Extreme Ultraviolet Light: Access to Nanometer Geometries

IEEE October 11, 2007

Hugh Grinolds

NSF Engineering Research Center for Extreme Ultraviolet Light Technologies

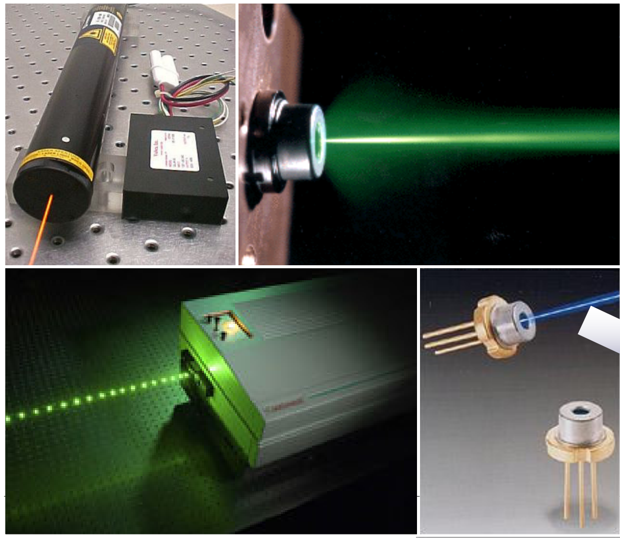
Topics for this Seminar

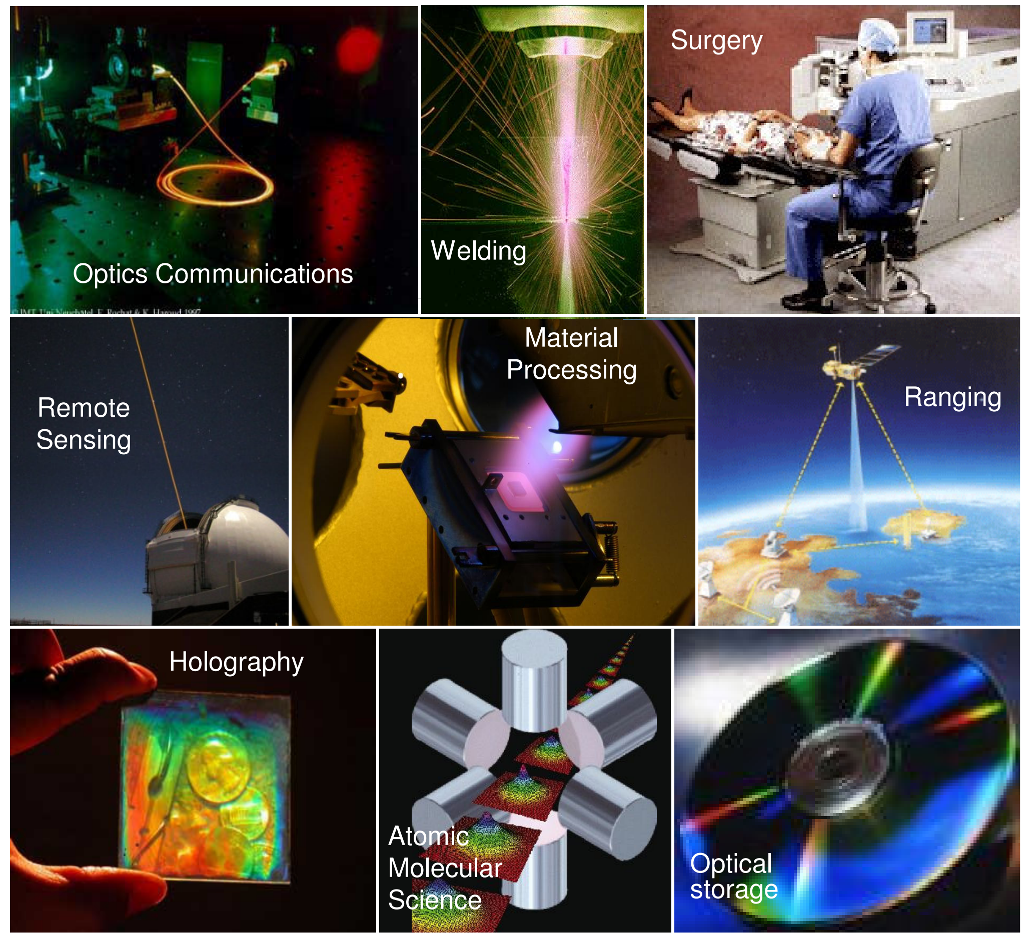
- Introduction.
- Lithography and the continued move to shorter wavelengths.
- Light sources for lithography.
- Widening materials and characterization uses for EUV.
- EUV NSF Engineering Research Center areas of study.

Acknowledgements

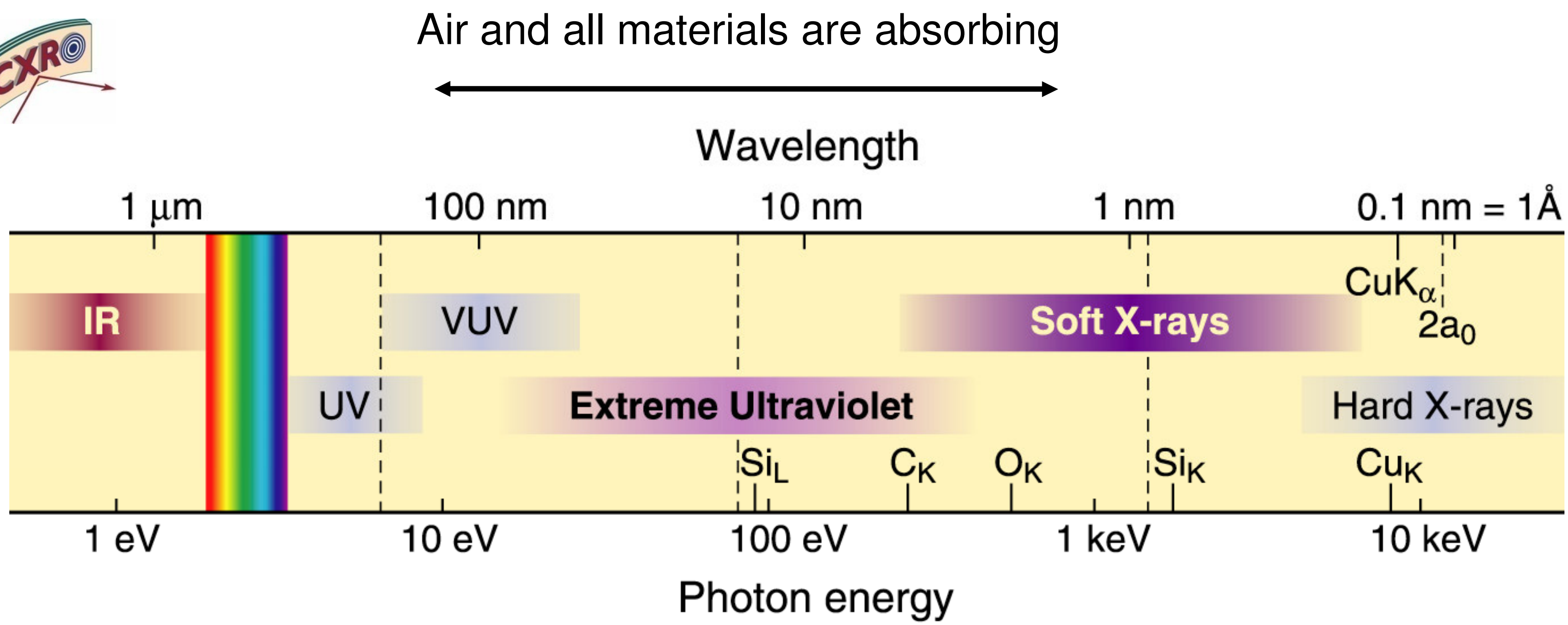
- All the principal investigators at the EUV ERC.
- Colleagues at Cymer, Nigel Farrar.
- Member companies of the EUV ERC.
- ASML.

The understanding, generation and control of visible/infrared light has broadly benefited society





The Short Wavelength Region of the Electromagnetic Spectrum



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

$$\hbar\omega \cdot \lambda = hc = 1239.842 \text{ eV nm}$$

Carmen Menoni
Mario Marconi
Elliot Bernstein

Jorge J. Rocca, Director

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EUV

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Rationale for Center Vision: numerous challenges and opportunities in scientific research and industrial technology are beyond the reach of visible light – but are accessible to EUV light

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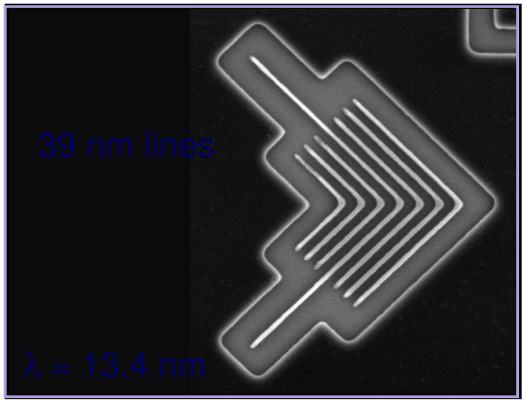
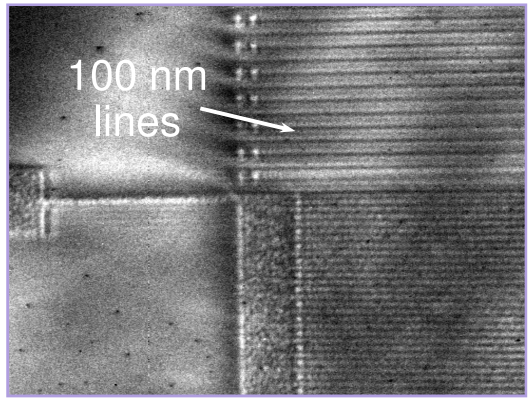
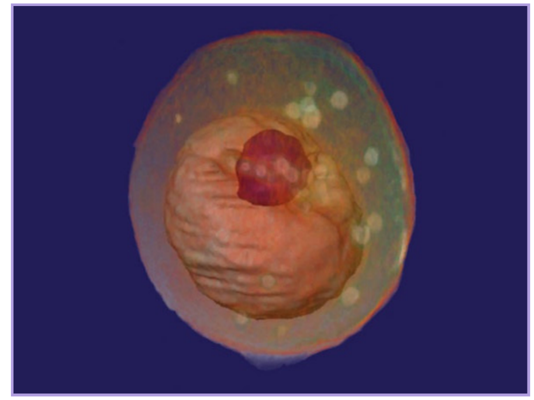
EUV Lithography Metrology for 20 GHz Computer Chips



