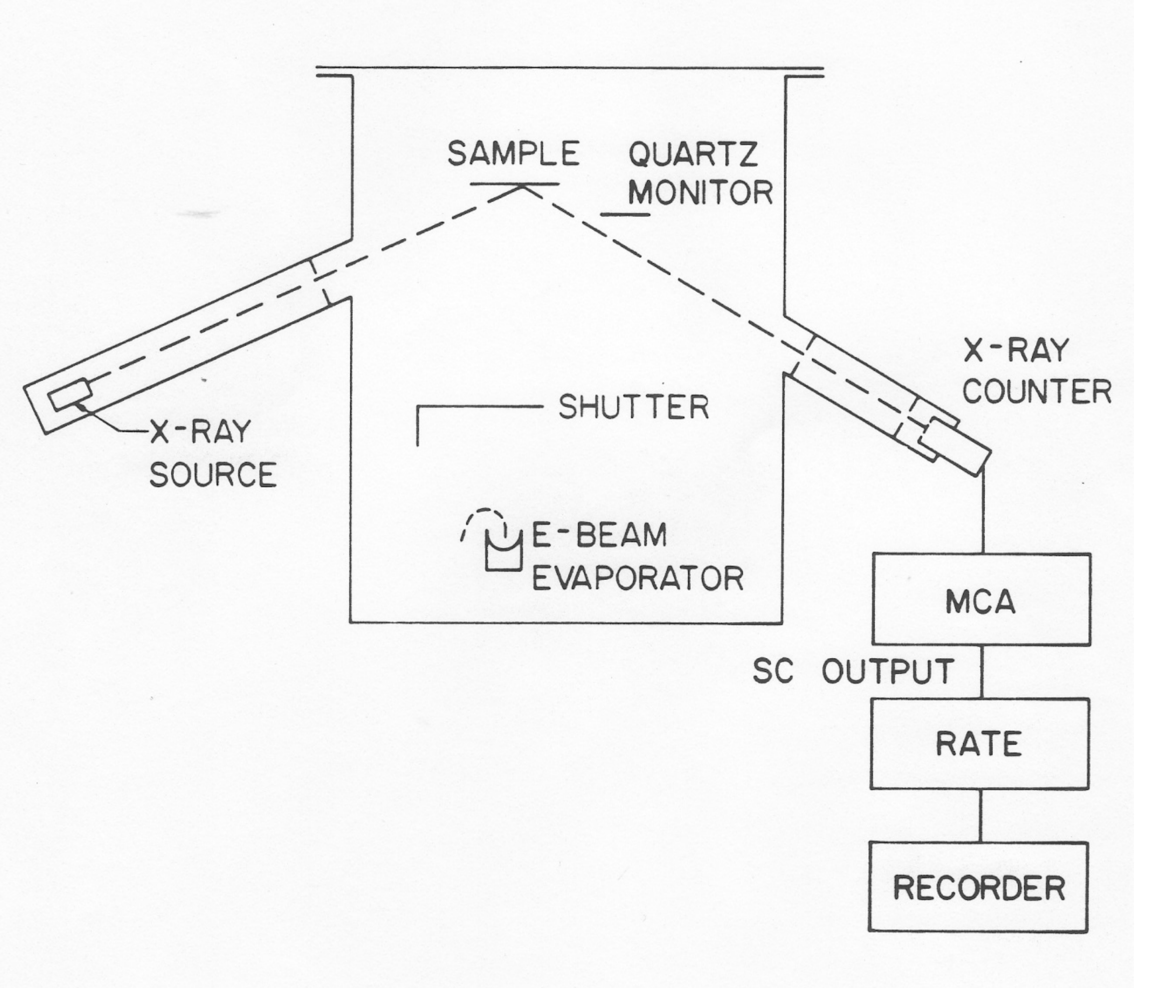
- E-beam evaporation+in-situ monitor+ion polish
- Magnetron Sputtering (Barbee)
- Ion beam sputtering
- Pulsed laser evaporation
- Ion beam sputter + ion etching

High energy produces better smoothing
Low energy produces less mixing of boundaries
Find best compromise

