High resolution full-field zone plate microscopy using a compact extreme ultraviolet 13.2/13.9 nm laser

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Conventional optical microscopes are convenient, but have limited resolving power

Advantages of conventional optical microscopes:

- Convenient
- Sample requires little preparation (do not have to be covered with a conductive coating or sliced very thin)
- Flexible sample environment (magnetic fields, temperature)
- Rapidly render images

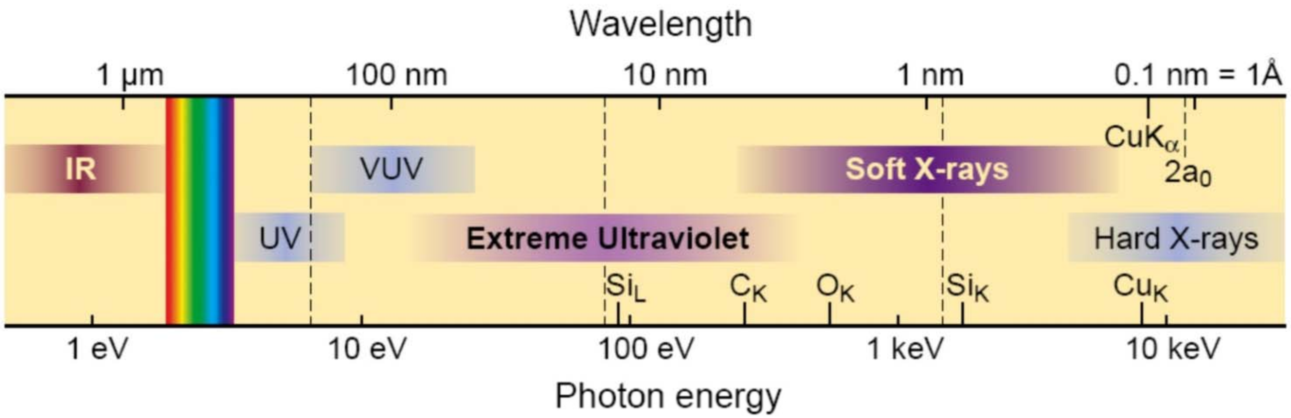
Disadvantage:

- Poor spatial resolution (~200 nm)

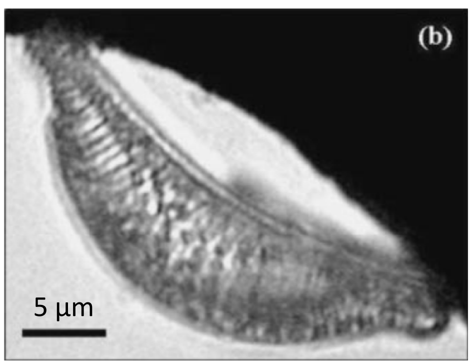
Solution: ??

www.microscopyu.com

An extension of conventional visible microscopy, EUV/SXR microscopy can obtain images with higher spatial resolution



Visible microscopy



λ = 400 -700 nm

Res > 200 nm

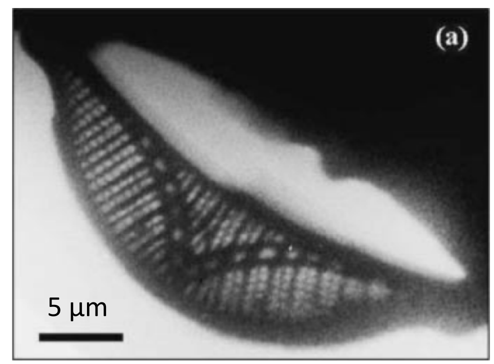
M. Hoshino, et al., Jap. J. App. Phys. 45, 989 (2006)

D.T. Attwood (1999)

$$\text{Resolution} = \frac{k_1 \lambda}{NA_{obj}}$$

EUV/SXR microscopy can potentially resolve full-field images with 10-100x smaller features than conventional visible microscopy.

EUV/ SXR microscopy



EUV: λ = 5 - 50 nm (250 - 25 eV)

SXR: λ = ~0.3 - 5 nm (4k-250 eV)

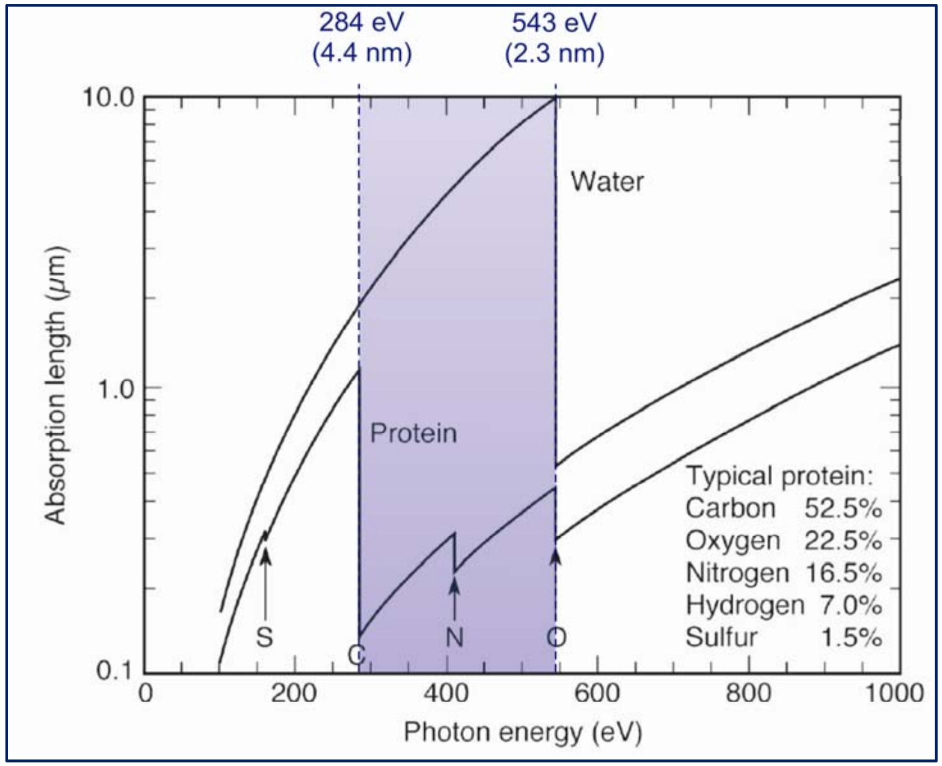
Res: 15 nm - 100 nm

Main difference between visible and EUV/SXR microscopes: presence of a large number of atomic resonances

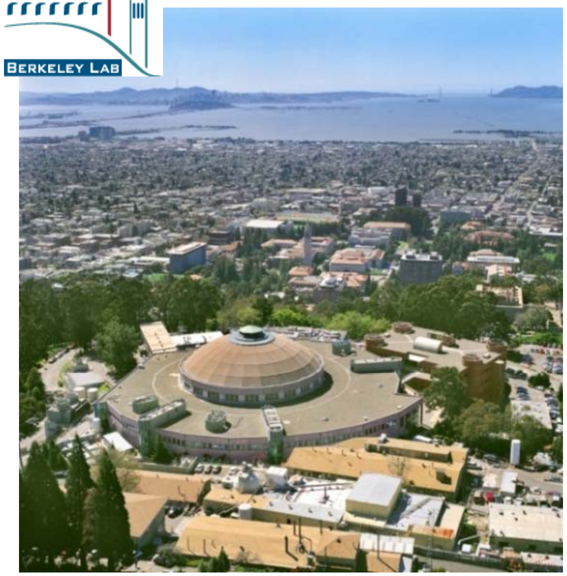
<u>Numerous atomic resonances exist in the EUV/SXR region</u>

- Strong absorption
  - Requires special optics
  - Vacuum environment for light to propagate over large distances
- \+ Elemental specificity/ Natural enhanced absorption contrast

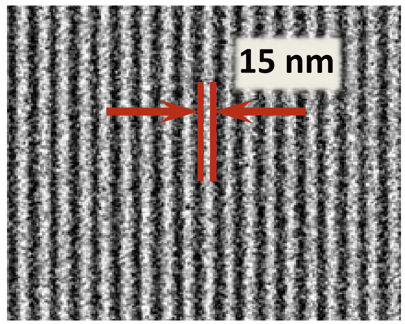
“Water window”



EUV/SXR microscopes provide unique advantages for nanoscience and nanotechnology applications



Best spatial resolution:

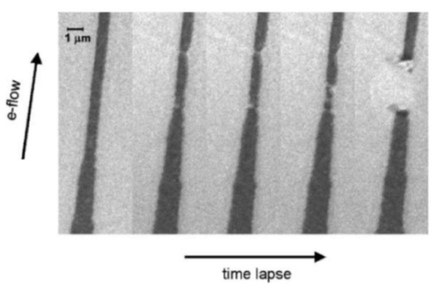


W. Chao, et al., Nature 435, 1210 (2005)

Advantages of EUV/SXR microscopy

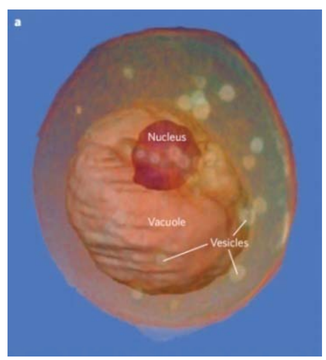
- High spatial resolution
- Large field of view (15 – 20 µm), can be tiled up to even larger images
- Elemental specificity of x-ray absorption
- Ease of sample preparation
- Can record images in varying environments
- Render images rapidly

Materials science: **investigating electromigration in IC interconnects**



G. Schneider, et al., Nucl. Instrum. Methods Phys. Res., Sect. B 199, 469 (2003)

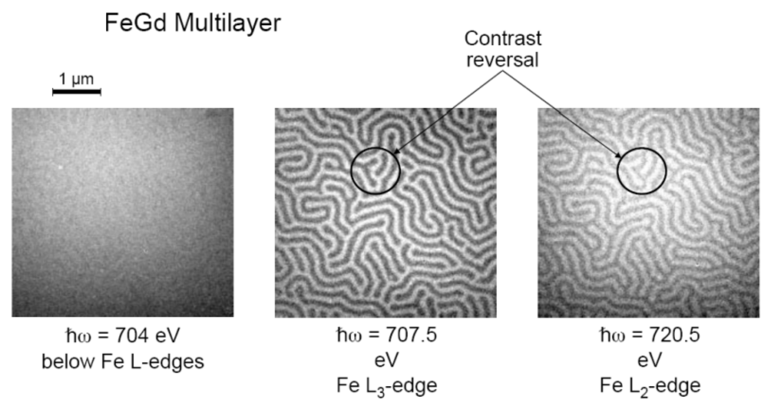
Biology: **imaging whole cells in their aqueous environment**



M. A. Le Gros, et al., Curr. Opin. Struc. Biol. 15, 593 (2005)

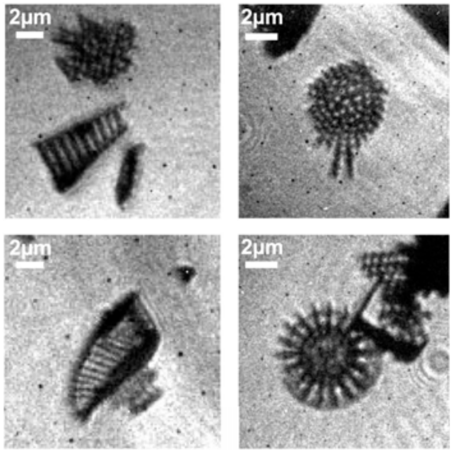
D. Attwood, Nature 442, 642 (2006)

Nanomagnetism: **imaging magnetic domains at different absorption edges**



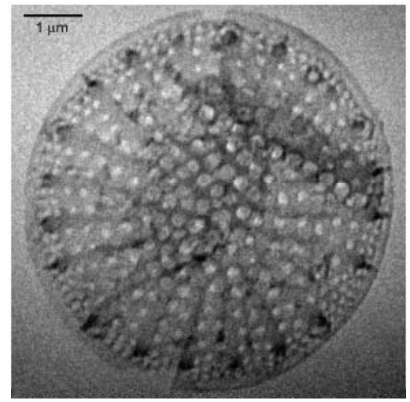
P. Fischer, *D. Attwood (2005) EE213 Berkeley Extension*

Laboratory-sized sources make EUV/SXR microscopy more accessible



Source: **HHG**
Wavelength: 13.6 nm
Resolution: **~200 nm**
Exposure time: **4 minutes**
Sample: diatoms

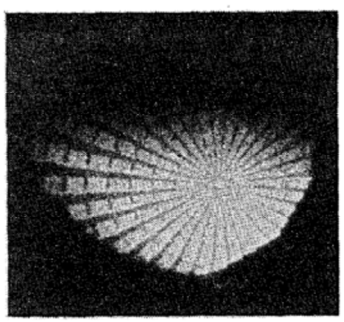
M. Wieland, et al., Ultramicr. 102, 93 (2005)



Source: **Plasma**
Wavelength: 2.48 nm
Resolution: **sub 30 nm**
Exposure time: **5 minutes**
Sample: diatom

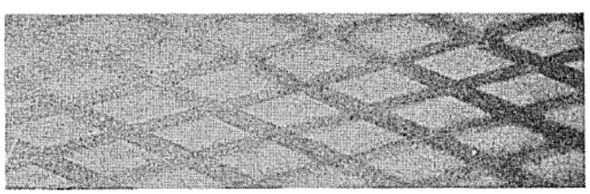
P.A.C. Takman, et al., J. Micr. 226, 175 (2007)

Source: EUV/SXR lasers



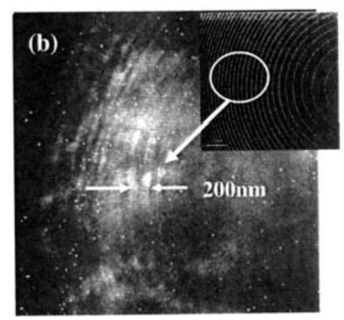
Early work in transmission:
Wavelength: 4.48 nm (NOVA laser)
Resolution: **~100 nm**
Exposure time: **single 200 picosecond pulse**
Sample: gold pattern on Si_3N_4 substrate

L.B. DaSilva, et al., Science 258, 269 (1992)