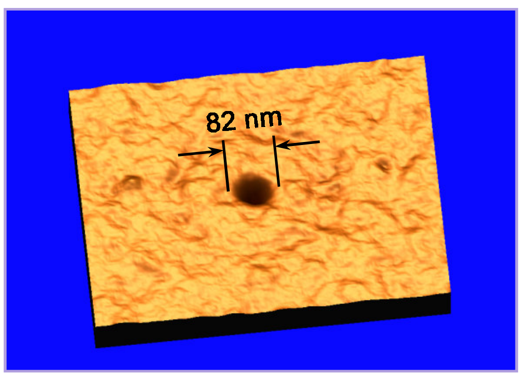
Nanoscale Imaging



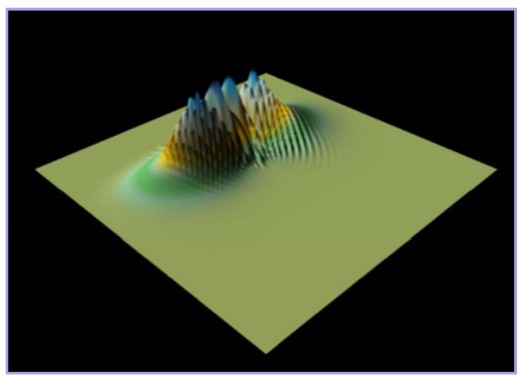
Tomography of Living Cells



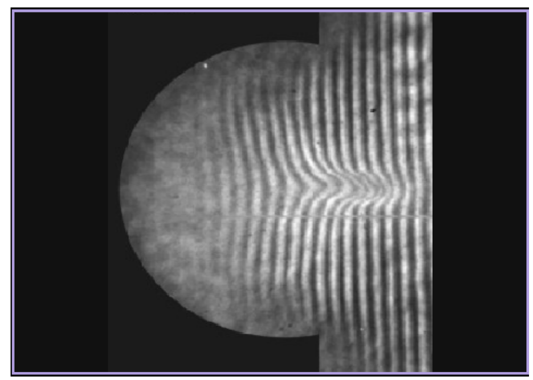
Probing at the Nanoscale



Attosecond Dynamics



Probing of ICF Plasmas



New tools for nanotechnology and science require shorter wavelength and faster pulses

Our Current IAB Members

EUV
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*Our industry membership increased from **14** (2006) to **17** (2007).*

Electronic and Materials Products

AMD Smarter Choice · IBM · intel Leap ahead · SAMSUNG · SEMATECH Accelerating the next technology revolution.

Equipment and Processes

APPLIED MATERIALS think it. apply it. · EUV TECHNOLOGY

Optics and Components

Newport Experience | Solutions · ALIO · CVI · LUXEL · BACH RESEARCH · Reflective X-ray Optics

Sources

CYMER · KMLabs Inc. · JMAR · ENERGETIQ

Web Site

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Industry Outreach

EUV radiation has played an important role for decades in scientific pursuits including surface science, atomic and molecular science, solar physics and others. A major acceleration, however, is presently underway. The widespread pursuit of nanoscience and nanoengineering benefits from the availability of radiation with comparable wavelengths for metrology and characterization, and in some cases for direct pattern formation. As a consequence many new scientific and technological opportunities are emerging that require compact, widely available tools. A particular case, and a strong driver of the current expansion of activities, is that of EUV lithography for the high volume manufacture of future computer chips. Current industry timelines call for this new technology to be used for the manufacture of 19 GHz microprocessors in the year 2009-2010. To meet these ambitious goals a substantial new infrastructure is required, including component vendors, instrument suppliers small and large, all requiring a well-trained staff.

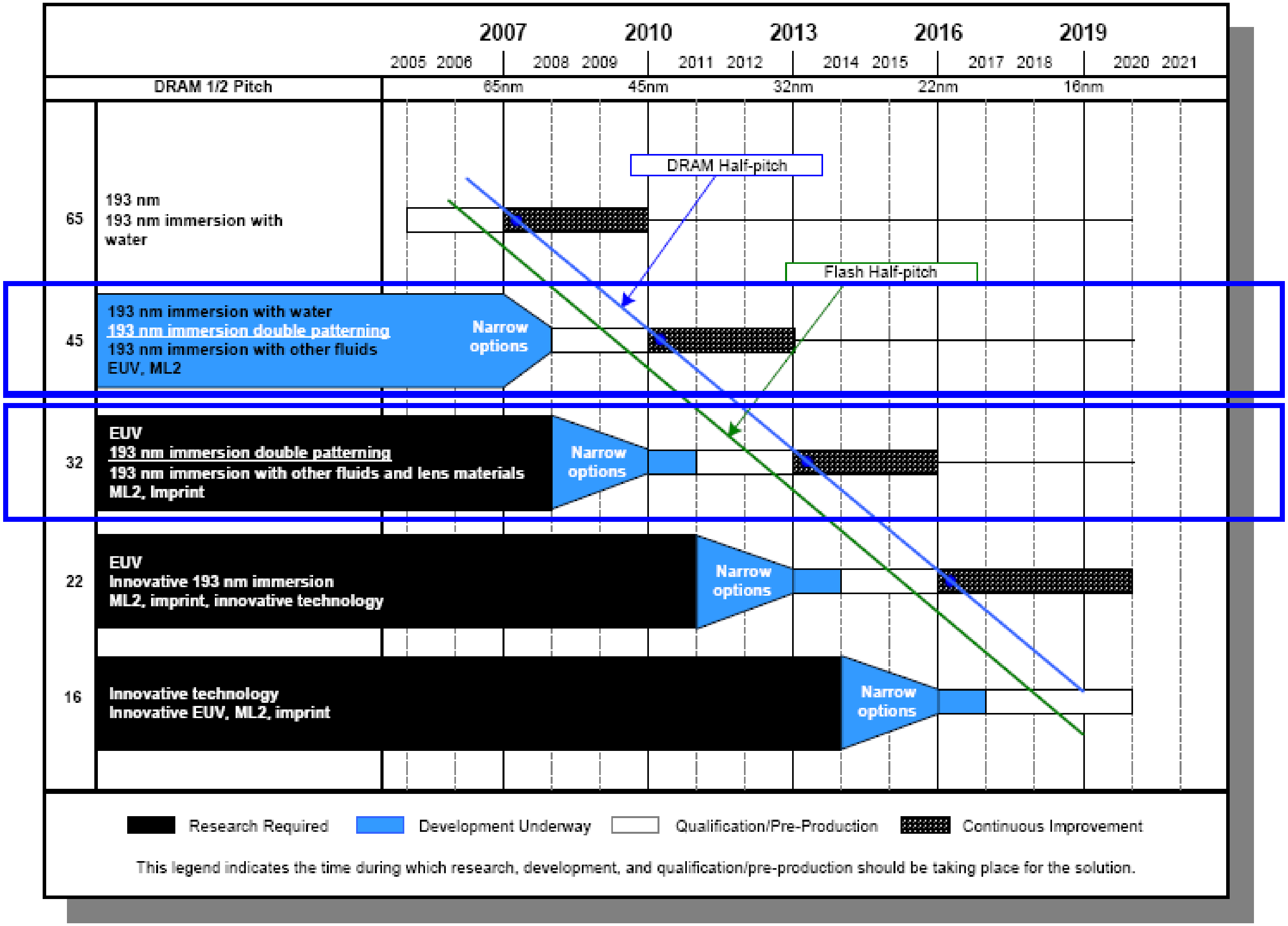
To help meet the needs of the emerging industry we have formed a broadly based Industrial Advisory Board (IAB), to help guide our EUV Engineering Research Center. Our goal is to have a broad impact on science and technology, from small scale university research to large scale manufacturing. Towards that end we organized an IAB with members from small, medium and large corporations, with as wide as possible scientific and technical interests. We receive their individual and collective advice, work closely with them on special projects, and serve as an intellectual center where they can come for EUV related expertise, interact with each other and, through our teaching and research, meet and hire well trained future employees.

- The first EUV ERC industry meeting was held in Berkeley Nov. 21 2003. Eleven industry representatives attended. Several other companies could not attend but contributed.
- Corporate Membership Agreements and Center Bylaws were prepared with inputs from all parties and finalized May 4, 2004.
- Currently, there are 17 industry members to the EUV ERC.

This work is supported primarily by the Engineering Research Centers Program of the National Science Foundation under NSF Award Number EEC-0310717. Any opinions, findings and conclusions or recommendations expressed in this material are those of the author(s) and do not reflect those of the National Science Foundation.

Last updated: 05/21/07

ITRS Lithography Roadmap 2006 Update



Lithography

- Continues to be a major factor in realizing greater density.
  - Material challenges.
  - Power dissipation.
  - Device physics limitations.

- Since ~ 1996, the wavelength of light used in lithography has been greater than the geometries patterned.
  - Enhanced 'process factor' → resists, anti-reflection coatings, resolution enhancement technology, double patterning.
  - Enhanced 'optic factor' → increased NA (lenses, lens elements → immersion

- Increasing system costs →
  - Demands for greater throughput.
  - Greater control of features, over chip, over wafer, over lots.

Litho Gap

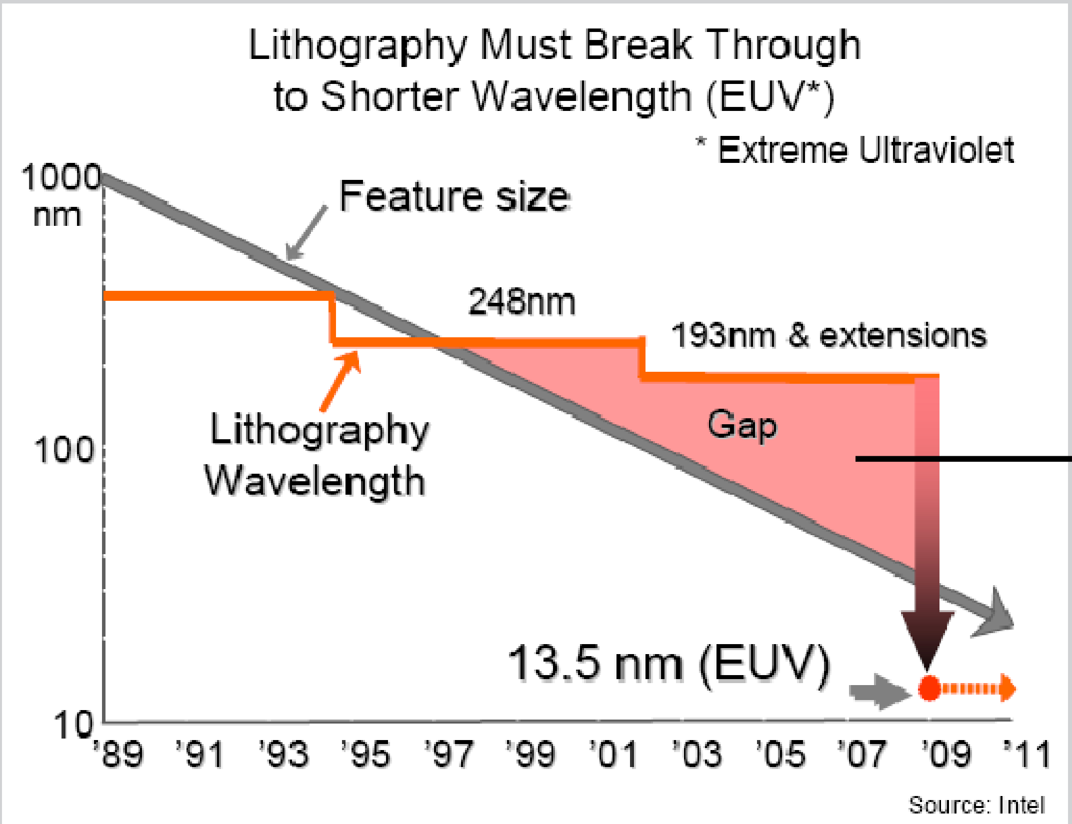


Figure 1.3.13: Scaling dimensions and lithography.

