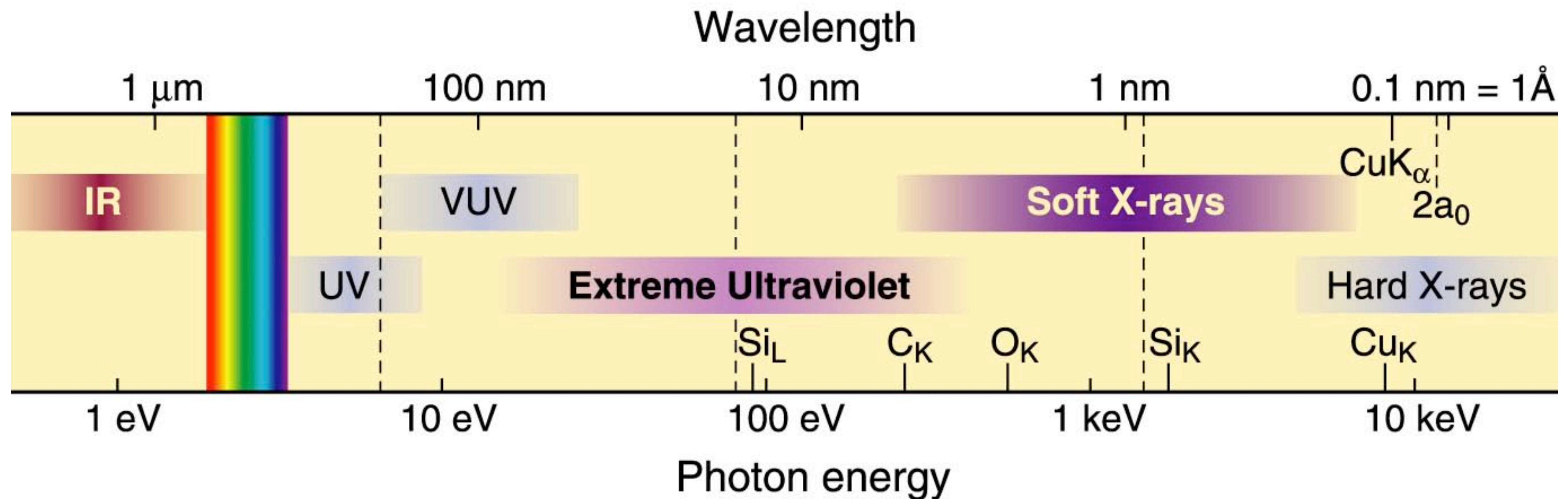
Imaging at High Spatial Resolution: Soft X-Ray Microscopy and EUV Lithography

David Attwood

University of California, Berkeley
and
Center for X-Ray Optics, LBNL

W. Chao, E. Anderson, A. Liddle, P. Naulleau, C. Chang (Drexel), Y. Liu, E. Gullikson, A. Sakdinawat, D. Olynick, B. Harteneck, G. Denbeaux (Albany), G. Schneider (BESSY), C. Larabell (UCSF), M. LeGros, P. Fischer (Max Planck), T. Tyliszczak

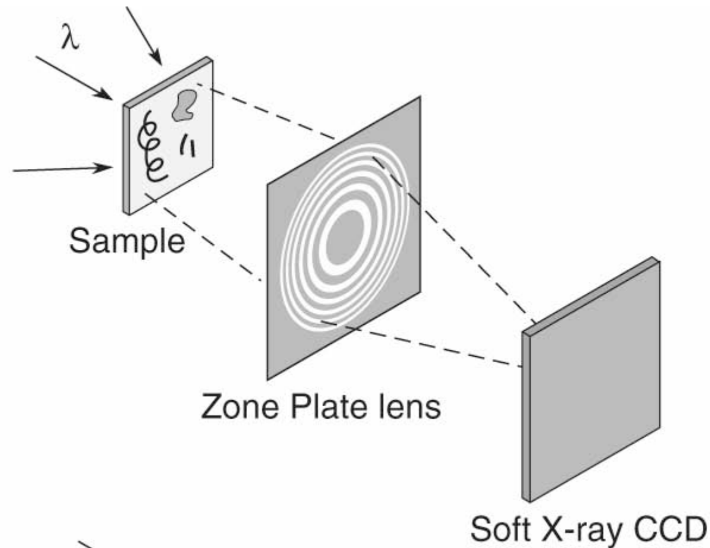
The Short Wavelength Region of the Electromagnetic Spectrum



- **See smaller features**
- **Write smaller patterns**
- **Elemental and chemical sensitivity**

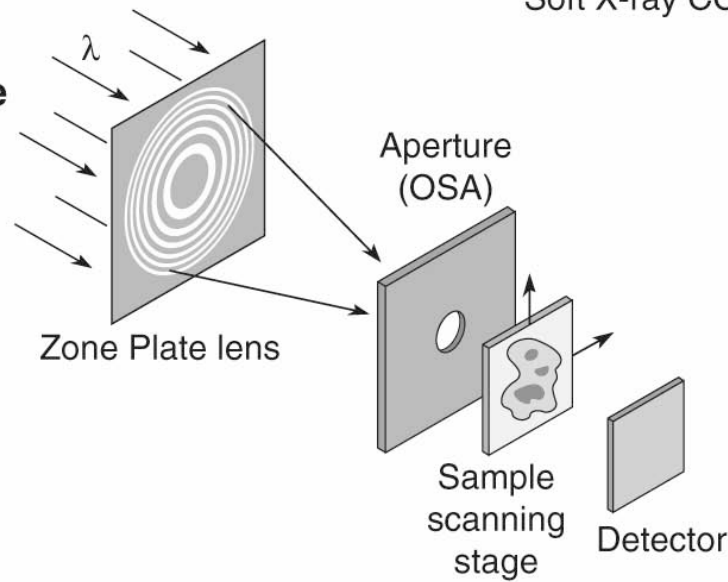
Two Common Soft X-Ray Microscopes

Full-Field Microscope



- Best spatial resolution
- Modest spectral resolution
- Shortest exposure time
- Bending magnet radiation
- Higher radiation dose
- Flexible sample environment (wet, cryo, labeled magnetic fields, electric fields, cement, ...)

Scanning Microscope



- Least radiation dose
- Good spatial resolution
- Best spectral resolution
- Requires spatially coherent radiation
- Long exposure time
- Flexible sample environment
- Photoemission (restricted magnetic fields), fluorescence imaging

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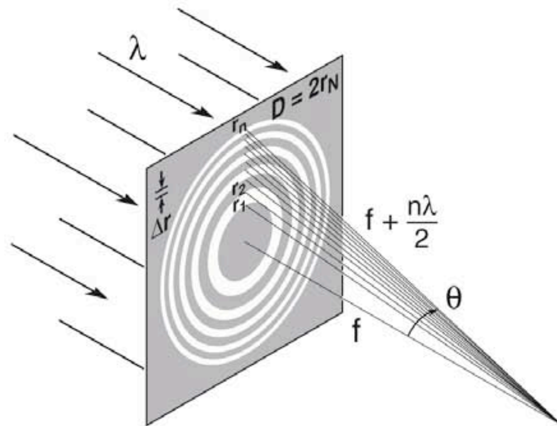
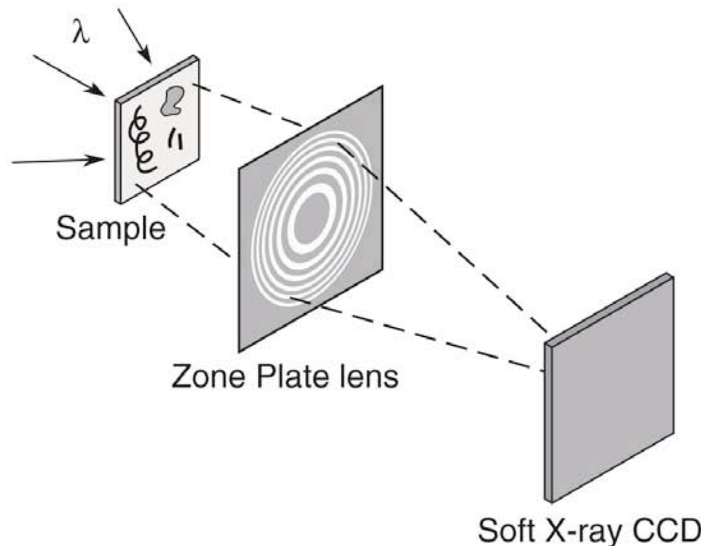
Zone Plates for Soft X-Ray Image Formation

Zone Plate Lens



Soft X-Ray Microscope



Zone Plate Formulae

Formula	Eq.	Value
$r_n^2 = n\lambda f + \frac{n^2\lambda^2}{4}$	(9.9)	$\lambda = 2.5$ nm, $\Delta r = 25$ nm, $N = 618$
$D = 4N\Delta r$	(9.13)	63 μm
$f = \frac{4N(\Delta r)^2}{\lambda}$	(9.14)	0.63 mm
$NA = \frac{\lambda}{2\Delta r}$	(9.15)	0.05
$\text{Res.} = k_1 \frac{\lambda}{\text{NA}} = 2k_1\Delta r$; $k_1 = 0.61$ $(\sigma = 0)$		$1.22\Delta r = 30$ nm
$k_1 = 0.4$ $(\sigma = 0.45)$		$0.8\Delta r = 19$ nm
$\text{DOF} = \pm \frac{1}{2} \frac{\lambda}{(\text{NA})^2}$	(9.50)	1 μm
$\frac{\Delta\lambda}{\lambda} \leq \frac{1}{N}$	(9.52)	1/700

Partially Coherent Illumination Permits Improved Spatial Resolution by a Factor Approaching Two

(a)

$\mathbf{k}_i$ $\mathbf{k}_s$ θ d

$\mathbf{k}_s$ θ $\frac{2\pi}{d}$ $\mathbf{k}_i$

(b)

$\mathbf{k}_i$ $\mathbf{k}_s$ 2θ $\frac{d}{2}$

$\mathbf{k}_s$ 2θ $\frac{2\pi}{(d/2)}$ $\mathbf{k}_i$

(c)

$\frac{d}{2}$

$$\sigma = \frac{\sin\theta_{illum}}{\sin\theta}$$

Optical Transfer Properties with Varying Degrees of Partially Coherent Illumination

Apparent transfer function

1.0

0.5

$\sigma = 0$ (coherent)

$\sigma = 0.3$

$\sigma = 0.6$

$\sigma = \infty$ (incoherent)

0 1 2

Spatial frequency (NA/λ)

A Fresnel Zone Plate Lens Used for X-Ray Microscopy

Courtesy of E. Anderson (LBNL)

The Nanowriter: High Resolution Electron Beam Writing With High Placement Accuracy

High brightness thermal field emission source and extraction electrodes

Condenser lens, beam defining aperture and transfer lens

Blanking plates and aperture

Deflection coils

Final electron focusing lens

Deflection electronics

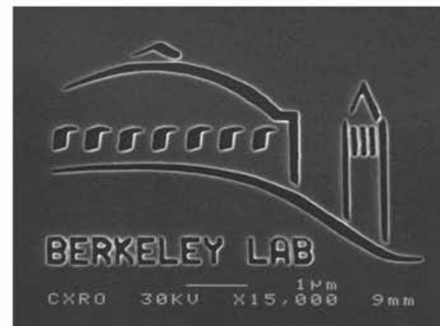
Pattern generator

System control computer

50-100 keV electron beam focused to 3-10 nm spot size

Thin resist recording layer on a multilevel wafer

Wafer stage (stationary during exposure)



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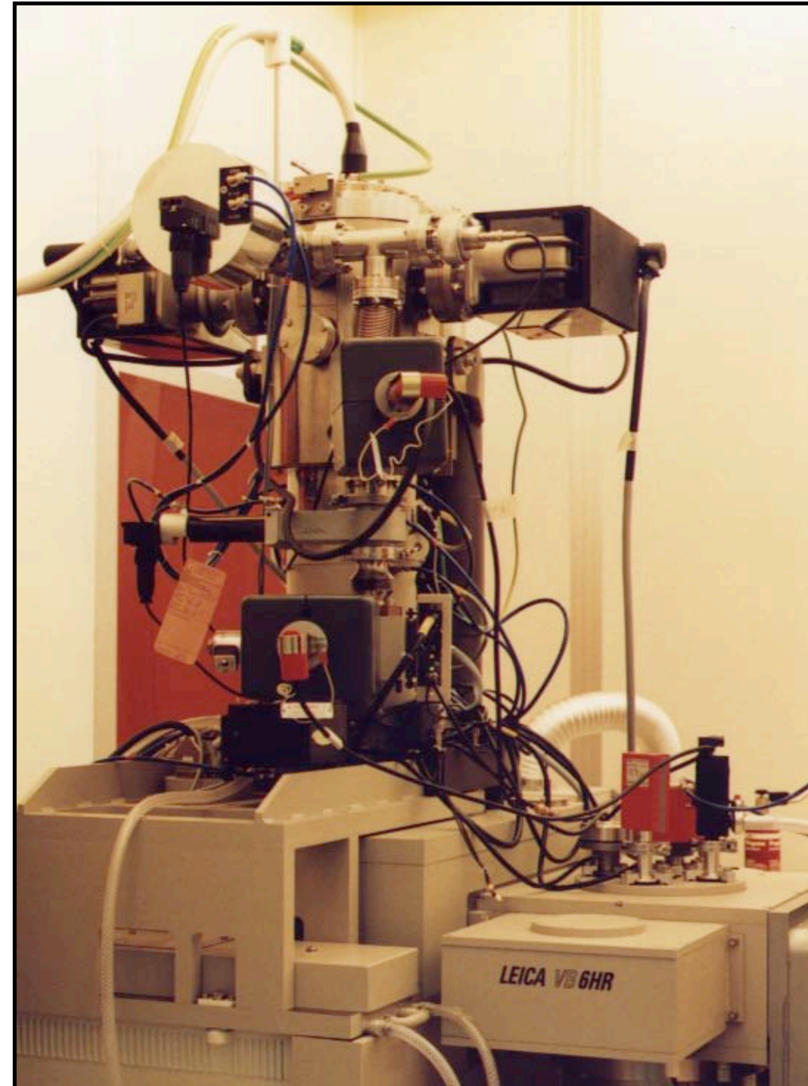
Courtesy of E. Anderson (LBNL)

LBNL Nanowriter: Unique Ultra-High Resolution, High Accuracy Electron Beam Lithography Tool

Key Specifications

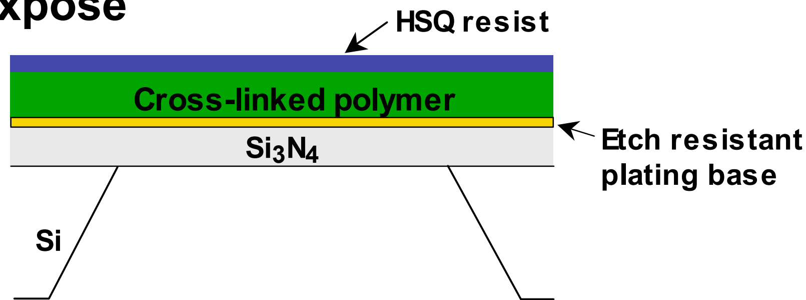
Parameter	Nanowriter
Beam size	5.0 nm 2.5 nm (New C3 lens)
Beam placement	2.5 nm (65 μm field) 20 nm (512 μm field)
Stitching	20 nm (1 cm field)
Beam voltage	20-100 kV
Beam current	1 nA at 10 nm 1.0-0.2 nA at 2.5 nm (new C3 lens)
Speed	25 MHz
Deflection field	16 bit
Interferometer	λ/1024
Wafer size	8"
Real time detection and feedback	Backscattered, transmitted and secondary electrons; digital image processing



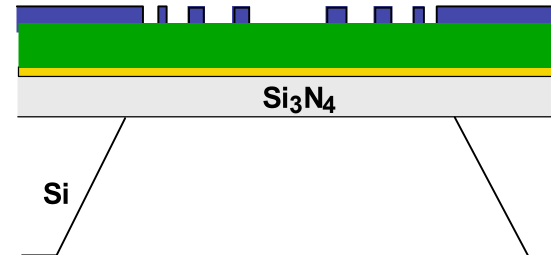
Courtesy of E. Anderson (LBNL)

Nanofabrication is Critical for High Fidelity, High Aspect Ratio Zone Plates

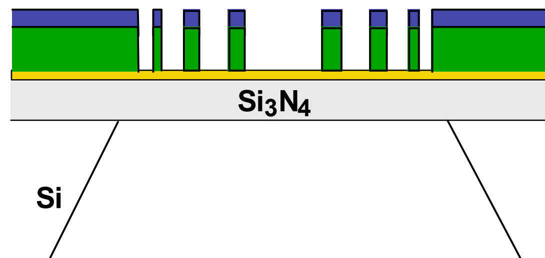
1. Expose



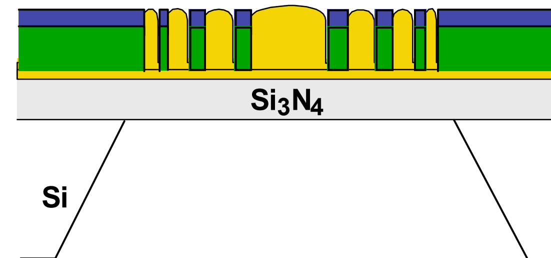
2. Develop



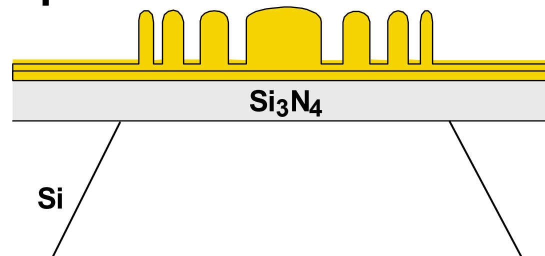
3. Cryogenic ICP Etch



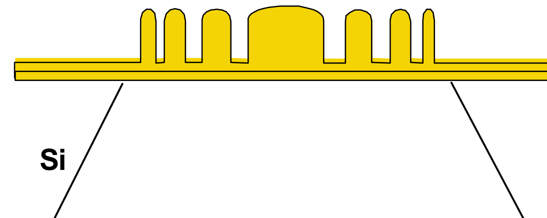
4. Plate



5. Strip Resist

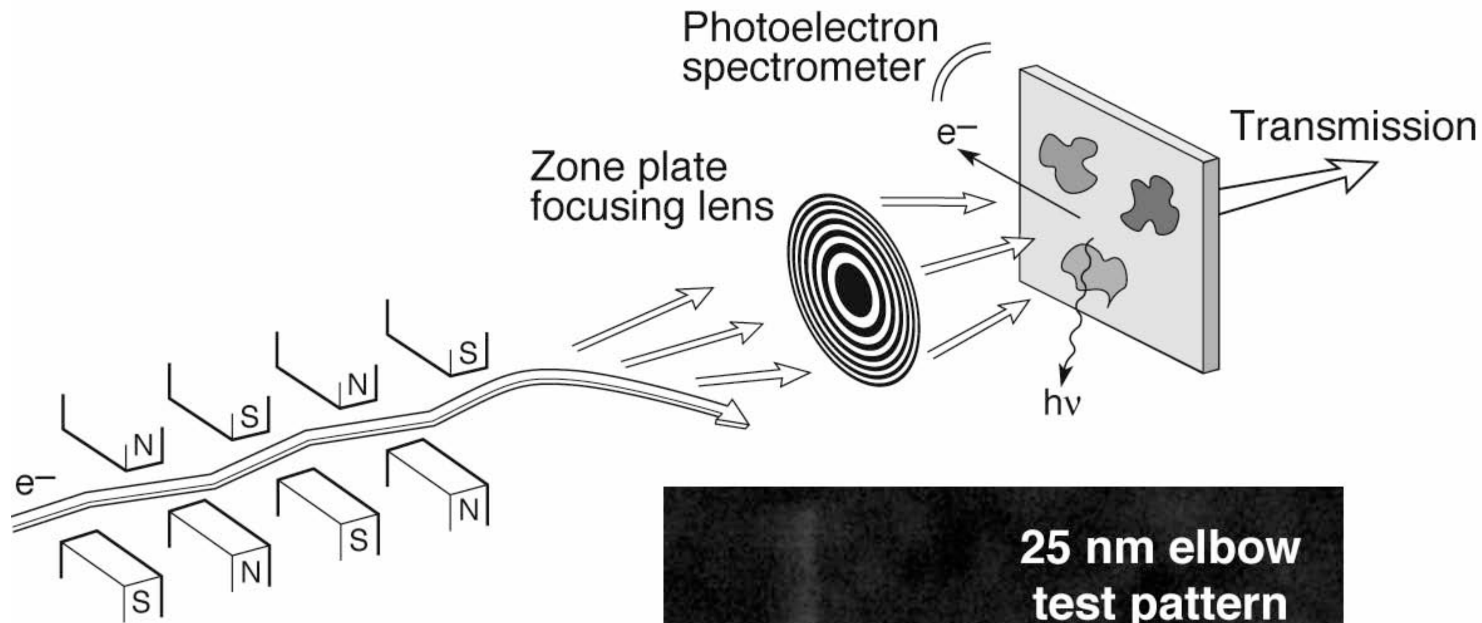


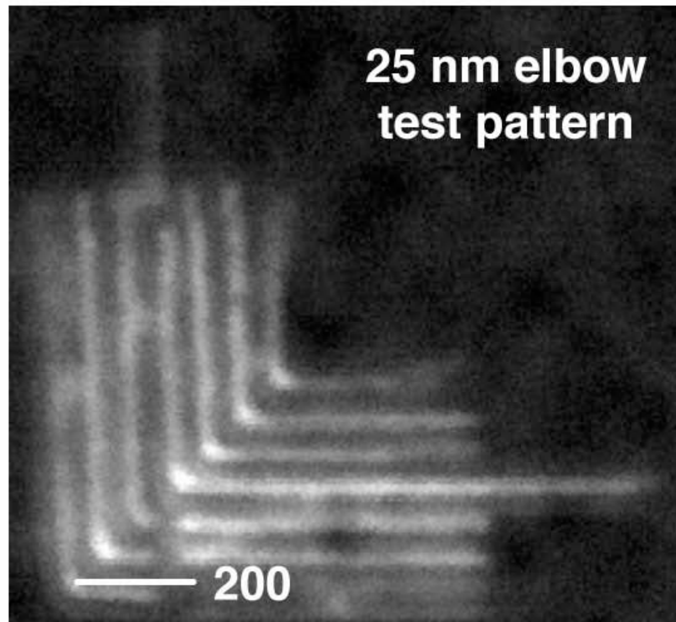
6. Strip Si_3N_4 and Cr/Au Plating Base



Courtesy of E. Anderson, A. Liddle, W. Chao, D. Olynick, and B. Harteneck (LBNL)

Spectromicroscopy: High Spatial and High Spectral Resolution Studies of Surface and Thin Films





Scanning Soft X-Ray Microscope

ALS beamline 11.0.2
395 eV; $\lambda/\Delta\lambda \simeq 6000$
240×240 pixels
$1.2\ \mu m \times 1.2\ \mu m$
2 ms dwell time

Courtesy of Tolek Tyliszczak (Dec. 2003)

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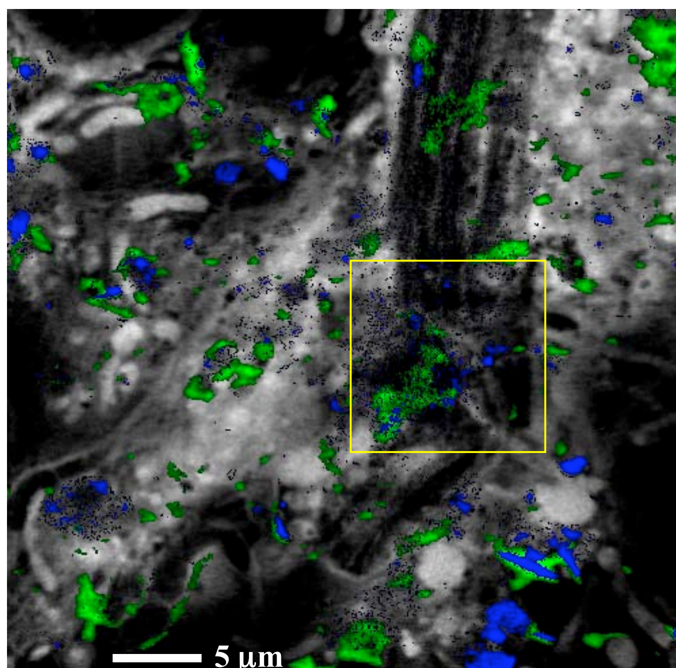
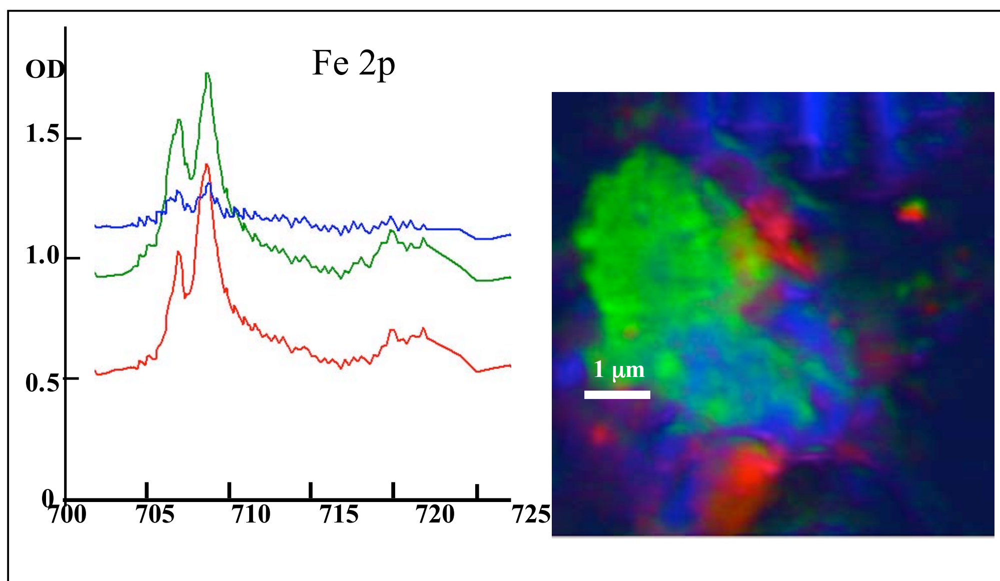
Biofilm from Saskatoon River