Early work in reflection:
Wavelength: 18.2 nm
Resolution: **~700 nm**
Exposure time: **8 shots**
Sample: gold squares on a glass substrate

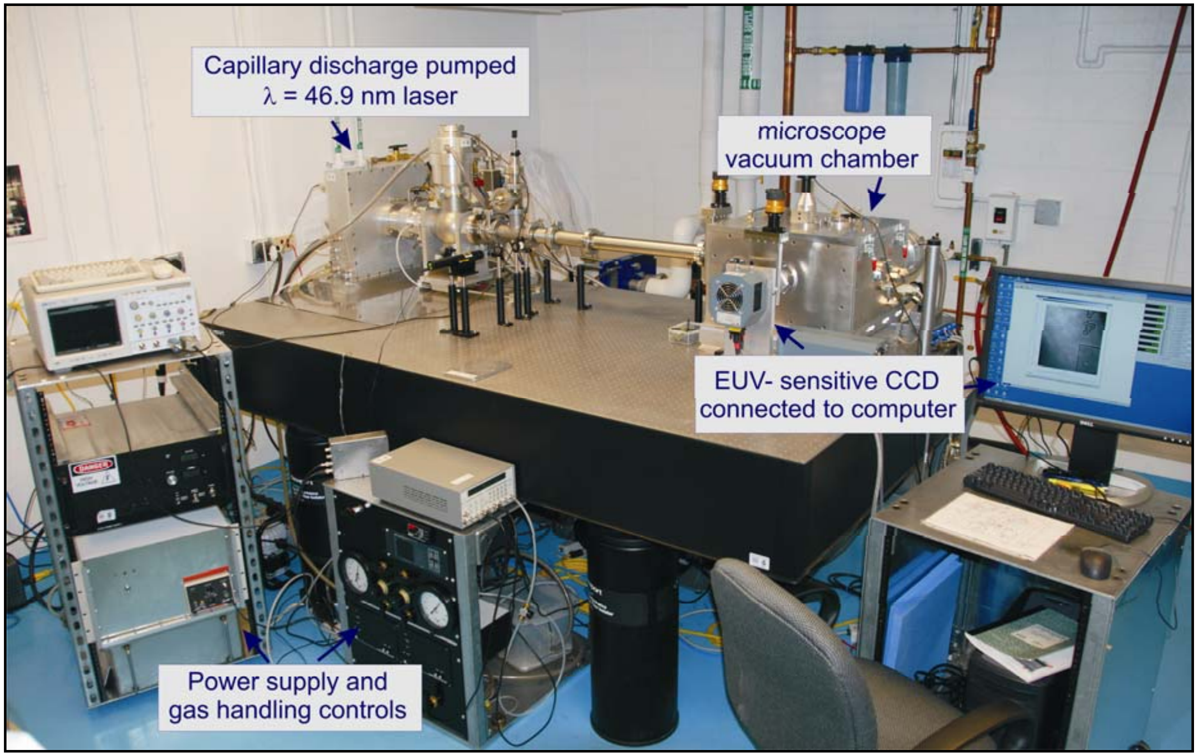
D.S. DiCicco, et al., Inst. Phys. Conf. Series 401 (1992)

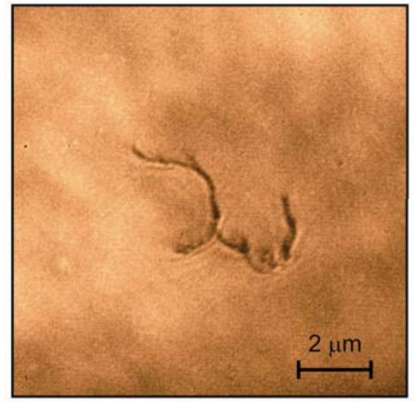


Source: **compact laser**
Wavelength: 13.9 nm
Resolution: **~200 nm**
Exposure time: **single picosecond pulse**
Sample: Cr/Si multilayer

M. Kishimoto, et al., J. de Phys. IV 104, 141 (2003)

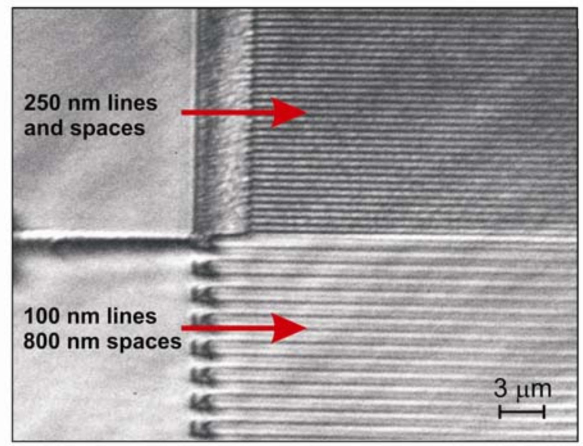
Desktop-size λ=46.9 nm CSU microscope with ability to obtain single laser shot images with near-wavelength resolution





Transmission single shot EUV image of an entanglement of 50 nm diameter carbon nanotubes.

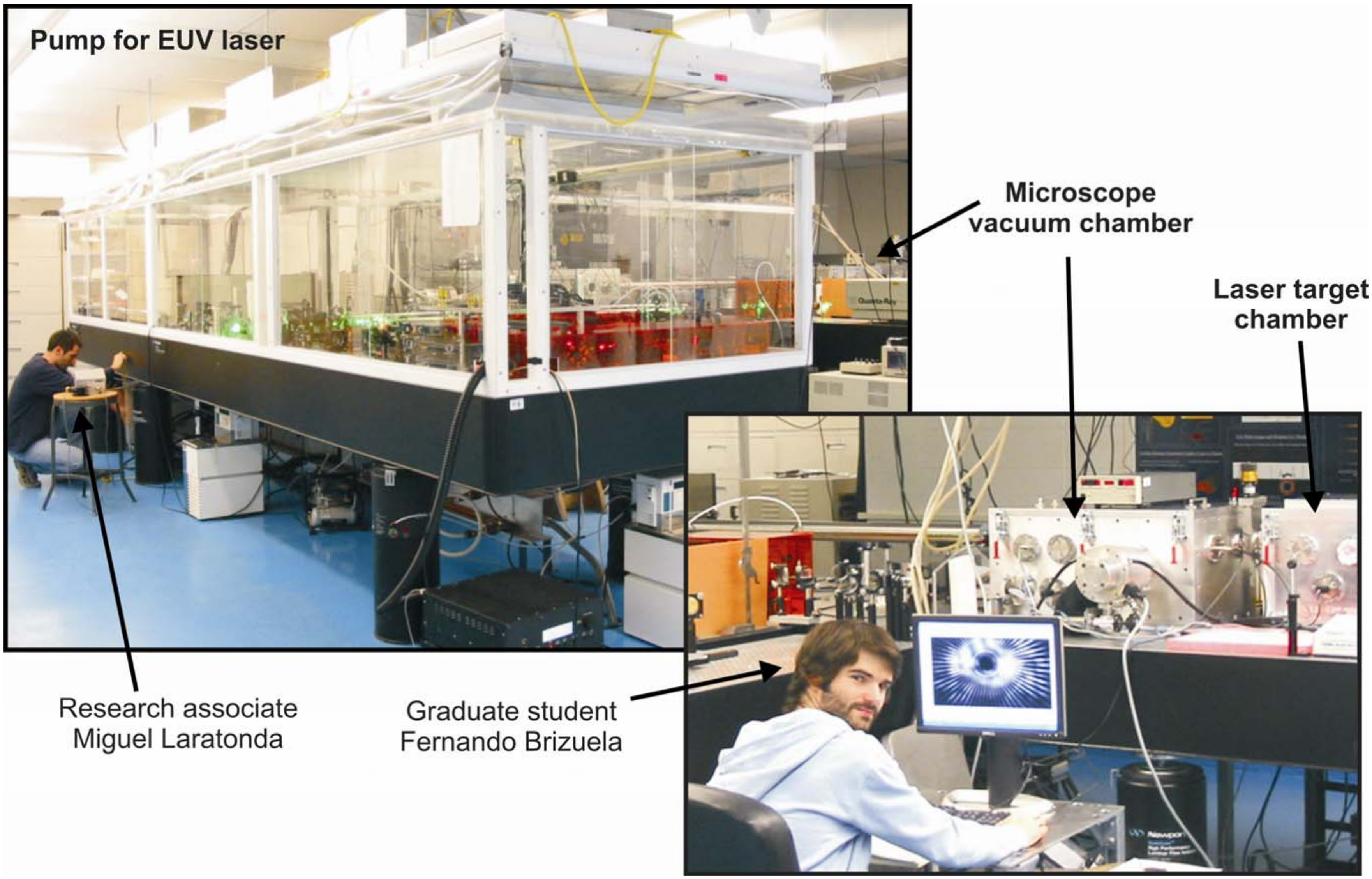
Resolution: **54 nm (Near wavelength)**
Exposure time: **Single laser shot (~1 ns)**



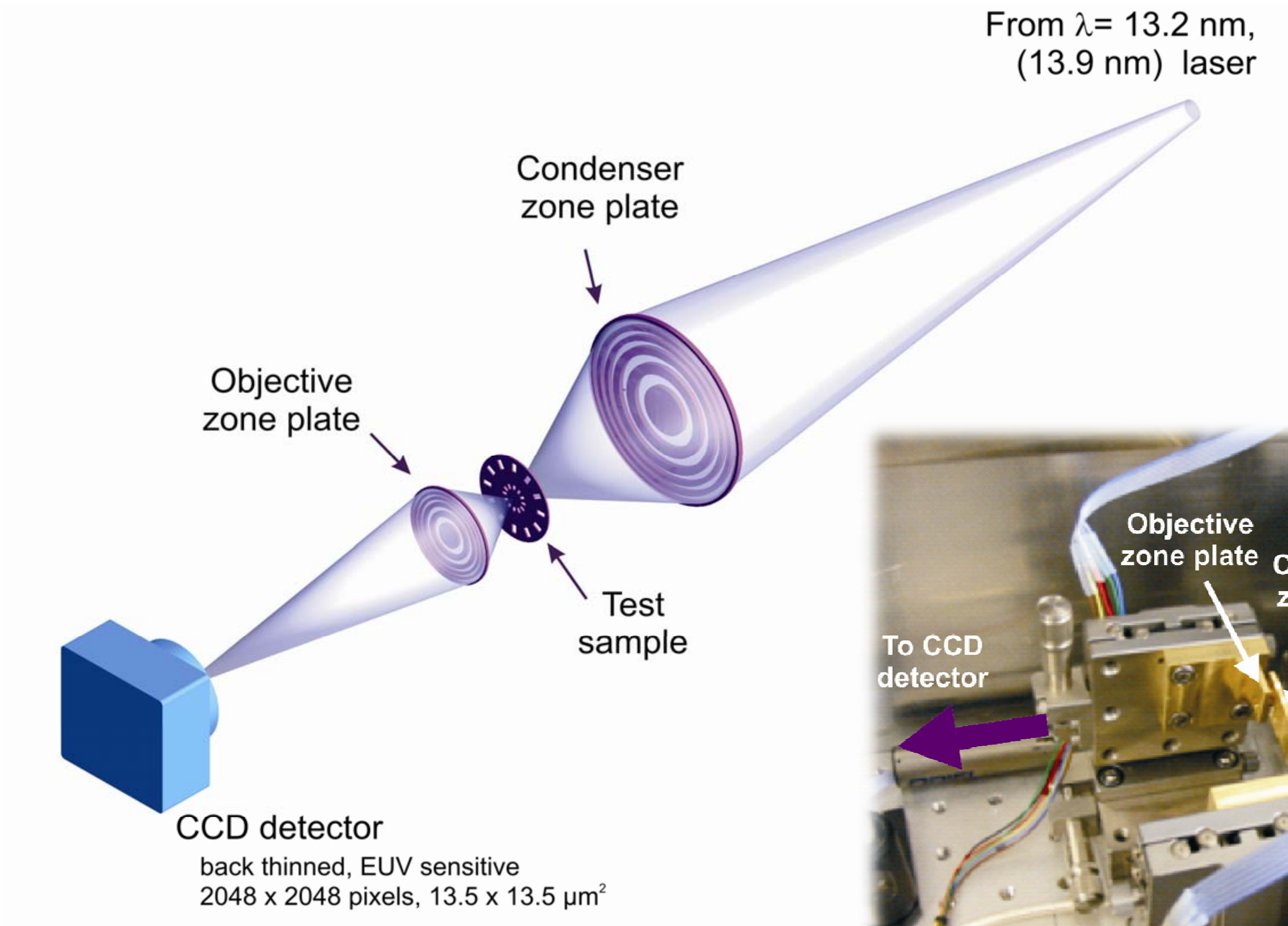
Reflection EUV image of a partially processed IC chip with PoSi lines on a Si wafer using 20 seconds exposure at 5 Hz.