- High mask costs
- Long design time
- Complex processing

Chou, Intel, ISSCC 2005

Basic Litho Relations

Resolution

$$R = k_1 \frac{\lambda}{NA}$$

λ = wavelength of illumination

NA = numerical aperture = $n\sin(\alpha_o)$

Depth of Focus

$$DOF = k_3 \frac{\lambda}{n \sin^2\left[\frac{1}{2}\sin^{-1}\left(\frac{1}{n}\sin\alpha_o\right)\right]}$$

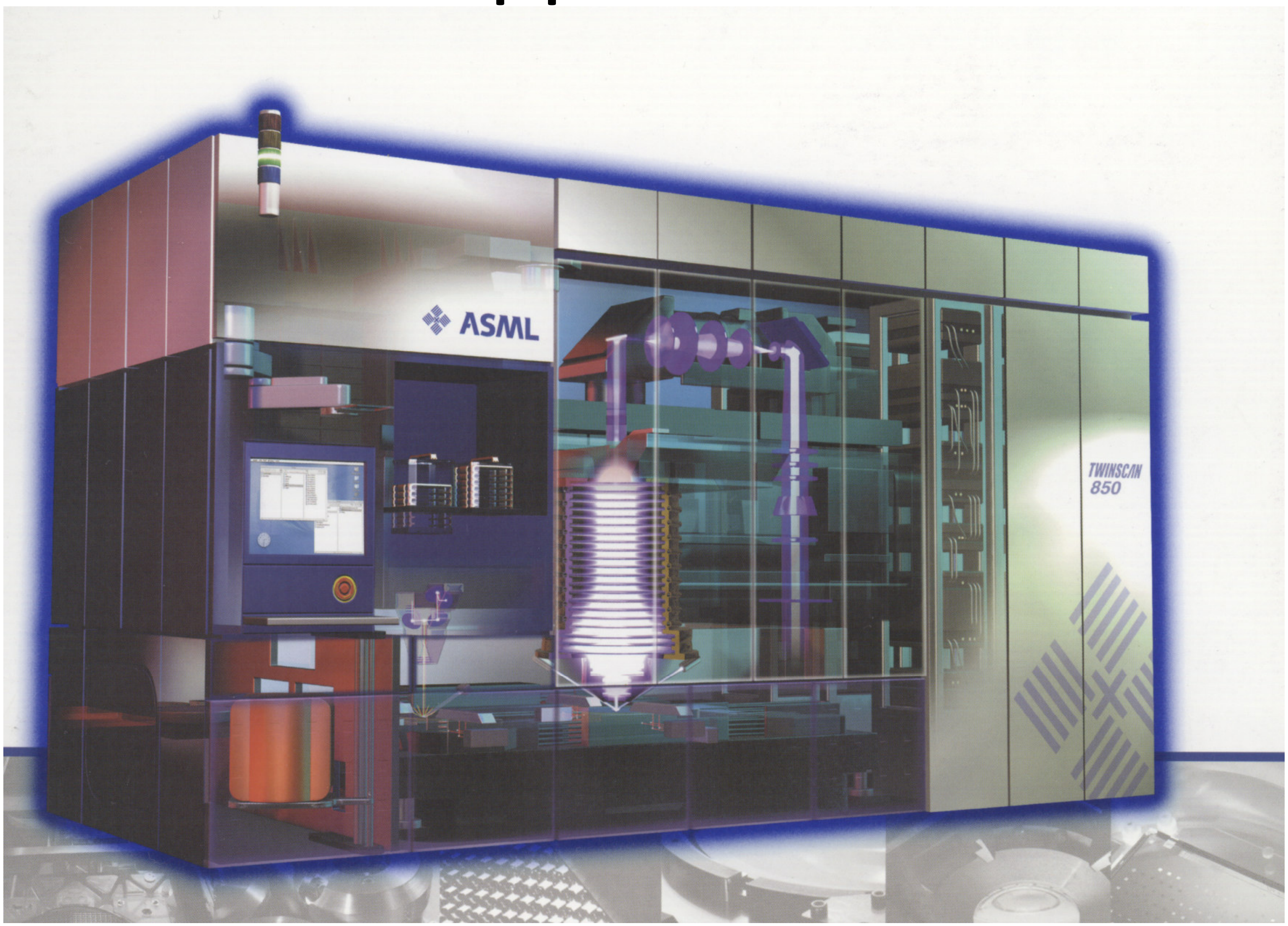
n = refractive index of imaging path

$$DOF \approx k_2 \frac{\lambda}{NA^2}$$

for n = 1 and $n\sin(\alpha_o) < 0.8$

k1, k2, k3 can be changed with resist, process, tool, pattern bias, process control and illumination properties

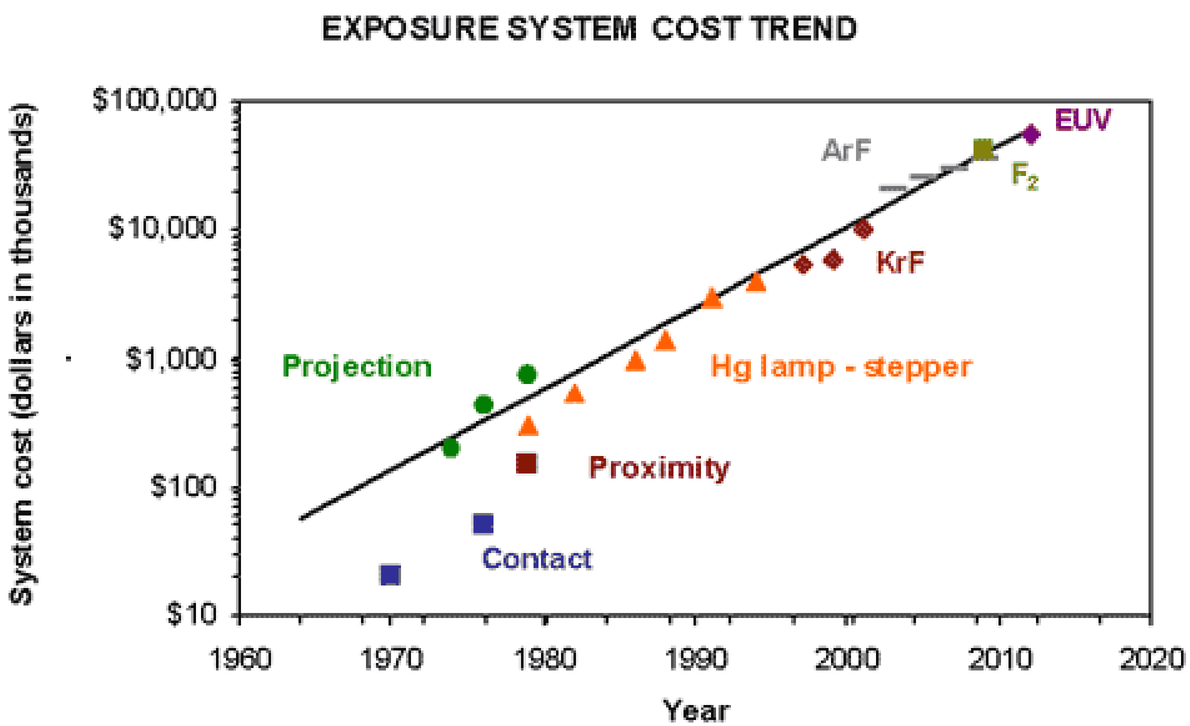
DUV Stepper-Scanner



Note: Light source not shown

Courtesy of ASML

Litho System Cost



Jones, IC Knowledge, Semi Int'l, 2005

Source: intel Leap ahead

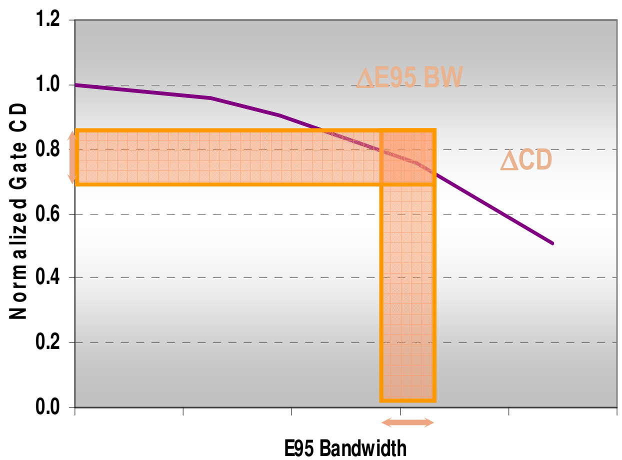
Light Sources

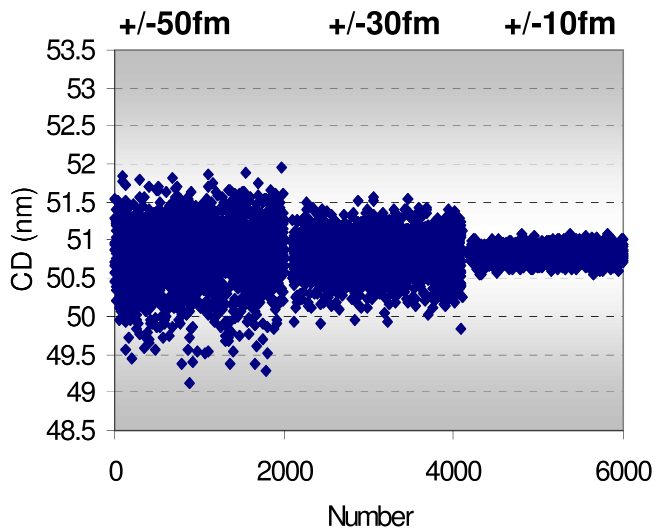
- The light source currently is ~ 5 to 6% of the total lithographic exposure capital costs.
    - It is relatively high for consumption costs (but less as a percentage than with Hg vapor lamps).
    - Reliability is very high for a complex 'instrument' in low volume production.