Protein (gray), Ca, K

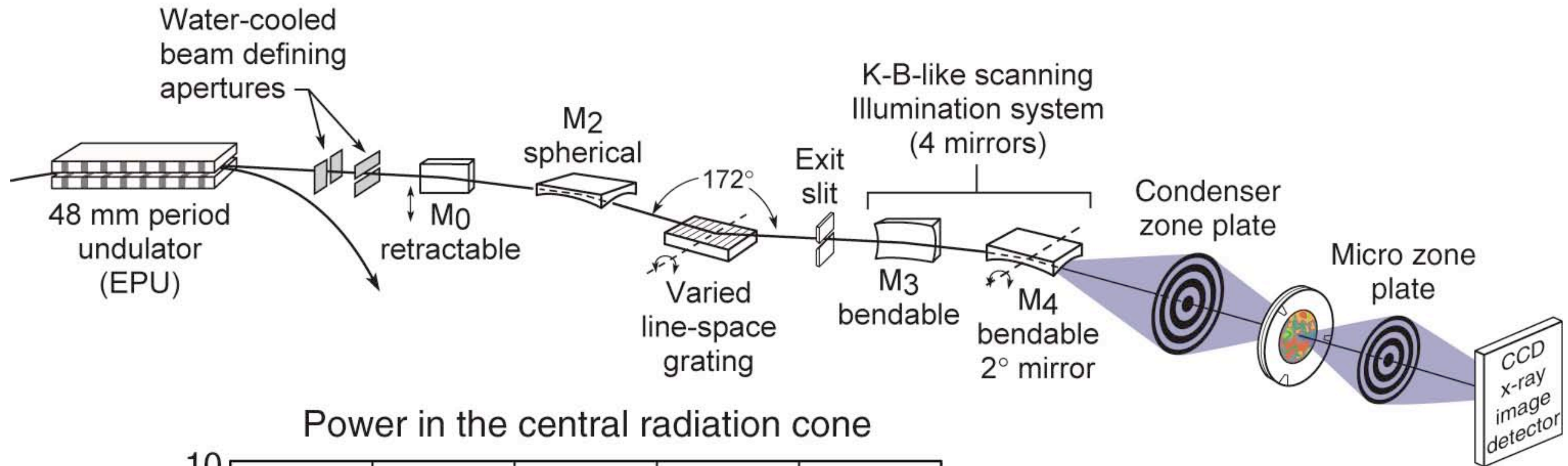
RESULTS
- Ni, Fe, Mn, Ca, K, O, C elemental map, (there was no sign of Cr.)
- Different oxidation states for Fe and Ni

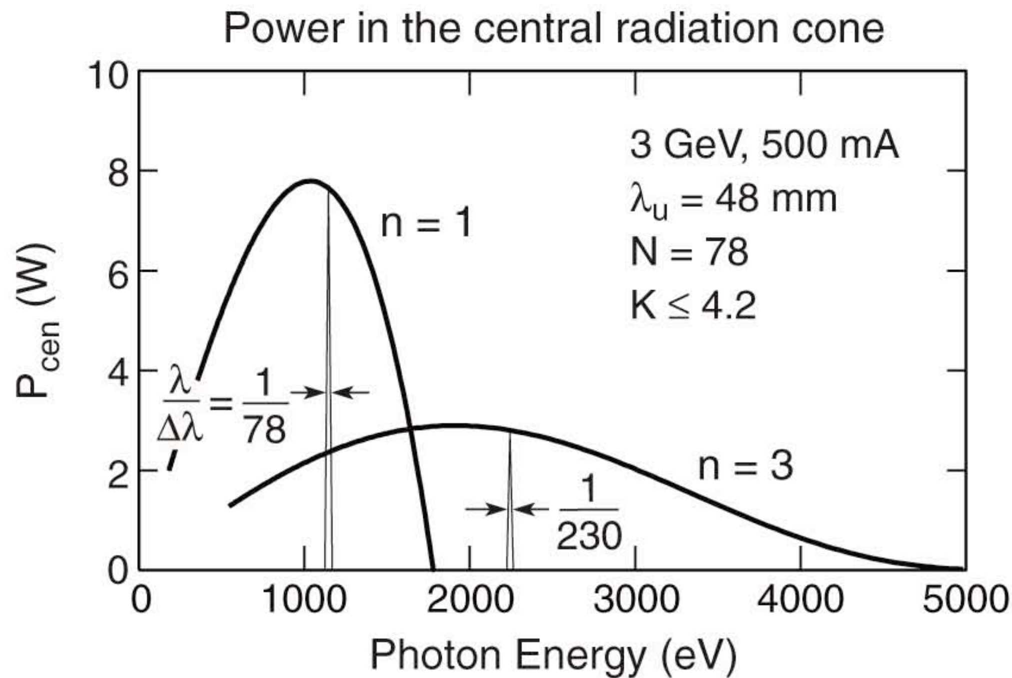


Different oxidation states (minerals) found for Fe & Ni

Tohru Araki, Adam Hitchcock (McMaster University)
Tolek Tyliszczak, LBNL
Sample from: John Lawrence, George Swerhone (NWRI-Saskatoon), Gary Leppard (NWRI-CCIW)

Beamline Layout for a High Spatial Resolution, High Spectral Resolution, Full Field Microscope





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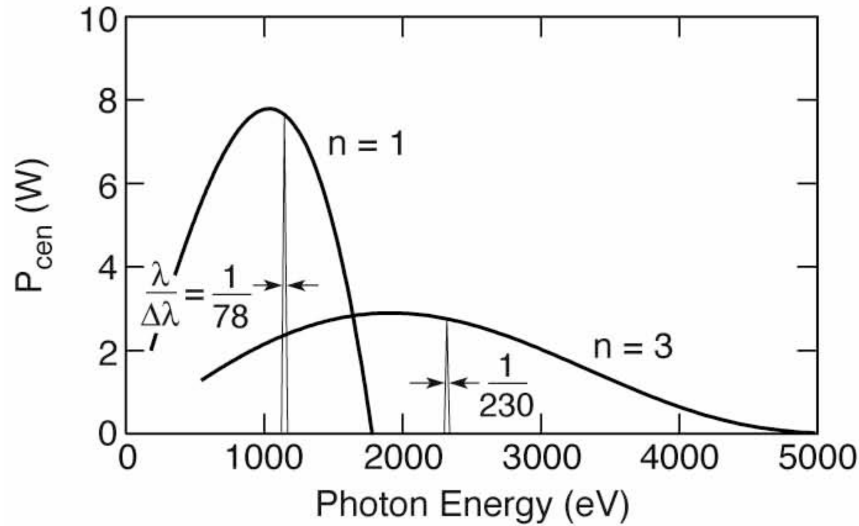
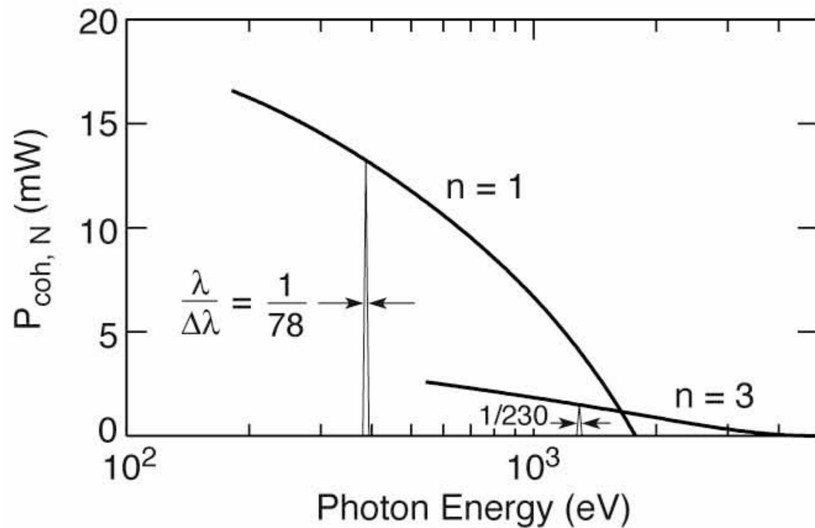
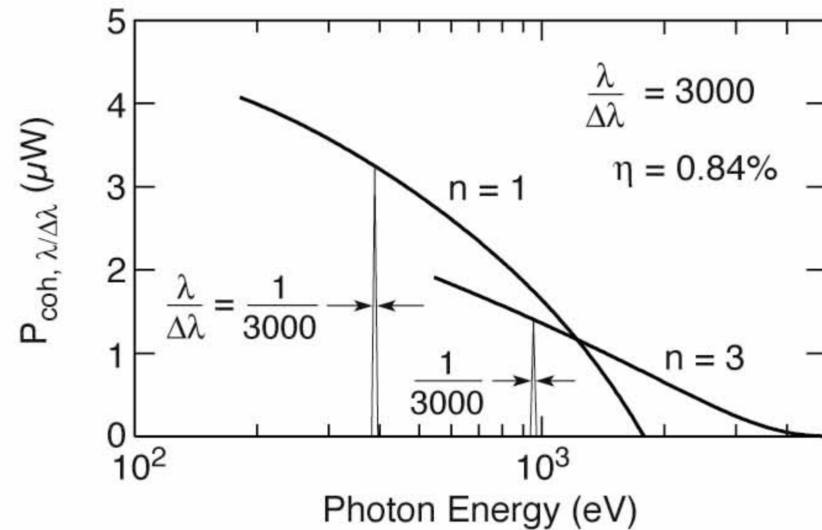
Power Curves for the Stanford EPU



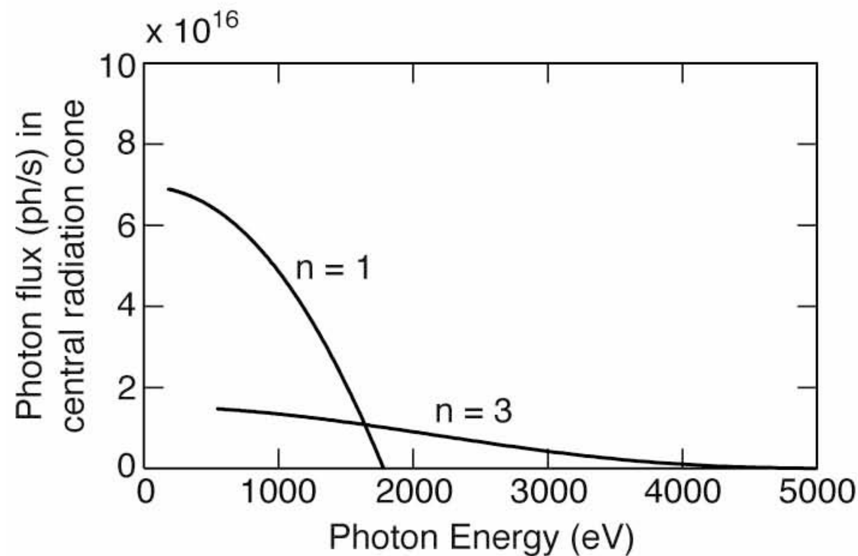
3 GeV, 500 mA
λ_u = 48 mm
N = 78
K ≤ 4.2
σ_h = 420 μm
σ_v = 42 μm
σ_h' = 42 μr
σ_v' = 6 μr
θ_{cen} = 30 μr



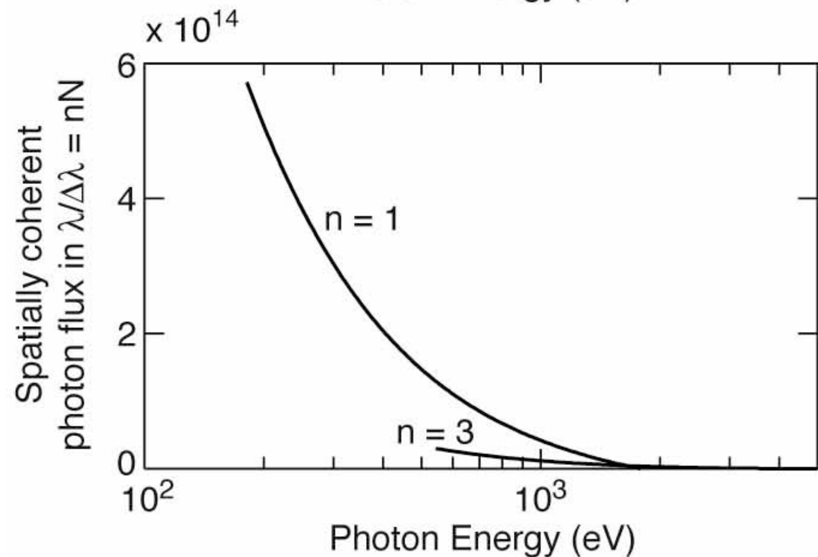


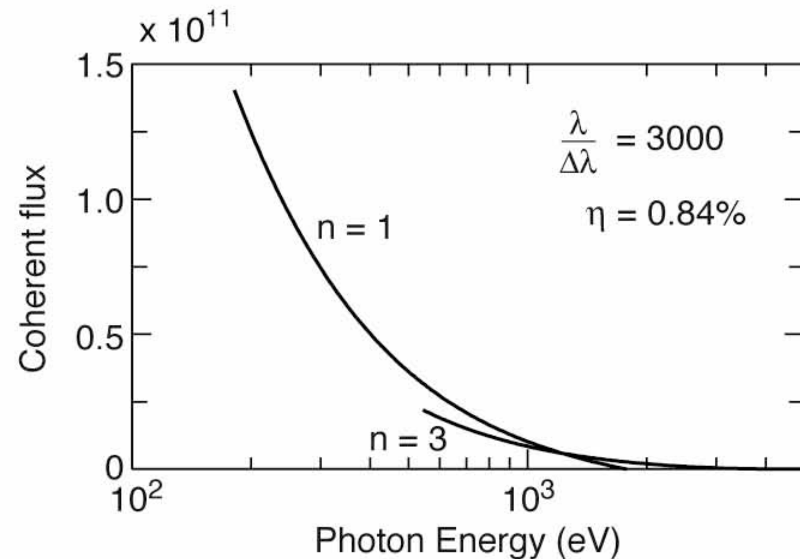
StanfordEPUpwr_Curves.ai

Photon Flux Curves for the Stanford EPU



3 GeV, 500 mA
λ_u = 48 mm
N = 78
K ≤ 4.2
σ_h = 420 μm
σ_v = 42 μm
σ_h' = 42 μr
σ_v' = 6 μr
θ_{cen} = 30 μr

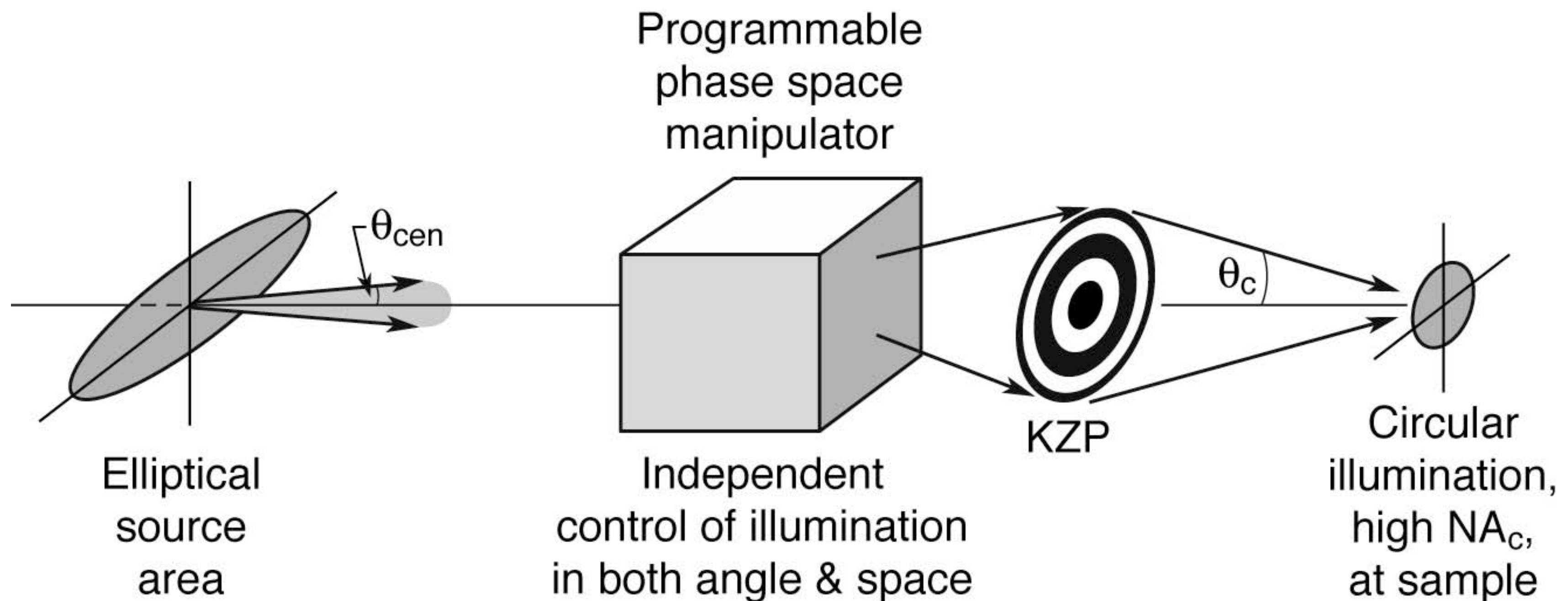




StanfordEPUflux_Curves.ai

A Novel Illuminator is Required

Scanning optics modify phase space, transforming elliptical spatial distribution to circular, and increasing the angular illumination to provide the desired degree of partial coherence. Based on experience with EUV lithographic imaging at ALS Beamline 12.0, P. Naulleau and P. Denham (CXRO), SRI-2003, p. 792.



P. Naulleau et al., *Optics Commun*. 234, 53 (2004)
P. Naulleau et al., *Appl. Optics* 42, 820 (2004)

Exposure Time for a Full Field, High Spatial and High Spatial Resolution, Soft X-Ray Microscope on an EPU at Stanford

Photon flux in central radiation cone / 6.43E+16 #/sec at 500 eV

(λ = 2.5 nm, $\lambda/\Delta\lambda$ = 78)

Spectral filter to $\lambda/\Delta\lambda$ = 3,000 / 1.7.76E+15

Beamline efficiency (0.84%)

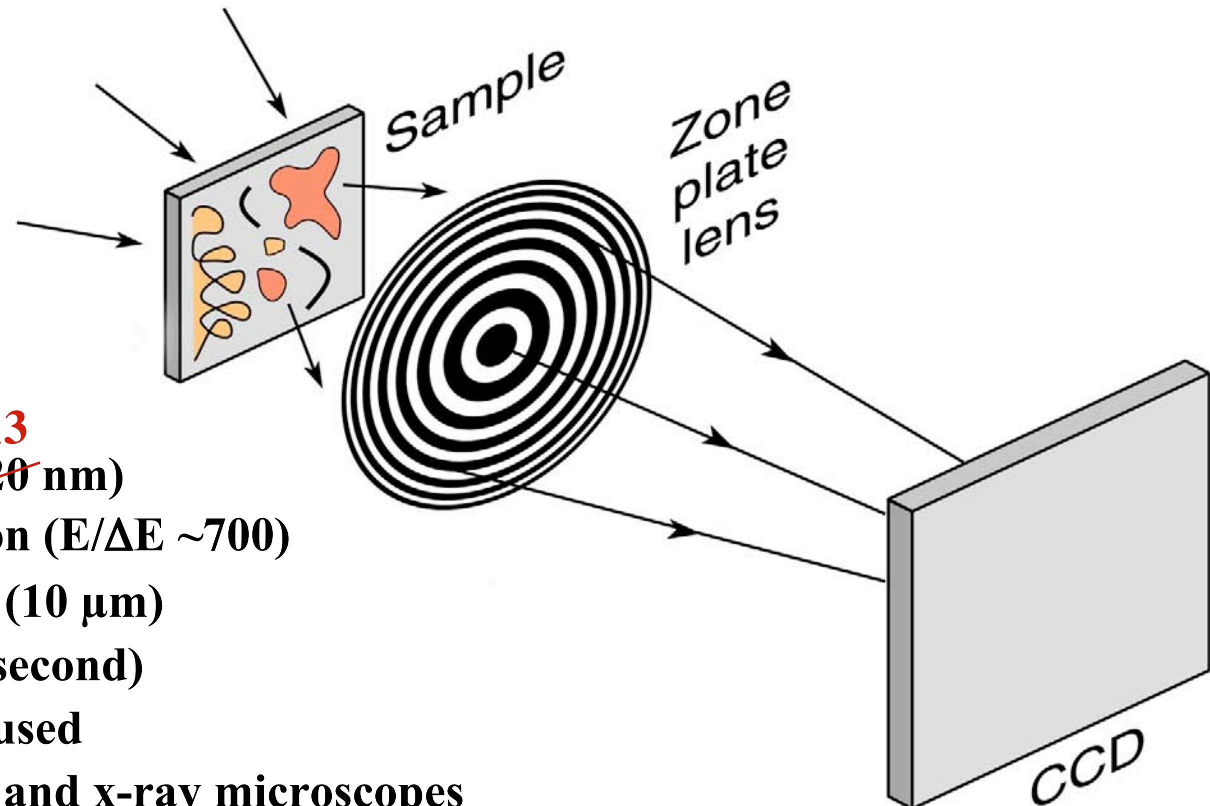
(7 mirrors plus 1 grating @ 10%) / 1.45E+13

CONDENSER		
type	ZP	D=10mm, Δr=30nm)
collection NA		rad
collection solid angle	8.26E-03	sr
magnification	5	
illumination NA	0.0413	rad
illumination solid angle		sr
sigma	6.70E-01	
KZP collection percetage	**100%**	
collected flux	**1.45E+13**	**#/sec at 2.5nm**
efficiency	**10%**	
post-condenser flux	**1.45E+12**	**#/sec at 2.5nm**
SAMPLE		
illumination area (ellipse)	20 x 20	μm^2
sample size	10 x 10	μm^2
illumination efficiency	**0.25**	
efficiency	**50%**	
flux after sample	**1.81E+11**	**#/sec at 2.5nm**
MZP		
MZP D	63	μm
MZP Δr	20	nm
MZP f	525	μm
MZP NA	0.06	
MZP efficiency	**8%**	
flux after MZP	**1.45E+10**	
CCD		
CCD pixel size	12.5 μm x 12.5 μm	
CCD pixels	(2048)^2	
CCD dimension	1" x 1"	
CCD efficiency	**80%**	
total flux onto CCD	**1.16E+10**	**#/sec at 2.5nm**
CCD counts per pixel per sec	**2.77E+03**	**#/sec at 2.5nm**
exposure time (for 10^3 counts per pixel)	**0.36**	**sec**

0.36 sec exposure time for full field microscope
λ = 2.5 nm, $\lambda/\Delta\lambda$ = 3000
Spatial resolution ~20 nm

C. Chang (Drexel), P. Naulleau, and D. Attwood

The XM-1 Soft X-Ray Microscope at the Advanced Light Source (ALS)



- High spatial resolution (~~20~~ 13 nm)
- Modest spectral resolution (E/ΔE ~700)
- Thick, hydrated samples (10 μm)
- Short exposure time (~1 second)
- Well engineered, pre-focused
- Mutually indexed visible and x-ray microscopes
- High throughput (hundreds of samples per day)
- Large image fields by tiling
- Easy access, user friendly
- Cryotomography

E = 250 - 1.8 keV
λ = 0.7 nm - 5 nm

High Resolution Zone-Plate Microscope XM-1 at the ALS

ALS Bending Magnet

Plane mirror

Condenser zone plate

Pinhole

Sample stage

Micro zone plate

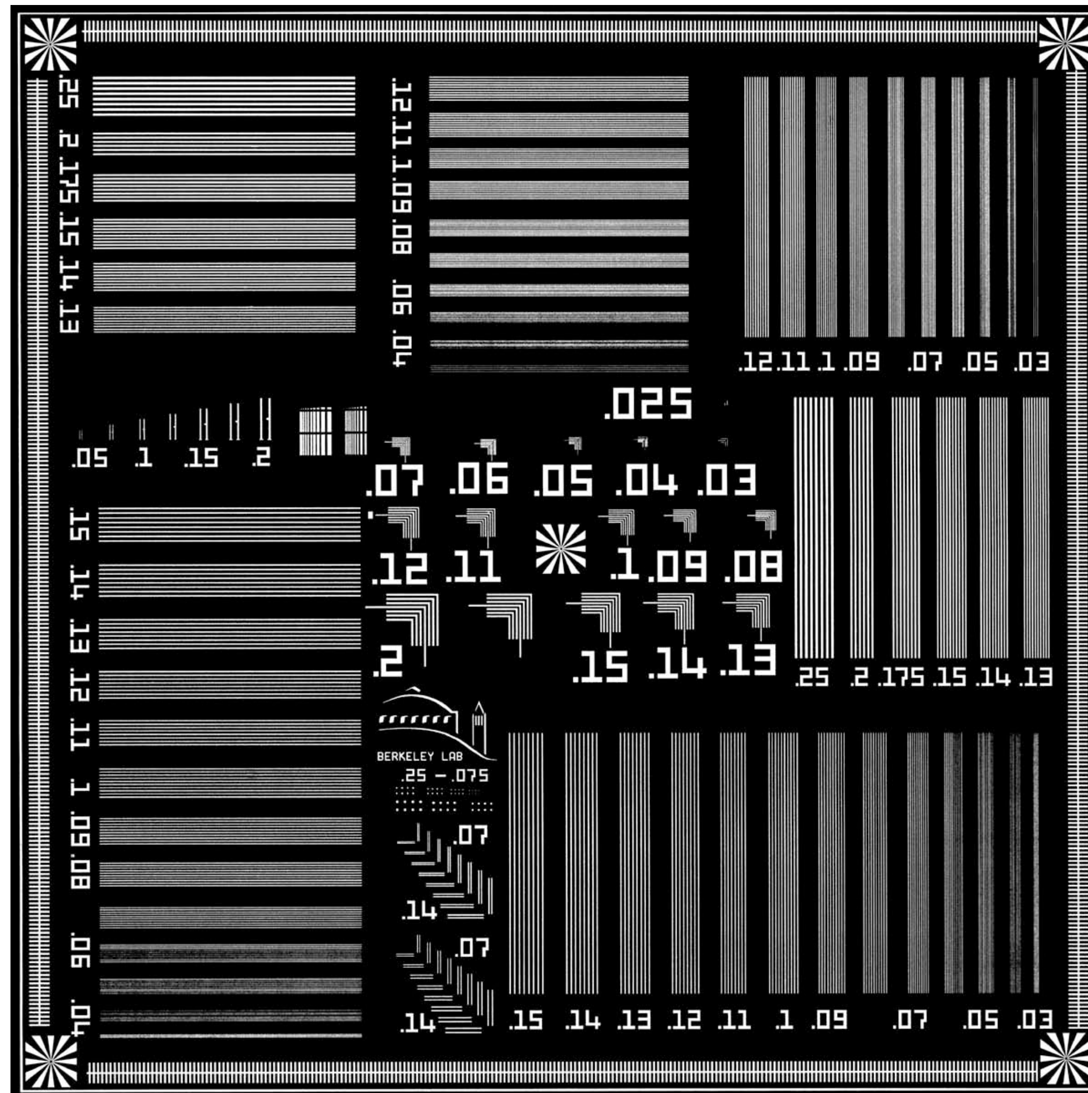
Soft x-ray sensitive CCD

Mutual Indexing System with kinematic mounts

Visible light microscope

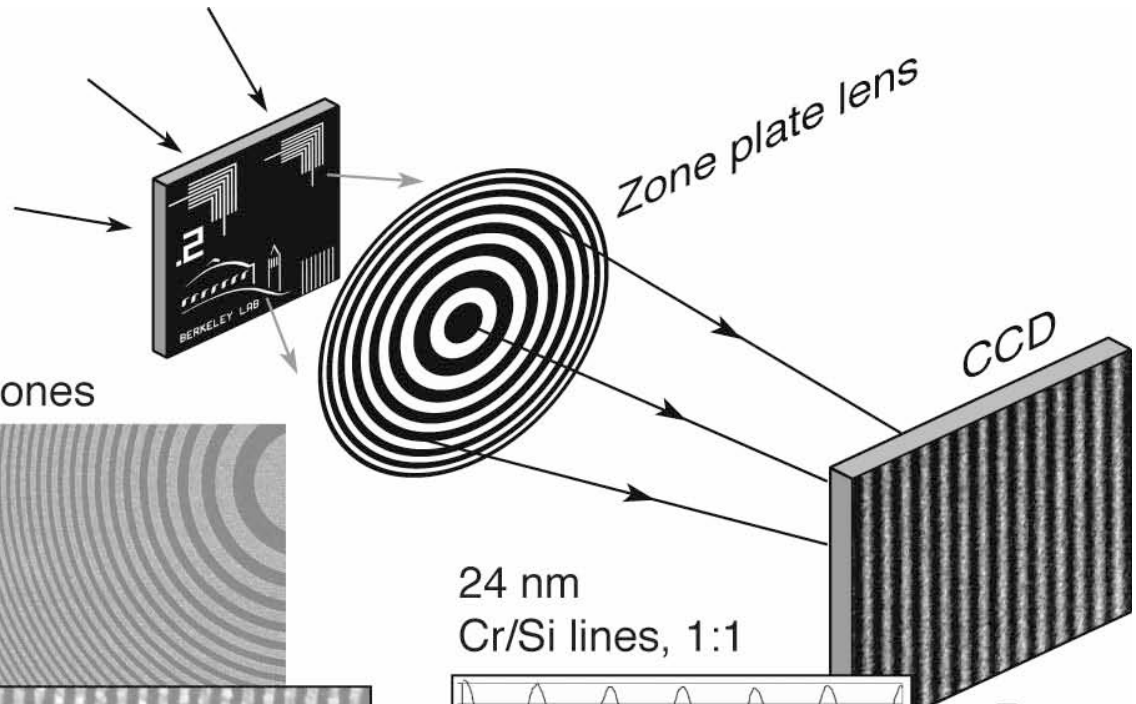
- Well engineered
- Sample indexing
- Tiling for larger field of view
- Pre-focused
- High sample throughput
- Illumination important
- Phase contrast