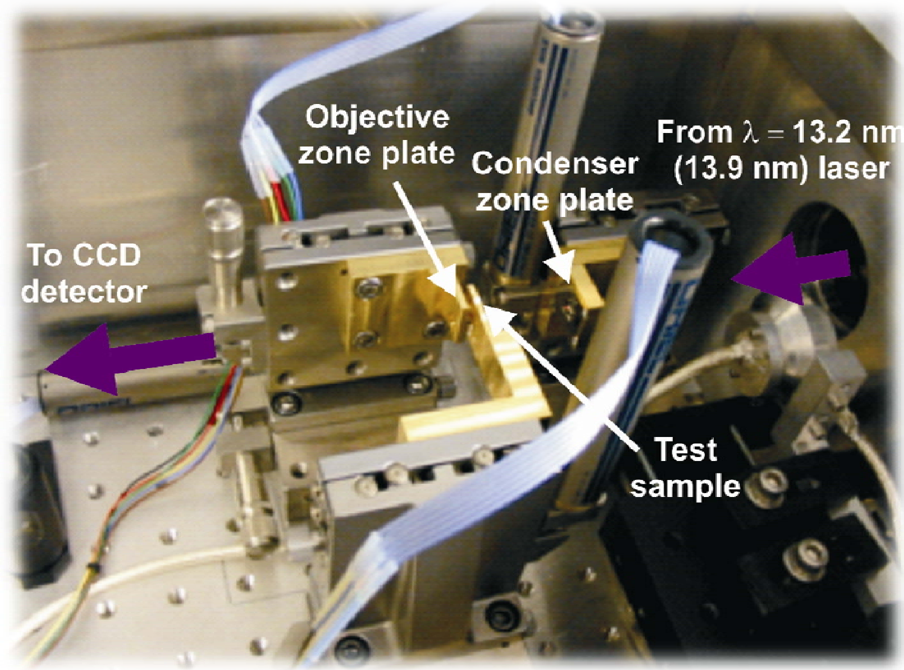
G. Vaschenko, et al., Opt. Lett. 30, 2095 (2005)
F. Brizuela, et al., Opt. Exp. 13, 3983 (2005)
C. Brewer, et al., Opt. Lett., (posted 4 Feb. 2008, in press)

Tabletop λ=13.2/13.9 nm CSU microscope, the EUVM2

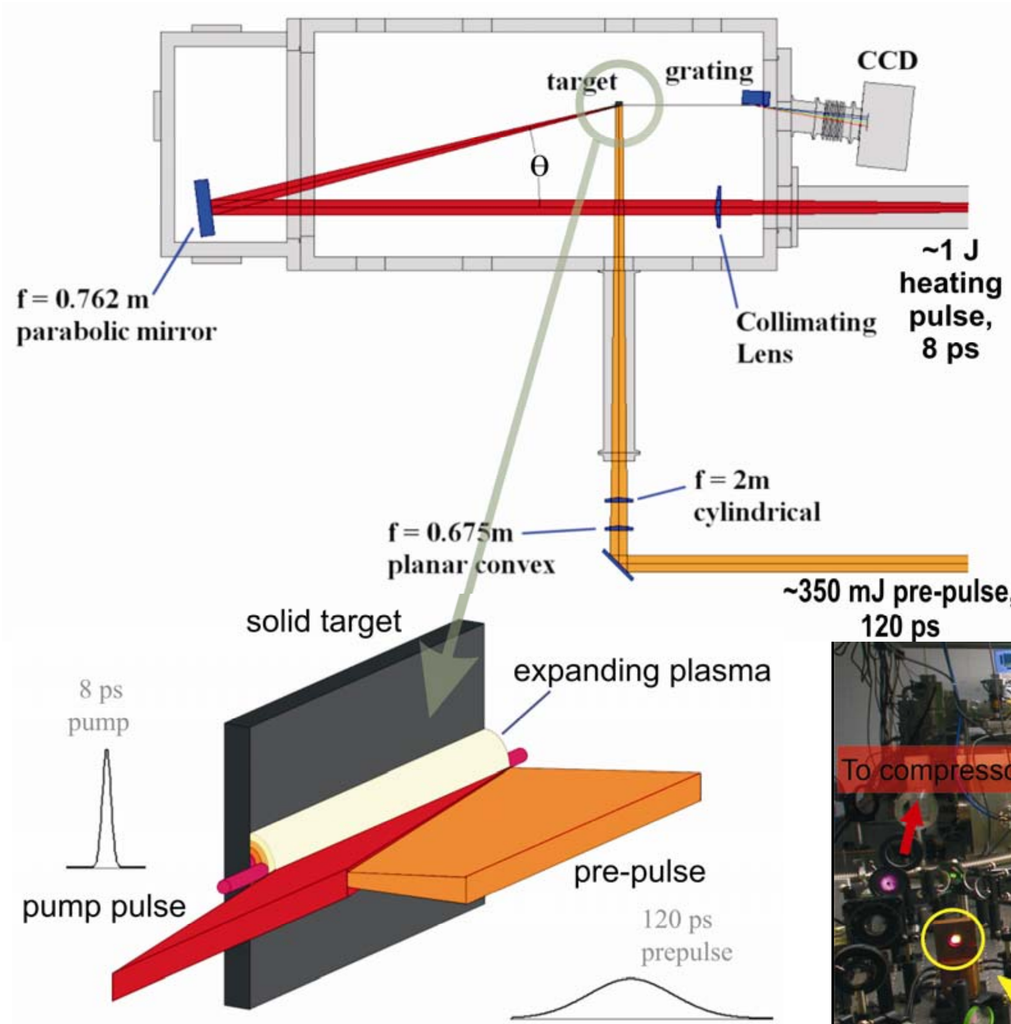


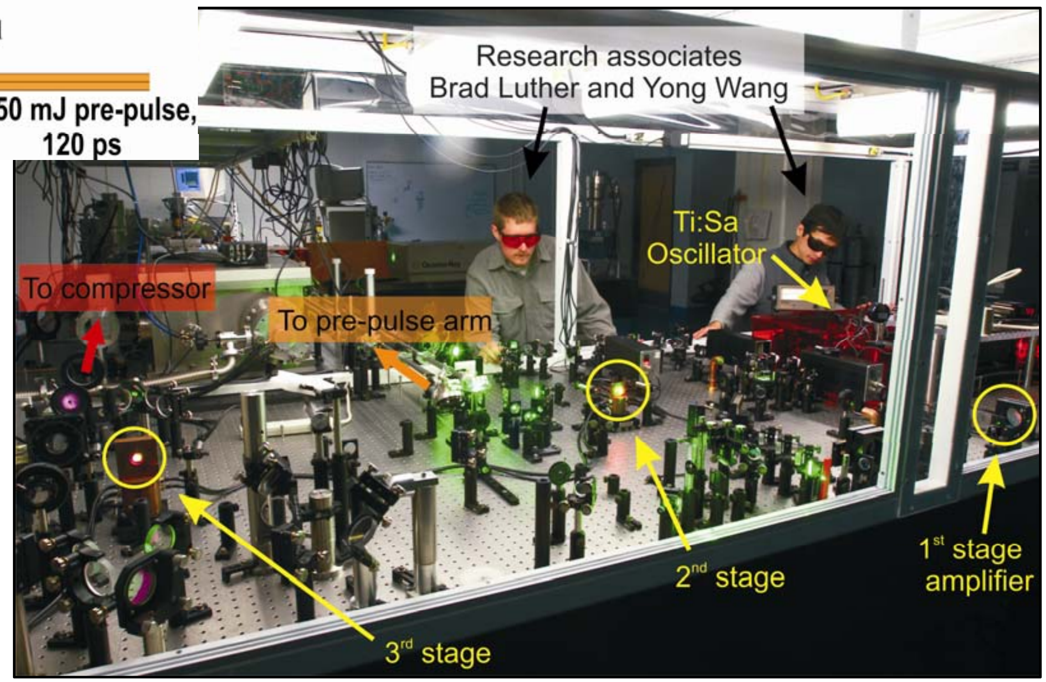
Schematic of the EUVM2





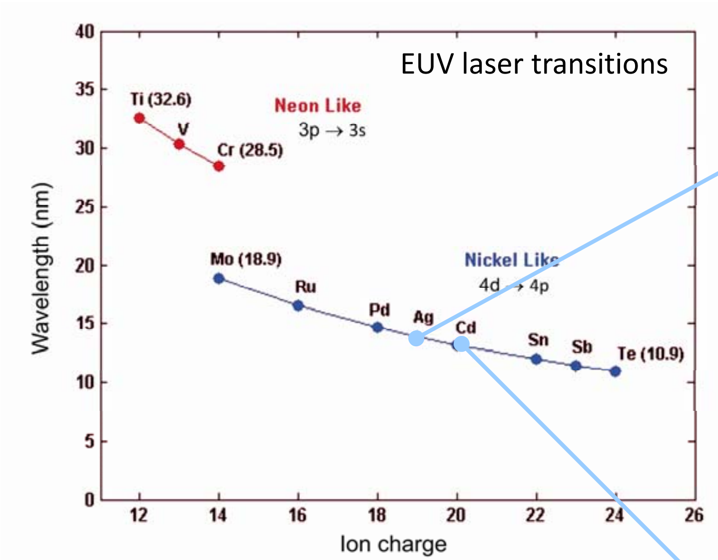
EUV laser is generated in a transient population inversion by ASE in a laser-created plasma



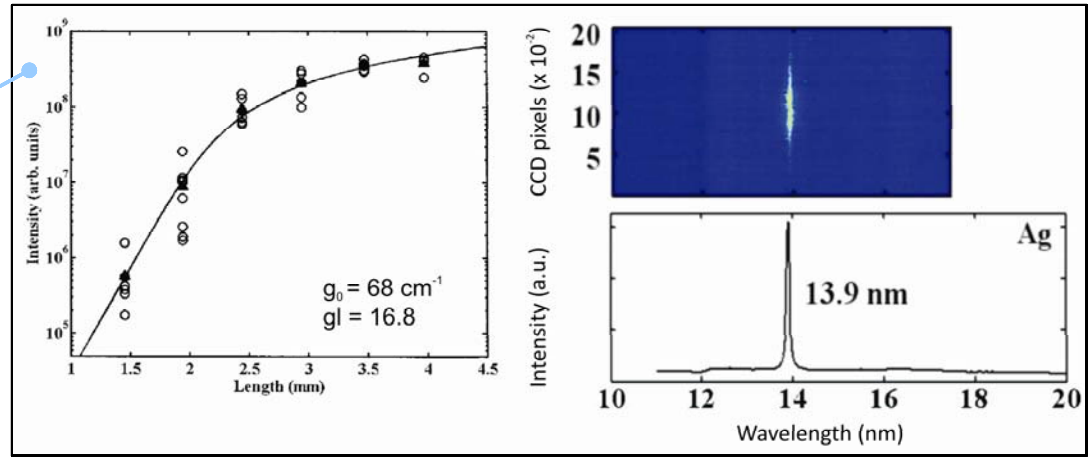


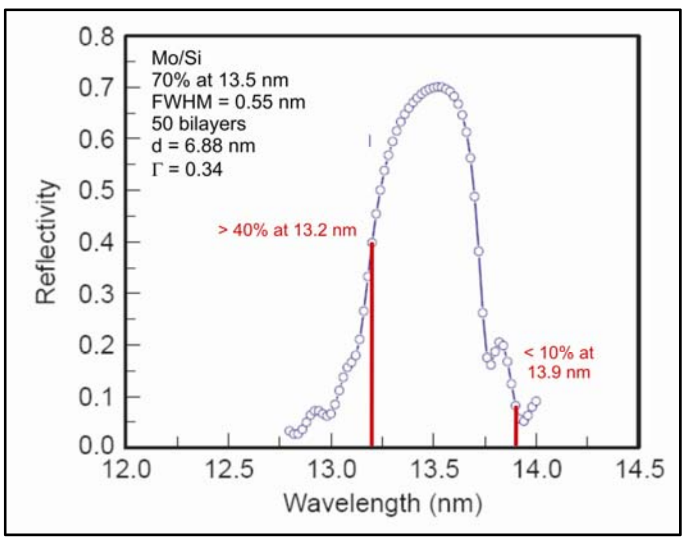
B.M. Luther, et al., IEEE J. Quantum Elec. 42, 4 (2006);

Laser operates in saturation regime for wavelengths down to 13.2 nm

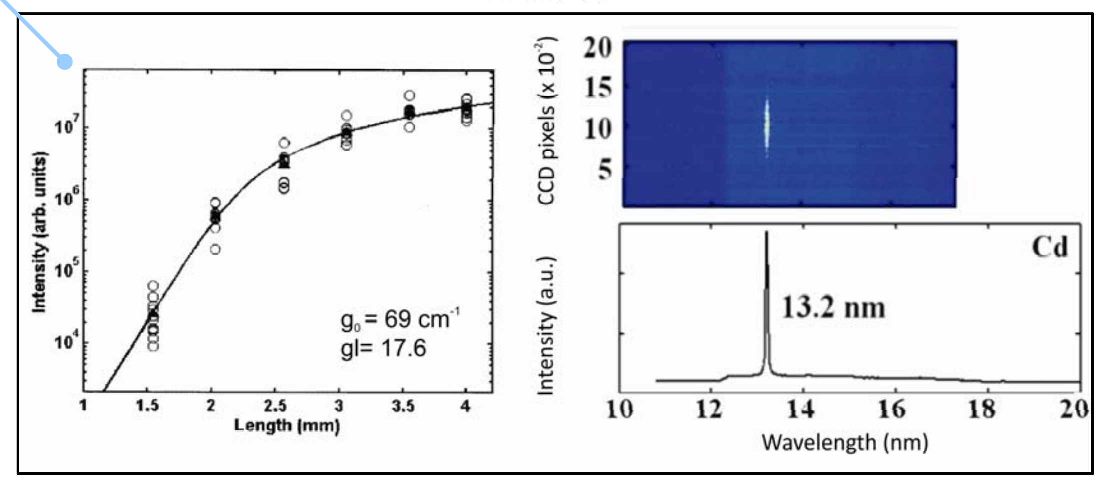


Ni-like Ag





Ni-like Cd



S. Bajt, et al., Opt. Eng. 41, 1797 (2002);

J. J. Rocca et al., Opt. Lett. 30, 2581 (2005); Y. Wang et al., Phys. Rev. A 72, 5 (2005)

Laser exhibits high spectral brightness, modest spectral coherence, and high directionality

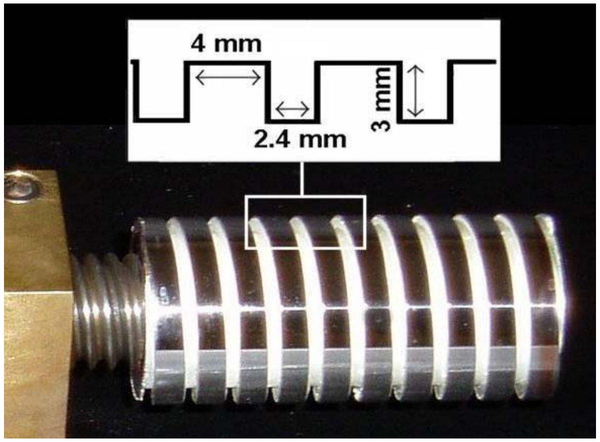
Output parameters

- λ = 13.2 or 13.9 nm
- Av. Pulse energy: ~200-400 nJ
- Rep rate: 5 Hz
- Av. Power: ~1-2 μW
  (>10^{11} photons/s)
- Pulse duration: ~5 ps
- Div. angle: 7-10 mrad
- Transverse coherence length: < 1/20 of beam diameter
- BW: $\Delta\lambda/\lambda < 10^{-4}$
- Peak spectral brightness: ~2-3 x 10^{23} photons mm^{-2} $mrad^{-2}$ s^{-1} $(0.01\%\ BW)^{-1}$