- Demands on the source (beyond moving to shorter wavelengths) include:
    - Higher power for greater throughput.
    - Narrow bandwidth for geometric control.
    - Dose control for geometric control.
    - Low pulse power for optic path stability and low damage.

Light Source Performance Stability is Key for Lithography Process Control

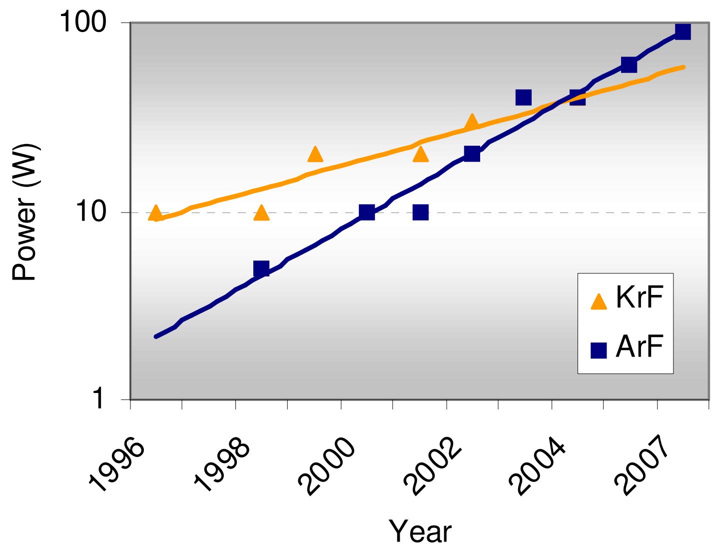
- Wavelength stability is required for focus control
- Bandwidth stability is required for image contrast and CD control
- Pulse energy stability is required for exposure dose control
- Beam property stability is required for illumination uniformity and pupil fill control

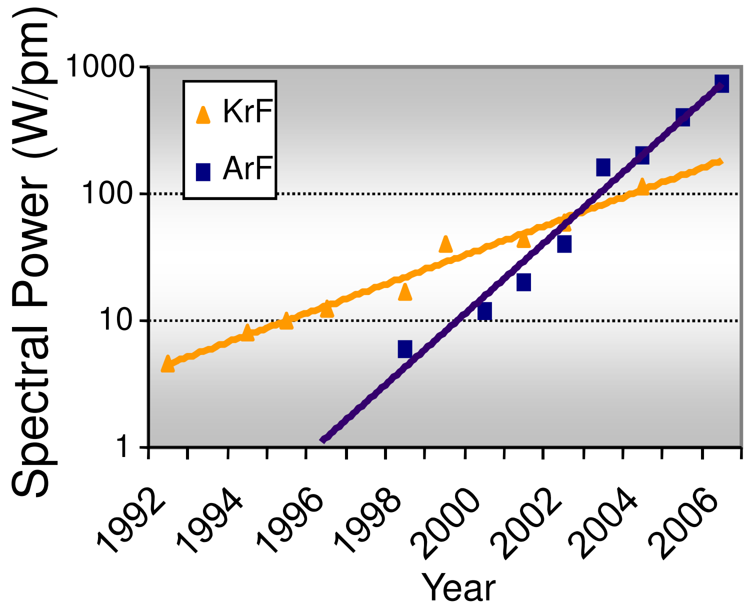




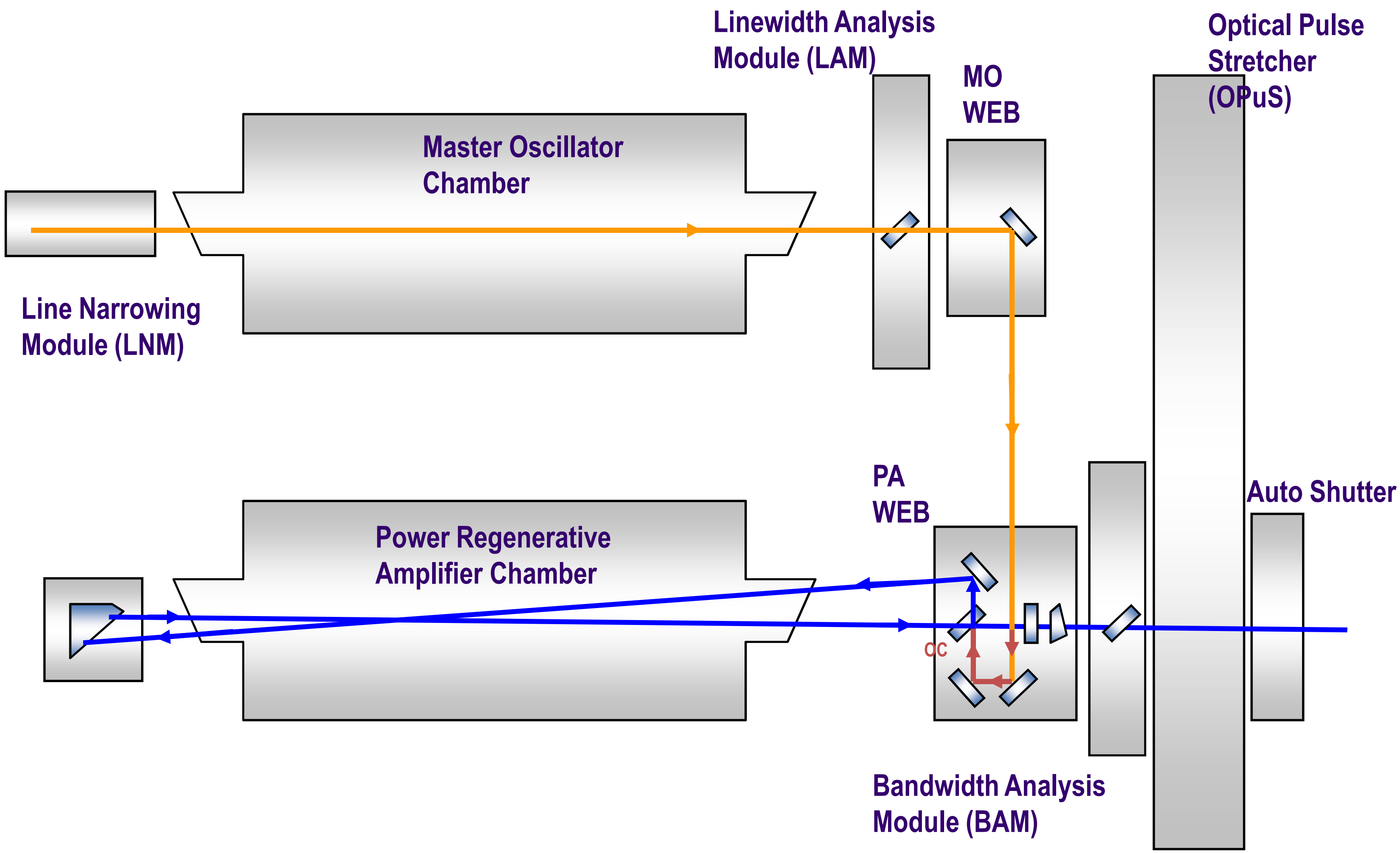
Light Source Performance Drivers

- Power and Bandwidth have been the traditional drivers for light source performance
  - High power supports higher stage speed and improved throughput
  - Low bandwidth supports high NA imaging
  - Dual chamber lasers were introduced to enable the continuation of spectral power (power/bandwidth) scaling
- EUV source power is a challenge because of the very low optical transmission of EUV scanners