Test Pattern for Nanometer Soft X-Ray Imaging

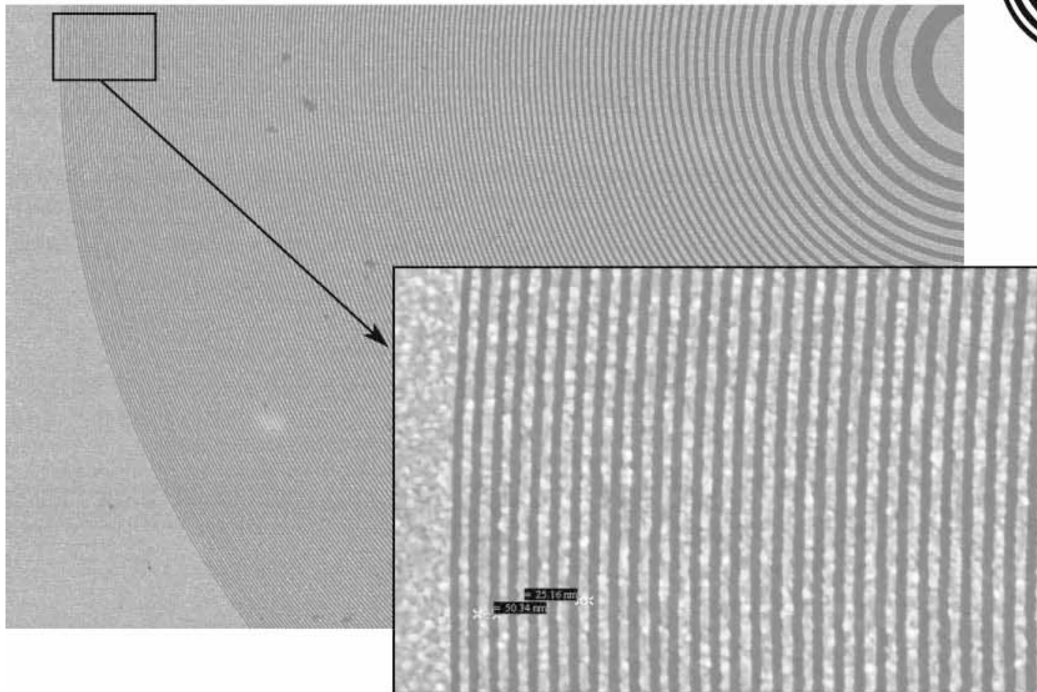


Courtesy of E. Anderson, D. Olynick, B. Harteneck, E. Veklerov

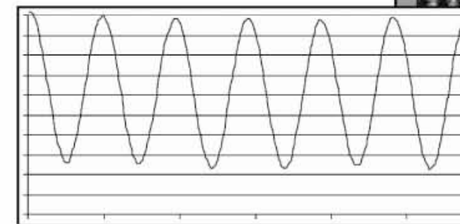
Soft X-Ray Microscopy at the ALS: 20 nm Spatial Resolution



Δr = 25 nm, D = 63 μm, N = 618 zones



E. Anderson (LBNL)

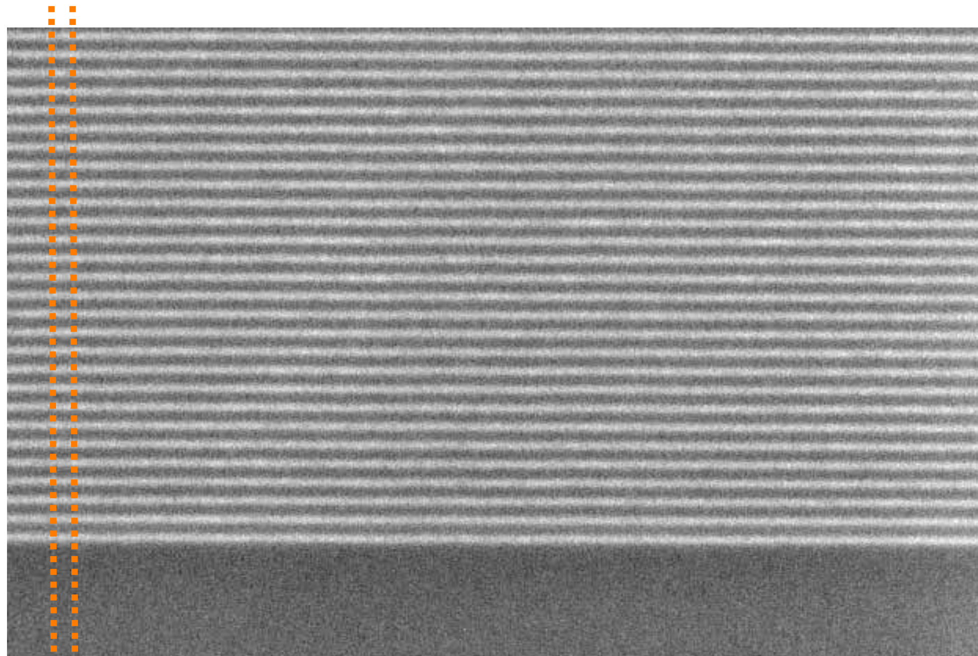


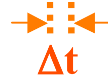
W. Chao (UCB & LBNL)

W. Chao et al.,
Opt. Lett. 28, 2019 (Nov 2003)

20nmSpatialResRev.7.04.ai

Multilayer Mirror Coatings Can Be Thinned and Used As Sub-20 nm Test Patterns



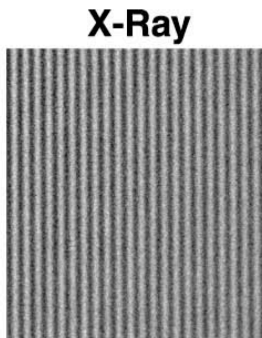


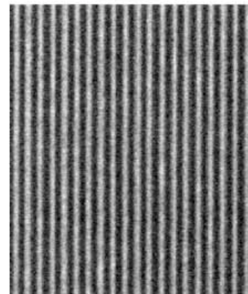
Courtesy of W. Chao (UCB & CXRO/LBNL)

SEM Micrograph of Cr/Si test pattern

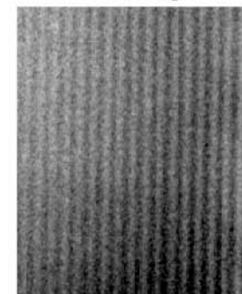
High quality test patterns can be fabricated with sections as thin as 5 nm.

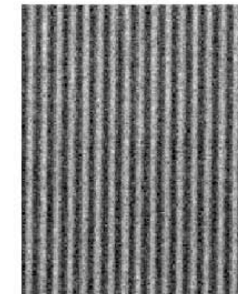
Near Diffraction Limited Soft X-Ray Microscopy: 20 nm Spatial Resolution at 2.07 nm Wavelength



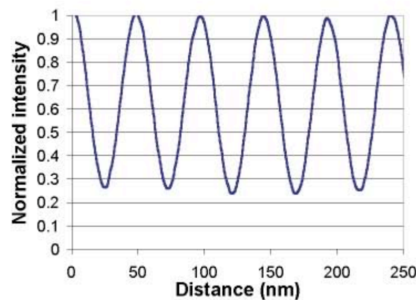


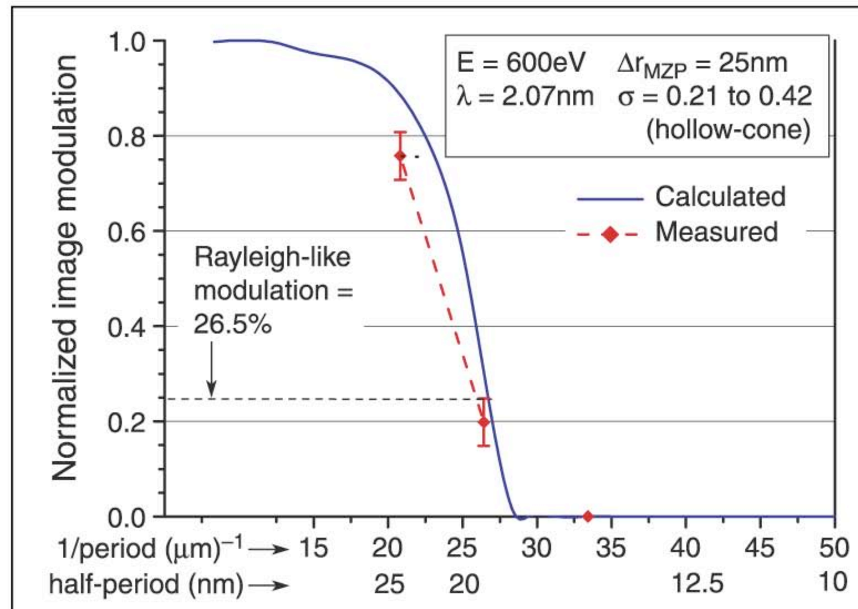
24 nm lines and spaces (Cr/Si)
75% modulation
600 eV (2.07 nm)





19 nm lines and spaces (Cr/Si)
20% modulation



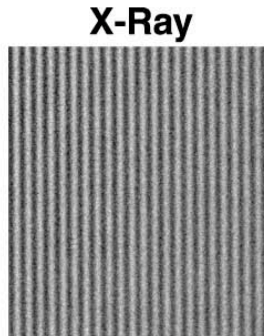


(Courtesy of Weilun Chao, UC Berkeley and CXRO/LBNL)

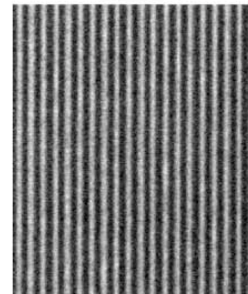
W. Chao et al.,
Opt. Lett. 28, 2019 (Nov 2003)

Near Diffraction Limited Soft X-Ray Microscopy: 20 nm Spatial Resolution at 2.07 nm Wavelength

X-Ray

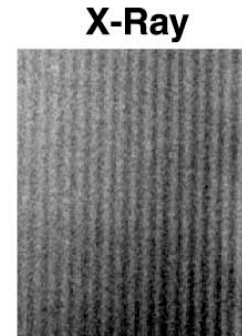


SEM

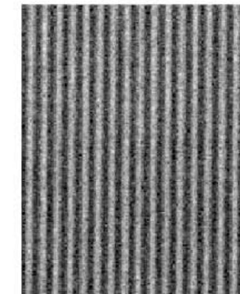


24 nm lines and spaces (Cr/Si)
75% modulation
600 eV (2.07 nm)

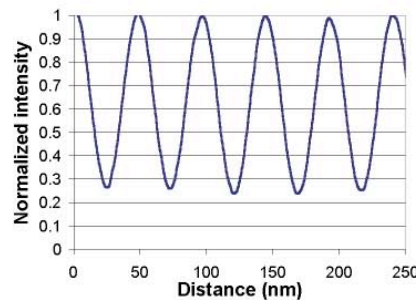
X-Ray

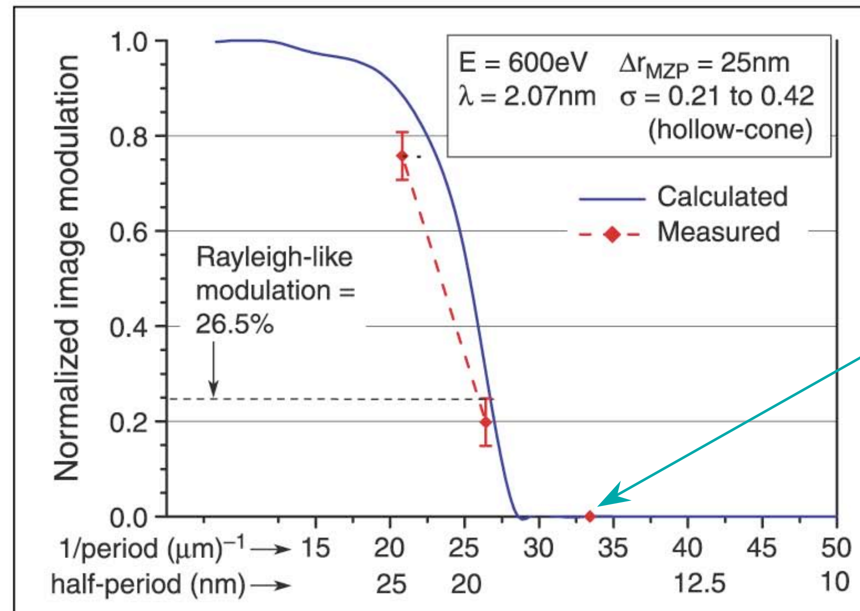


SEM



19 nm lines and spaces (Cr/Si)
20% modulation (barely "resolved")



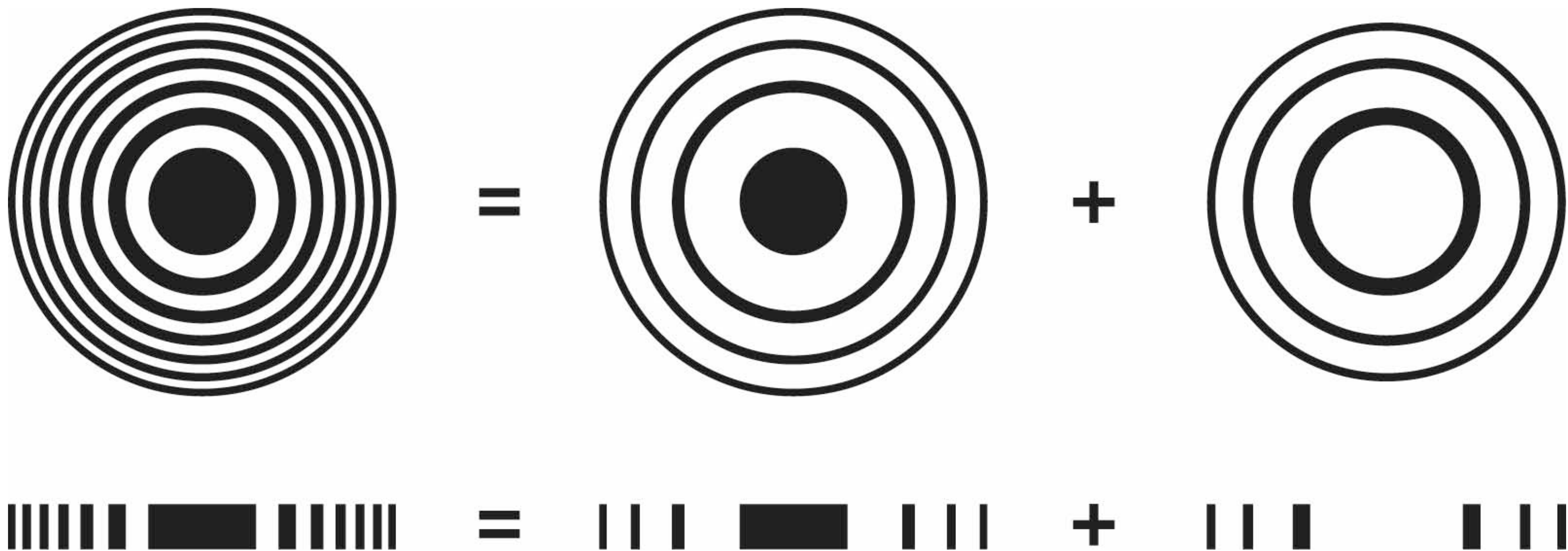


15 nm lines
not resolved,
no modulation

(Courtesy of Weilun Chao, UC Berkeley and CXRO/LBNL)

W. Chao et al.,
Opt. Lett. 28, 2019 (Nov 2003)

New Overlay Nanofabrication Technique for Narrower Outer Zones



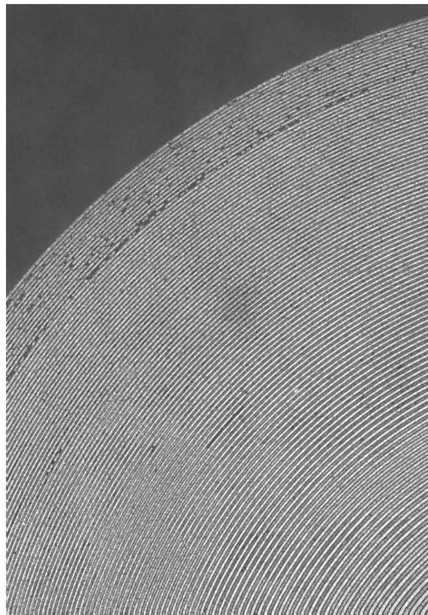
$\Delta r = 15$ nm
$\Delta t = 90$ nm
Overlay $\simeq$ 2 nm accuracy

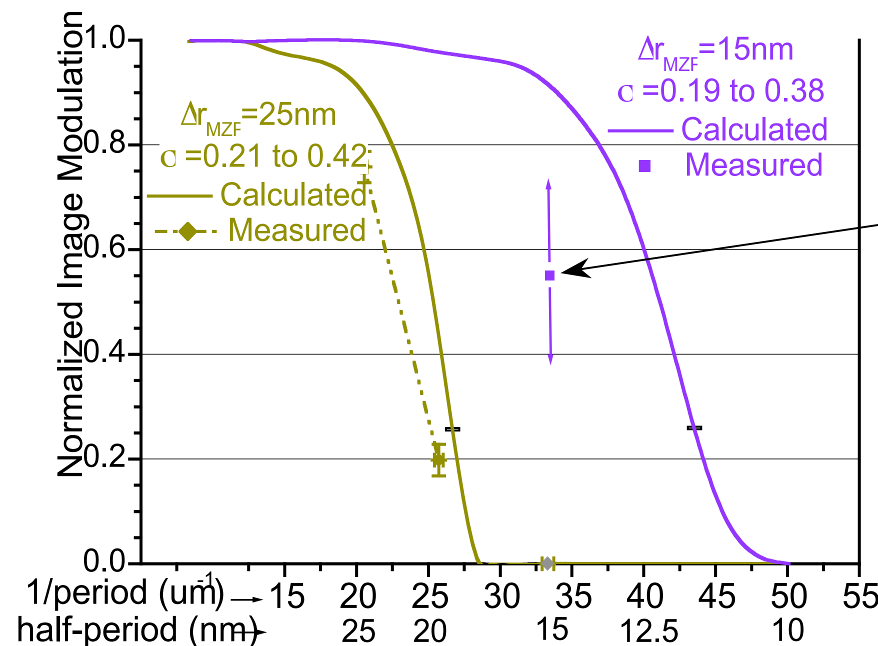
Courtesy of J.A. Liddle, E.H. Anderson, B. Harteneck and W. Chao, LBNL

New Results Using Overlay Nanofabrication: Outer Zone Width of 15 nm

- Zone plate lenses made using a new, e-beam based nanofabrication technique have extended outer zones from 25 nm to 15 nm.
- The new lenses work as expected, resolving fine patterns not seen previously
- Shorter depth of focus (λ/NA^2) opens the opportunity for soft x-ray "optical sectioning" of biological material.

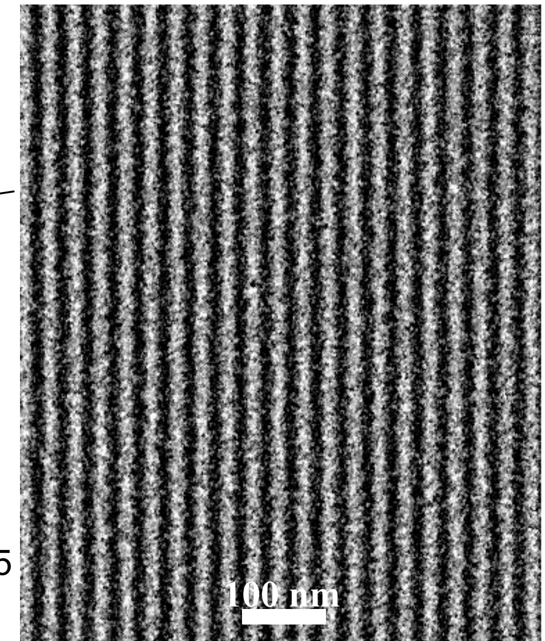
New zone plate lens with 15 nm outer zone width





Courtesy of W. Chao, A. Liddle, E. Anderson, and B. Harteneck (CXRO/LBNL)

Soft x-ray image of 15 nm Cr/Si lines & spaces

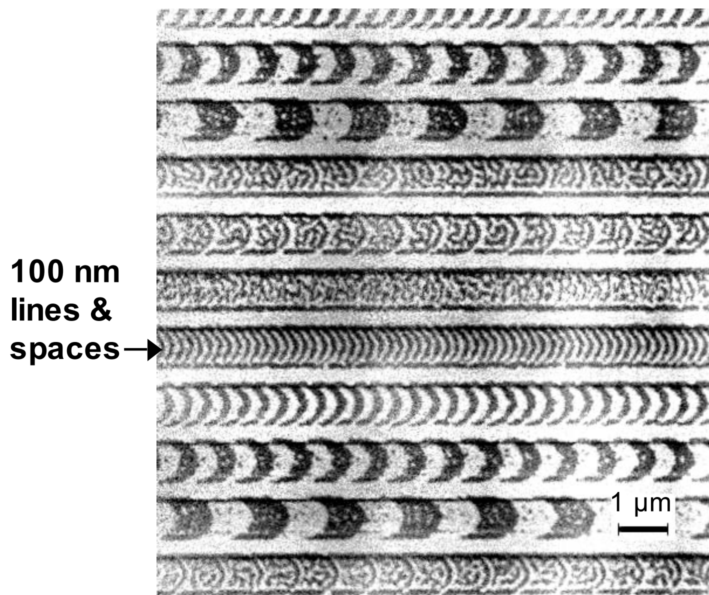


(Nature, in press)

Applications of Soft X-Ray Microscopy

Magnetic Recording Materials

100 nm lines & spaces

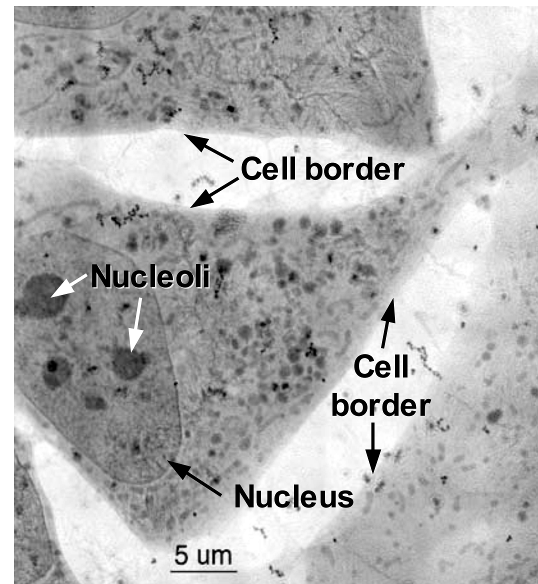


Fe L_3 @ 707.5 eV

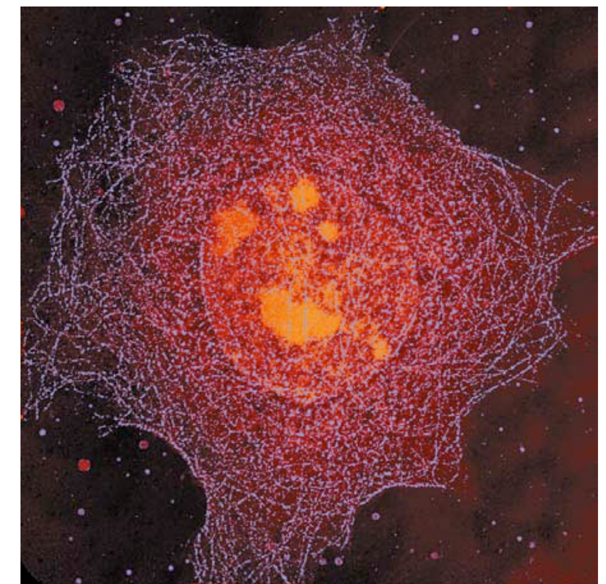
FeTbCo Multilayer
with AL Capping Layer

Courtesy of P. Fischer (Max Planck)
and G. Denbeaux (CXRO/LBNL)

Cryo Microscopy for the Life Sciences



Cryo X-Ray Microscopy
of 3T3 Fibroblast Cells



Protein Labeled
Microtubule Network

Courtesy of C. Larabell (UCSF)
and W. Meyer-Ilse (CXRO/LBNL)

The Water Window for Biological X-Ray Microscopy

Absorption length (μm)

10.0
1.0
0.1

Water

Protein

S C N O

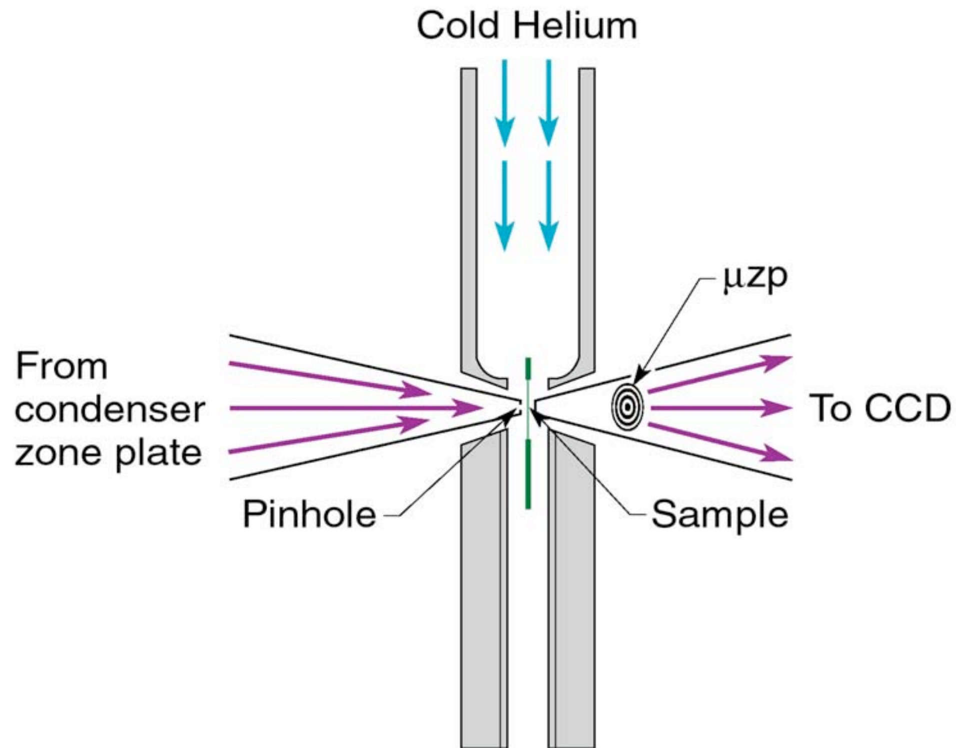
Typical protein:
Carbon 52.5%
Oxygen 22.5%
Nitrogen 16.5%
Hydrogen 7.0%
Sulfur 1.5%