A. Weith, et al., Opt. Let. **31**, 1994 (2006)

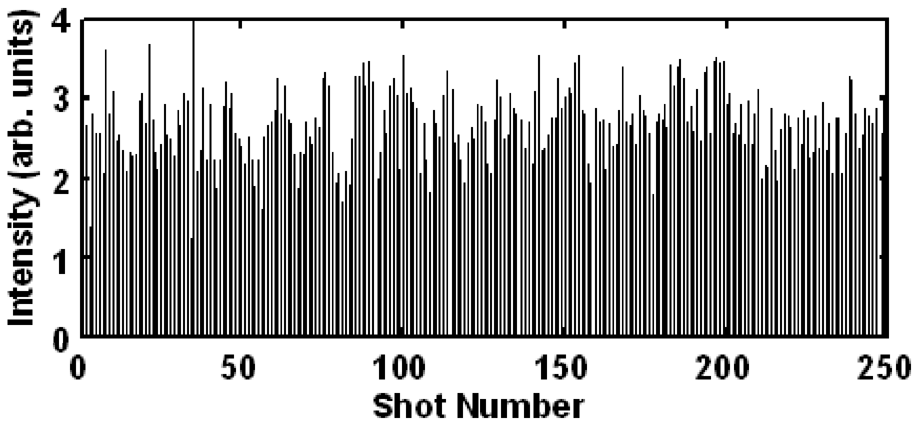
Y. Liu, et al., Opt. Exp. 14, 12872 (2006)

rotating helicoidal target

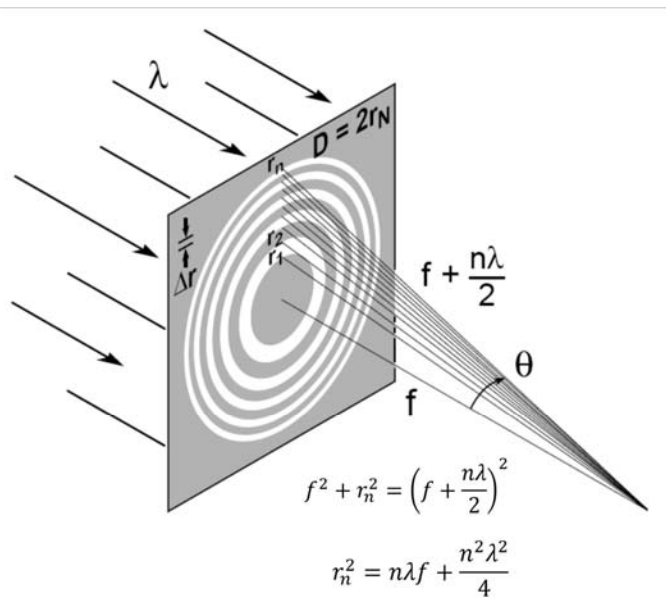


More than 20,000 shots/ target → 100-670 images/target

5 Hz repetition rate



Resolution of a zone plate- based microscope is largely determined by the objective outermost zone width



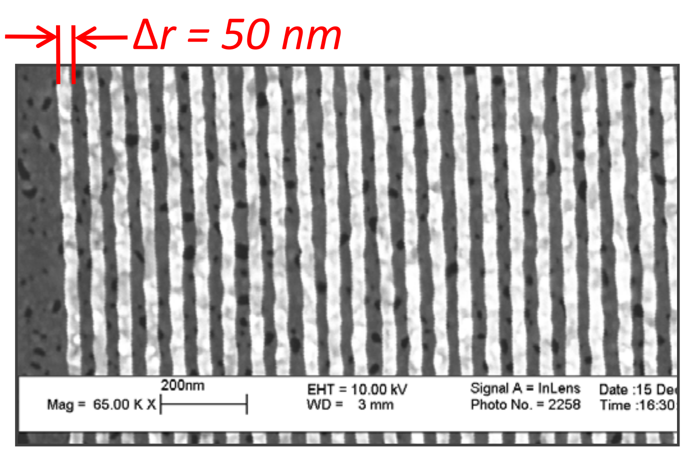
D. T. Attwood, "Soft X-rays and Extreme Ultraviolet Radiation." (Cambridge Univ. Press, New York, 1999).

$$NA = \frac{\lambda}{2\Delta r}$$

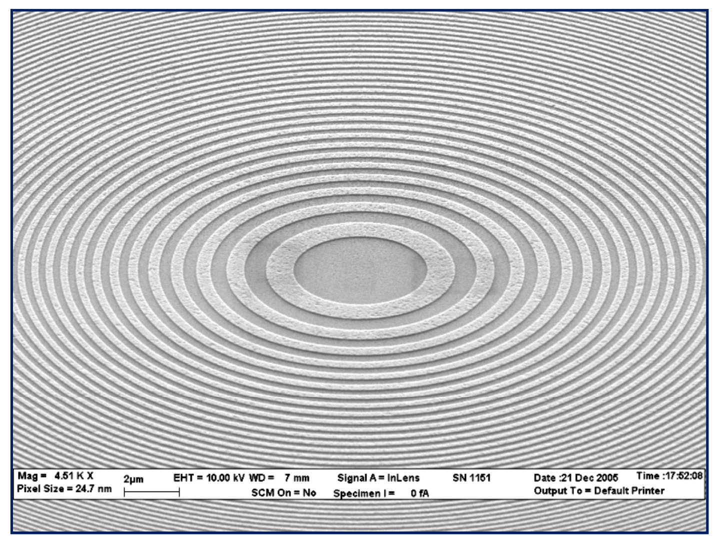
$$resolution = k_1 \frac{\lambda}{NA_{obj}} = 2k_1 \Delta r$$

$$f = \frac{4N(\Delta r)^2}{\lambda}$$

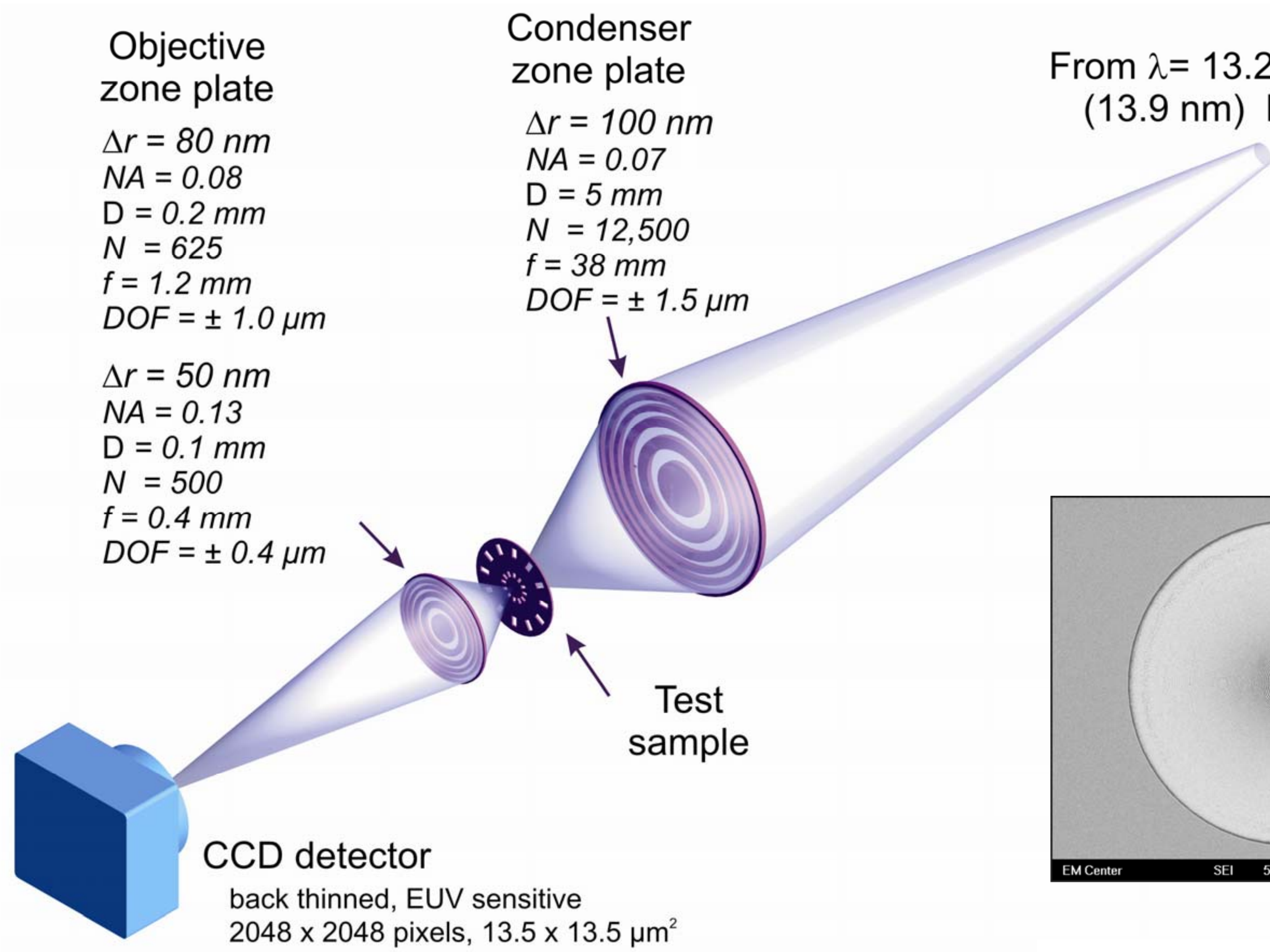
$$DOF = \pm \frac{1}{2} \frac{\lambda}{(NA_{OZP})^2} = \pm \frac{2(\Delta r)^2}{\lambda}$$

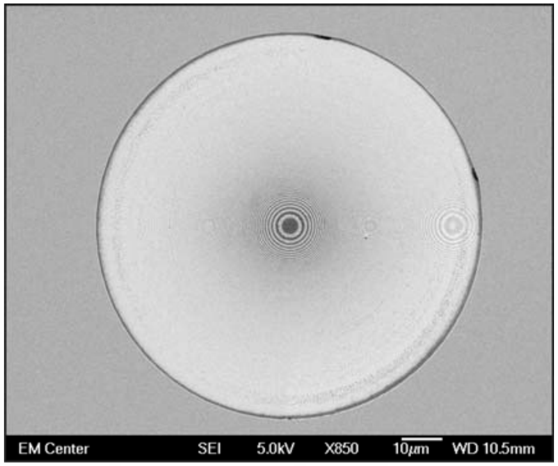


SEM Images of a zone plate



EUVM2 zone plates produced by e-beam lithography

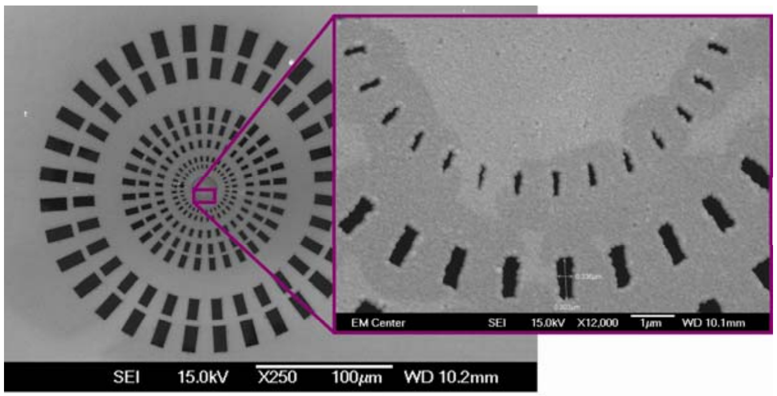




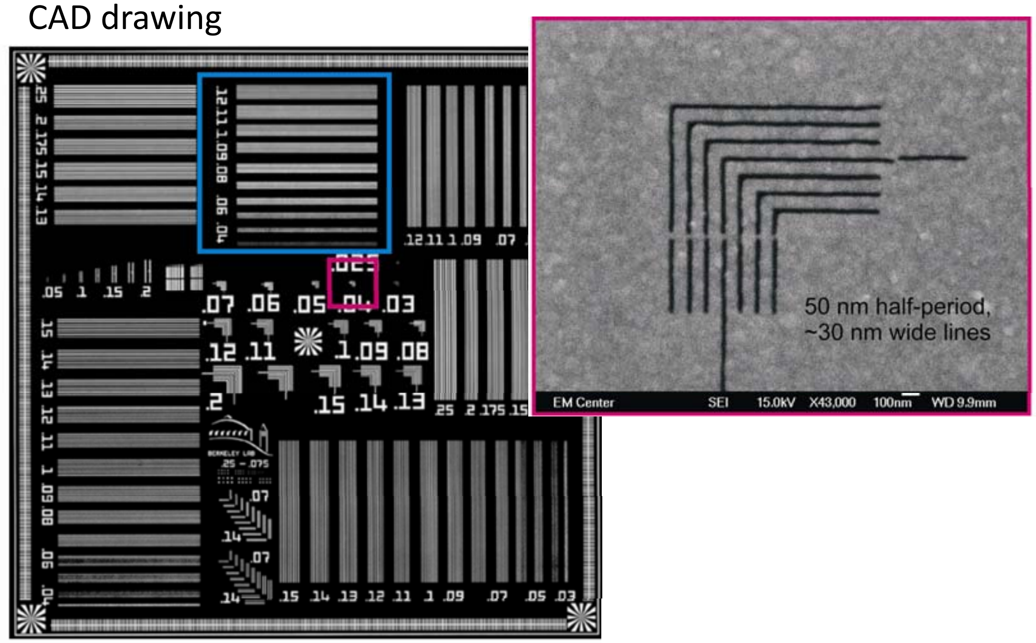
E.H. Anderson, IEEE J. Vac. Sci. and Tech. B, 18, 2970 (2006)