Cymer XLR Dual Chamber Laser for DUV Lithography



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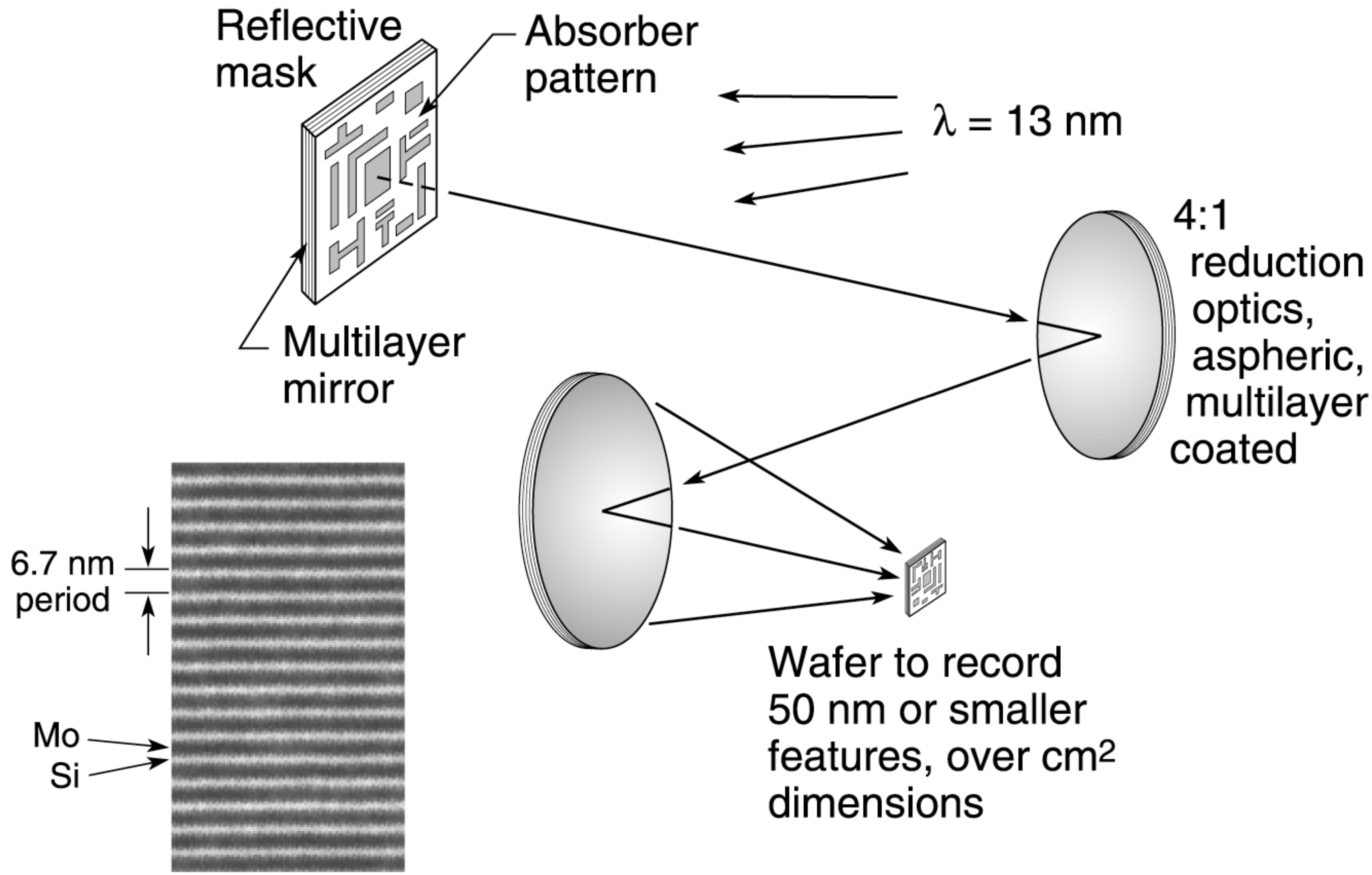
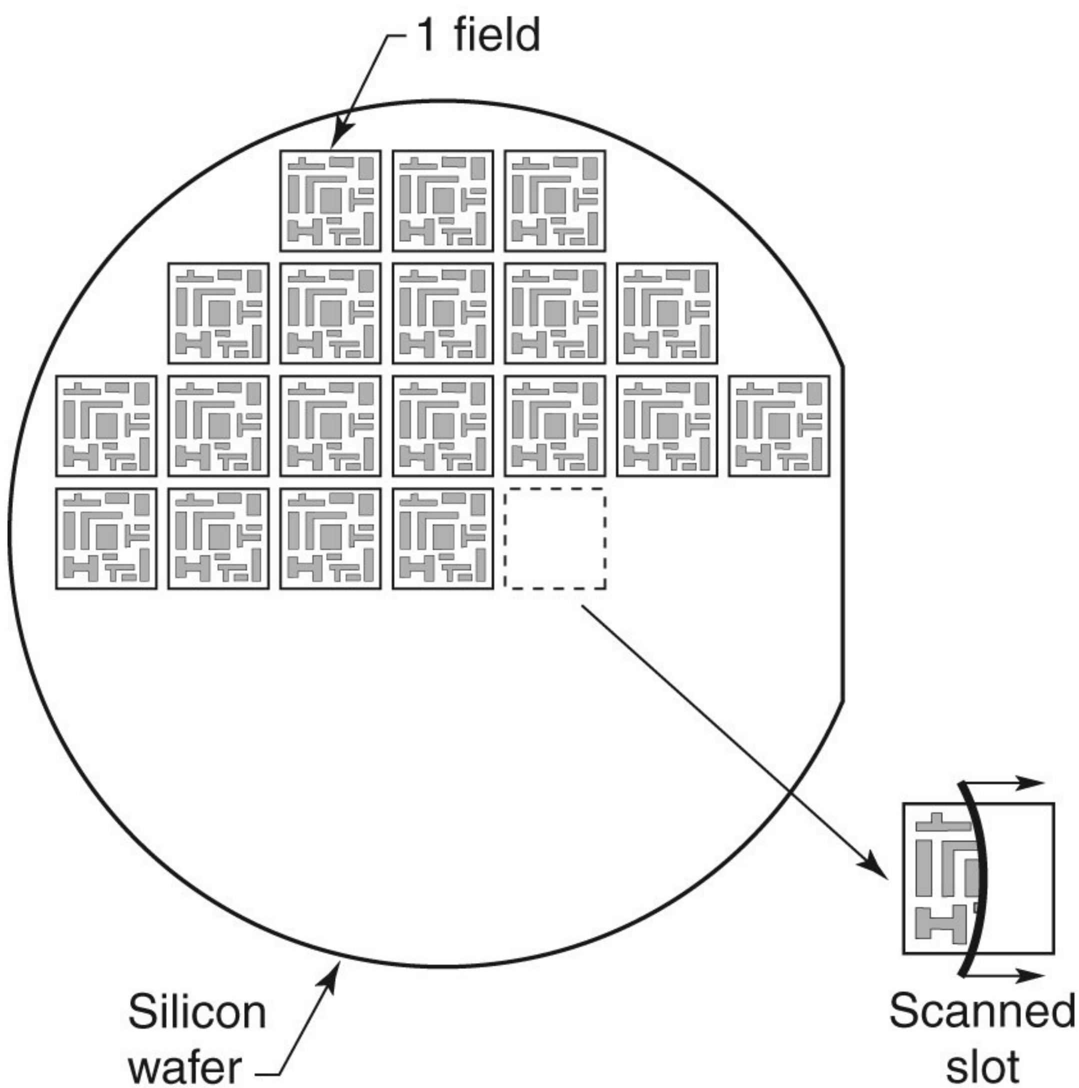
Extreme Ultraviolet (EUV) Lithography Based on Multilayer Coated Optics