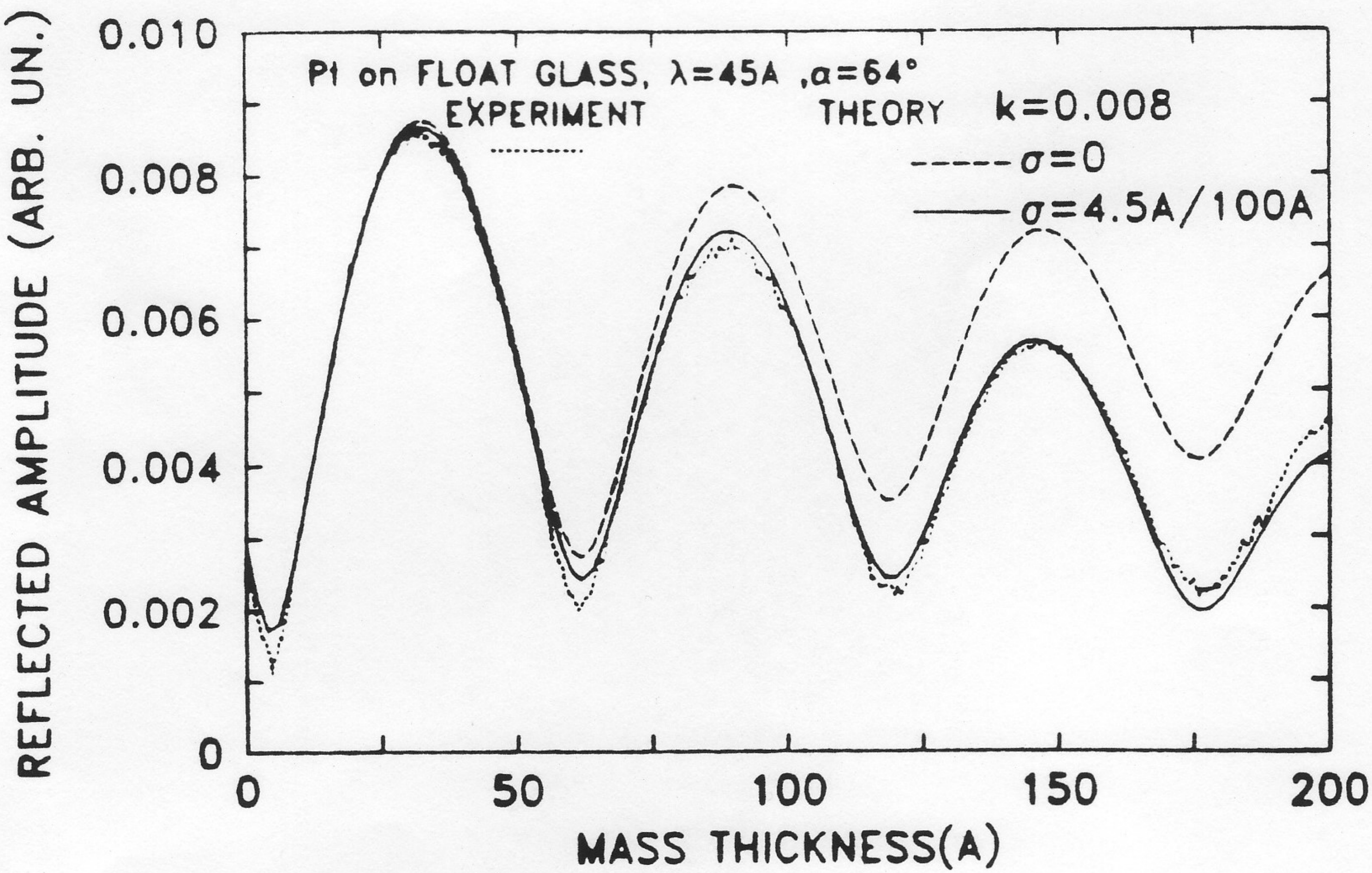
Virtual National Laboratory

EUVL

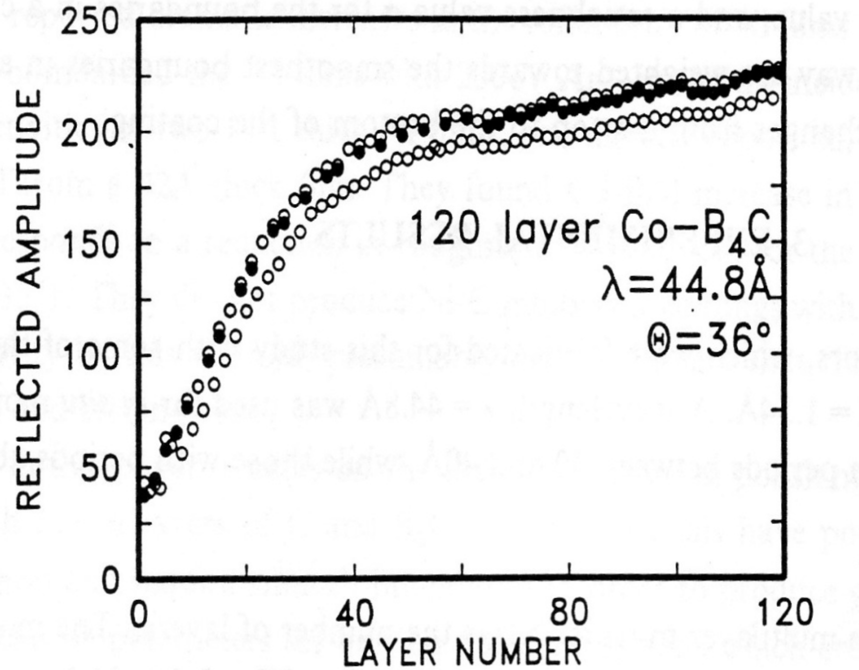
Deposition+in-situ monitor+ion polish

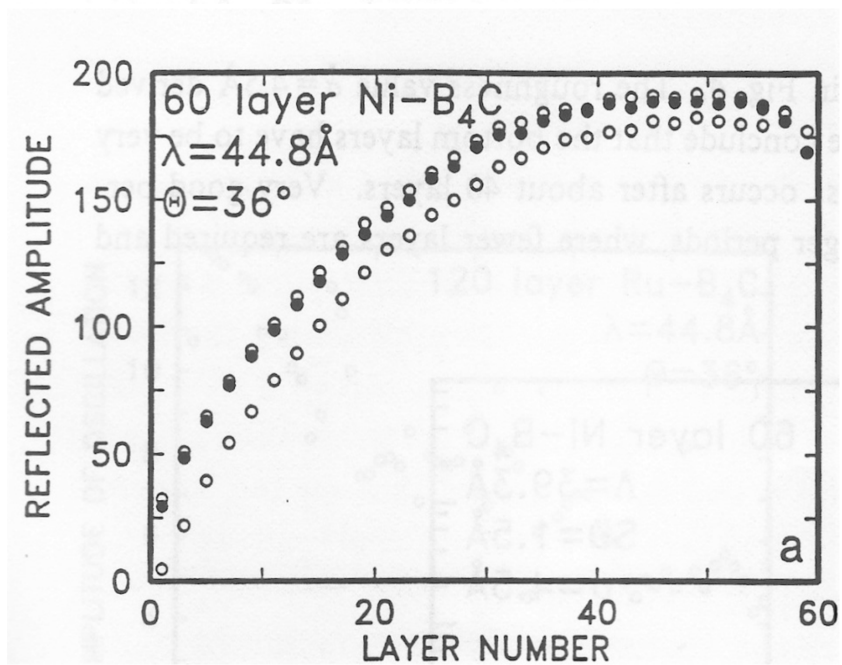


Performance can be optimized during deposition

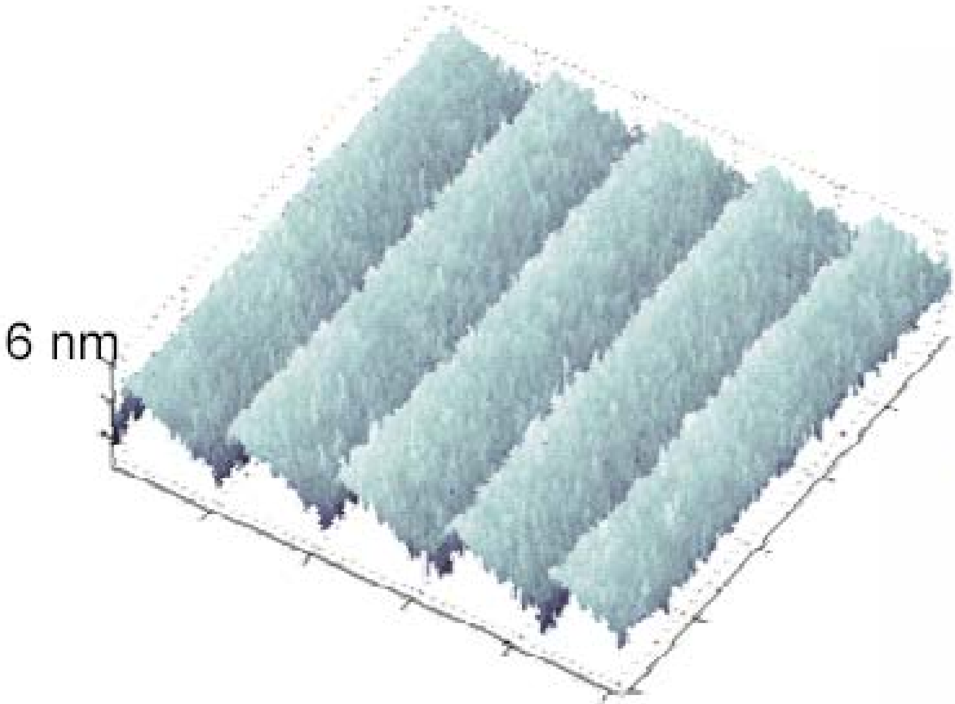


Pt on FLOAT GLASS, λ=45A ,α=64°
EXPERIMENT
THEORY k=0.008
σ=0
σ=4.5A/100A
REFLECTED AMPLITUDE (ARB. UN.)
0.010
0.008
0.006
0.004
0.002
0
0
50
100
150
200
MASS THICKNESS(A)

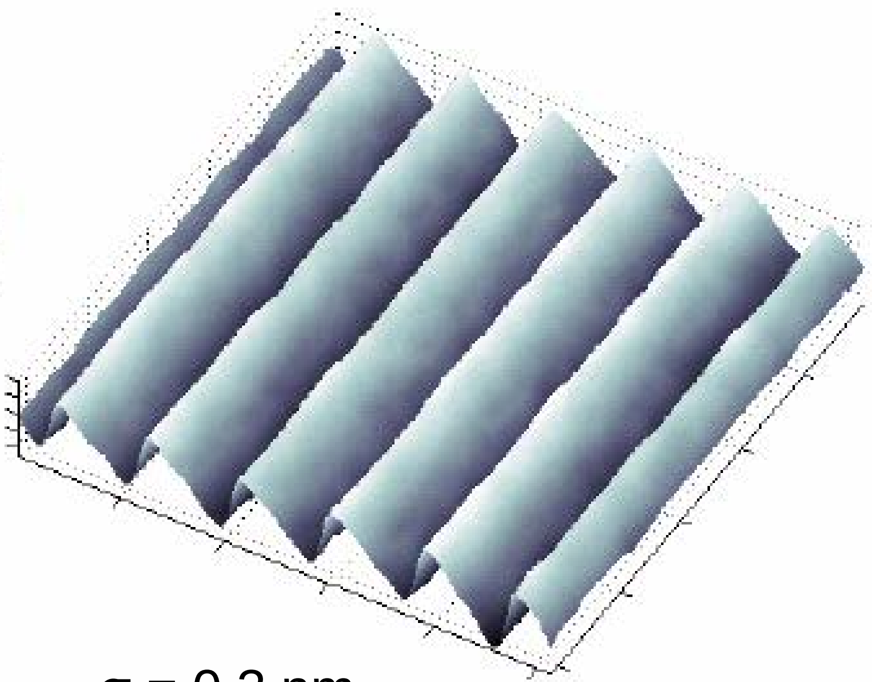

120 layer Co−B4C
λ=44.8Å
Θ=36°
REFLECTED AMPLITUDE
LAYER NUMBER
0
50
100
150
200
250
0
40
80
120


60 layer Ni−B4C
λ=44.8Å
Θ=36°
a
REFLECTED AMPLITUDE
LAYER NUMBER
0
50
100
150
200
0
20
40
60

Grating before and after coating/polishing



σ = 0.9 nm



σ = 0.3 nm

Eberhard Spiller

Precision Optics with Thin Film

Tradition:

Alternate Figuring and Precision Measurement

Many loops, very slow

Modern Method:

One precision figure measurement only

Correction by a thin film of the proper thickness

Combine ion-polish and interferometry in one unit and to adjust the thickness of the film

New Applications

- Improve properties of solids:
  electrons, phonons etc are described by wave functions
- Method to maximize Tc:
  Measure Tc(d) in situ. Look for oscillations during depo
  Find 2 materials with different oscillation amplitudes
  Deposit material 1 to maximum, material 2 to minimum
- Capacitors, batteries:
  Go from 2D surfaces to 3D
    Past: 2 electrodes
    Future: thick ML, each period on set of electrodes