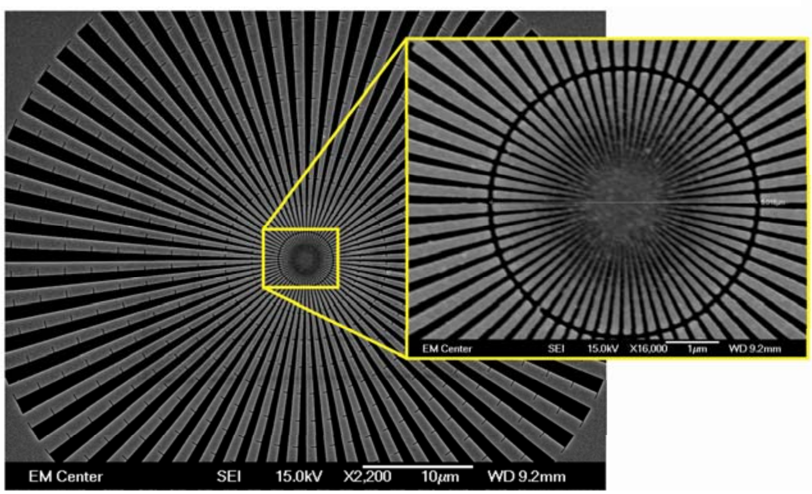
EUVM2 nanoscale test patterns produced by e-beam lithography

SEM images of test patterns

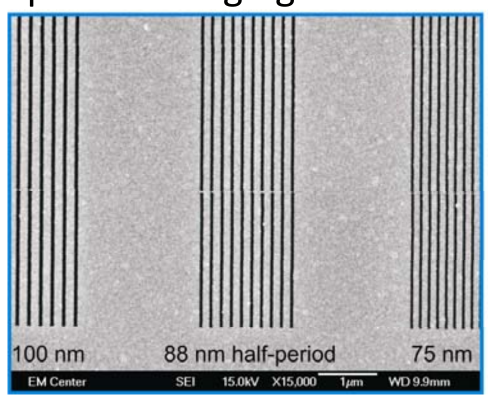


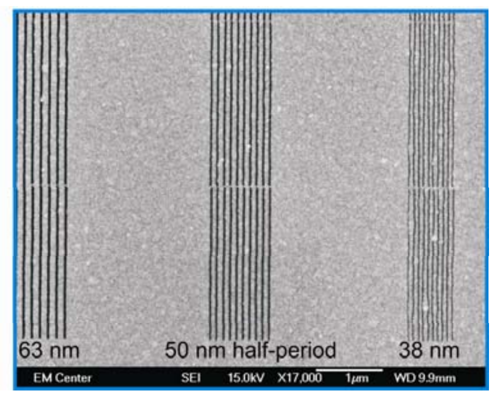
CAD drawing



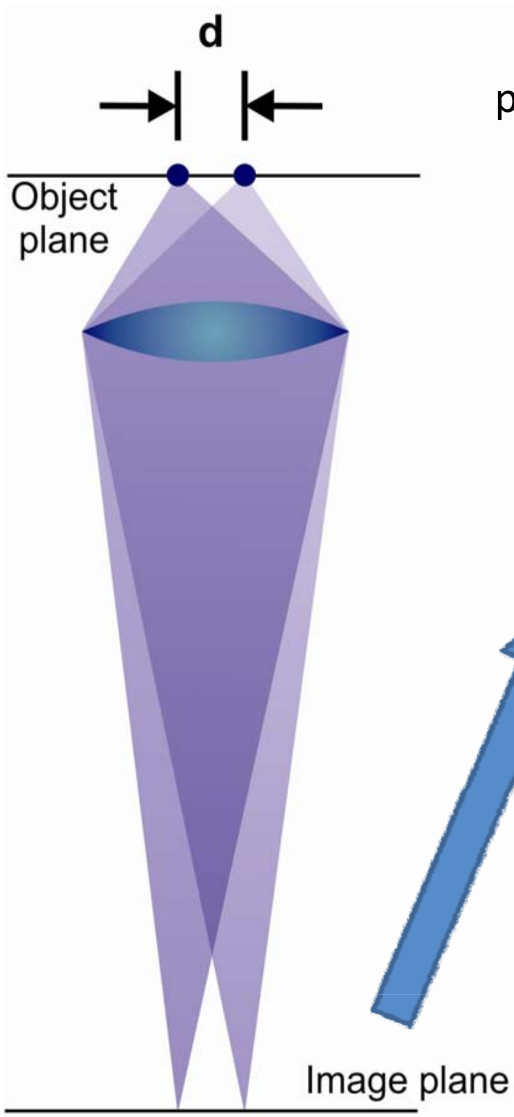


Contains nominally 1:1 line/space patterns with half periods ranging from 310-38 nm

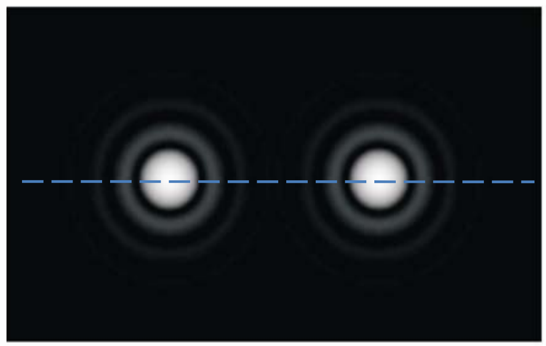


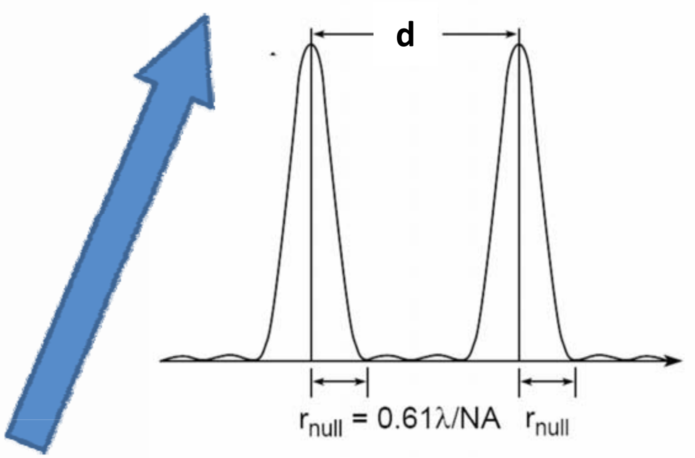


Rayleigh resolution criterion for two mutually incoherent, equal intensity point sources



Intensity in image plane of a point source is an Airy pattern

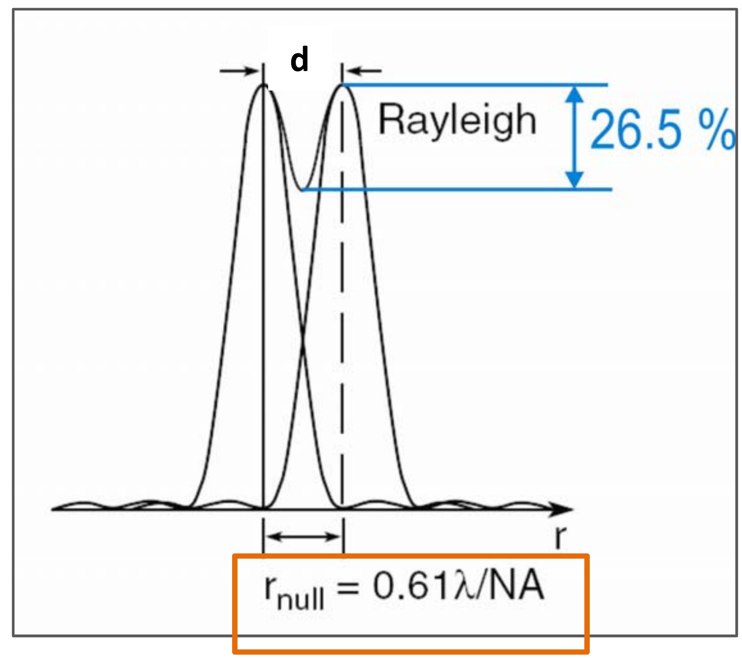




D.T. Attwood (1999)

$$\text{Resolution} = \frac{0.61\lambda}{NA}$$

For mutually incoherent point sources

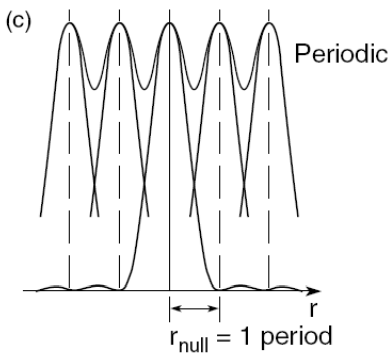


Modulation:

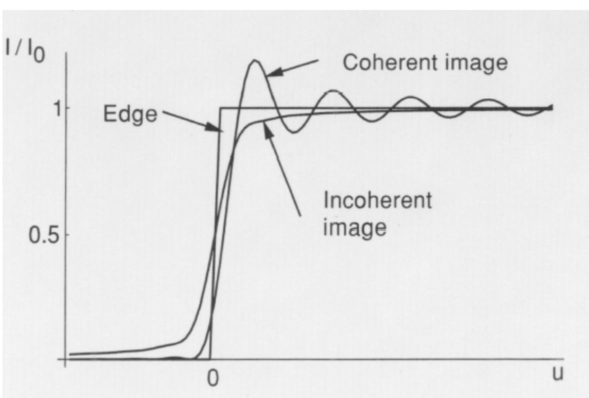
$$\frac{I_{max} - I_{min}}{I_{max}} = 0.265$$

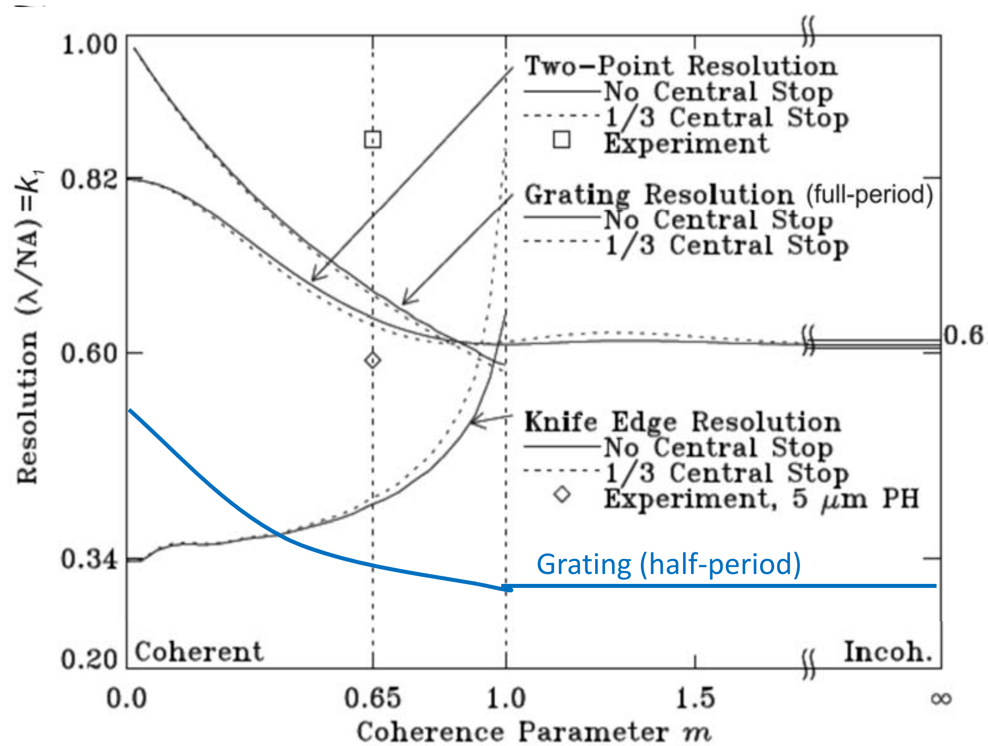
Degree of coherence of the illumination and nature of the resolution test object affect the resolution

Grating resolution (M=26.5%)



Knife Edge (transition =10%-90%)





J. M. Heck et al. (2005)

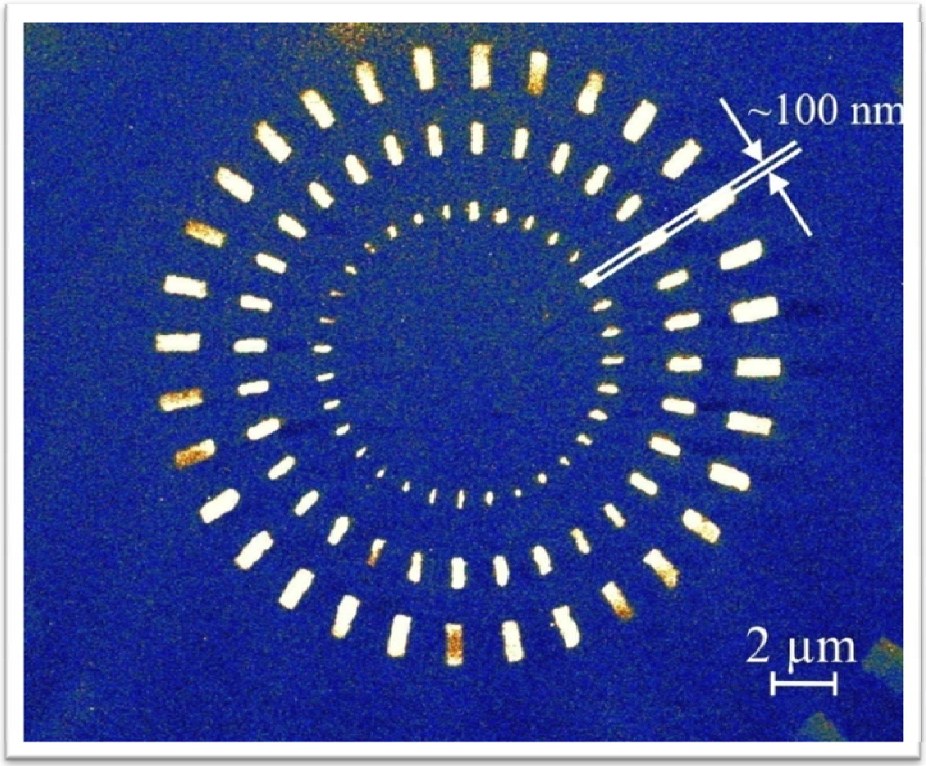
$$\text{Resolution} = \frac{k_1 \lambda}{NA_{obj}} = 2k_1 \Delta r$$