0 200 400 600 800 1000

Photon energy (eV)

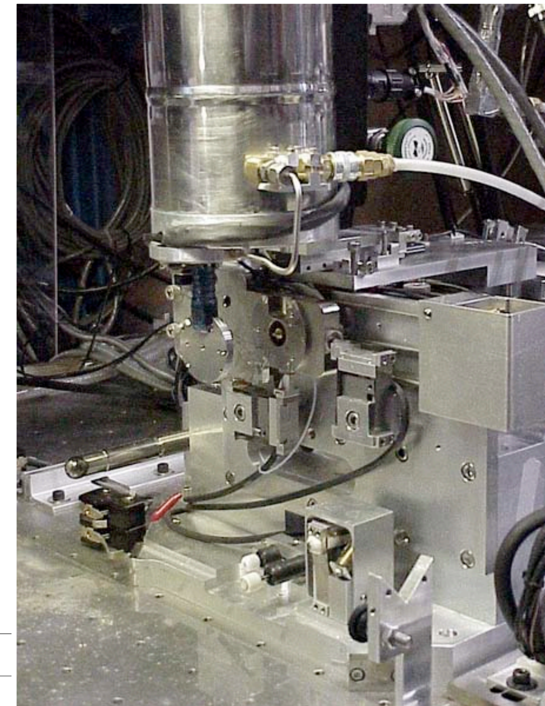
Ch09_F25VG.ai

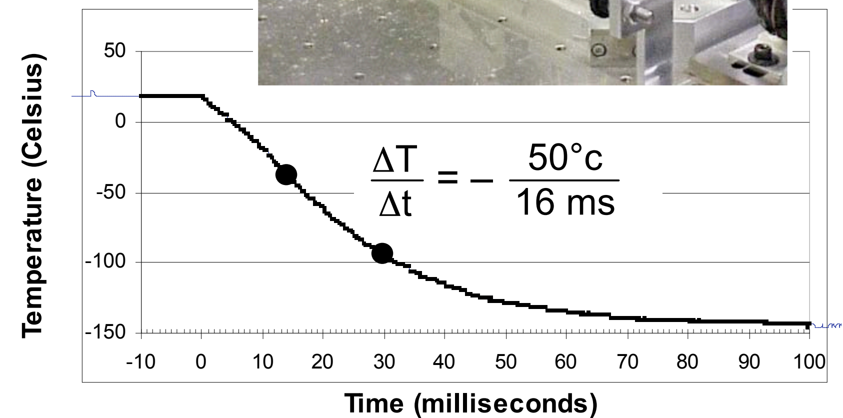
Fast Freeze Cryo Fixation Strongly Mitigates Radiation Dose Effects



Helium passes through LN, is cooled, and directed onto sample windows

Fast Freeze

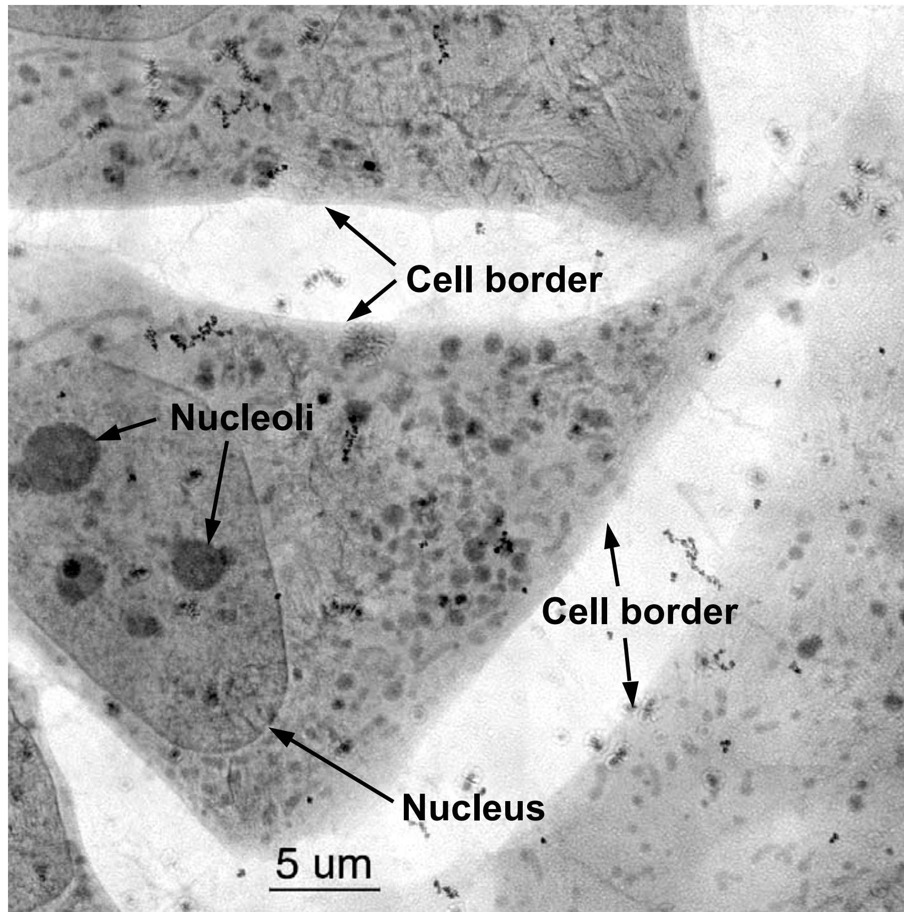


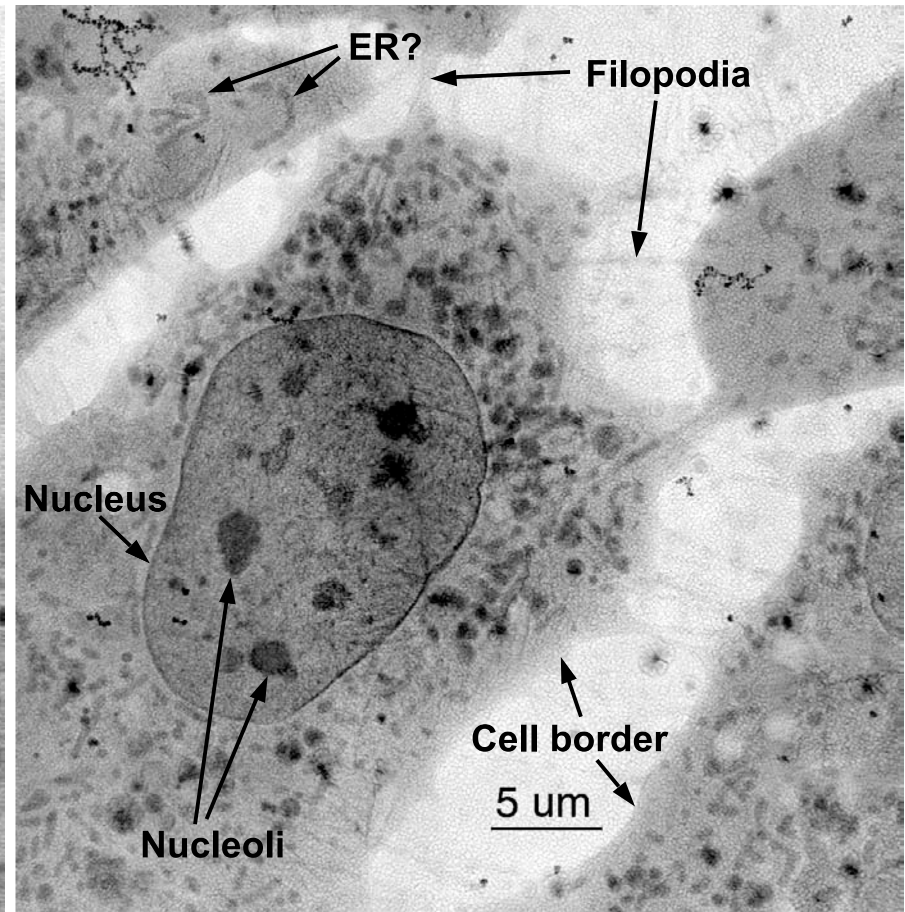


W. Meyer-Ilse, G. Denbeaux, L. Johnson, A. Pearson (CXRO-LBNL)

Organelle Details Imaged with Cryogenic Preservation and High Spatial Resolution

Cryo x-ray microscopy of 3T3 fibroblast cells





C. Larabell, D. Yager, D. Hamamoto, M. Bissell, T. Shin (LBNL Life Sciences Division)
W. Meyer-Ilse, G. Denbeaux, L. Johnson, A. Pearson (CXRO-LBNL)

Bending Magnet Radiation Used With a Soft X-Ray Microscope to Form a High Resolution Image of a Whole, Hydrated Mouse Epithelial Cell

$\hbar w$ = 520 eV

32 μm x 32 μm

Ag enhanced Au labeling of the microtubule network, color coded blue.

Cell nucleus and nucleoli, moderately absorbing, coded orange.

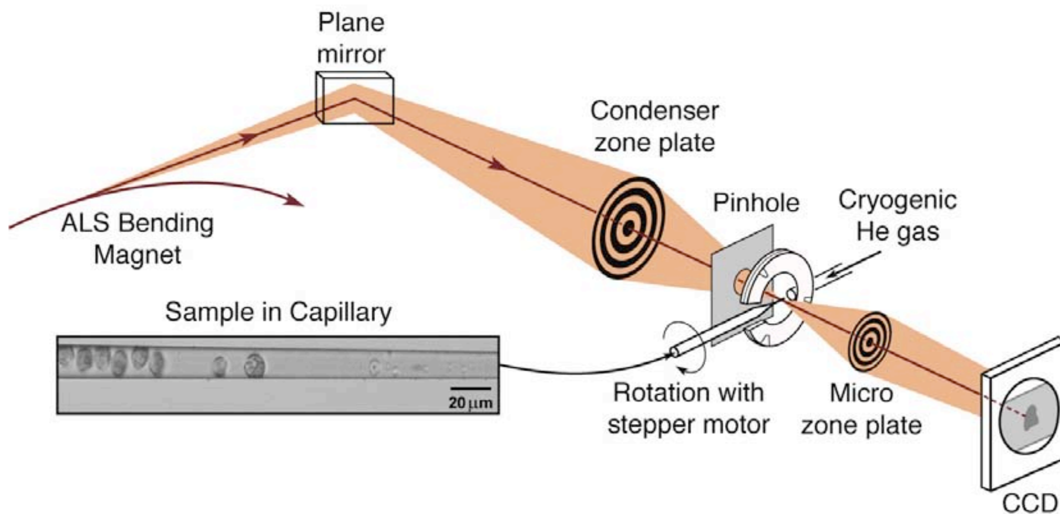
Less absorbing aqueous regions coded black.

W. Meyer-Ilse et al.
J. Microsc. 201, 395 (2001)

Courtesy of C. Larabell and W. Meyer-Ilse (LBNL)

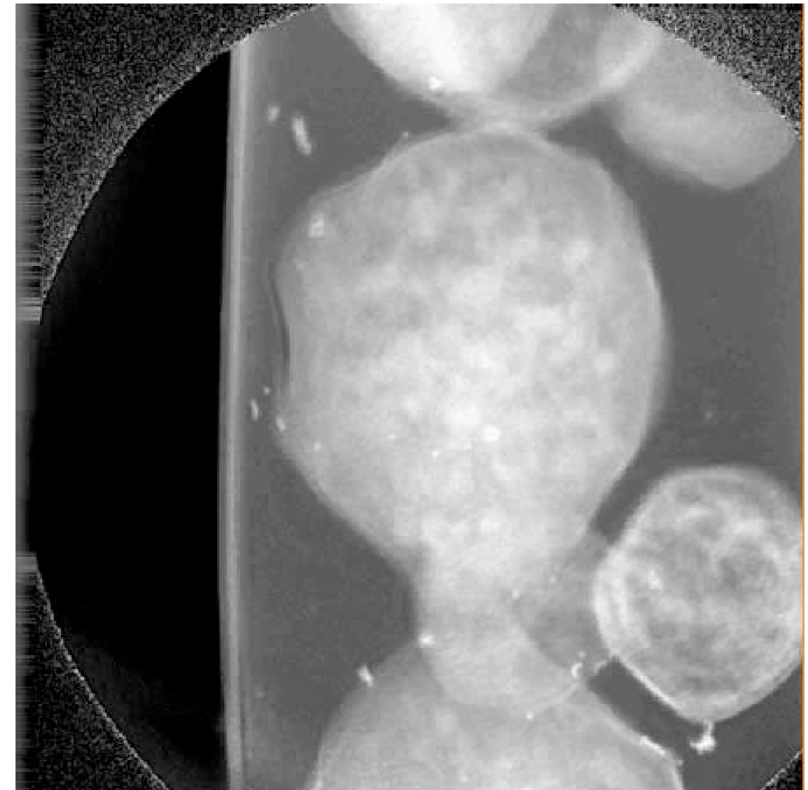
Bio-Nanotomography for 3D Imaging of Cells

Nanotomography of Cryogenic Fixed Cells



Courtesy of G. Schneider (BESSY)
Surf. Rev. Lett. 9, 177 (2002)

Soft X-Ray Nanotomography of a Yeast Cell

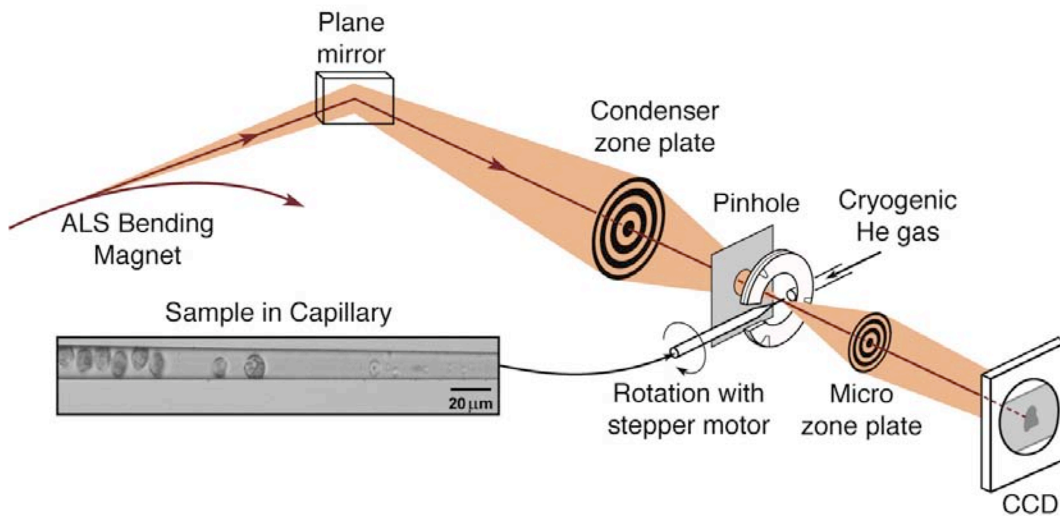


λ = 2.5 nm

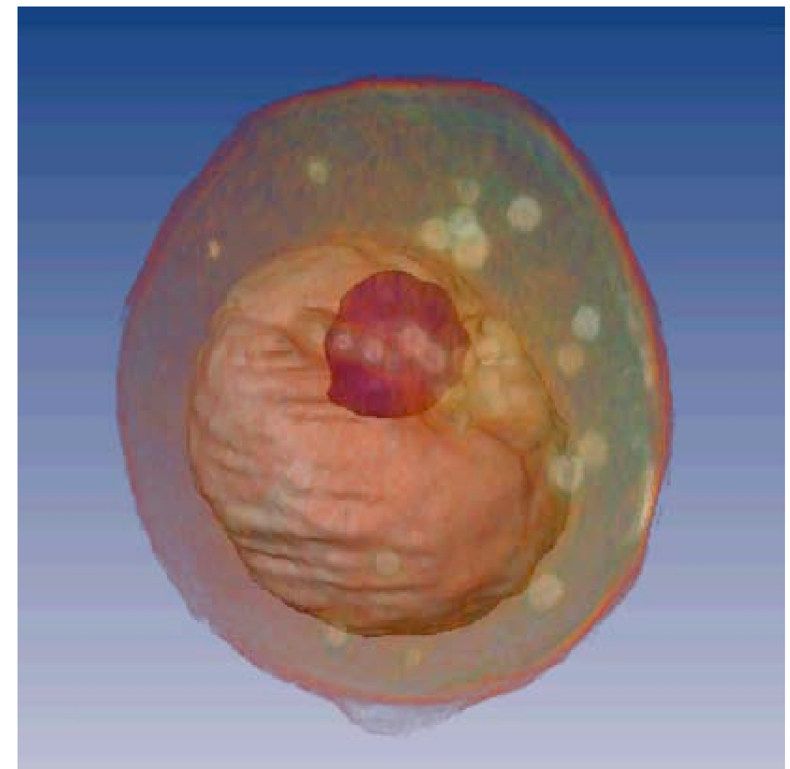
Courtesy of C. Larabell (UCSF & LBNL) and M. LeGros (LBNL)

Bio-Nanotomography for 3D Imaging of Cells

Nanotomography of Cryogenic Fixed Cells



Soft X-Ray Nanotomography of a Yeast Cell



λ = 2.5 nm

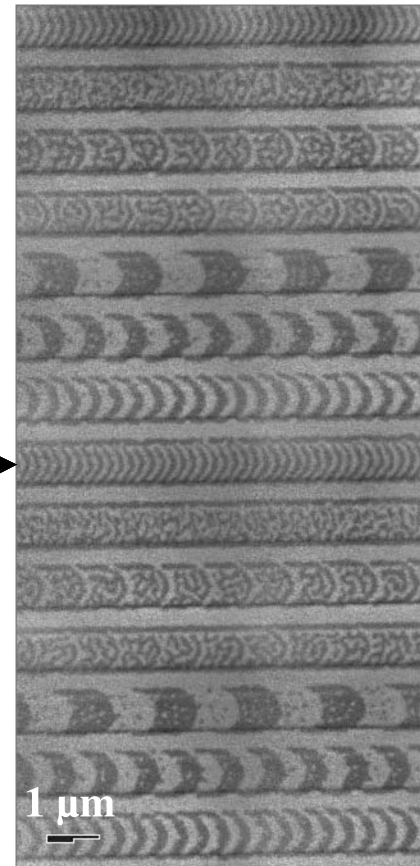
C. Larabell and M. LeGros,
Molec. Bio. Cell 15, 957 (2004)

Magnetic X-Ray Microscopy Using X-Ray Magnetic Circular Dichroism (XMCD)

Magnetic X-Ray Microscopy

- High spatial resolution in transmission
- Bulk sensitive (thin films)
- Complements surface sensitive PEEM
- Good elemental sensitivity
- Good spin-orbit sensitivity
- Allows applied magnetic field
- Insensitive to capping layers
- In-plane and out-of-plane measurements

100 nm lines & spaces →



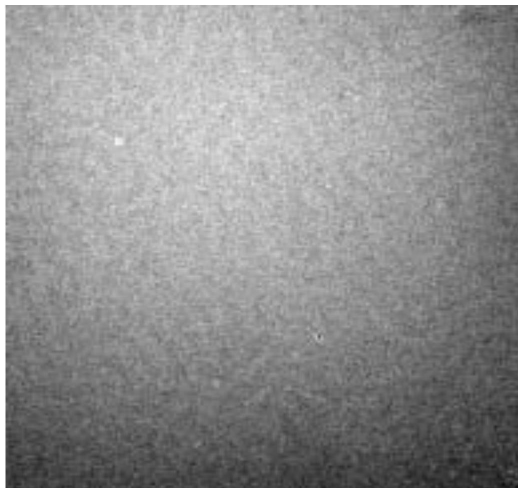
Courtesy of P. Fischer, (MPI, Stuttgart) and G. Denbeaux (CXRO/LBNL)

Magnetic Domains Imaged at Different Photons Energies

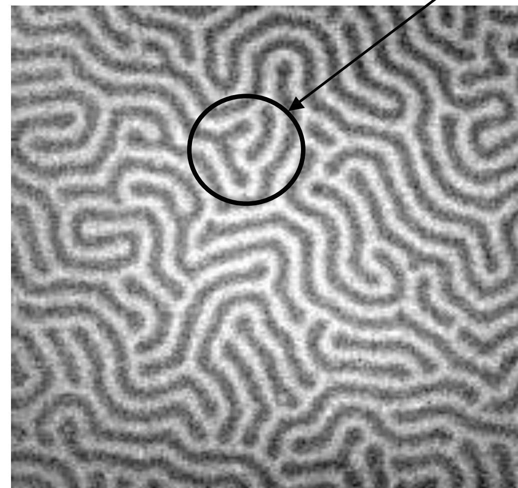
FeGd Multilayer

Contrast reversal

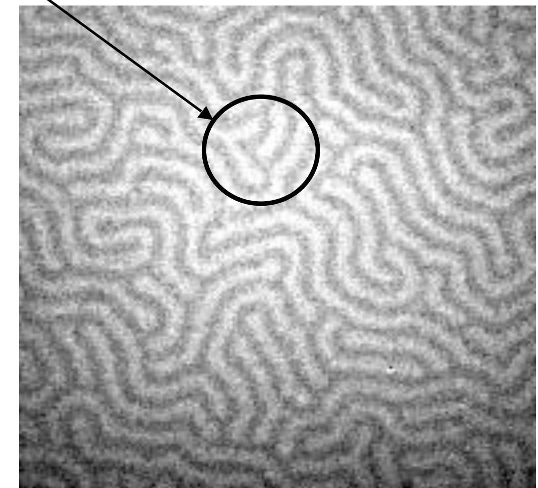
1 μm



$\hbar\omega$ = 704 eV
below Fe L-edges



$\hbar\omega$ = 707.5 eV
Fe L_3-edge



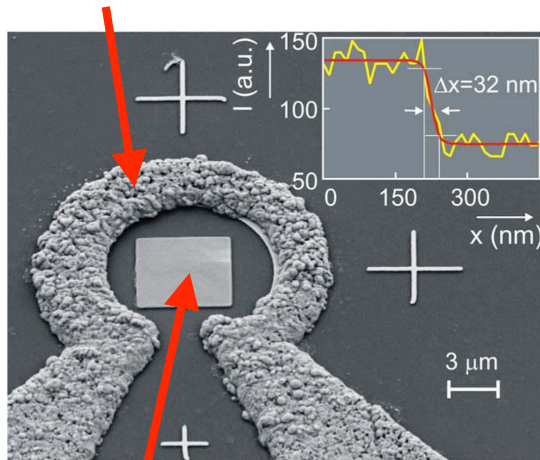
$\hbar\omega$ = 720.5 eV
Fe L_2-edge

P. Fischer, T. Eimueller, M. Koehler (U. Wuerzberg)
S. Tsunashima (U. Nagoya) and N. Tagaki (Sanyo)
G. Denbeaux, L. Johnson, A. Pearson (CXRO-LBNL)

Imaging of Ultrafast Spin Dynamics with Magnetic Soft X-Ray Transmission Microscopy

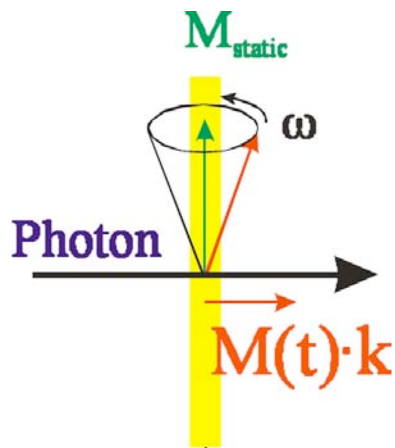
P. Fischer et al., MPI-MF, Stuttgart, Germany (now LBNL)

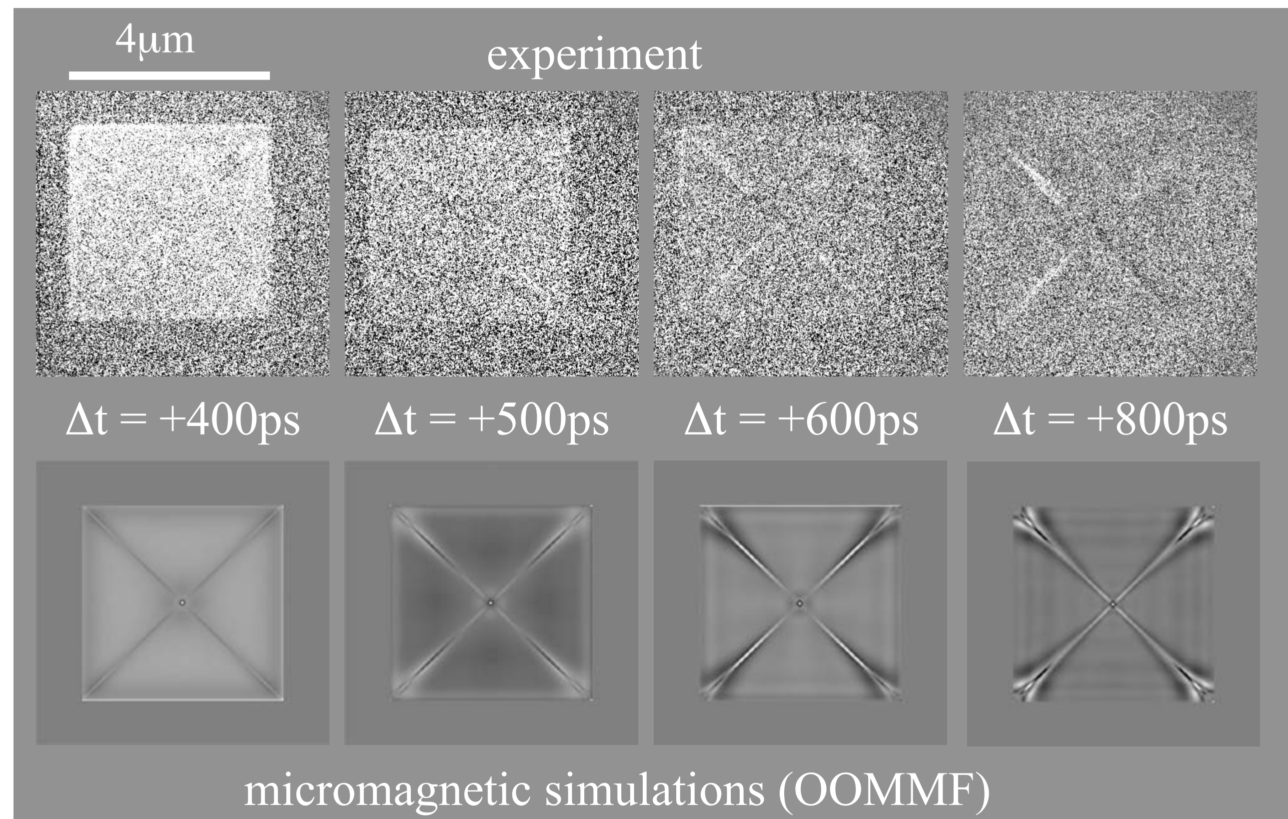
Microcoil



Sample: 4x4μm² PY element

- stroboscopic pump-and-probe technique at variable delay times (Δt)
- high lateral resolution (<20nm) provided by Fresnel zone plates
- high temporal resolution given by SR pulse width (<100ps)
- inherent chemical sensitivity provided by XMCD magnetic contrast