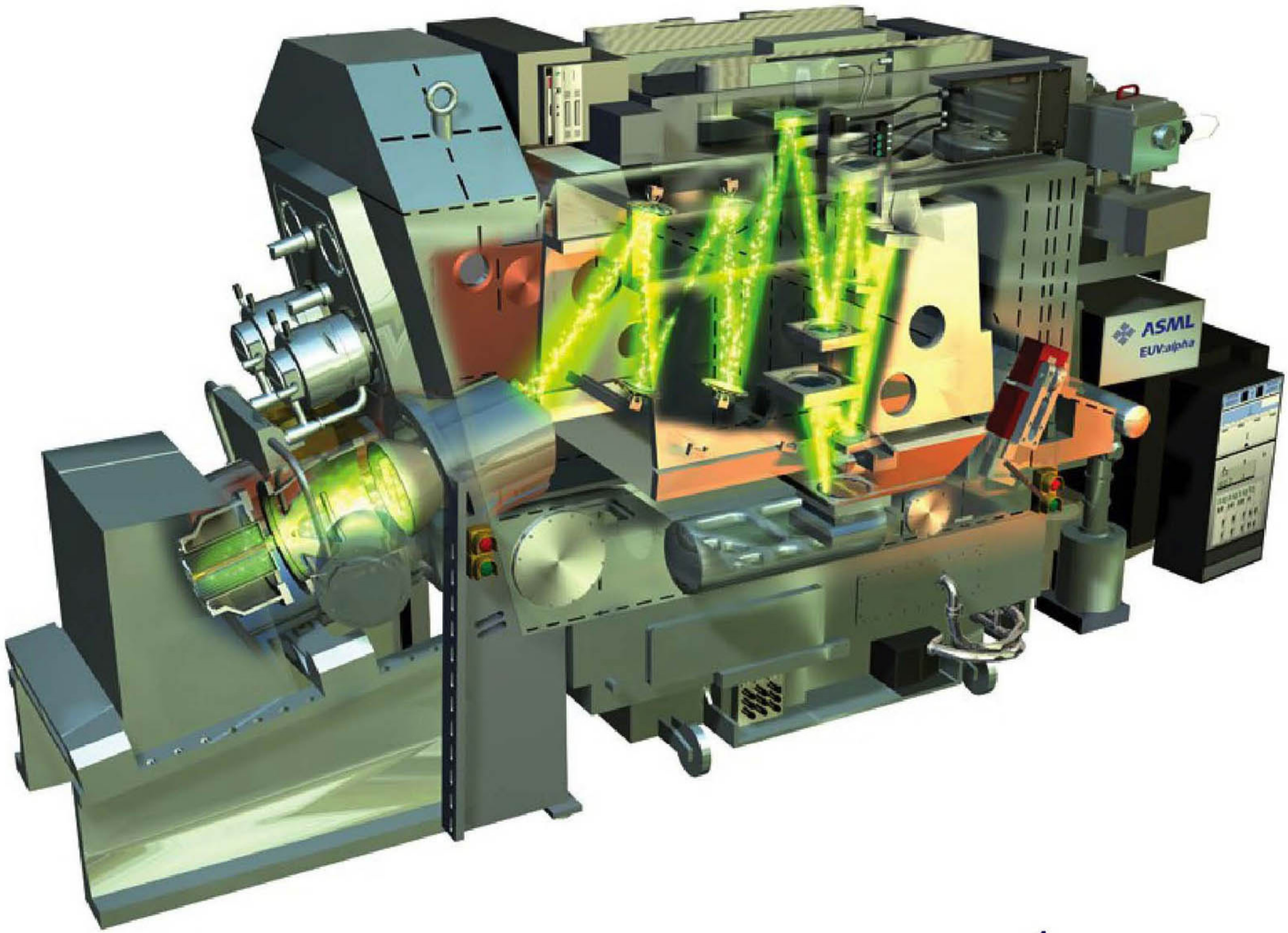


EUV Lithography Will Use a Step and Scan Ring Field System



Ch10_F05_modif.ai

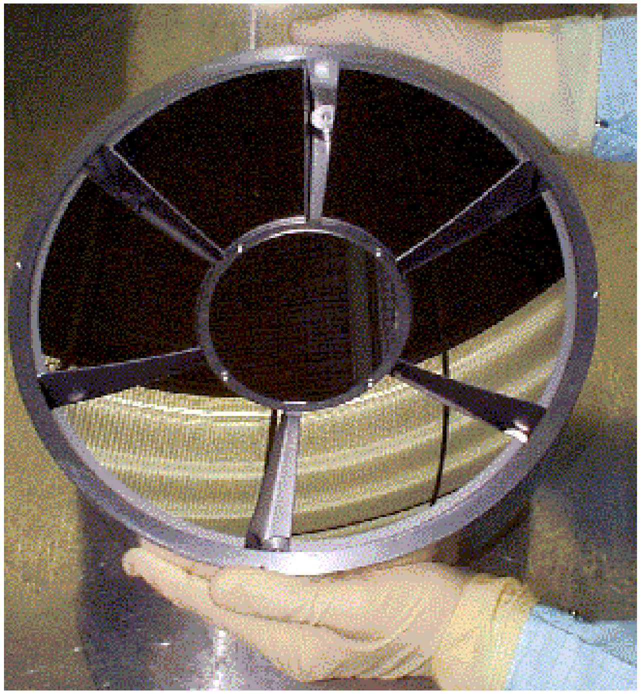
The ASML EUV alpha demo tool



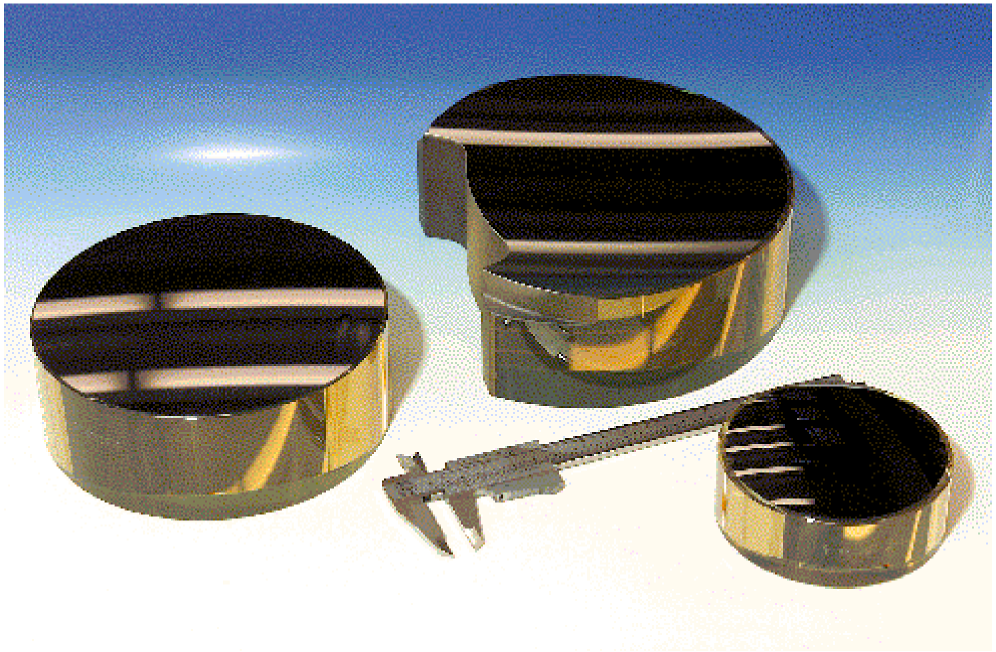
Courtesy of Dr. Hans Meiling, ASML

ASML

ETS Optics Meet Tight Specifications

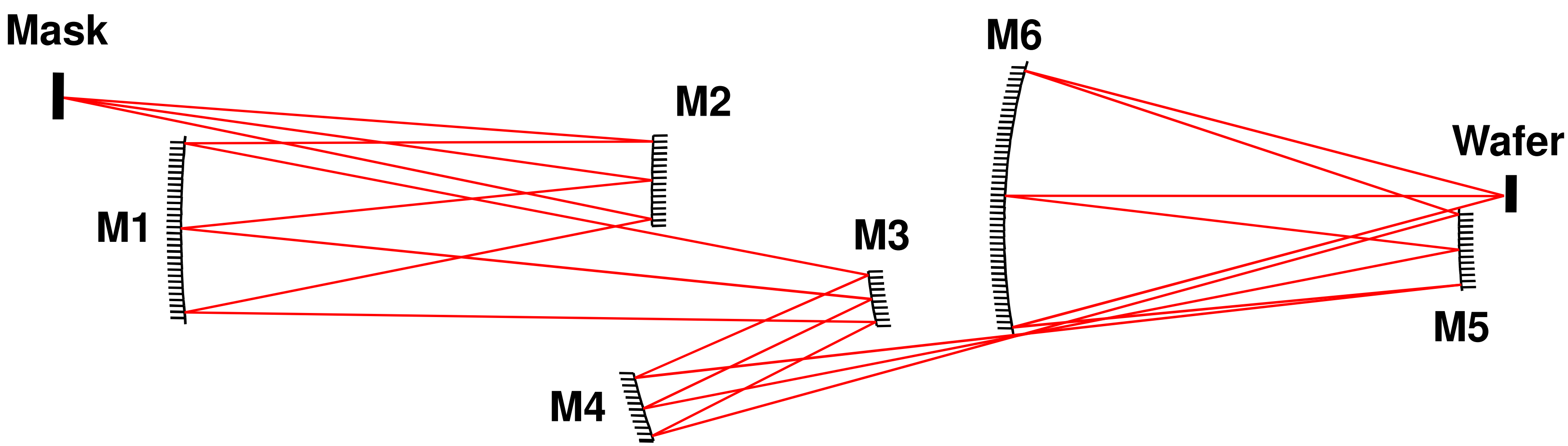


Condenser optic



Projection optic

EUV Production Tools Will Use a 0.25 N.A., 6-Mirror Optical System



39 nm @ 0.1 NA (isolated line in resist)

16 nm @ 0.25 NA (isolated line in resist)

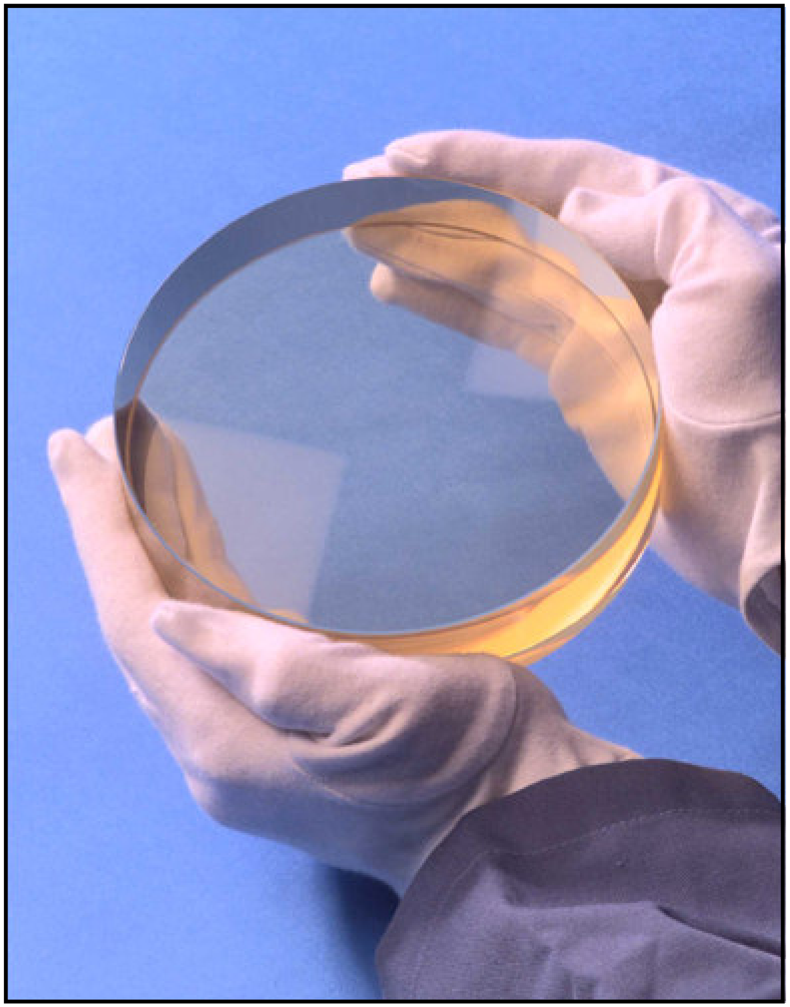
Note: The demands on NA increase in time.

Courtesy of R. Hudyma and D. Sweeney, LLNL

Diffraction Limited Aspherical Optics Are Critical to the Success of EUV Lithography

λ_{euv} /50 figure

- Low flare
- Ultrasmooth finish
- 10 µm departure from a sphere

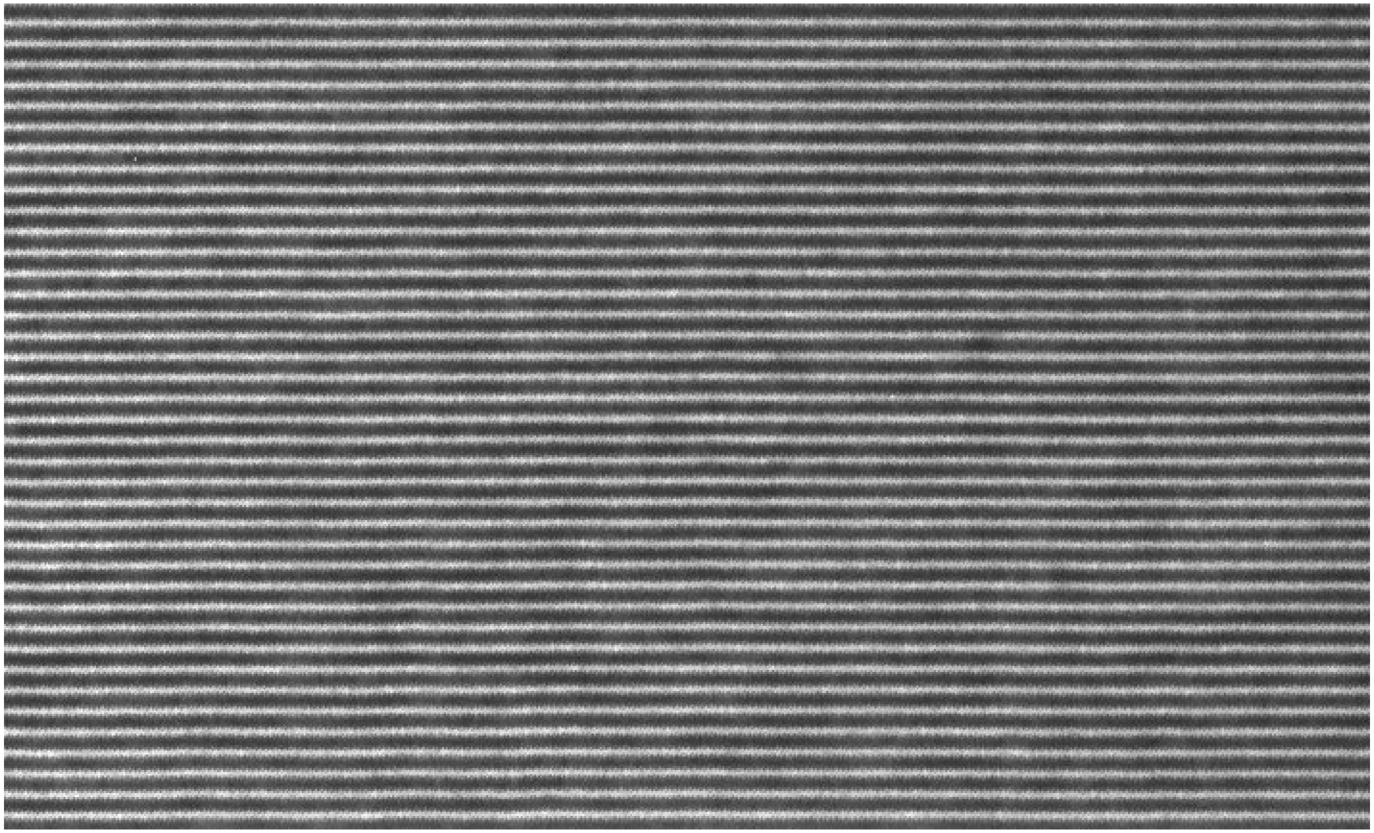


Tinsley Sample C
Zerodur-M
150 mm diameter

Courtesy of John Taylor, LLNL.