Multilayers at LLNL

EUV LLC: λ=13.5 nm, METs

Solar telescopes: NIXT, SOHO, TRACE, SAO

Grazing Incidence telescopes: NUSTAR

Optics for NIF: KB, Wolter for around 15keV

Optics for FEL:

Very Large Optic Coater

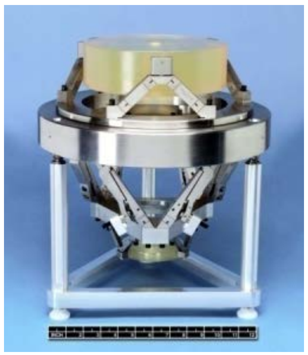
Nanolaminate layers:

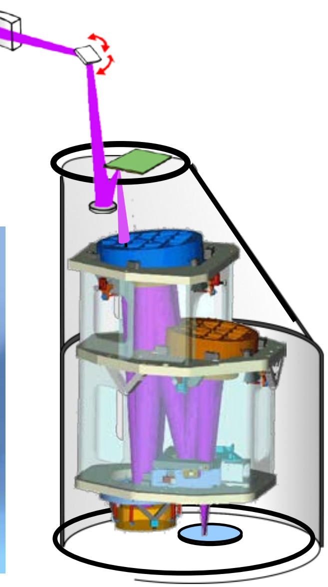
- A few Å of A-C for release layer
- Au layer for outer surface
- 446 periods of:
  - 43.5 nm crystalline Zr layer
  - 3.4 nm amorphous Zr/Cu layer

Finished 1.52 m nanolaminate being removed from VLOC Very Large Optical Coater

The LLNL group has participated in the development of EUV/x-ray multilayer optics for various applications

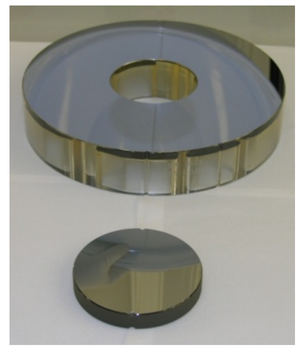
EUV Lithography

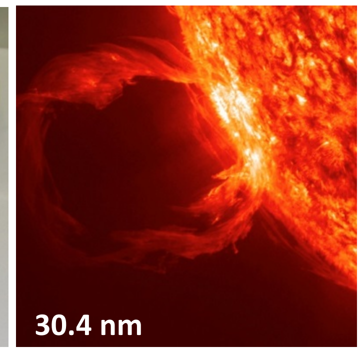


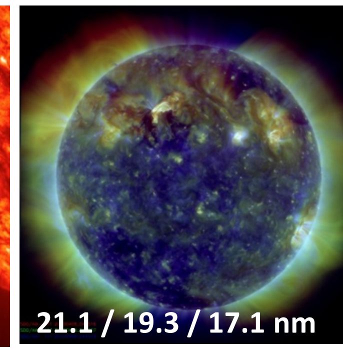


EUV solar physics telescopes (NASA's SDO and NASA/NOAA's GOES-R)

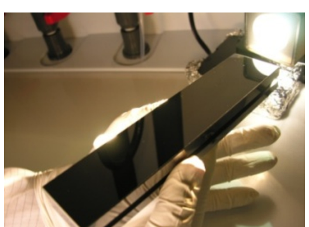
Solar Dynamics Observatory (SDO). Launched Feb.11, 2010.



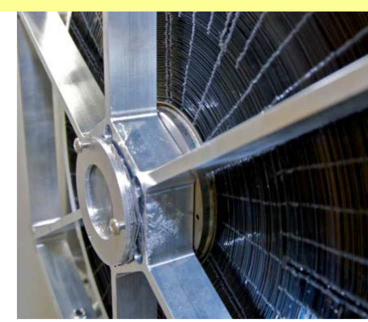




X-ray optics for the LCLS free-electron laser



Hard x-ray /gamma-ray optics for target diagnostics, astrophysics and radiation detection