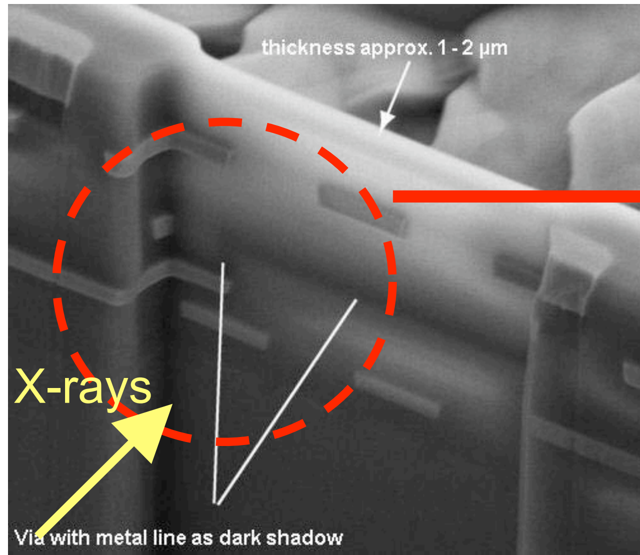




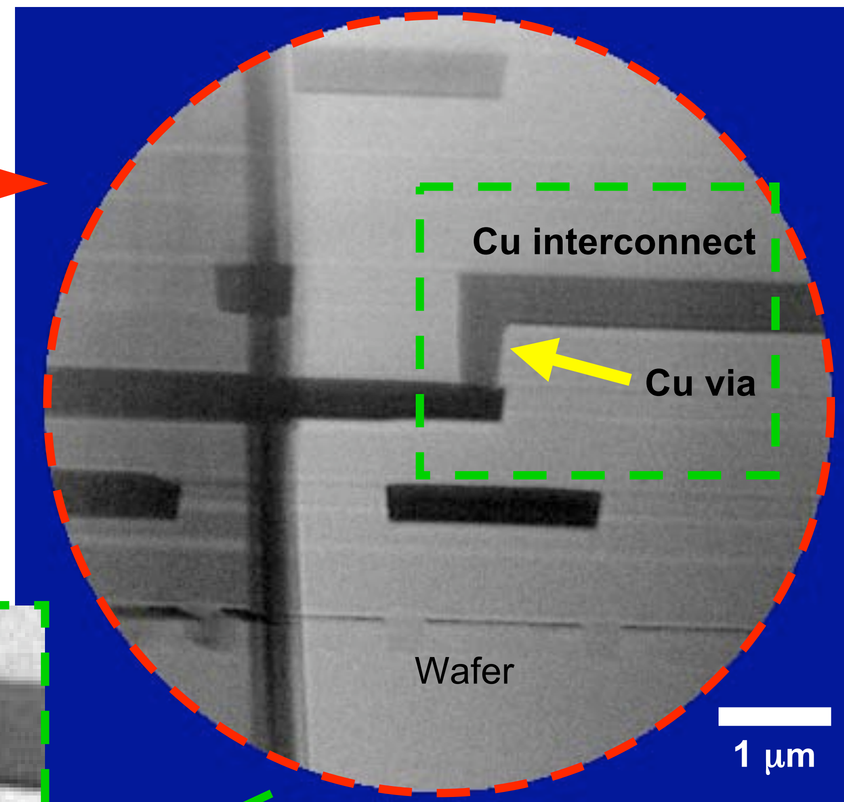
Electromigration in Latest Technology Computer Chips with Cu vias Connecting Multilevel Metallization Layers

AMD | Berkeley Lab

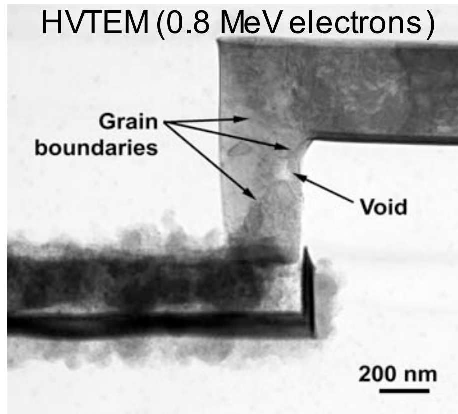
SEM micrograph



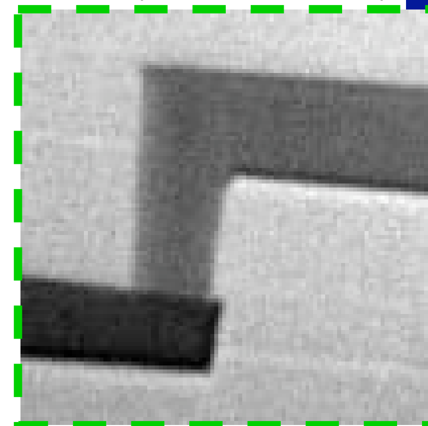
X-ray micrograph imaged at 1.8 keV



HVTEM (0.8 MeV electrons)



TXM (1.8 keV photons)



High current density

Courtesy of Gerd Schneider (BESSY)

G. Denbeaux, E. Anderson, A. Pearson and B. Bates (CXRO)
M. Meyer and E. Zschech (AMD Saxony Manufacturing GmbH) / E. Stach (NCEM / LBNL)

Extreme Ultraviolet (EUV) Lithography Based on Multilayer Coated Optics

Reflective mask

Absorber pattern

λ = 13 nm

Multilayer mirror

4:1 reduction optics, aspheric, multilayer coated

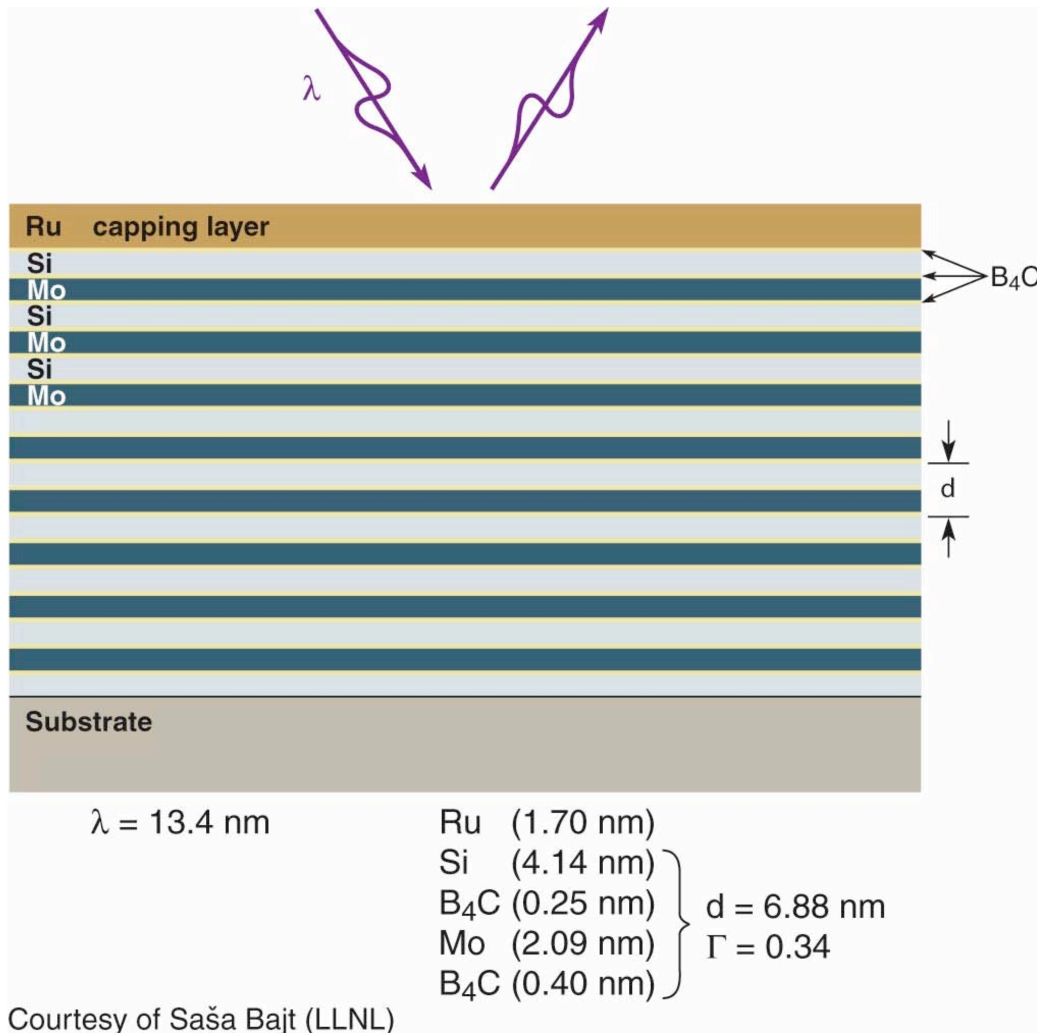
6.7 nm period

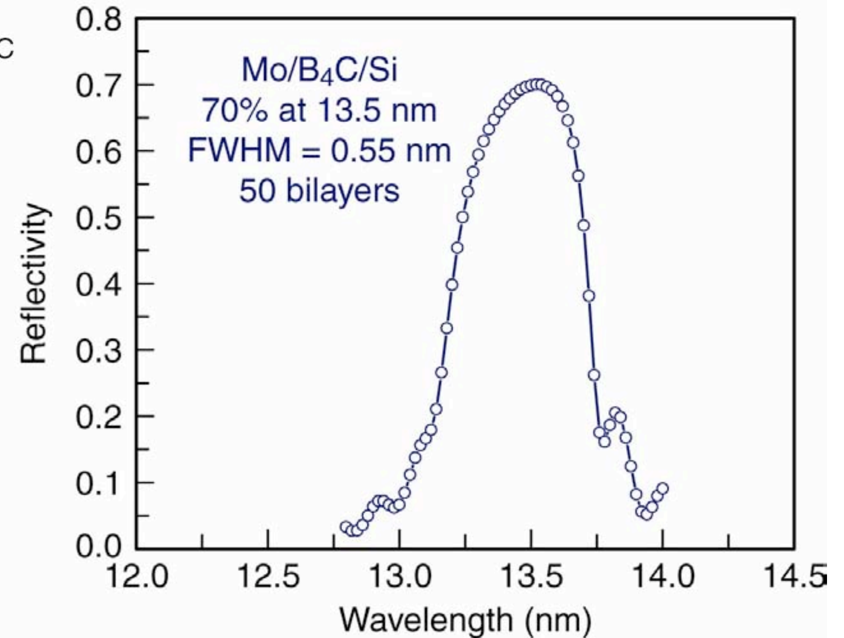
Mo

Si

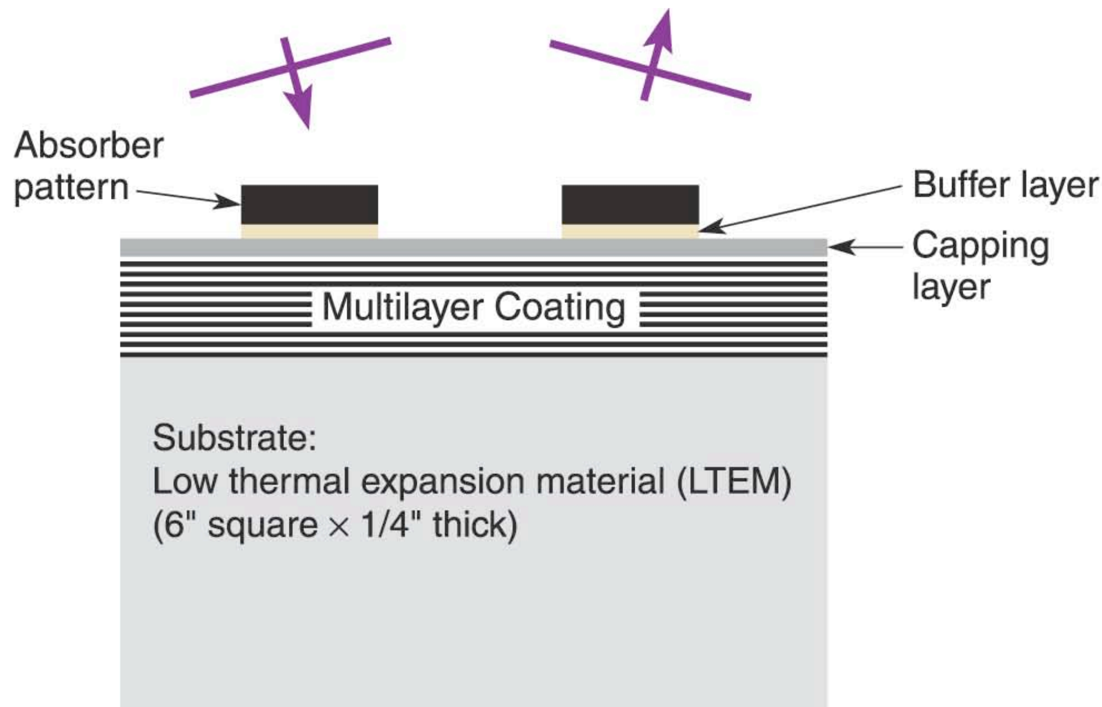
Wafer to record 50 nm or smaller features, over cm^2 dimensions

High Reflectivity, Thermally and Environmentally Robust Multilayers Coatings for High Throughput EUV Lithography





Reflective Mask for EUV Lithography



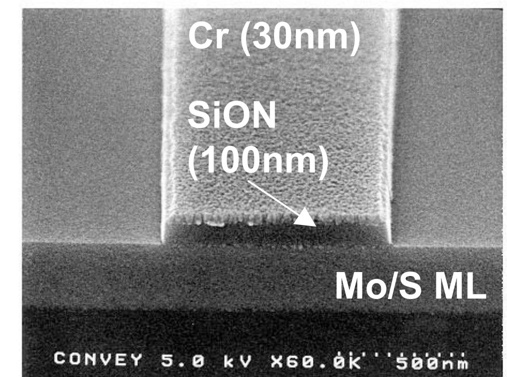
Typically

Mo/Si multilayer (d = 6.7 nm) with 30 nm SiO_2 capping layer

Cr or TaN absorber (~70 nm) with 50 nm Ru Buffer layer

LTEM substrate (Ti-doped fused silica) ULE (Corning), or Zerodur (Schott)

Attribute	TaN	Cr	Comments
CD control	✓		TaN has smaller RIE CD bias
Cleaning			Both resistant to standard cleans
Emissivity		✓	
Inspection contrast	✓		TaN has higher contrast
Repair selectivity			Both need small improvement
Aspect ratio	✓		TaN can be 8 nm thinner than Cr



The Engineering Test Stand (ETS): A Pre-Manufacturing EUV Stepper

Mask stage

Projection optics

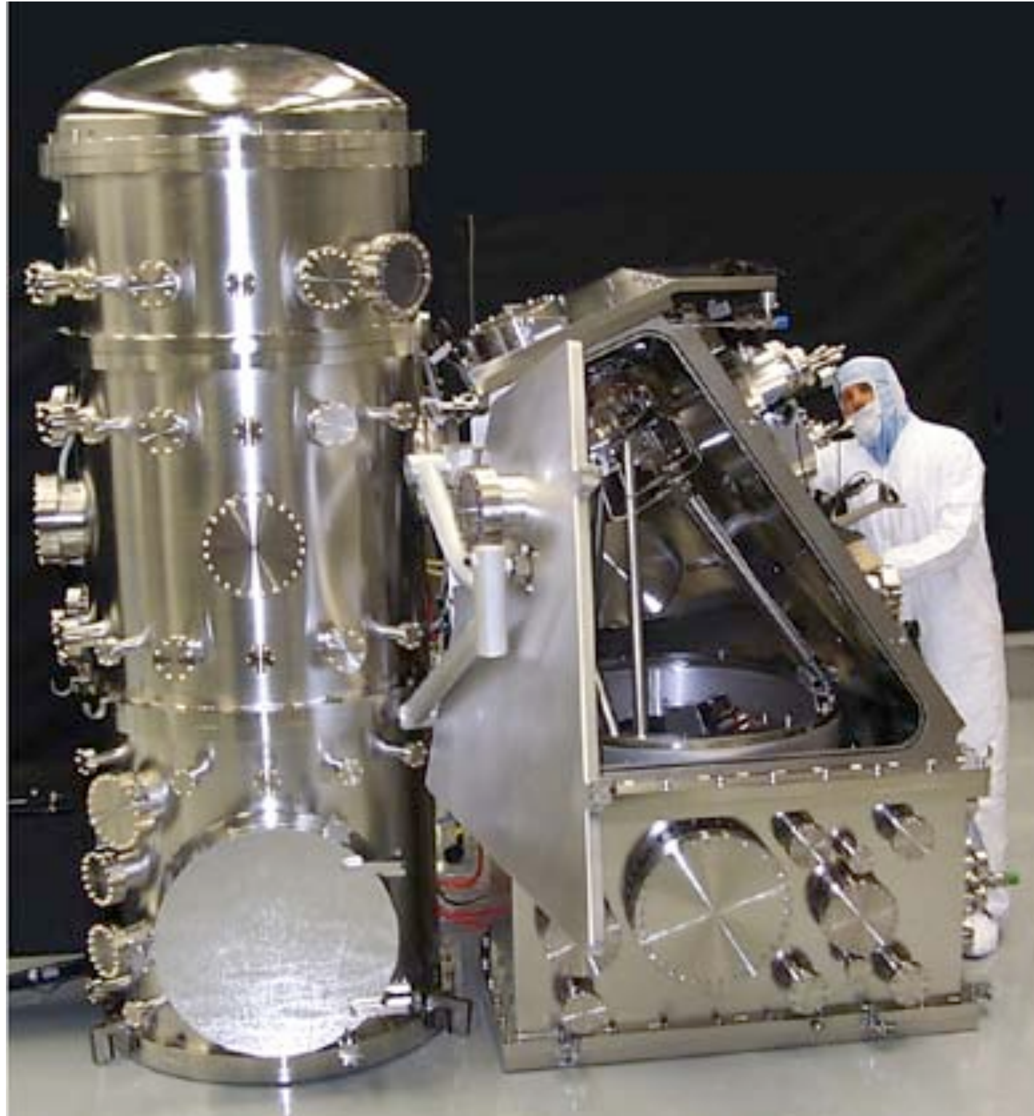
Wafer stage

Collection optic

EUV Plasma source

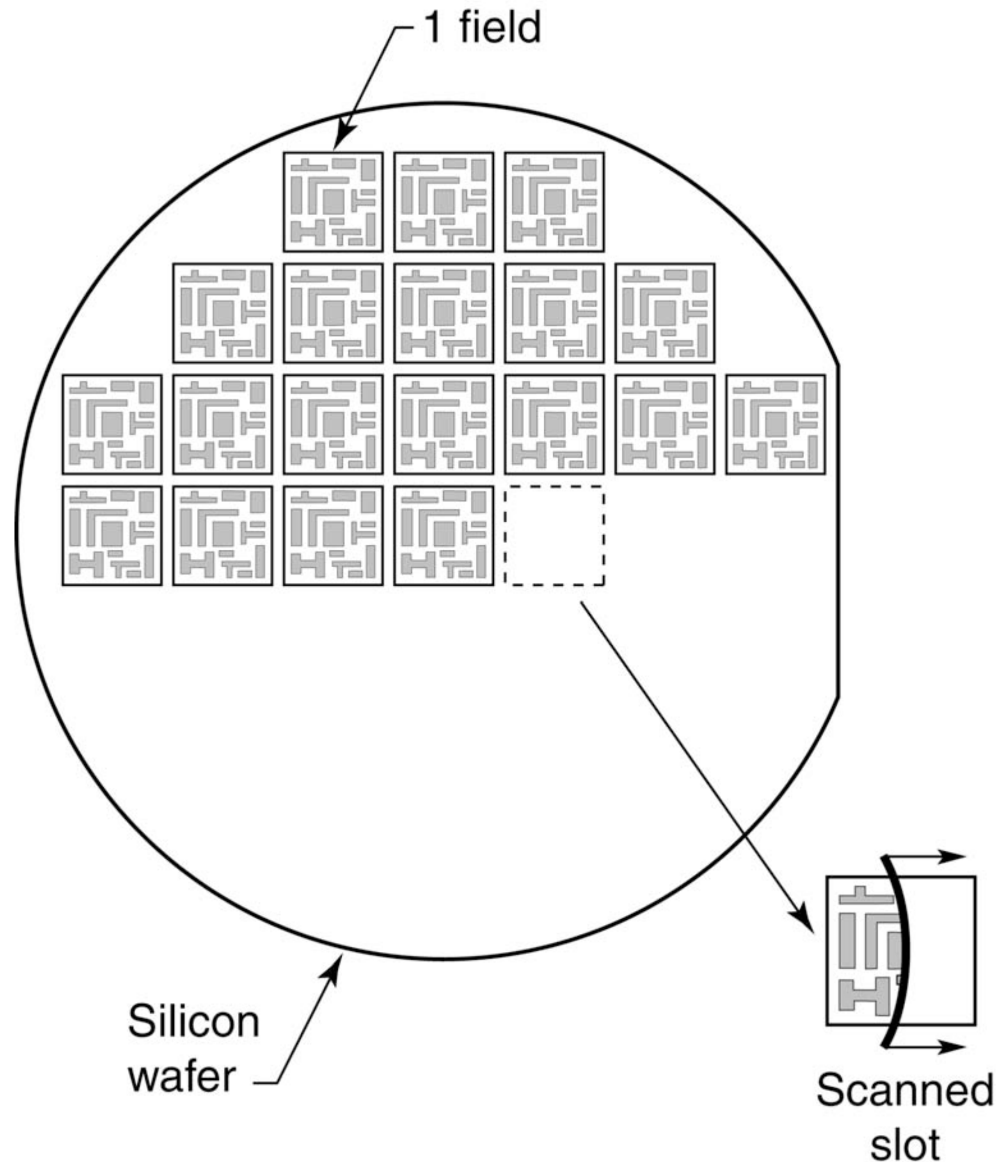
Condenser optics

The Engineering Test Stand (ETS)

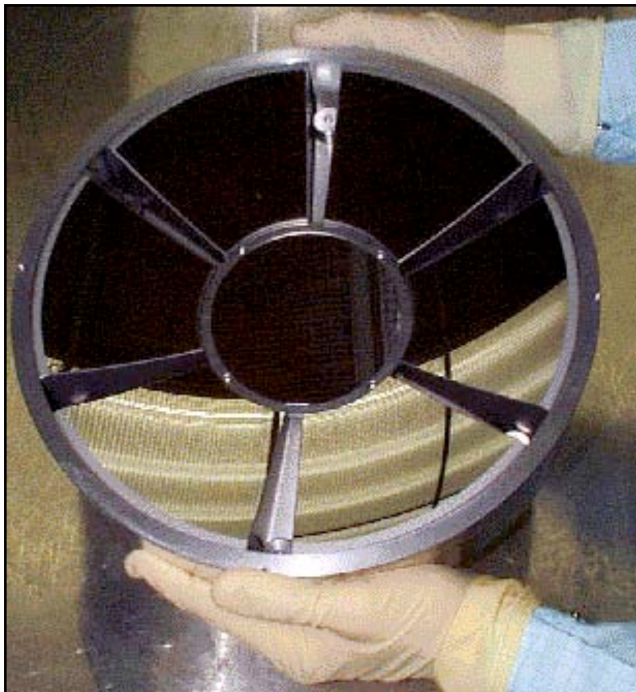


Courtesy of
Bill Replogle,
Sandia National
Laboratories

EUV Lithography Will Use a Step and Scan Ring Field System



ETS Optics Meet Tight Specifications

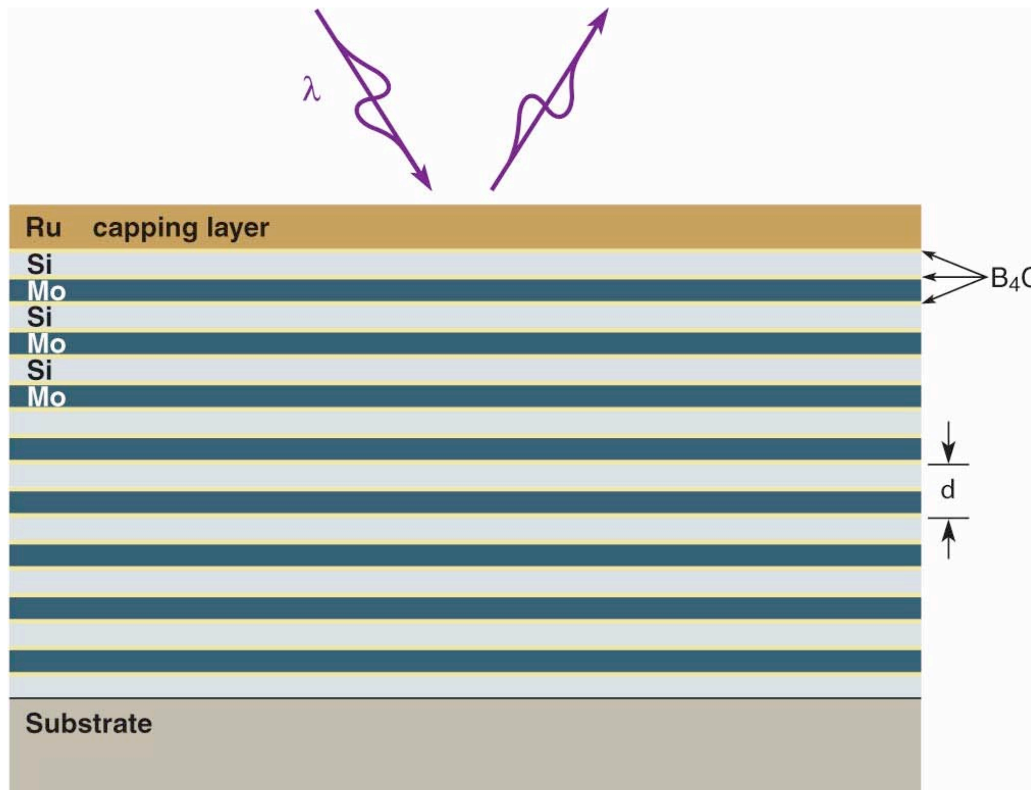


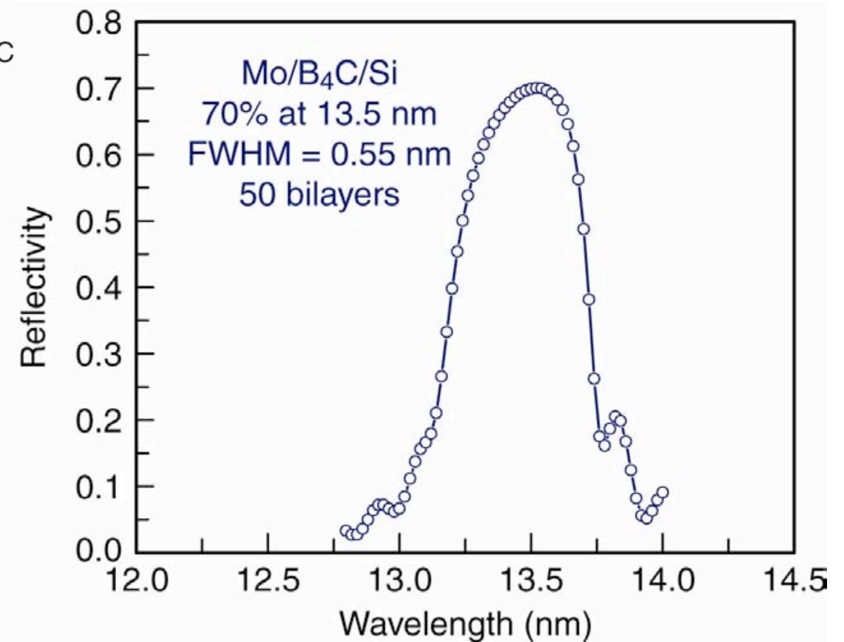
Condenser optic

Projection optic

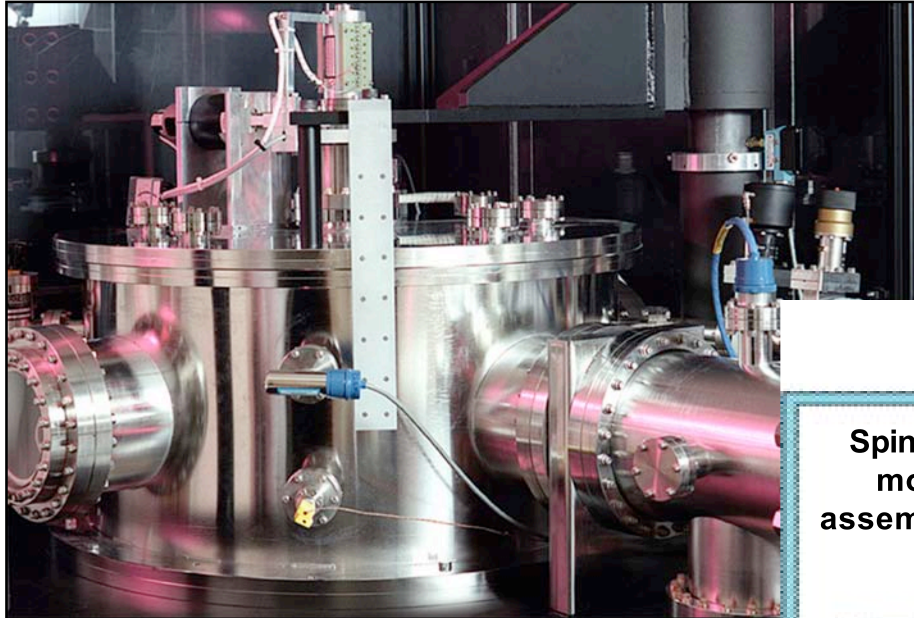
Courtesy of D. Sweeney (LLNL)