For any degree of coherence

HP grating resolution for Δr=50 nm: **29- 50 nm**

J.M Heck, et al., J. X-Ray Sci. and Technol. 8, 95 (1998), D.T. Attwood, (1999)

Sample test pattern with large through-holes aids in critical initial alignment of EUVM2

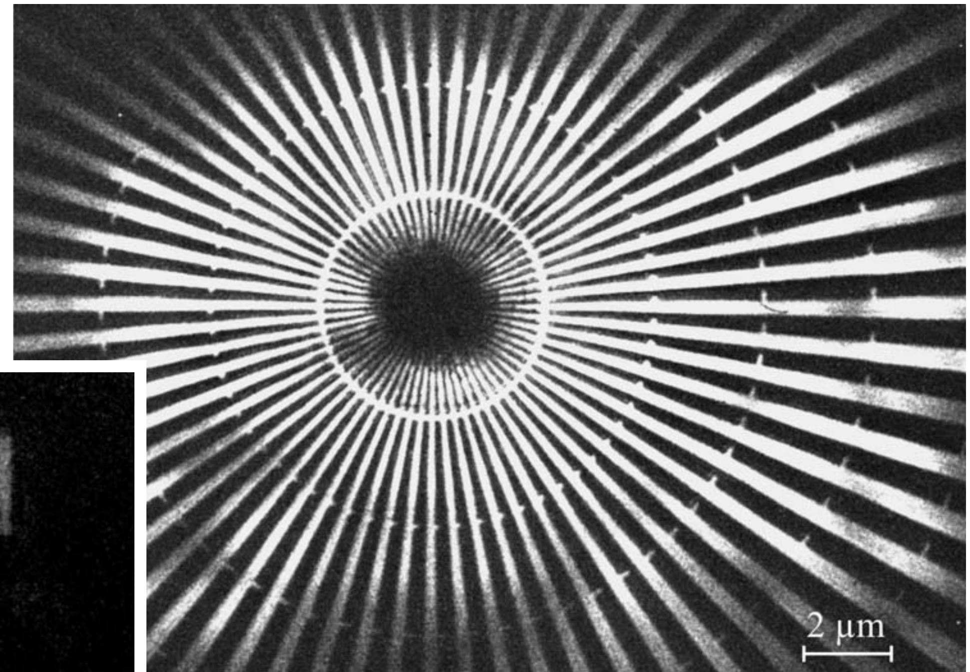


- λ = 13.9 nm
- Δr = 80 nm (NA = 0.087)
- 20 second exposure
- M ~540 x (image element pixel size = 25 nm)

Large field-of-view EUV2 images

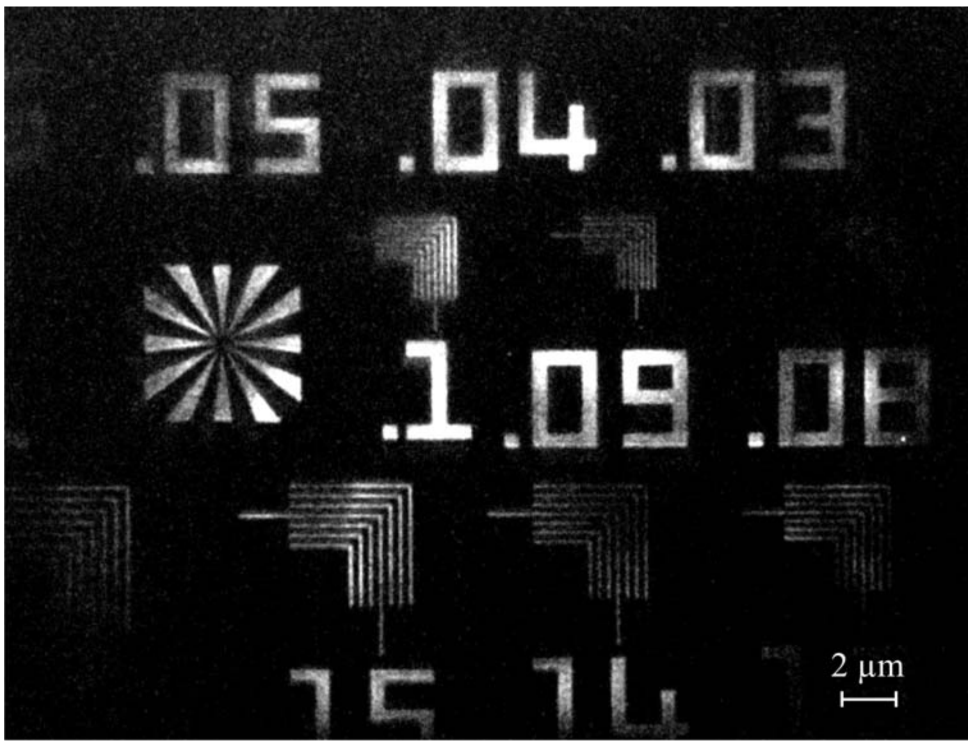
- λ = 13.2 nm
- Δr = 80 nm (NA = 0.083)
- 40 second exposure
- M ~275 x (image element pixel size = 50 nm)

15 µm



22 µm

27 µm



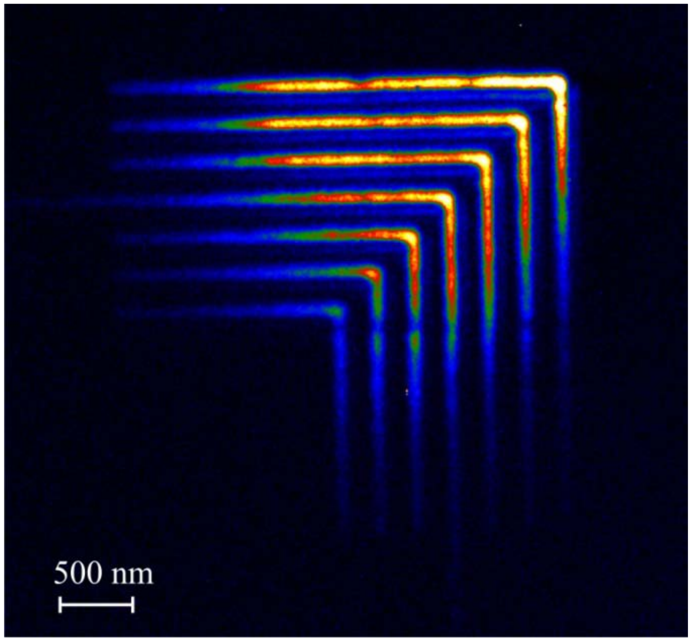
36 µm

- λ = 13.9 nm
- Δr = 80 nm (NA = 0.087)
- 20 second exposure
- M ~540 x (image element pixel size = 25 nm)

G. Vaschenko, C. Brewer, et al., Opt. Lett. 31, 1214 (2006)

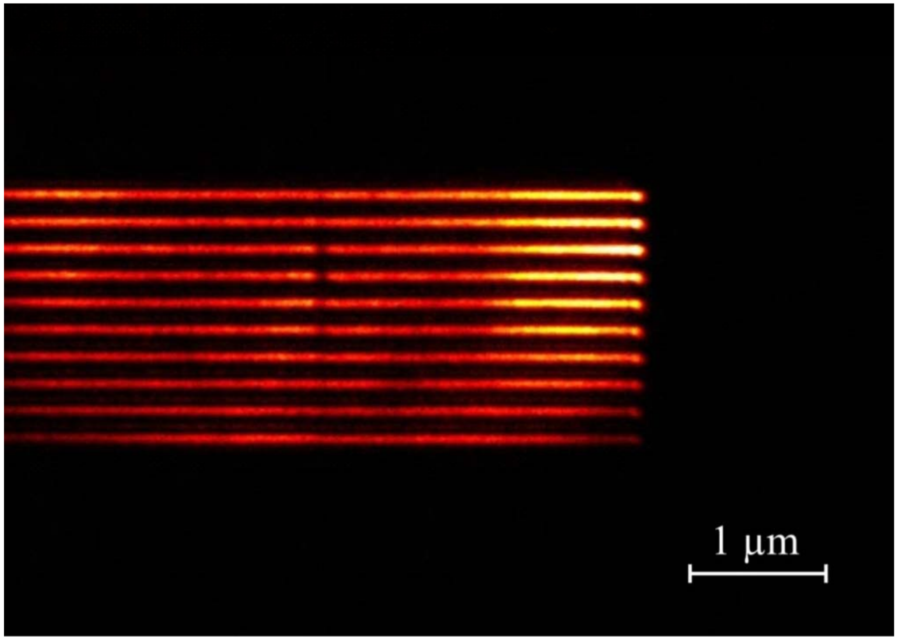
EUVM2 images of 100 nm half-period pattern acquired in only 6 seconds

120 nm elbows



- λ = 13.9 nm
- Δr = 50 nm (NA = 0.139)
- 20 second exposure
- M ~1220 x (image element pixel size = 11 nm)

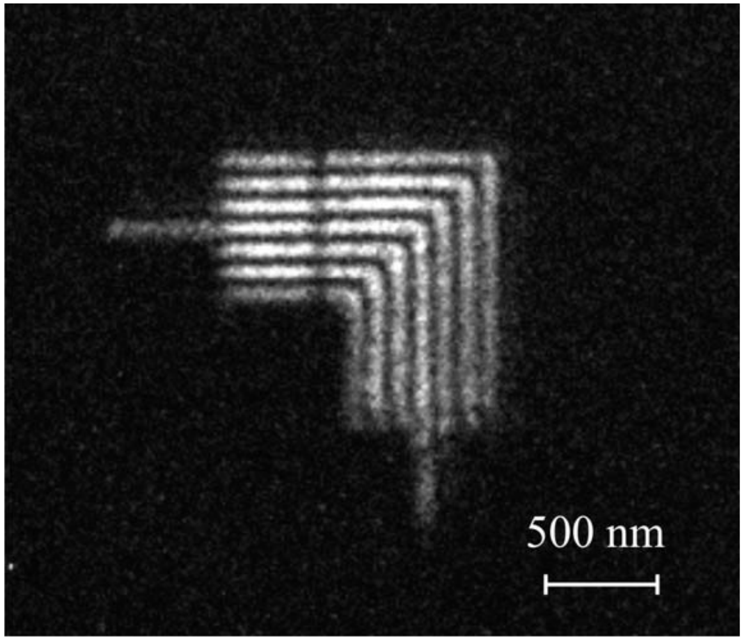
100 nm grating



- λ = 13.2 nm
- Δr = 50 nm (NA = 0.132)
- **6 second exposure**
- M ~1080 x (image element pixel size = 12.5 nm)

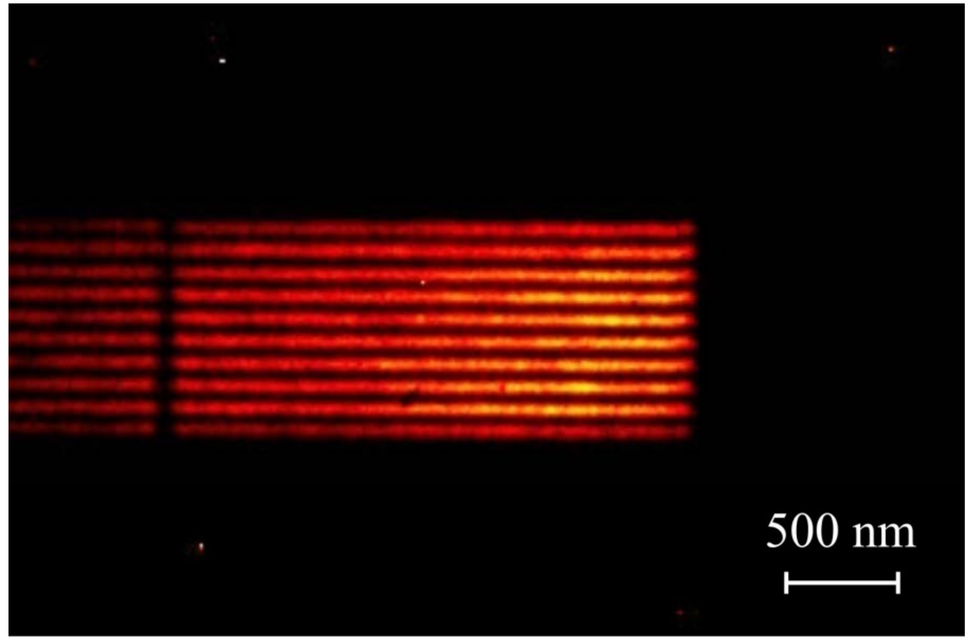
EUVM2 images of 50 nm half-period patterns

50 nm elbows



20 second exposure

50 nm grating



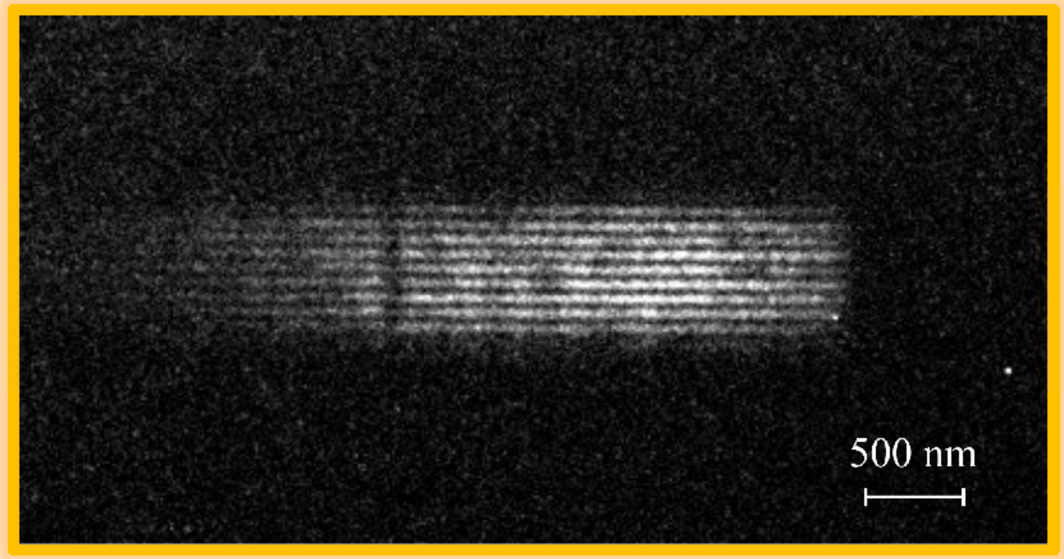
40 second exposure

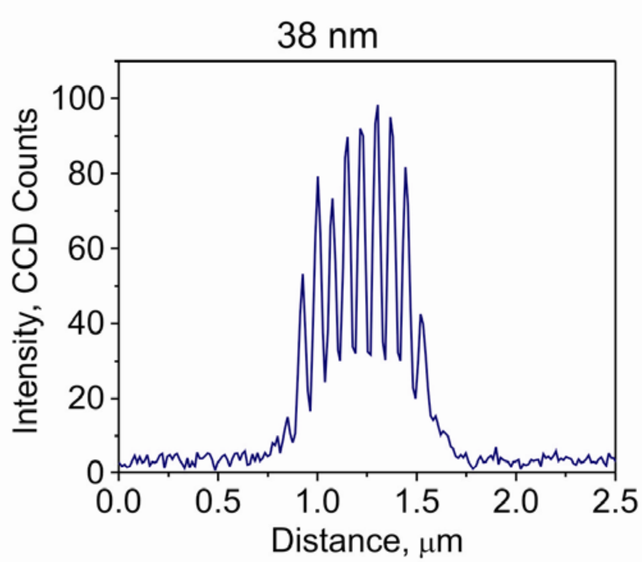
- λ = 13.2 nm
- Δr = 50 nm (NA = 0.132)
- M ~1080 x (image element pixel size = 12.5 nm)