A High Quality Mo/Si Multilayer Mirror

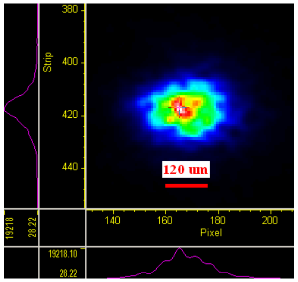
N = 40
D = 6.7 nm



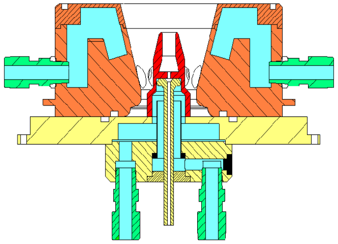
Courtesy of Saša Bajt / LLNL

Types of EUV Sources

- 13.5nm EUV light is produced from a highly excited plasma of tin, lithium or xenon
- LPP – Laser Produced Plasma
  - Scalable
  - Small source size – more efficient collection
  - Normal incidence collector – spectral filter, low obscuration, easier to cool

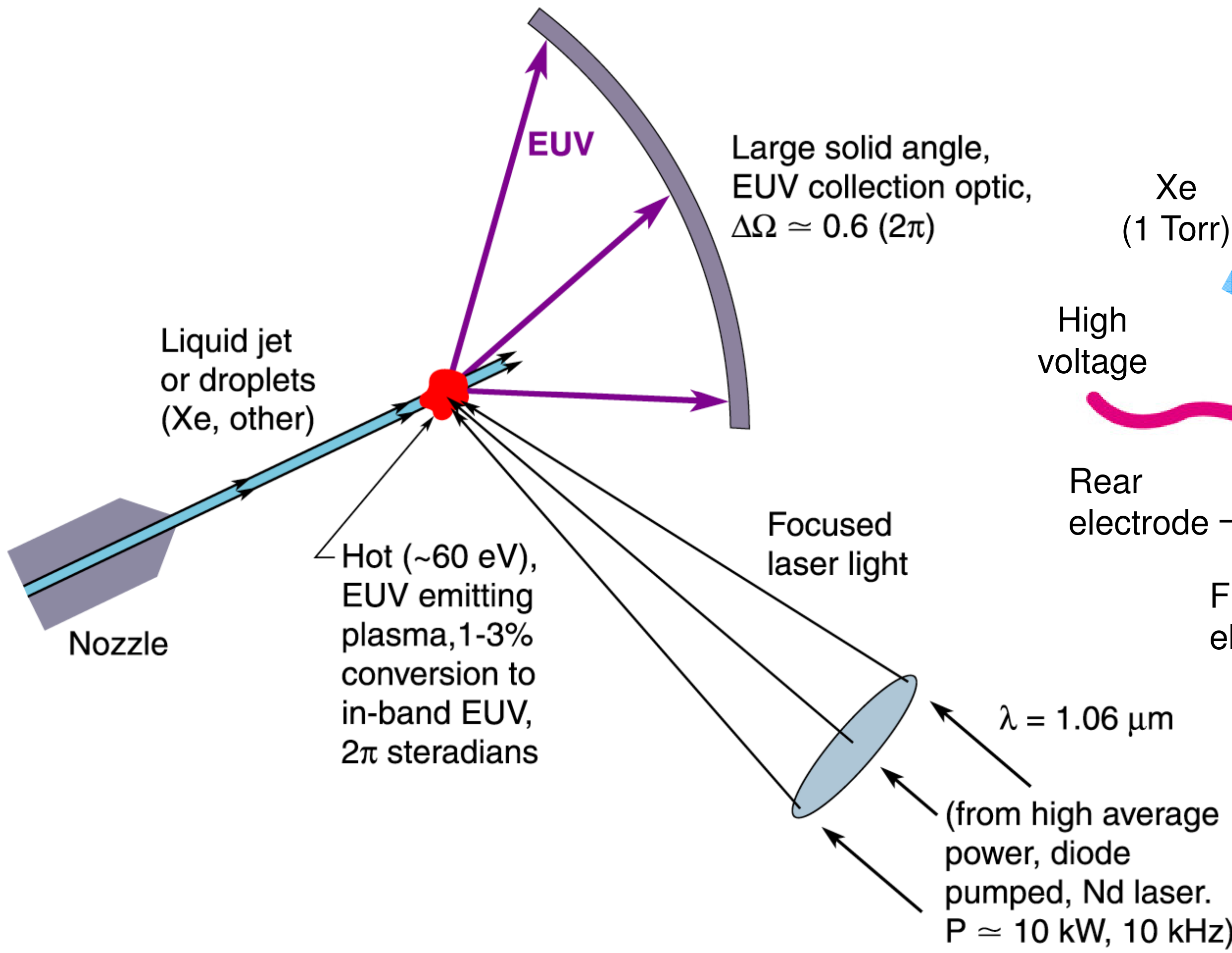


- DPP – Discharge Produced Plasma
  - Difficult to scale
  - Electrodes close to plasma – bigger debris issue
  - Grazing incidence collector – low efficiency, difficult to cool

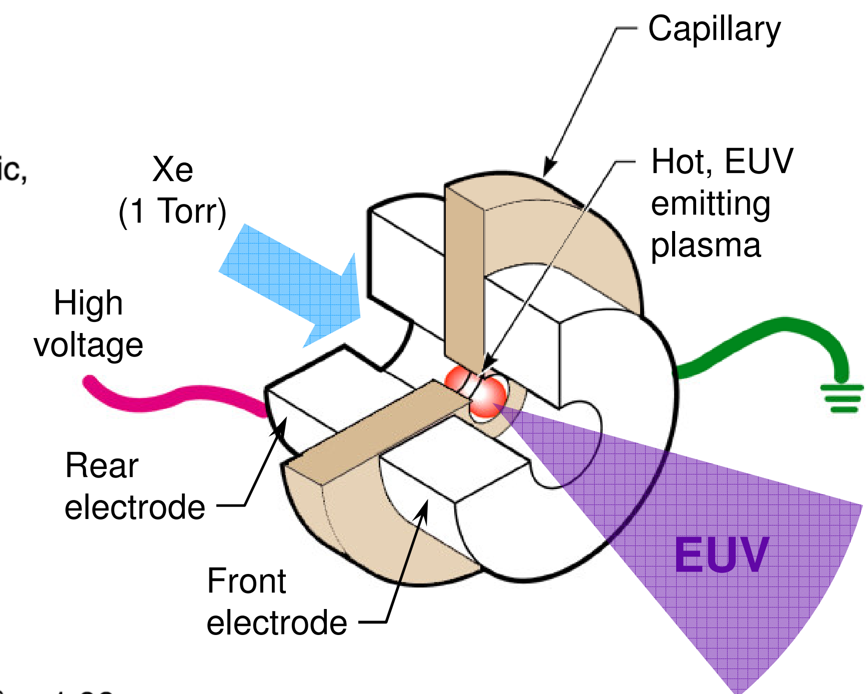


EUV Source Candidates for Clean, Collectable 13-14 nm Wavelength Radiation

Laser Produced Plasma Source

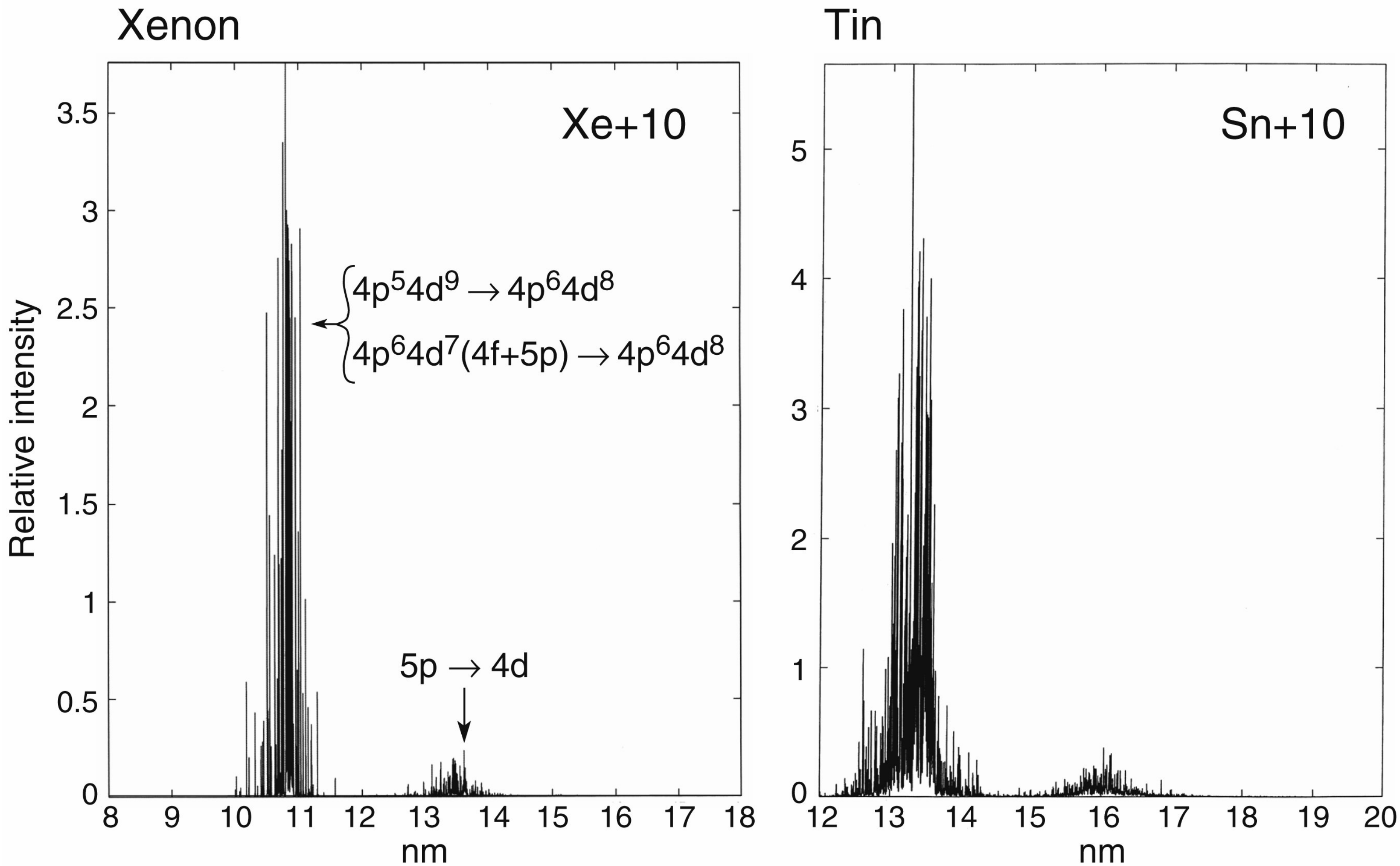


Electrical Discharge Plasma Source



Courtesy of Neil Fornaciari and Glenn Kubiak, Sandia.