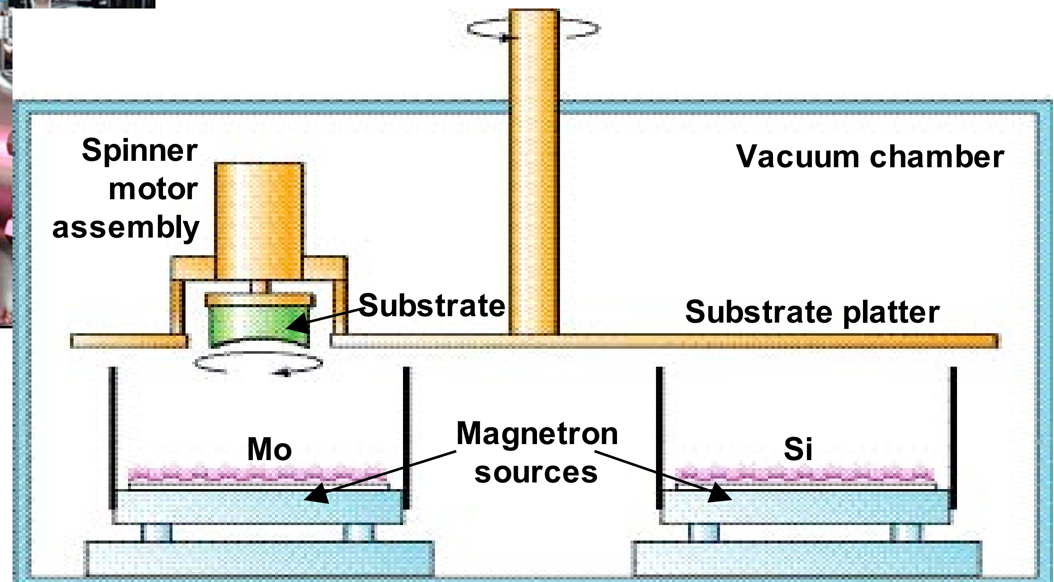
High Reflectivity, Thermally and Environmentally Robust Multilayer Coatings for High Throughput EUV Lithography





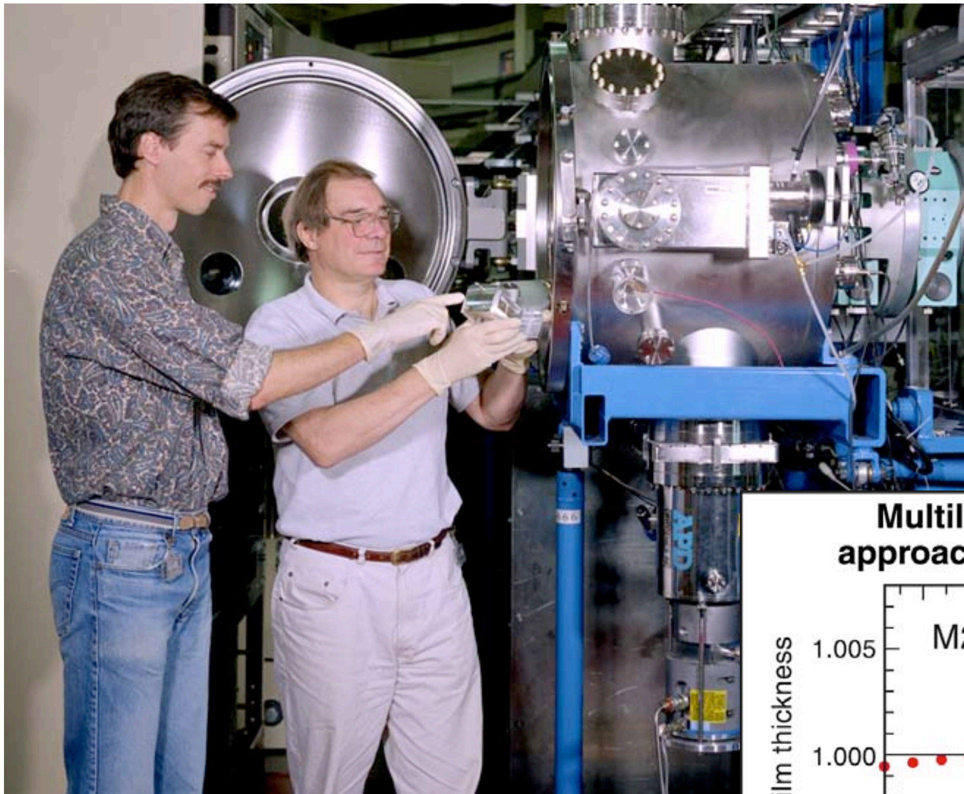
DC Magnetron Sputtering Is Used to Deposit Multilayer Coatings Onto Optical Substrates



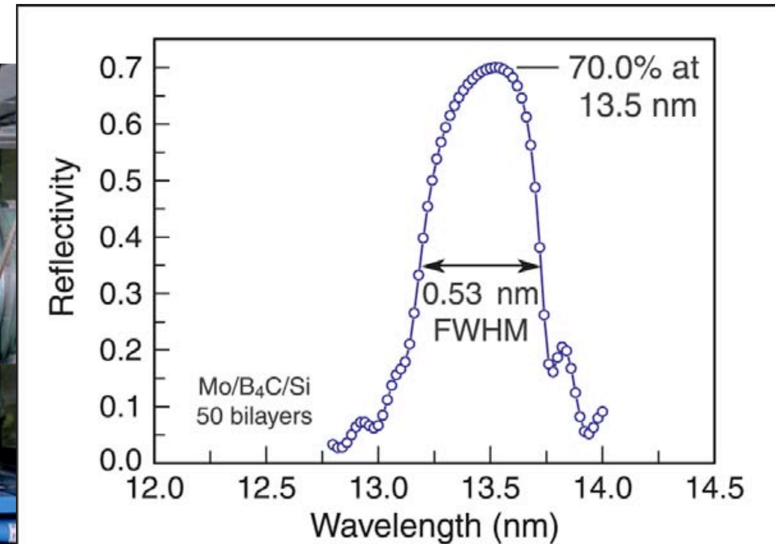


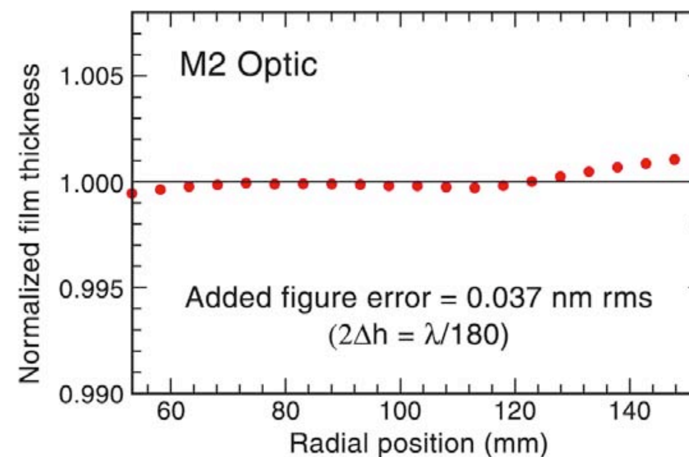
Substrates mounted on a rotating platter are swept across each sputter source sequentially to form the multilayer. Modulating the platter velocity provides precision control of radial thickness distribution and absolute film thickness. The substrate is also spun fast about its own axis for azimuthal uniformity.

Multilayer Reflectivity and Uniformity



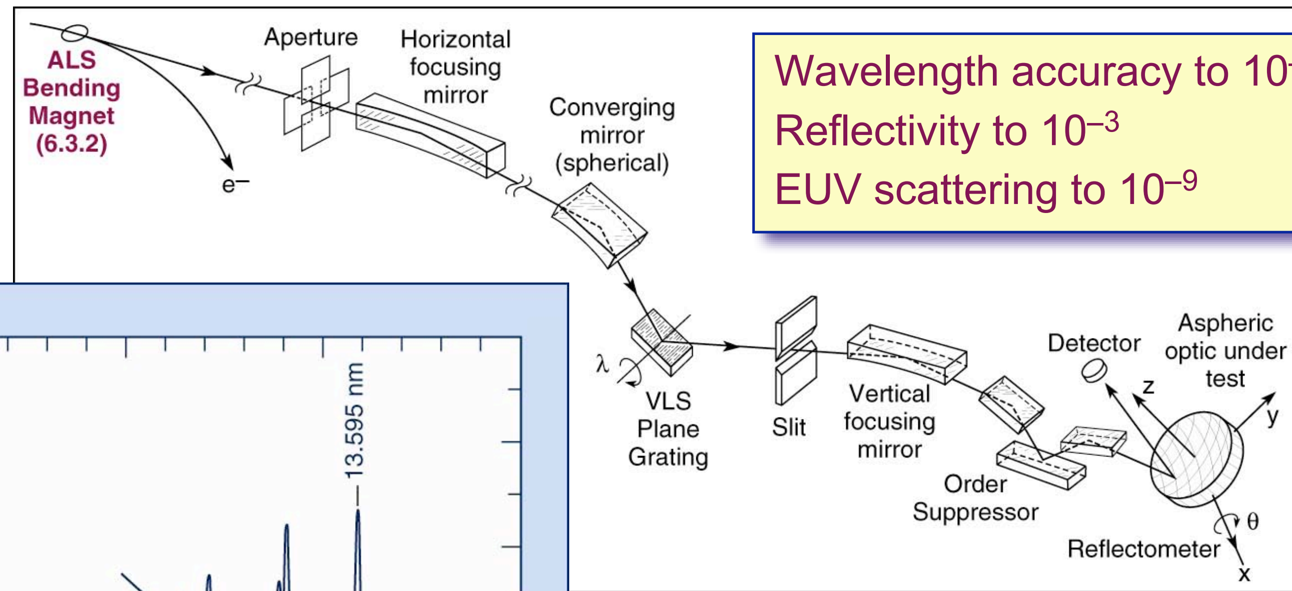
Courtesy of E. Gullikson and J. Underwood,
Lawrence Berkeley National Laboratory.



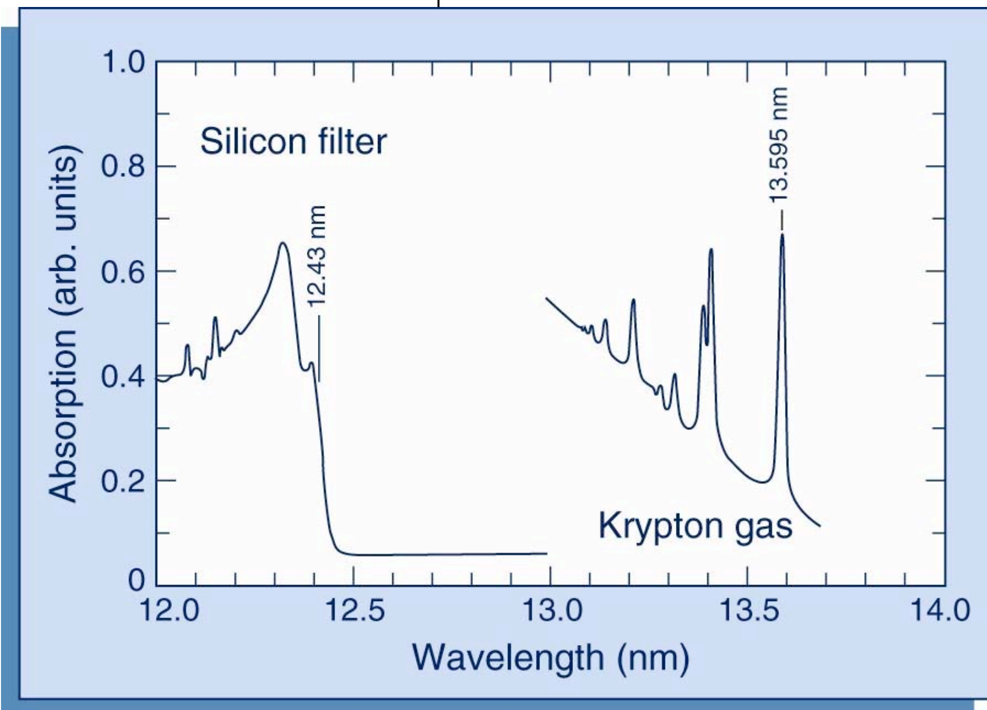


High Accuracy EUV Metrology for Multilayer Coated Optics

Multilayer Reflectivity and Uniformity



Wavelength accuracy to 10^{-4}
Reflectivity to 10^{-3}
EUV scattering to 10^{-9}



Calibration lines

Xe	$4d_{5/2} - 6p$	19.0423 nm
Kr	$3d_{5/2} - 5p$	13.5948 nm
Ar	$2p_{3/2} - 4s$	5.0736 nm
CO	$1s - \pi^*$	4.3140 nm
N_2	$1s - \pi^*$	3.0911 nm

Courtesy of E. Gullikson and J. Underwood (LBNL)

Multilayer Coatings for the ETS Projection Optics Approach Production Specifications

Systematic d-space variations suggest path to further improvements.

ETS M1 Mirror
Added figure error = 0.032 nm rms
$\Delta d/d$ = 1/8800
(λ/420)

ETS M2 Mirror
Added figure error = 0.037 nm rms
$\Delta d/d$ = 1/7600
(λ/360)

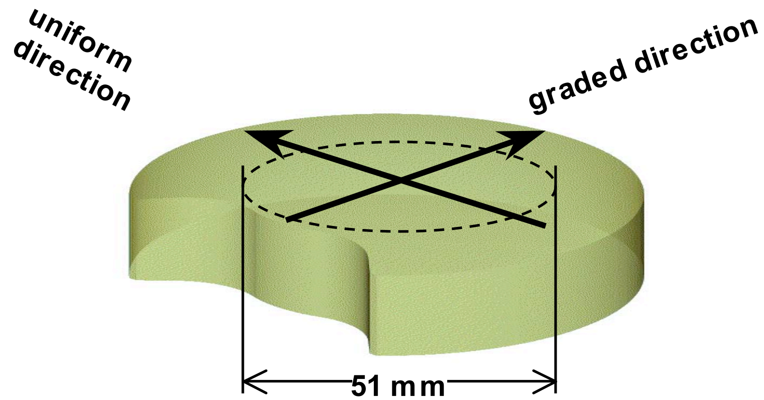
ETS M3 Mirror
Added figure error = 0.040 nm rms
$\Delta d/d$ = 1/6900
(λ/340)

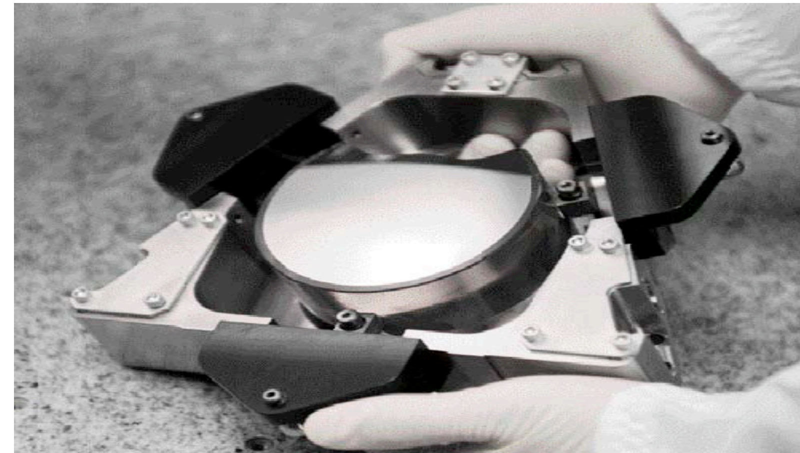
ETS M4 Mirror
Added figure error = 0.015 nm rms
$\Delta d/d$ = 1/19,000
(λ/890)

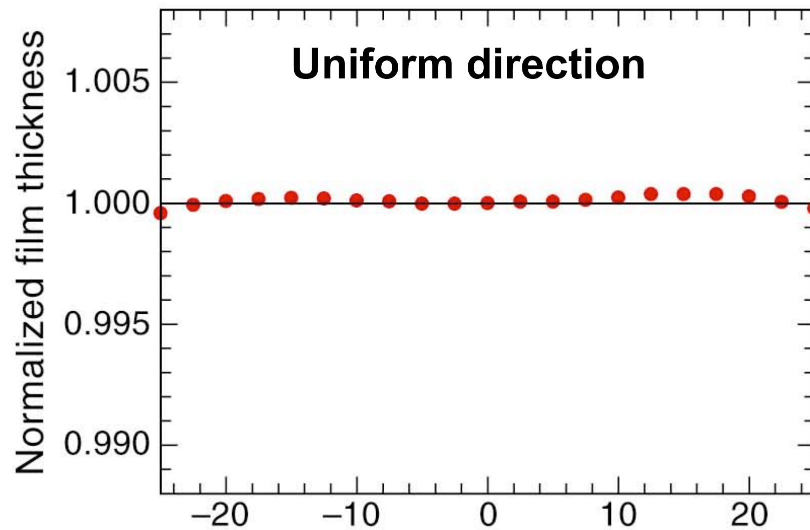
Normalized film thickness
Radial Position (mm)
Radial position (mm)

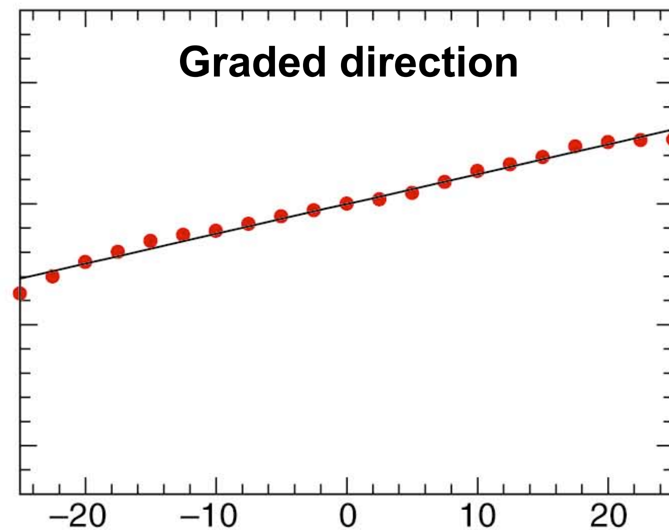
Courtesy of R. Soufli and E. Spiller, LLNL.

ETS Mirror M3 Was Successfully Coated While Preserving the Surface Figure





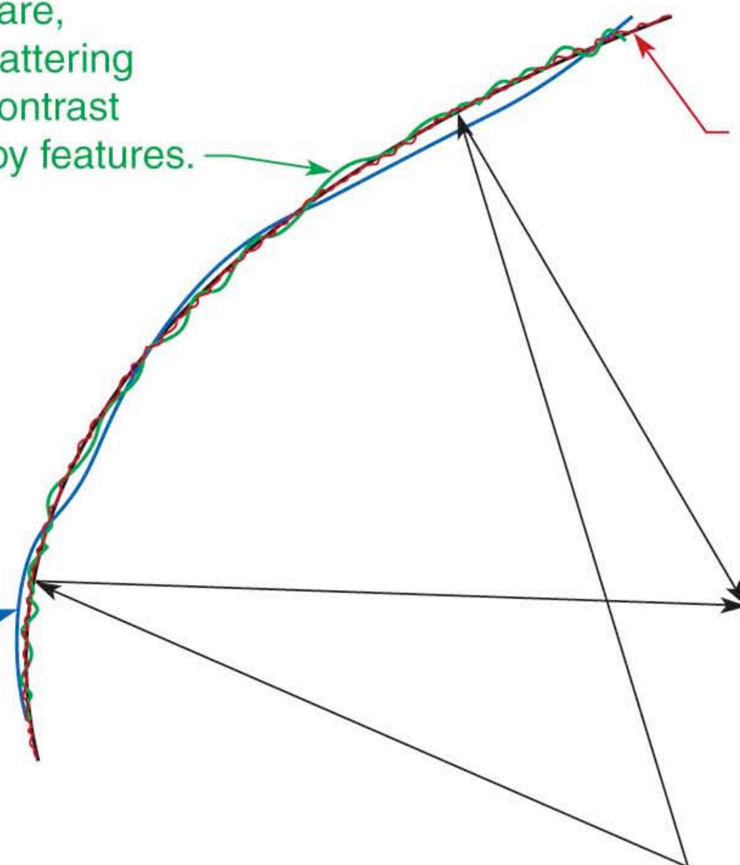




Radial Position (mm)

Figure and Finish Low, Mid, and High Spatial Frequency Variations from the Perfect Optical Surface

Mid spatial frequency surface variations contribute to flare, small angle scattering that reduces contrast between nearby features.



High spatial frequency roughness scatters radiation to large angles, reducing power throughput to the image (wafer).

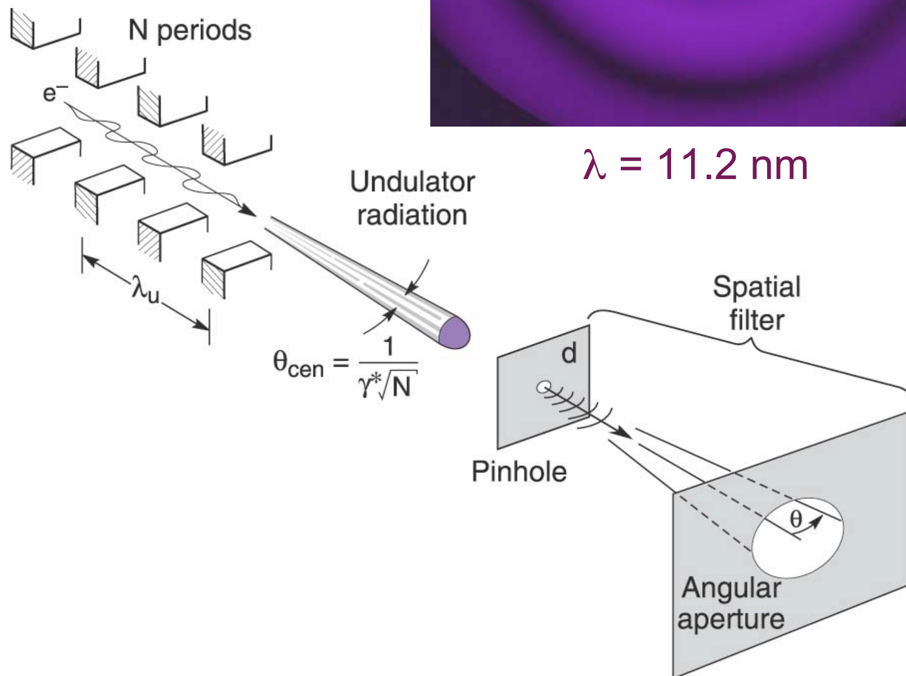
Low spatial frequency substrate errors are associated with aberrations, blurred features.

Note: Multilayer coatings must be sufficiently uniform that they do not contribute significantly to the top surface error budget. For an rms d-space variation Δd, the coating thickness variation $\Delta h = N\, \Delta d < \lambda_{euv}/500$.