EUVM2 images of 38 nm half-period pattern are resolved

38 nm grating

- λ = 13.2 nm
- Δr = 50 nm (NA = 0.132)
- 40 second exposure
- M ~1080 x (image element pixel size = 12.5 nm)

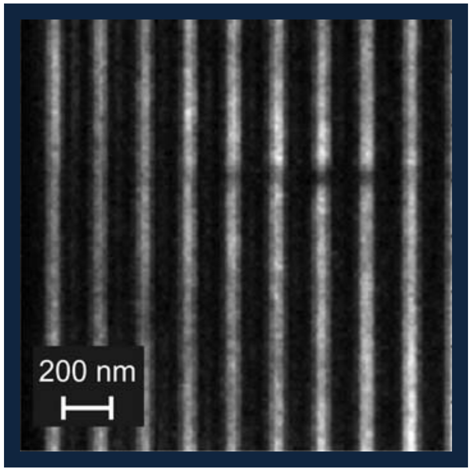




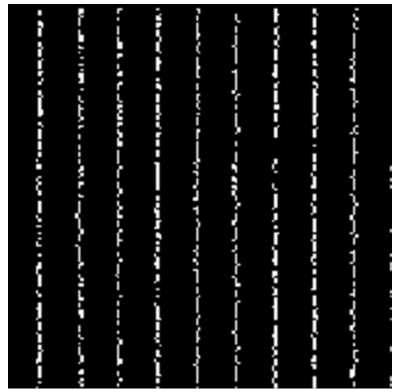
Intensity profile of 38 nm lines shows ~67% intensity modulation → **Resolution is better than 38 nm** ($k_1 < 0.38$)

Computer algorithm gives global assessment of resolution and feature size

Original EUVM2 image of 100 nm half period grating

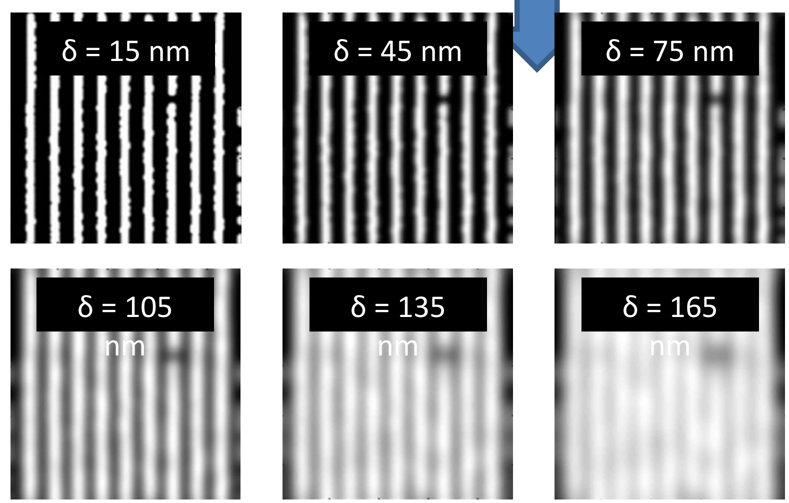


Step 1: Smooth and skeletonize

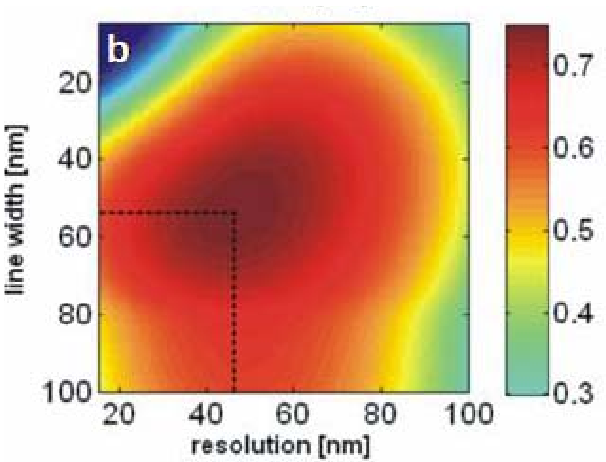


Step 2: Convolve skeleton with K circles of different radii to create K binary templates

Step 3: Convolve each binary template with L different FWHM Gaussian filters to generate KxL templates



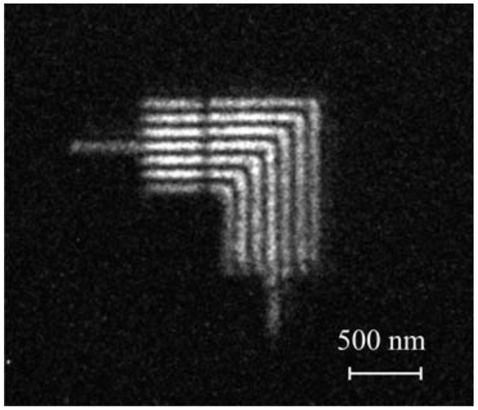
Step 4: Correlate each template with original image (bi-cubic interpolation)

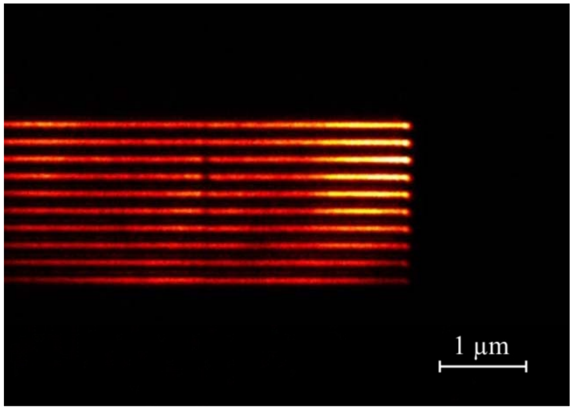


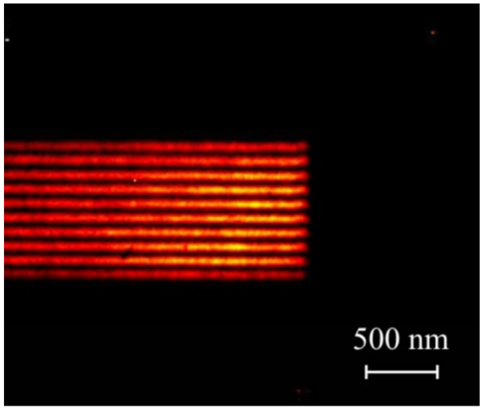
P. Wachulak, et al., JOSA B. (posted 11 Feb. 2008, in press)

Computer algorithm's assessment of periodic pattern images confirms resolution

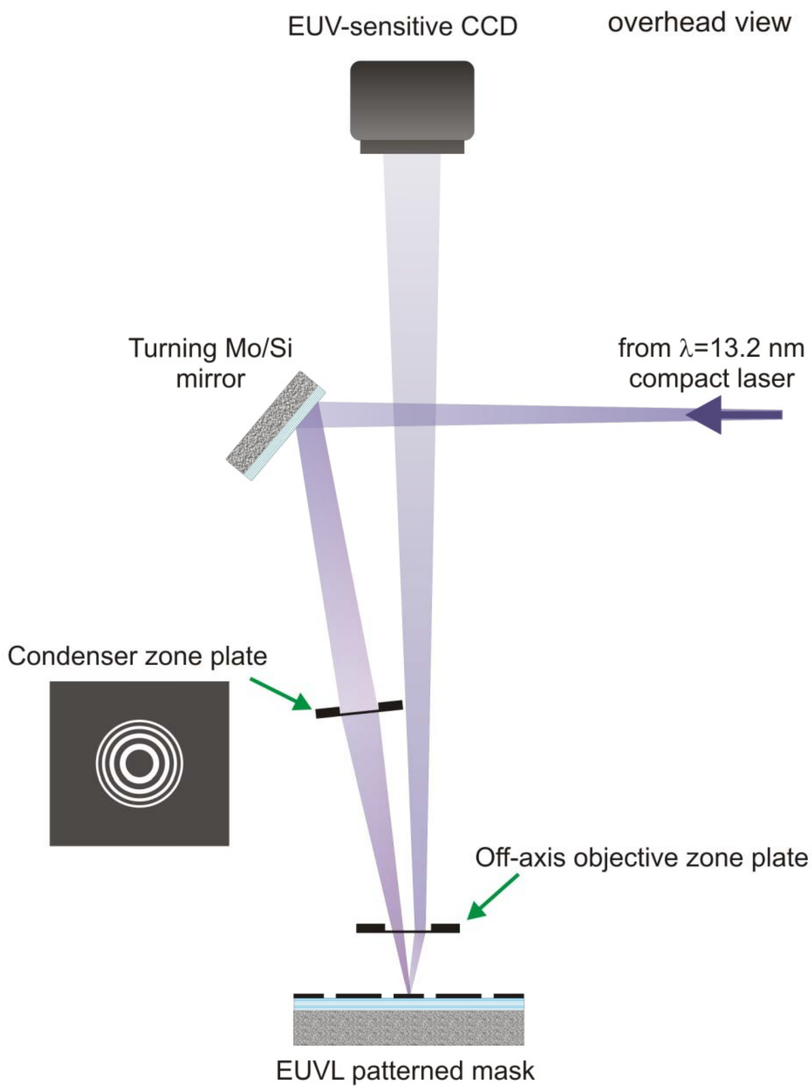
	Objects		
	50 nm half-period elbow grating	100 nm half-period grating	50 nm half-period grating
SEM linewidth measurements	31.3 ± 2.4 nm	53.8 ± 1.8 nm	31 ± 2.6 nm
Algorithm linewidth estimates	**29 ± 5 nm**	**54 ± 5 nm**	**31 ± 5 nm**
Instrument resolution from half-period grating test measurement	< 38 nm	< 38 nm	< 38 nm
Image resolution determined by algorithm	**29 ± 5 nm**	**30 ± 5 nm**	**27 ± 5 nm**



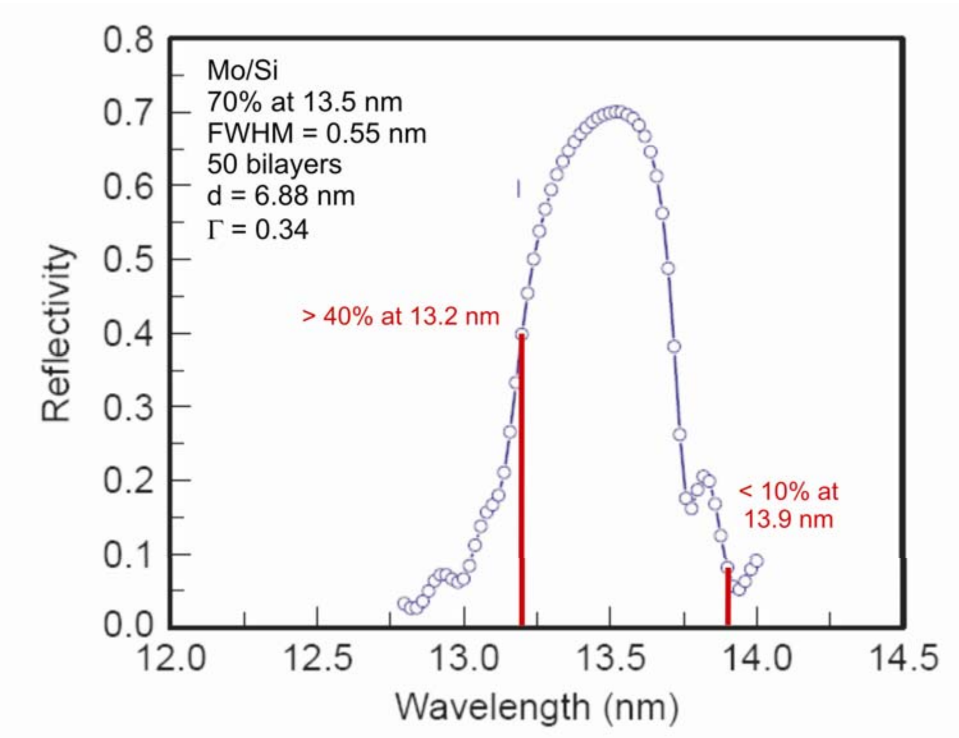




Currently EUVM2 is being modified and improved to operate in reflection-mode at λ = 13.2 nm



Narrow bandwidth reflectivity curve of Mo/Si multilayer mirrors to be used in EUVL