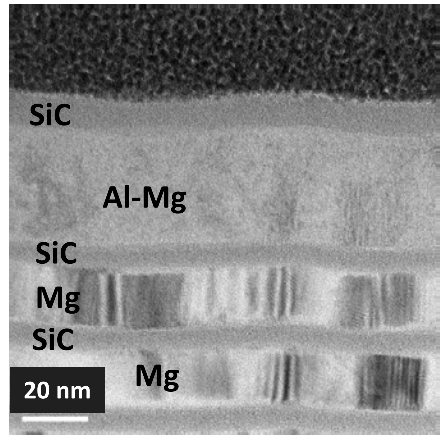


Highlights from recent EUV/x-ray multilayer research by the LLNL group

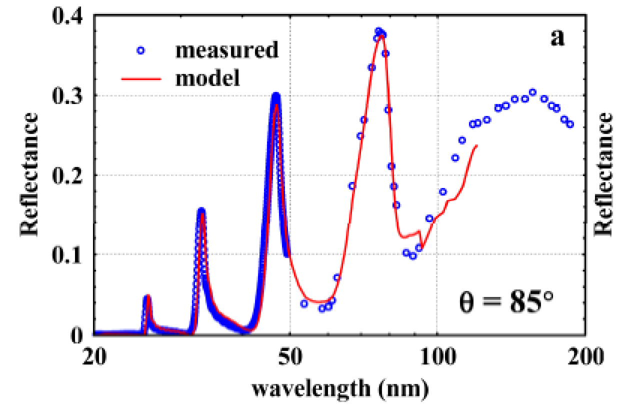
Mo/Si with low-stress, high-R at 13.5 nm
20 pm rms figure error

Soufli et al, EUVL Workshop (2016)

Corrosion-resistant Al-Mg/SiC (25-80 nm)

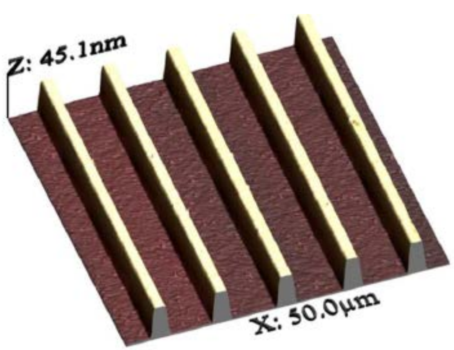


Soufli et al, APL (2012)



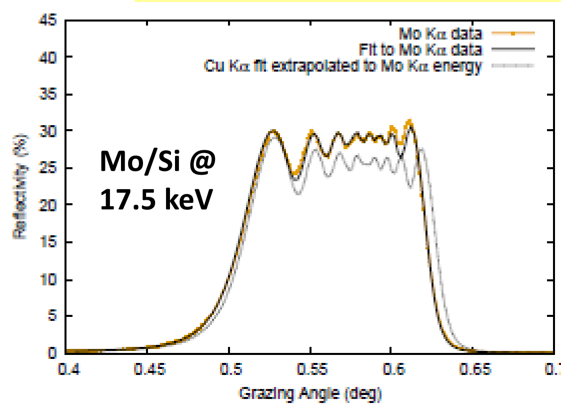
Fernandez-Perea et al, Opt. Expr. (2012)

Reduced-stress B4C and SiC coatings for LCLS (0.5 – 24 keV)

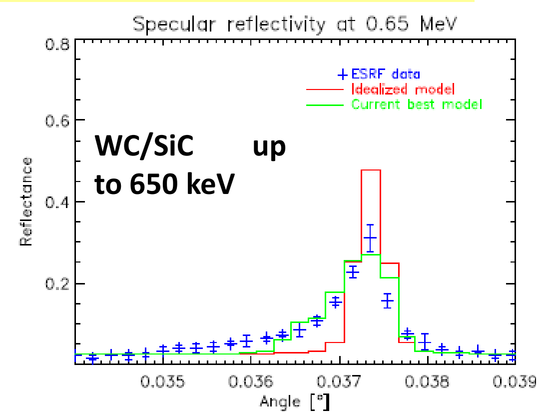


Soufli et al, Appl. Opt. (2012)

Hard x-ray /gamma-ray multilayers for target diagnostics, astrophysics and radiation detection



Pardini et al, Opt. Expr. (2016)



Brejnholt et al, Opt. Expr. (2014)

Challenges

- Atoms are too big
- Positions of atoms are random
  - Could we control position of each atom?
- Our MLs are 1D
  - 2D: gratings
  - 3D: Lithography and MLs

Future Challenges

- Diffraction limited telescopes
- Phase contrast for medical x rays
- Atomic resolution for general objects

Thank You!