Spatially Coherent Radiation for At-Wavelength EUV Interferometry

$\lambda = 11.2$ nm

$\lambda = 13.4$ nm

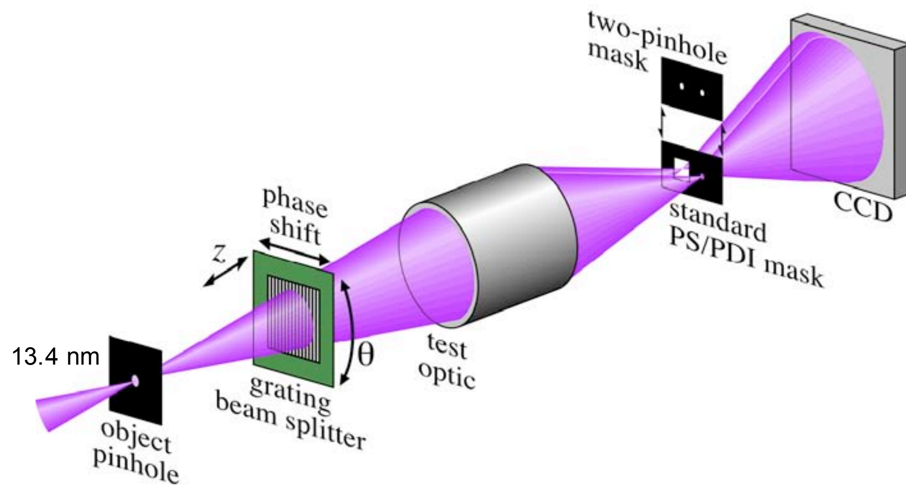


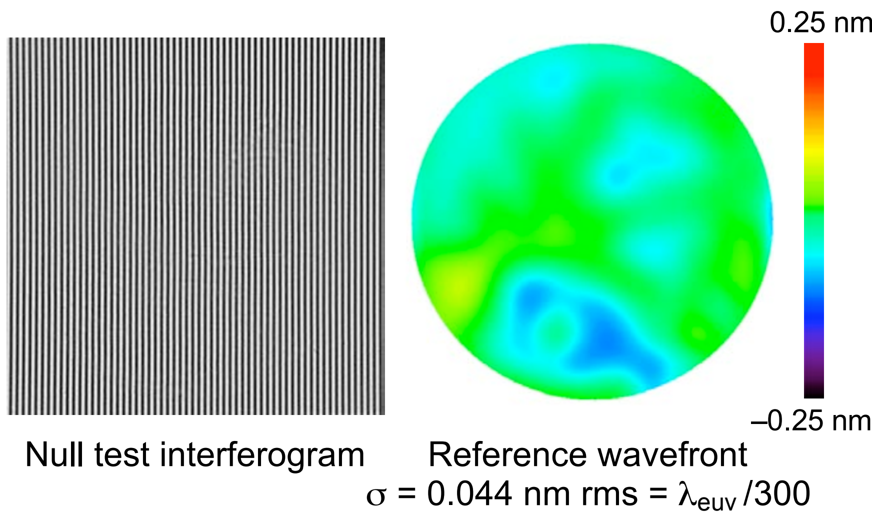
1 μm^D pinhole

25 mm wide CCD at 410 mm

At-Wavelength EUV Interferometry

Wavefront Accuracy to $\lambda_{euv}/300$



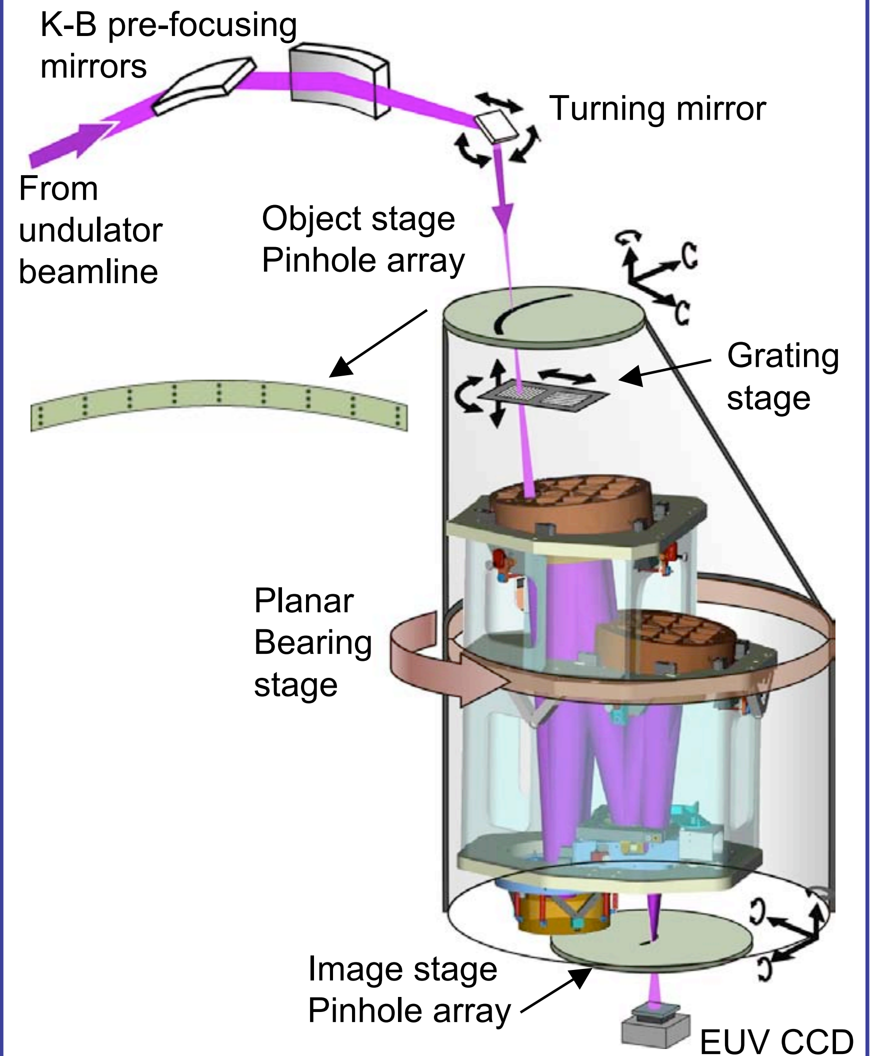


Null test interferogram

Reference wavefront

σ = 0.044 nm rms = $\lambda_{euv}/300$

EUV Interferometry of ETS Optics



Courtesy of K. Goldberg, P. Naulleau and P. Batson (LBNL) and J. Bokor (UCB/LLNL)

EUV Interferometry of the ETS Projection Optics

From undulator beamline

K-B pre-focusing mirrors

Turning mirror

Object stage pinhole array

Grating beam splitter And phase shifter

Spatially coherent EUV radiation

Planar Bearing stage

Image stage pinhole array

EUV CCD

Object and image plane pinhole stages rotate with the projection optics to cover the field of view.

VNL Virtual National Laboratory

Courtesy of K. Goldberg, P. Naulleau and P. Batson (LBNL) and J. Bokor (UCB/LLNL)

EUVL Extreme Ultraviolet Lithography

EUV Lithography at the Advanced Light Source in Berkeley

Courtesy of P. Naulleau, S. Rekawa, and E. Anderson (LBNL)

At-Wavelength Interferometry of ETS Set 2 Optics

0.0997 NA

[nm]
0.69 2.07

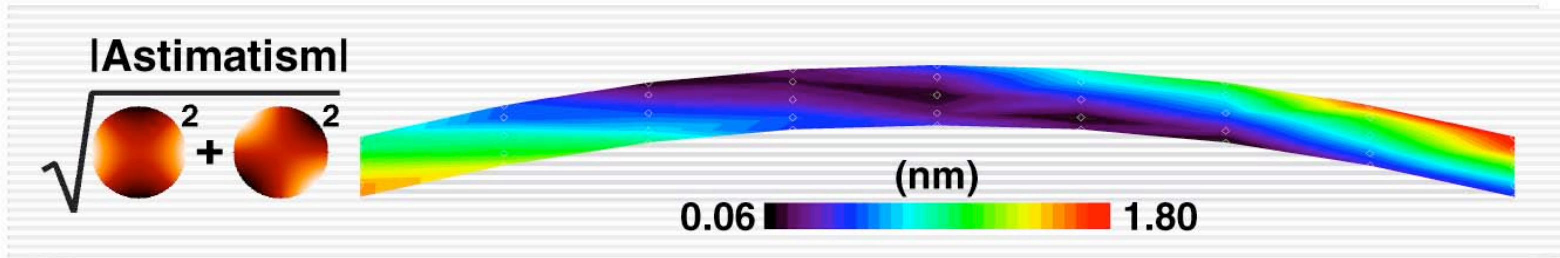
1.39 1.14 0.87 0.82 0.93 1.18 1.46 1.94 2.07
1.38 1.04 0.85 0.75 0.78 1.09 1.22 1.54 1.94
1.57 1.18 0.88 0.74 0.69 0.90 1.11 1.32 1.52
1.75 1.30 1.02 0.88 0.74 0.84 0.99 1.13 1.17
1.79 1.53 1.21 0.86 0.86 0.90 1.02 1.06 1.12

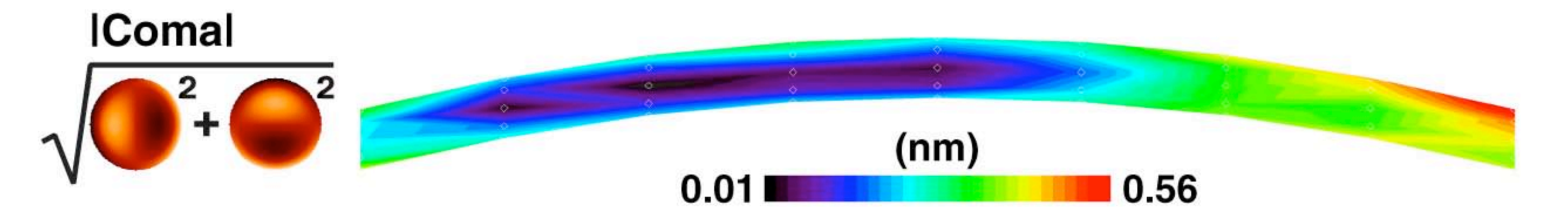
[nm]
RMS in a 37-term series

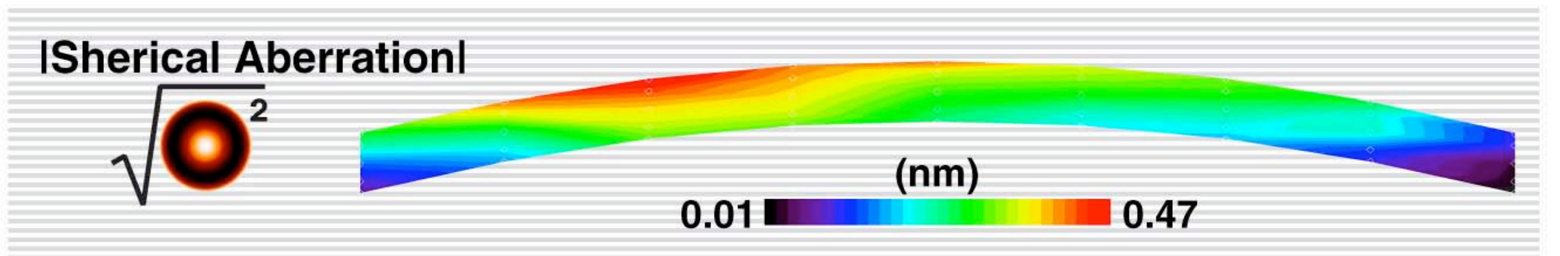
- Quantitative agreement with visible light interferometry to 0.25 nm rms
- Best field points chosen for static imaging

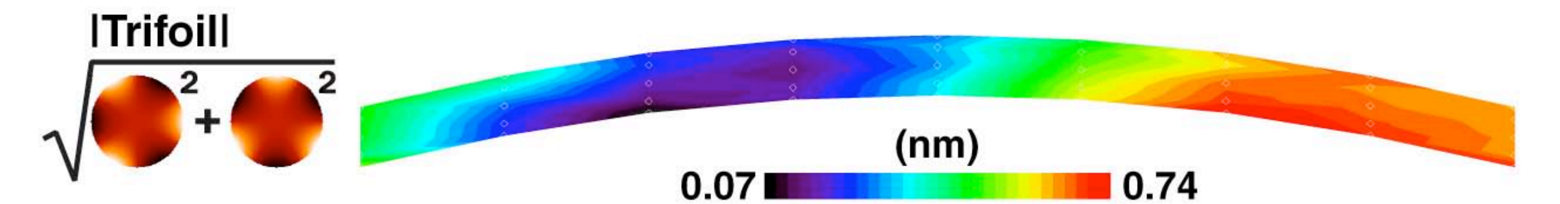
Courtesy of K. Goldberg, P. Naulleau, J. Bokor, et al. (LBNL)

EUV-Wavelength Aberration Breakdown for the ETS Set-2 Optics

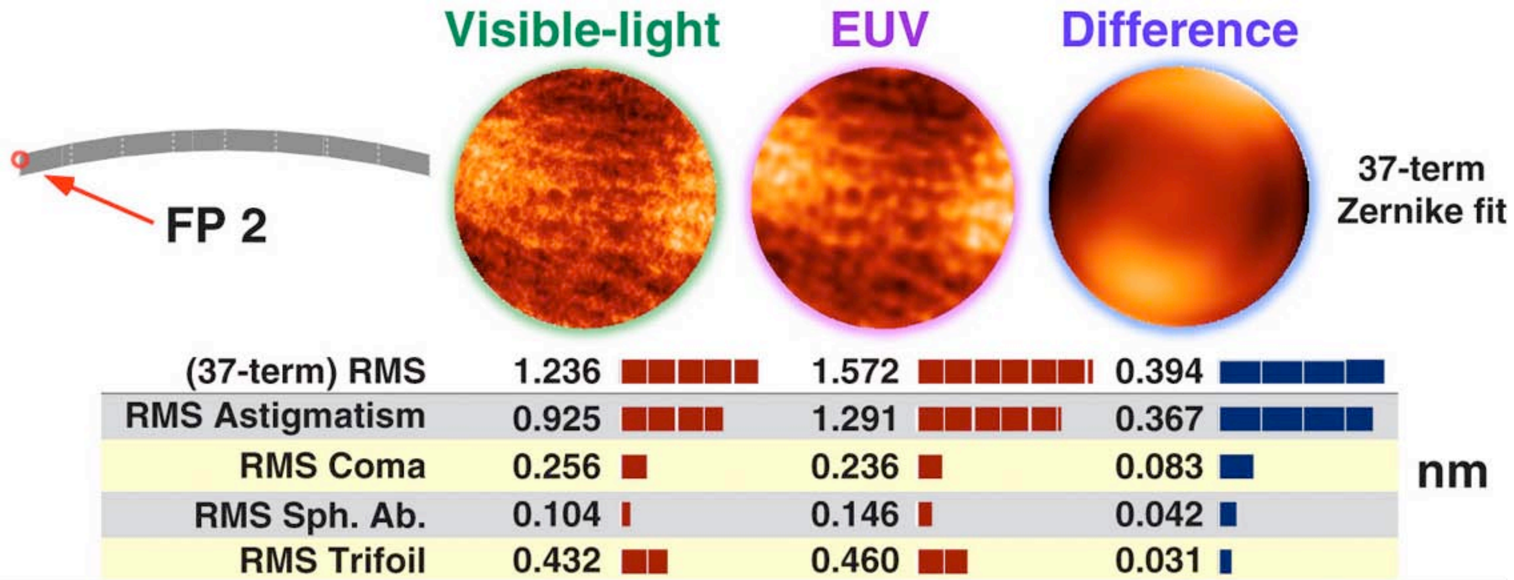




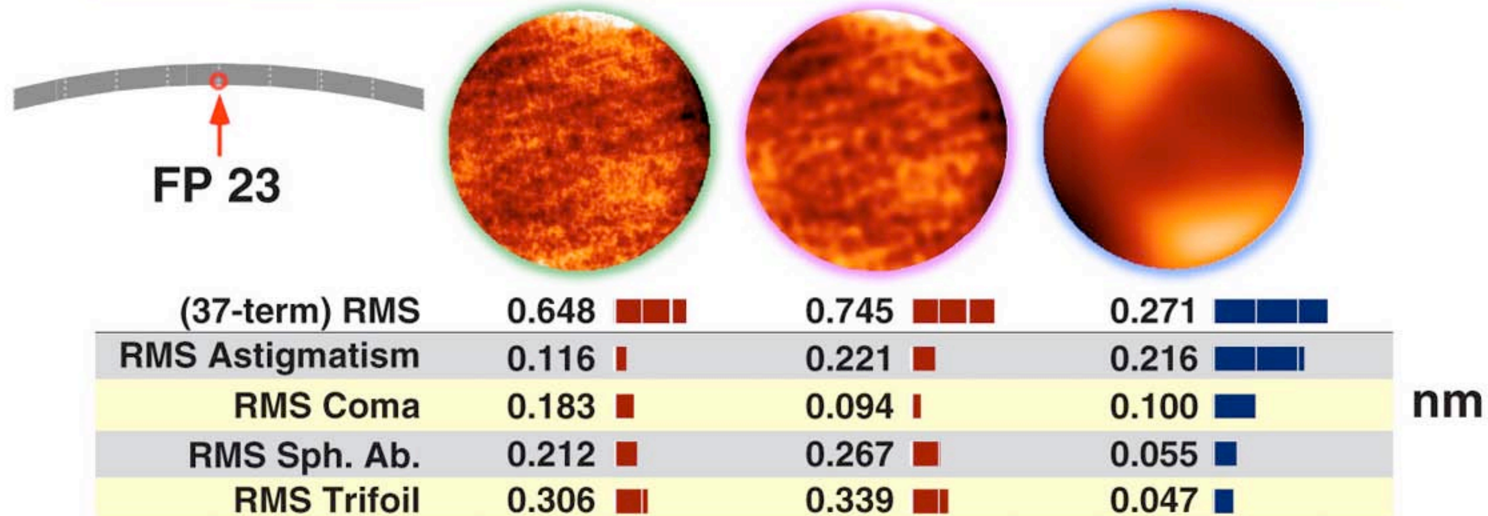




Visible and EUV Wavefront Comparison by the Numbers



	Visible-light	EUV	Difference	
(37-term) RMS	1.236	1.572	0.394	
RMS Astigmatism	0.925	1.291	0.367	
RMS Coma	0.256	0.236	0.083	nm
RMS Sph. Ab.	0.104	0.146	0.042	
RMS Trifoil	0.432	0.460	0.031	

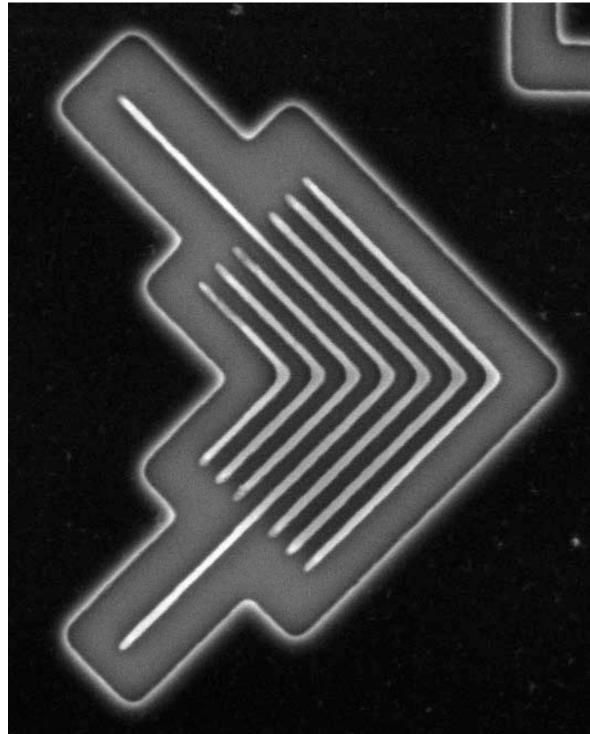


	Visible-light	EUV	Difference	
(37-term) RMS	0.648	0.745	0.271	
RMS Astigmatism	0.116	0.221	0.216	
RMS Coma	0.183	0.094	0.100	nm
RMS Sph. Ab.	0.212	0.267	0.055	
RMS Trifoil	0.306	0.339	0.047	

Courtesy of K. Goldberg (LBNL)

EUV Static Exposures Demonstrated to 39 nm Linewidth

39 nm Isolated Line



Coded as 80 nm (1:1) narrowed by exposure bias (x1.4)

ETS Set 2 optics

Static images at ALS

13.5 nm

$\sigma = 0.7$

DOF = ± 1/2 μm

EUV 2D resist, 120 nm thick

6.2 mj/cm^2, 4-6 nm LER

Courtesy of P. Naulleau (LBNL)

A 0.30 NA Micro-Exposure Tool (MET) has been Fabricated by Zeiss and LLNL

Mask

Illumination

Fold Flat

Button

Bipod

Secondary

MET
NA = 0.30
13.4 nm
5X
200 X 600 µm field

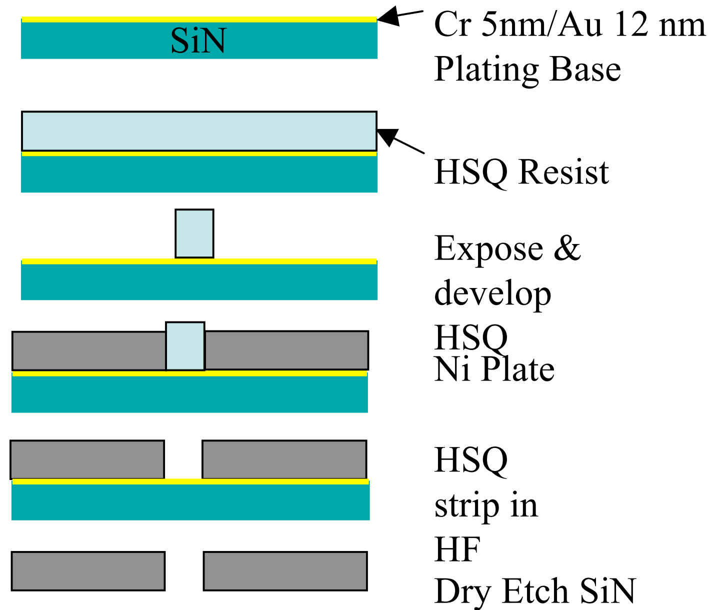
Primary

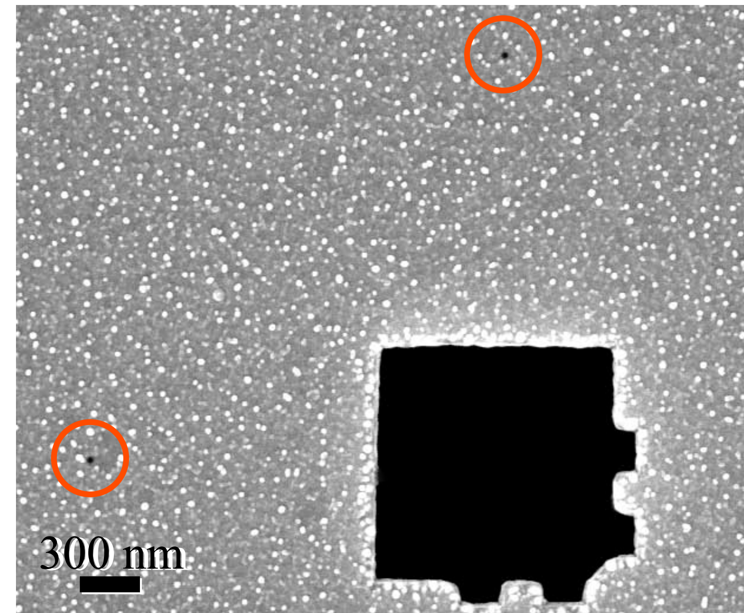
Bipods

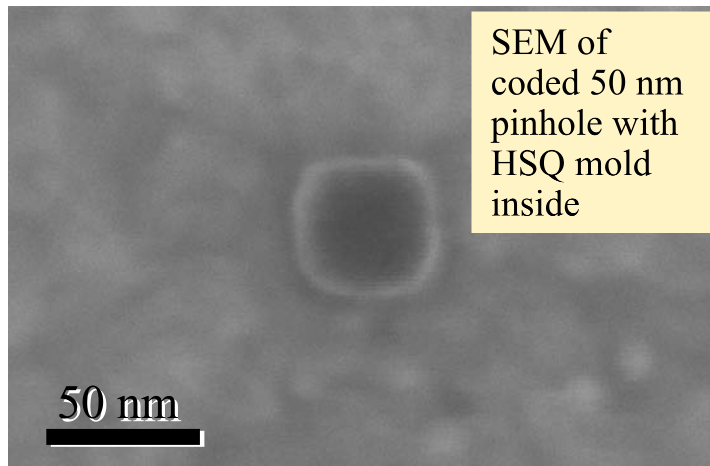
Wafer

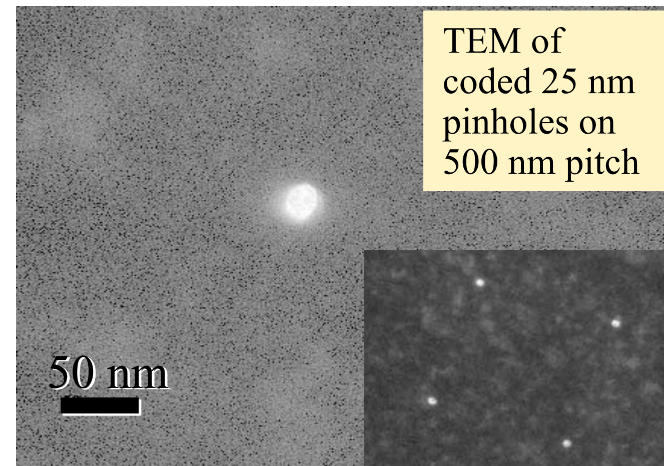
Courtesy of J. Taylor (LLNL)

25 nm Pinhole Fabrication









Courtesy of J. Alex Liddle, Deirdre Olynick and Erik Anderson (LBNL)

Measured Pinhole Performance

NA = 0.3

20 nm | 25 nm Airy
25 nm | 30 nm Airy
30 nm | 35 nm Airy
35 nm | 40 nm Airy
40 nm | 45 nm Airy
50 nm | 55 nm Airy

.8
.4
0

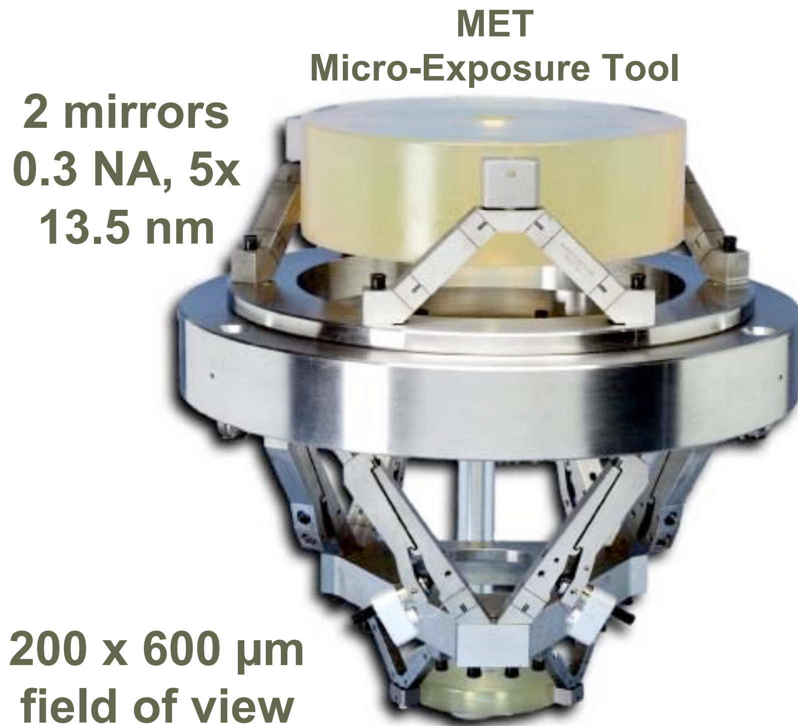
- Pinholes show a consistent 5 nm bias
- Aspect ratio of pinholes is limited by mechanical stability of resist
- 20 nm coded pinholes produce almost 50% diffracted power at an NA of 0.3

Courtesy of E. Gullikson, K. Goldberg, J.A. Liddle, D. Olynick, E. Anderson, (LBNL)

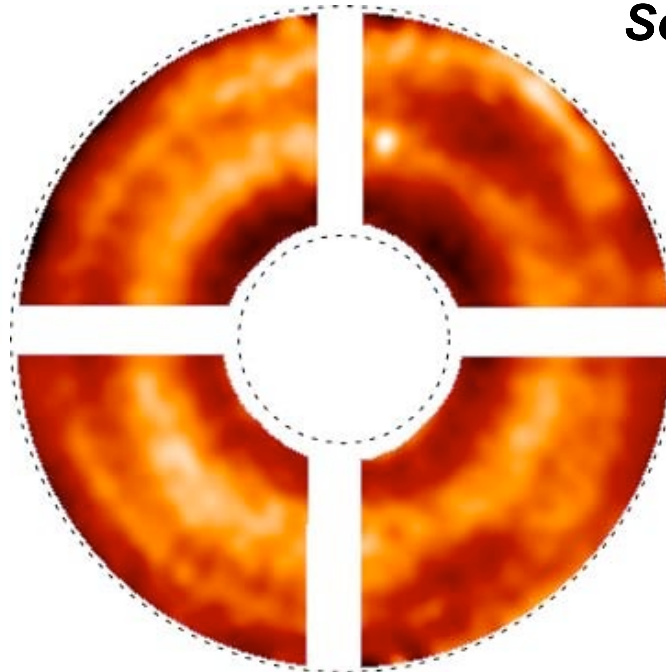
MET At-Wavelength Interferometry and Alignment Preparation for Static Microfield Imaging

MET
Micro-Exposure Tool

2 mirrors
0.3 NA, 5x
13.5 nm



200 x 600 µm
field of view



Alignment in progress
September 3, 2003

central field point

astig	0.1 nm
coma	0.3 nm
sph ab	0.4 nm
trifoil	0.2 nm
h-o s.	0.4 nm
RMS	0.8 nm
	$\lambda/17$

aberrations may be reduced in final alignment

- Visible-light alignment at Livermore
- EUV interferometry at Berkeley includes PS/PDI and shearing at 9 points across the field of view and in *z.*
- Higher-order spherical aberration dominates the wavefront
- A large part of the higher-order spherical is contained in Z35 and Z36. Higher-order spherical magnitude depends strongly on NA.