EUVL- the next generation of volume manufacturing

“The number of transistors incorporated in a chip will approximately double every 24 months.”
Gordon Moore, Intel Co-founder

www.intel.com

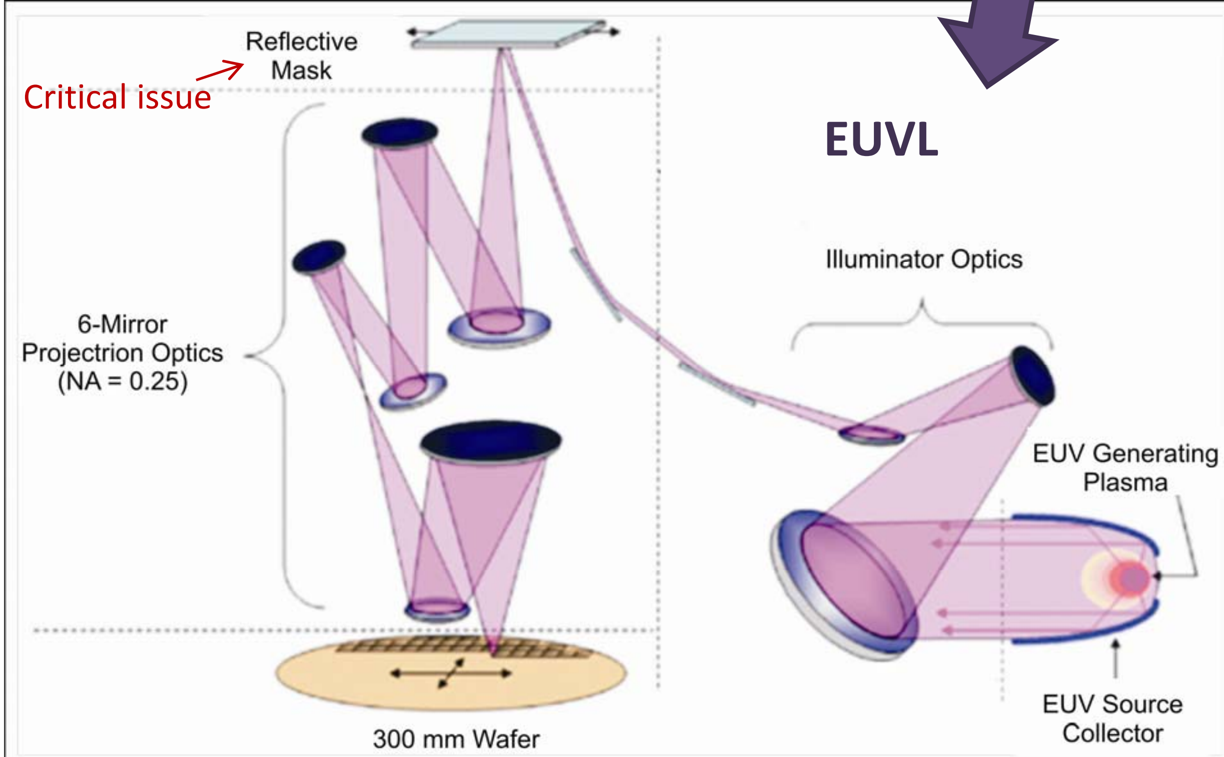
	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
DRAM contacted metal ½ Pitch (nm)	65	57	50	45	40	36	32	28	25	22
Flash Uncontacted PolySi ½ Pitch (nm)	54	45	40	36	32	28	25	23	20	18

International technology roadmap for semiconductor, table B (2007)

$$L_w = \frac{k_1^{'}\lambda}{NA}$$

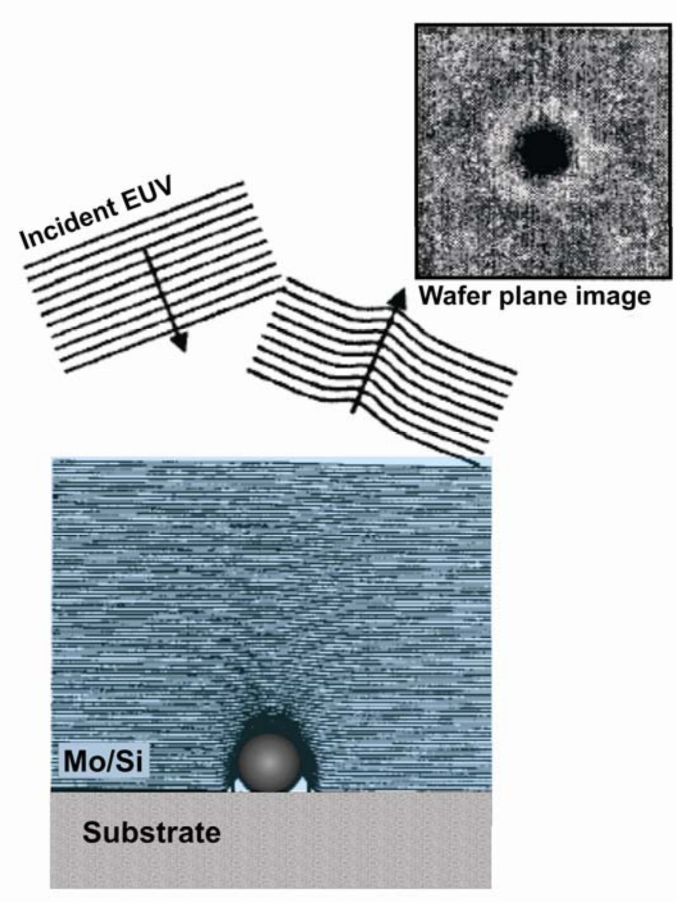
- λ : wavelength
- k_1 = constant dependent on optical system and photoresist recording and processing (~0.5)
- NA: numerical aperture seen by wafer

Critical issue



S. Wurm, et al., SPIE pressroom (2006)

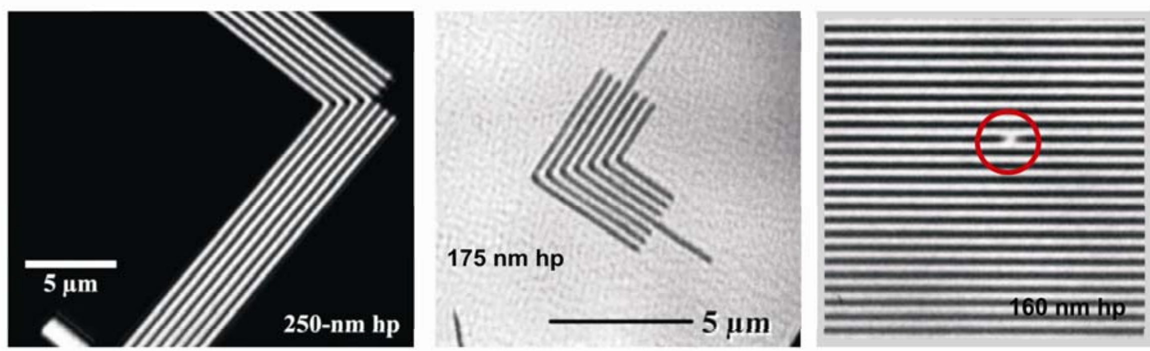
Need inspection tools that can find and assess printable defects to be able to make defect-free masks



A. Barty, et al., SPIE Emerging Lith. Tech. VI 4688 (2002)

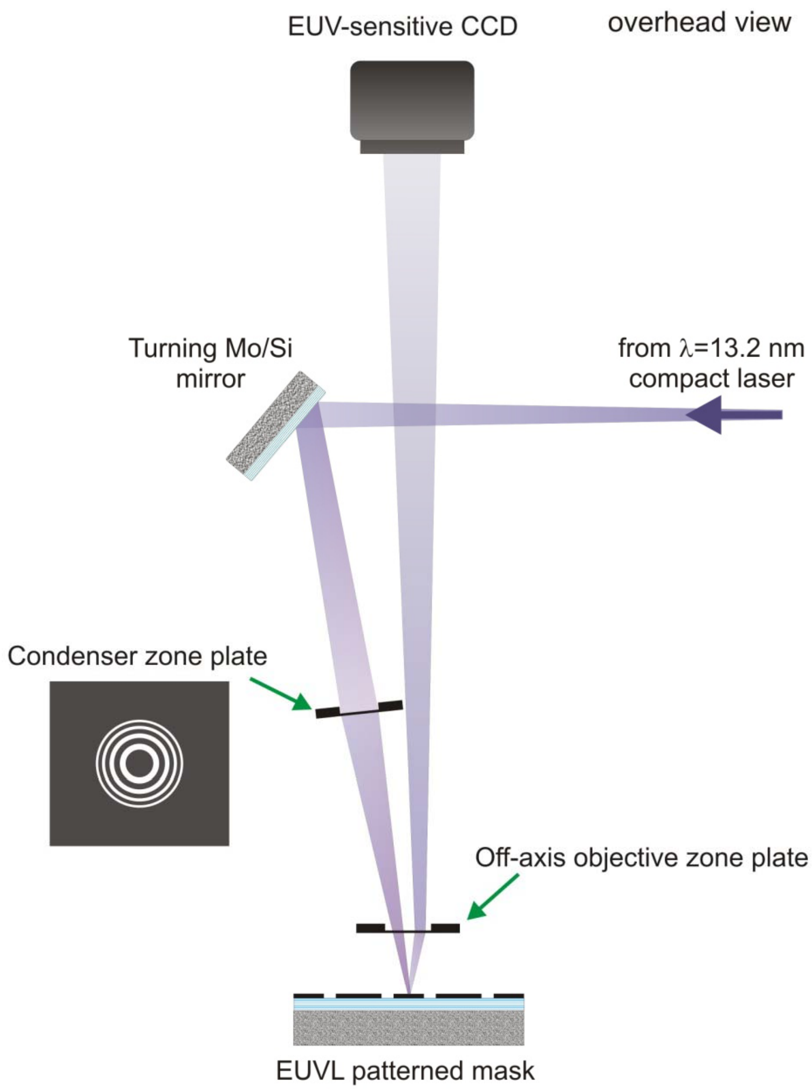
- Masks must meet strict flatness, smoothness, and surface quality specifications
  - 32 nm node requirements: Area of 142 x 142 mm^2 on a mask blank must have < 0.003 defects/ cm^2 with dimensions >25 nm
- Only one tool in the world with *actinic aerial imaging capability* that EUVL developers can use to test the printability of defects- the SEMATECH/Berkeley AIT at the ALS synchrotron

S. Wurm, Jap. J. App. Phys. 46, 6105 (2007)



K.A. Goldberg, et al., SPIE Photomask Tech. 67305E (2007), W. Cho, et al., SPIE Photomask Tech. 673013 (2007)

Reflection- mode imaging inspection tool using the 13.2 nm tabletop laser



<u>Goals of project</u>

- Develop an inspection tool by modifying our compact 13.2 nm microscope
- Obtain images of patterned masks with sub-100 nm hp spatial resolution (25 nm wafer-size features for a 4x stepper)

<u>Future opportunities</u>

- Reflection-mode imaging of surfaces
- Image samples undergoing rapid changes with ps temporal resolution
- Explore phase contrast microscopy
- Continue developing the microscope as compact EUV lasers continue to increase in brightness and emit shorter wavelength light to access more inner shell absorption edges

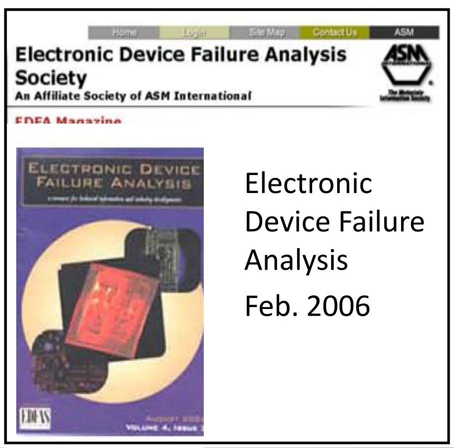
CSU tabletop EUV microscopy has made a significant contribution to the field

Laser Focus World, Dec. 2006

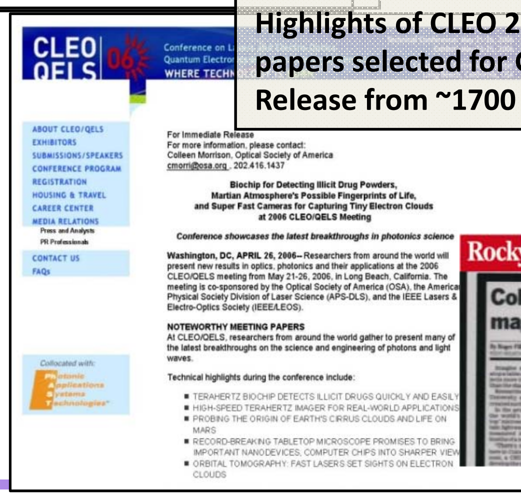
Optics in 2006, Dec. 2006

Optics in 2005, Dec. 2005

- Developed and built a full-field zone plate microscope based on a tabletop 13.2/13.9 nm laser
- Obtained images with **sub-38 nm spatial resolution** in short exposure times
- Brought forth awareness to the scientific and biological community that short wavelength, convenient, lab-based microscopes will be available in the near future and will be an enabling tool



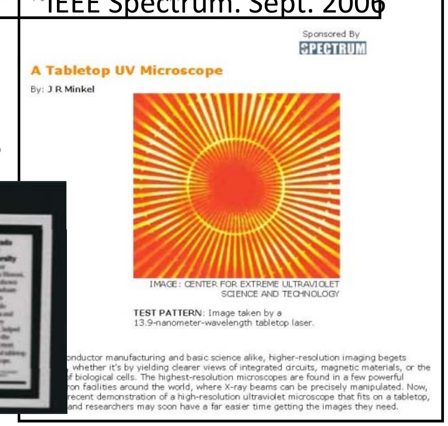
Electronic Device Failure Analysis Feb. 2006



Highlights of CLEO 2006 - 1 of 6 papers selected for General News Release from ~1700 submissions

Rocky Mountain News, Jul. 2006

IEEE Spectrum. Sept. 2006



Thank you, Gracias, Merci, Danke, Grazie, Dziękuję (sounds like jian-coo-ye), Спасибо (sounds like spa-cee-ba), 谢谢你

- Committee members:
  - Dr. Carmen Menoni- advisor
  - Dr. Jorge Rocca
  - Dr. Carl Patton
- Team members
  - Dr. Georgiy Vaschenko
  - Fernando Brizuela
- Collaborators
  - Center for X-Ray Optics at LBNL
  - P.N. Physical Institute in Moscow, Russia
  - National Technical University Kharkov Polytechnical Institute in Kharkov, Ukraine
- Everyone at the lab
- Family, friends, and Jamison