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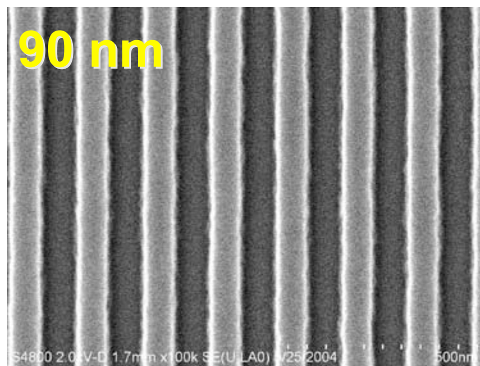
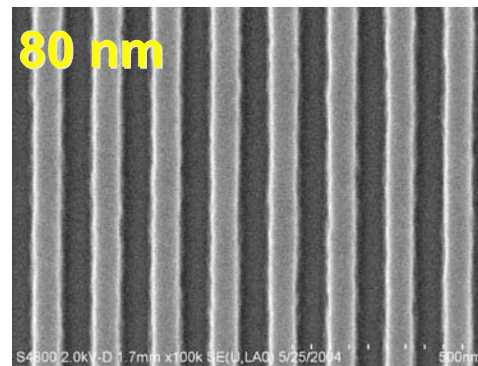
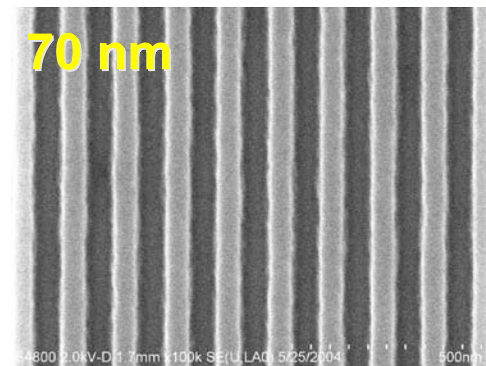
Courtesy of K. Goldberg and P. Naulleau (LBNL)

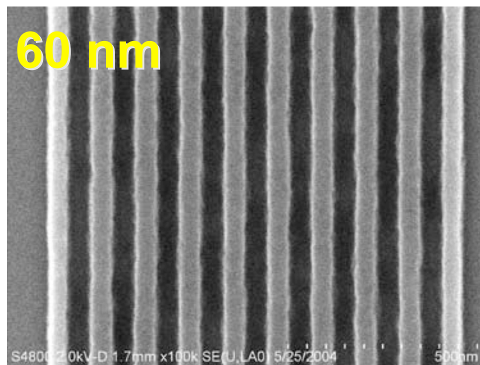
EUVL Extreme Ultraviolet Lithography

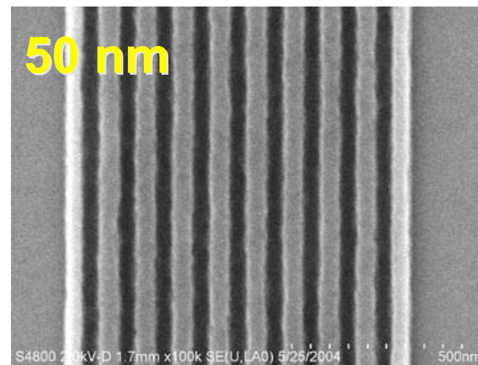
Rohm and Haas MET 1K Resist Shows 10-15 nm Resolution Improvement Over EUV 2D

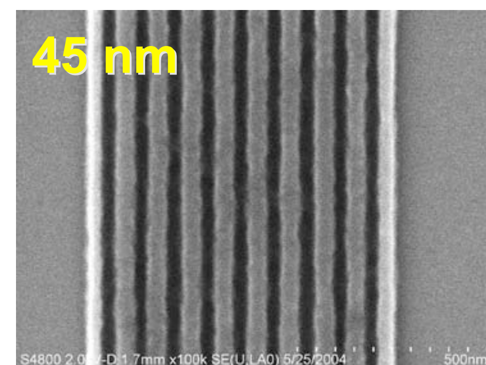


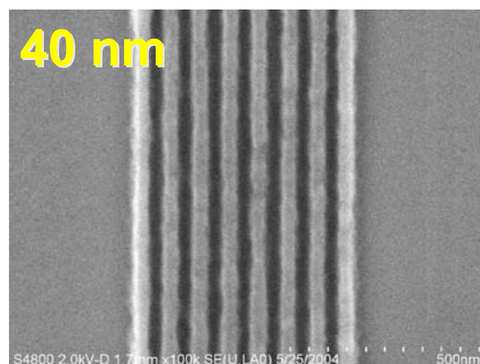


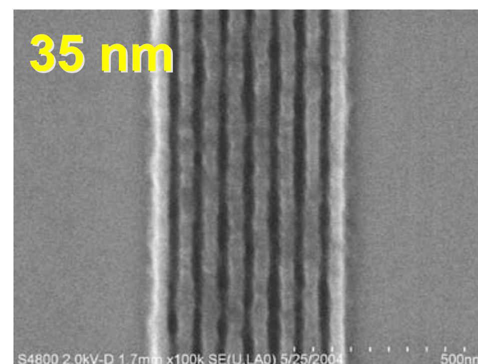












Processing Conditions:

- Thickness 125-nm
- PEB 130 °C 90 Sec
- Develop 45 Sec
- E_{size} 50-nm 21 mJ/cm^2

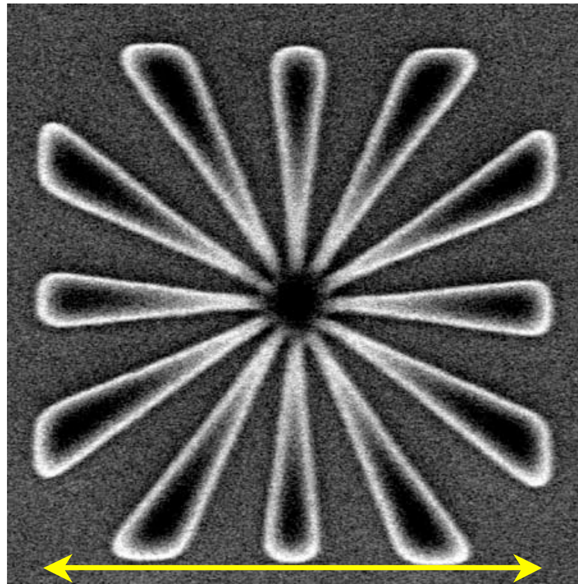
Courtesy of P. Naulleau (LBNL), R. Brainard & T. Koehler (Rohm & Haas)

SPIE Microlithography March, 2005,

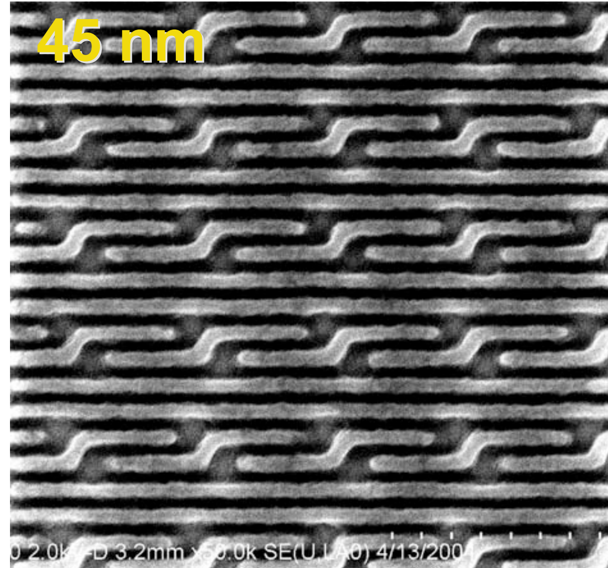
VNL Virtual National Laboratory

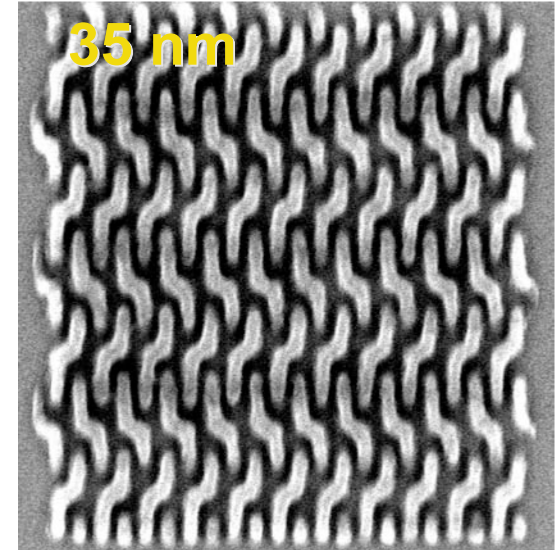
SEMATECH

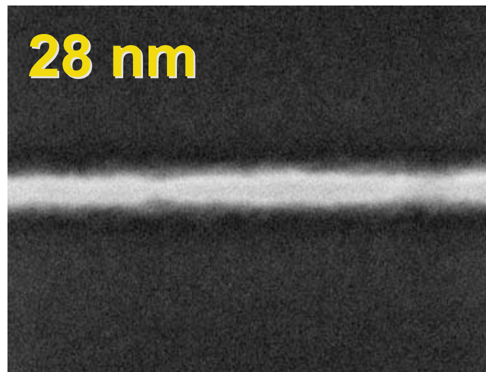
MET 1K Resist Shows Modulation Down to the 25-nm Level

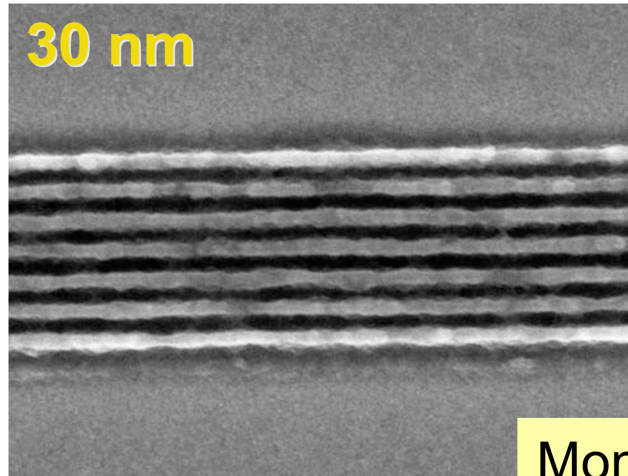


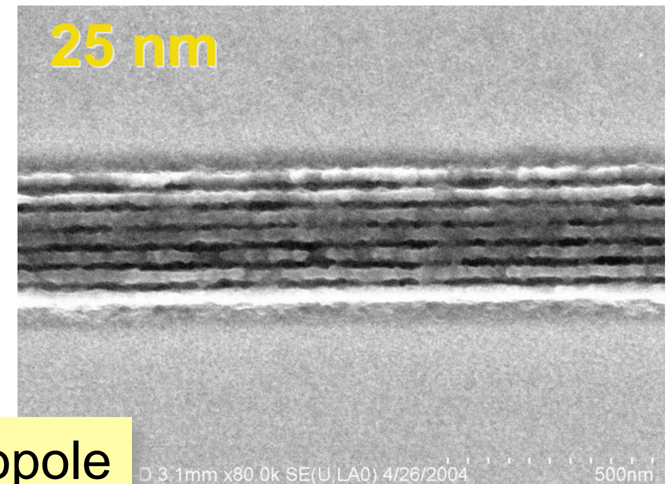
1.8 μm











Monopole

Courtesy of Patrick Naulleau (LBNL)

SPIE Microlithography March, 2005,

VNL Virtual National Laboratory

SEMATECH

Exitech

MS-13 tool chamber – *subsystem testing*

Courtesy of Malcolm Gower (Oxford, UK)

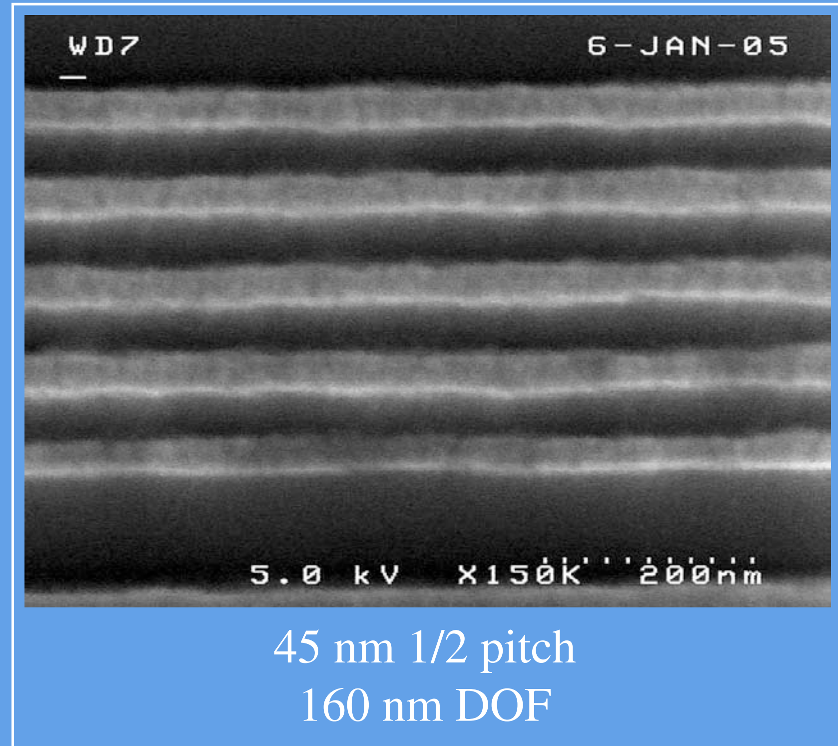
Intel EUV MET Installation

16 crates
17+ tons
15 pumps
All for . . . .

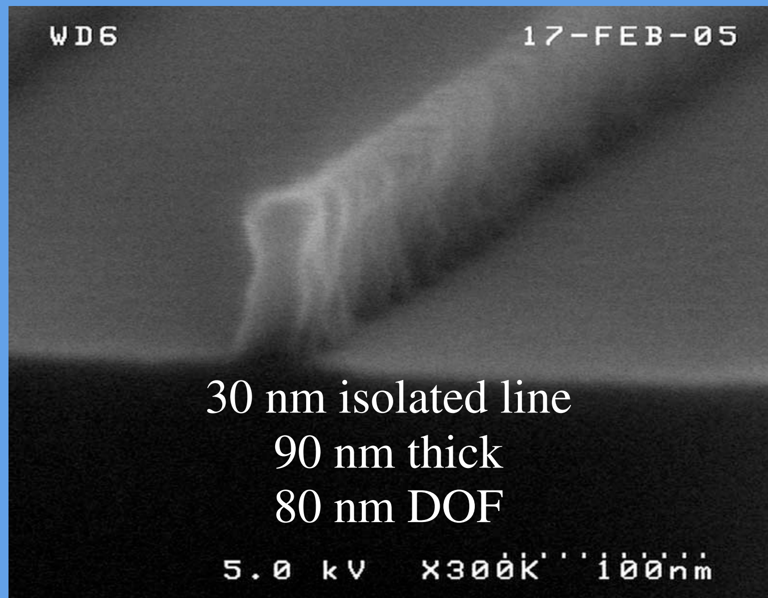
intel.

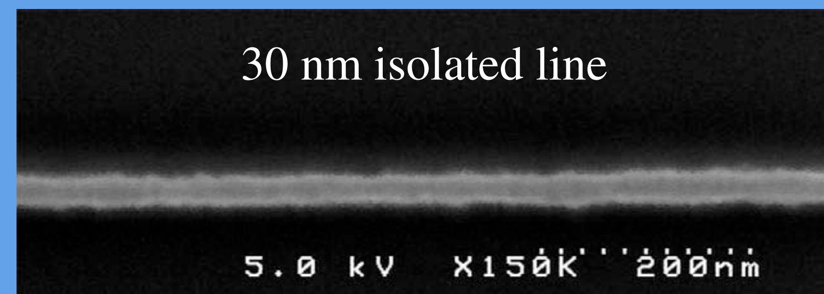
Imaging Performance

0.3 NA
0.55/0.36 σ
8 mJ/cm^2



45 nm 1/2 pitch
160 nm DOF





intel

Exitech

MS-13 EUV Microstepper *- at SEMATECH North, Albany, New York, USA*

Courtesy of Malcolm Gower, Oxford, UK

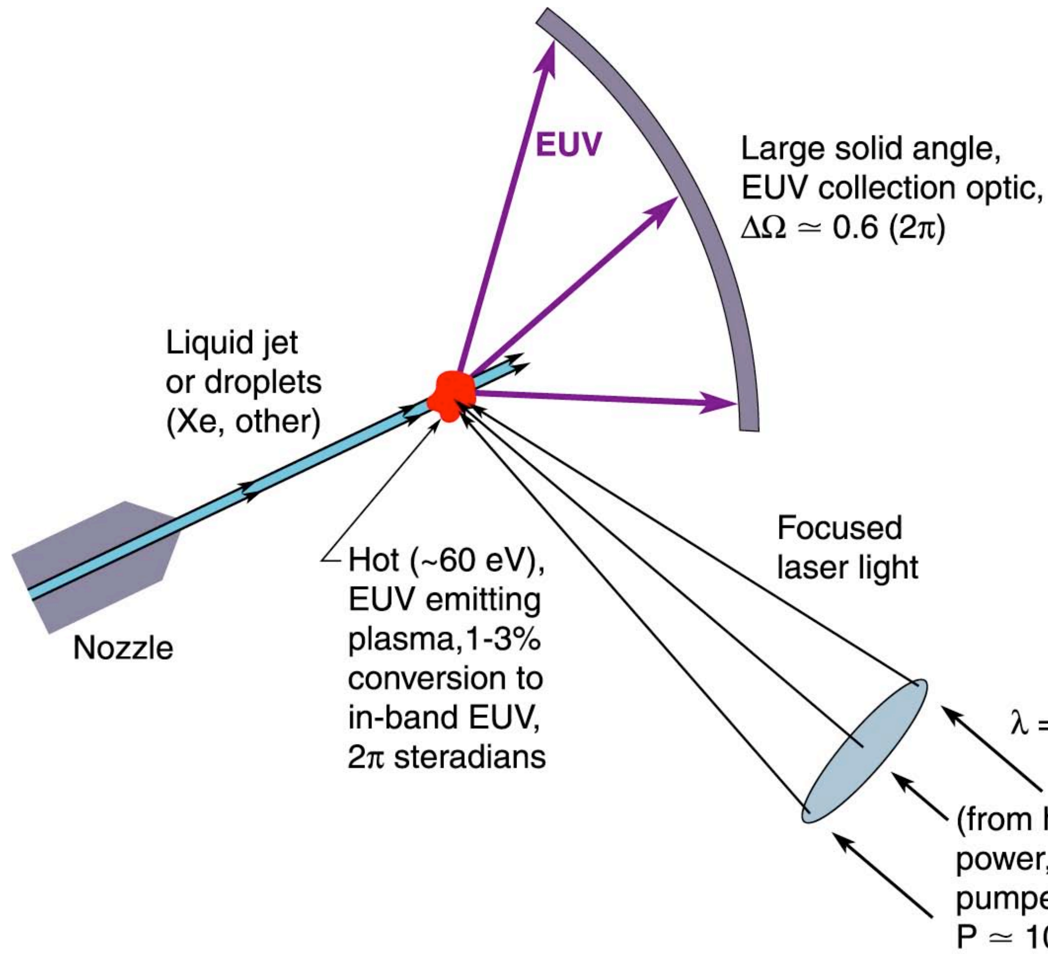
International Technology Roadmap for Semiconductors*

First year of volume production	2001	2003* ~~2004~~	2005* ~~2007~~	2007* ~~2010~~	2009* ~~2013~~	2011* ~~2016~~
Technology Generation (Dense lines, printed in resist)	130 nm	90 nm	65 nm	45 nm	32 nm	23 nm
Isolated Lines (in resist) [Physical gate, post-etch]	90 nm [65 nm]	53 nm [37 nm]	35 nm [25 nm]	25 nm [18 nm]	18 nm [13 nm]	13 nm [9 nm]
Chip Frequency	1.7 GHz	4.0 GHz	6.8 GHz	12 GHz	19 GHz	29 GHz
Transistors per chip (HV) (3 × for HP ; 5 × for ASICs)	100 M	190 M	390 M	780 M	1.5 B	3.1 B
DRAM Memory (bits)	510 M	1.1 G	4.3 G	8.6 G	34 G	69 G
Gate CD Control (3σ, post-etch)	5 nm	3 nm	2 nm	1.5 nm	1.1 nm	0.7 nm
Field Size (mm × mm)	25 × 32	25 × 32	22 × 26	22 × 26	22 × 26	22 × 26
Chip Size (mm) (2.2 × for HP ; to 4 × for ASIC)	140	140	140	140	140	140
Water Size (diameter)	300 mm	300 mm	300 mm	450 mm	450 mm	450 mm

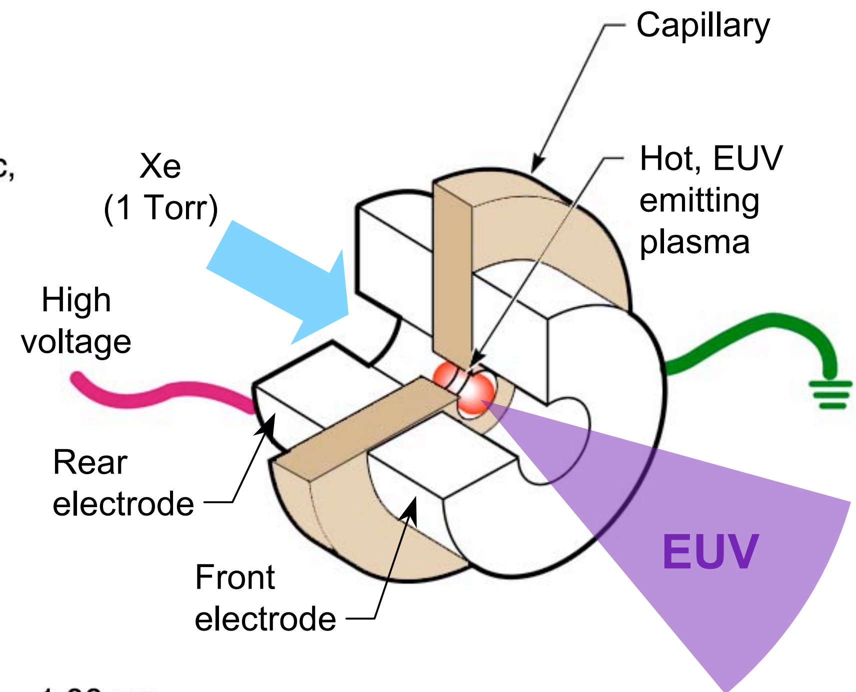
*Semiconductor Industry Association (SIA), December 2001. ***Possible 2-year cycle.**

EUV Source Candidates for Clean, Collectable 13-14 nm Wavelength Radiation

Laser Produced Plasma Source



Electrical Discharge Plasma Source

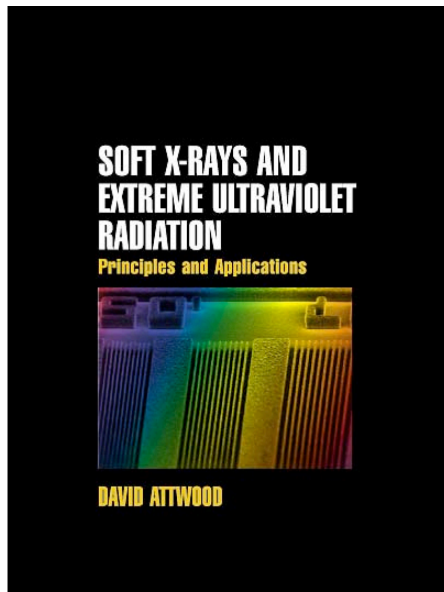


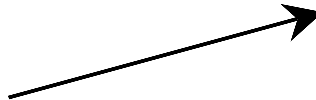
Courtesy of Neil Fornaciari and Glenn Kubiak (Sandia)

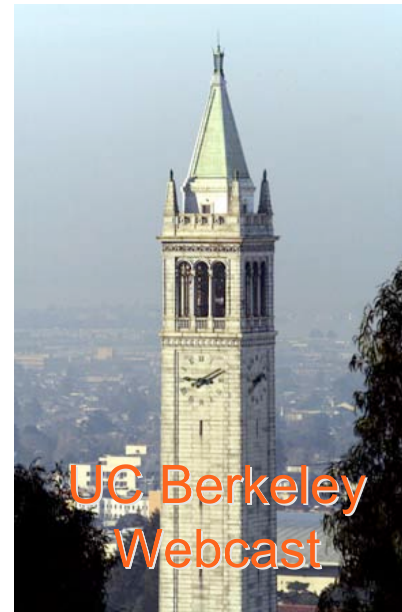
Critical Issues for EUV

- 120W compact EUV Source
- EUV source debris mitigation
- Sensitive (5m/cm^2) EUV resist with 15 nm resolution and low LER
- Defect free mask
- Environmental controls

Lectures Available Over the Web Free







www.coe.berkeley.edu/AST/sxreuv

AST 210 / EECS 213

(offered Fall 2005,
starts Aug. 30, 2 pm PDT,
live over internet plus archived)