Comparative Spectra: Xe and Sn

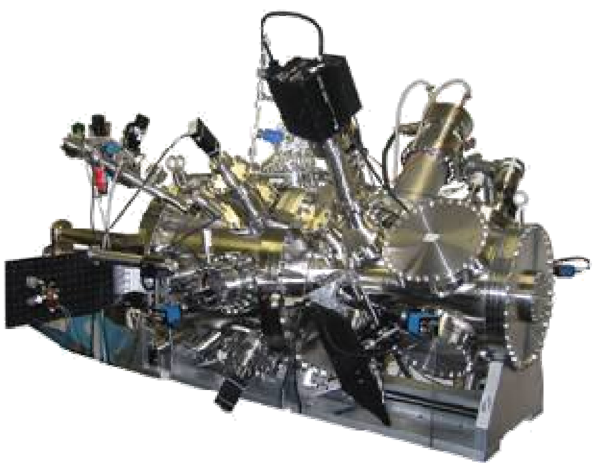


- Debris is the issue

Courtesy of G. O'Sullivan (Univ. College Dublin)
R. Faulkner (UCD Ph.D, 1999)
A. Cummings (Nahond Univ. Ireland)

Ch06_Xe_Sn_Spectra.ai

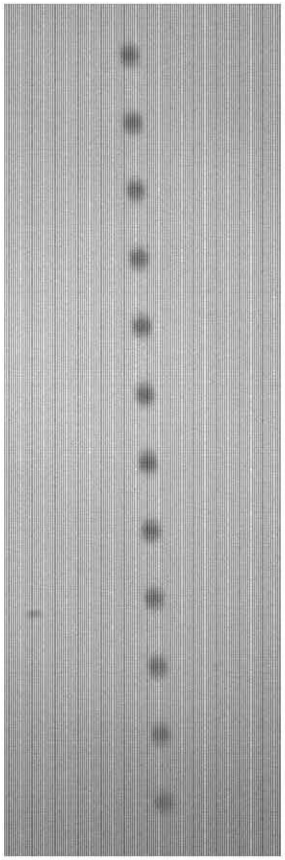
Laser Produced Plasma (CO_2-Sn LPP) Technology Development Challenges



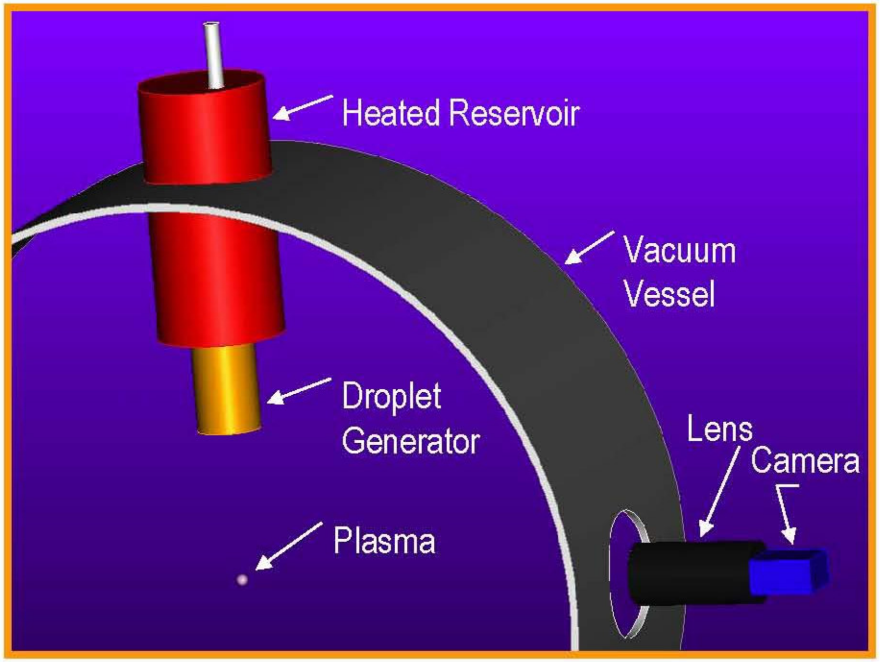
Development Focus Disciplines

- High Power Laser
- High Reflectivity Collectors
- Liquid Sn Droplet Generation
- Debris Mitigation
- Collector Lifetime
- Vacuum Technology
- Beam Transport and Focusing
- Droplet Targeting Control
- Plasma Metrology
- IF Metrology
- Scanner Interface

Liquid Metal Droplet Generator Developed



100 μm Sn droplets at 36 kHz, captured using strobe lighting



- Continuous stimulated droplet generation of liquid metals (Li and Sn) at temperatures up to 250°C
- Droplets diameter $\leq$100 μm
- Droplet rates up to 48 kHz
- Working distance of 50mm

Ref: Poster #5751-108, Algots, Cymer

CYMER®

Performance Roadmap to HVM and Beyond

Performance Roadmap					
	Beta -	**Beta**	**HVM**	**HVM+**	**HVM++**
Number of laser frames	1	2	2	3	4
Power amplifiers per frame	2	2	2	2	2
Rep rate per amplifier (kHz)	6	6	8	8	8
Drive laser rep rate (kHz)	12	12	16	16	16
Total rep rate (kHz)	12	24	32	48	64
Pulse energy (mJ)	190	210	220	220	220
Drive laser power (W)	**2280**	**5040**	**7040**	**10560**	**14080**
Transmission BTS	96%	96%	96%	96%	96%
In-band CE	2.0%	3.2%	4.0%	4.0%	4.0%
Geometric collection effy (sr)	5	5	5.5	5.5	5.5
Collector obscurations	6%	4%	4%	4%	4%
Collector average reflectivity	50%	50%	50%	50%	50%
Collector Lifetime (k hrs)	1	5	10	10	10
Buffer gas transmission	90%	90%	90%	90%	90%
Total power at IF (W)	**15**	**53**	**102**	**153**	**204**

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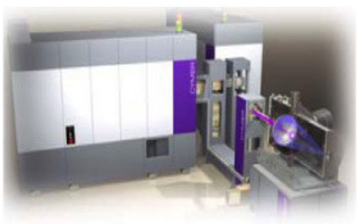
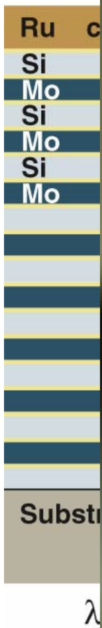
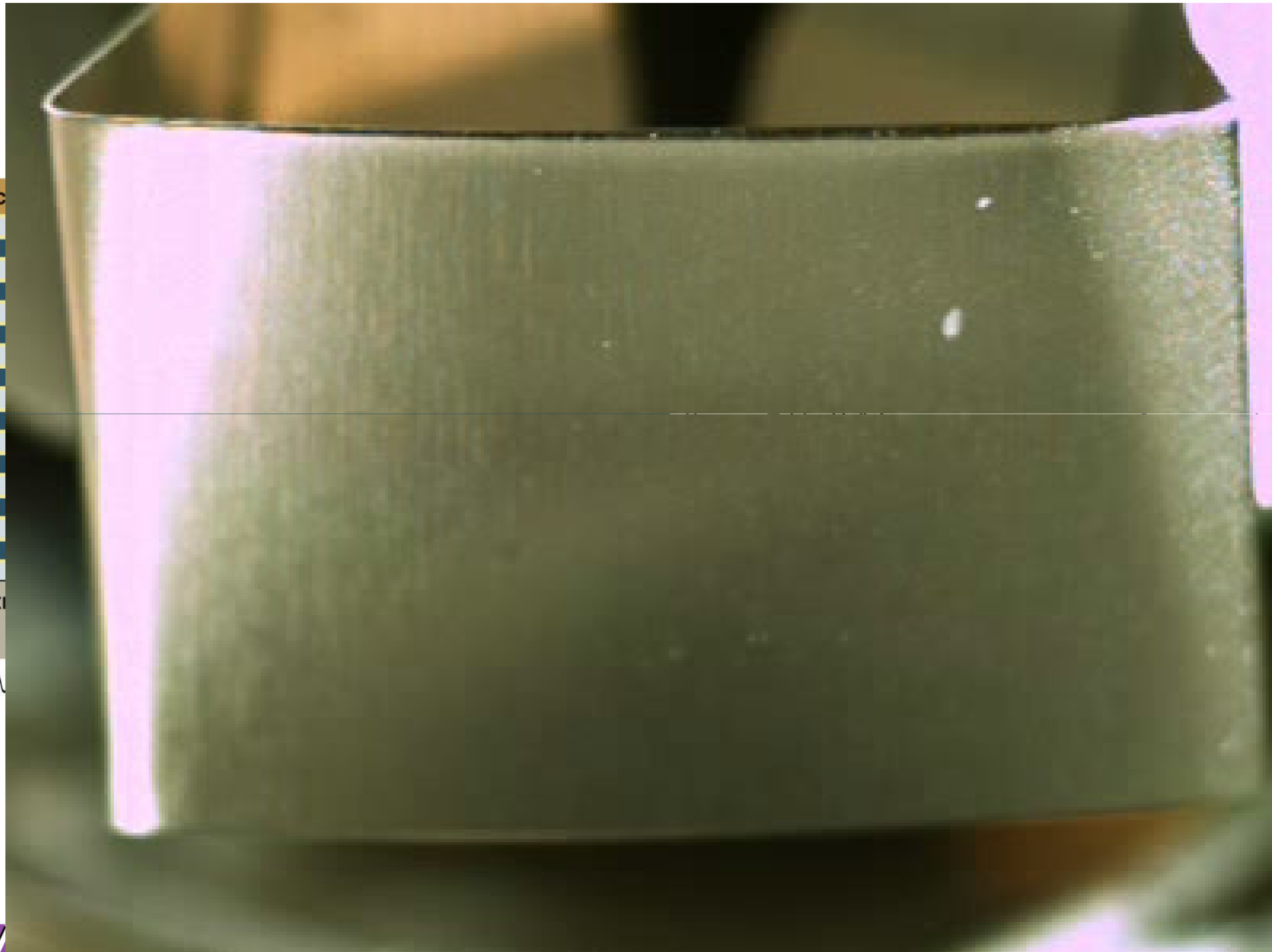


Power scalability is essential to the success of EUV Lithography

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





EUV Lithography

- Viable ?

The wrong question. There is sufficient economic motivation for going to smaller geometries. Shorter wavelengths are necessary for the patterns.

- When ?

When the present capabilities of DUV become more expensive than the projected move to shorter wavelengths.

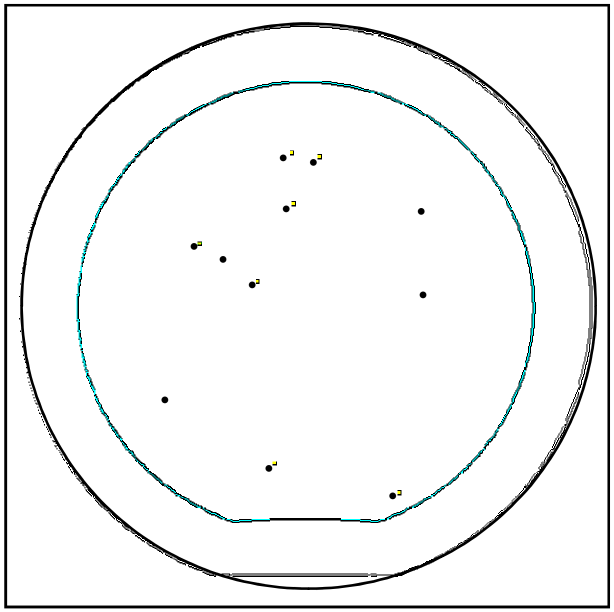
- Will the systems look like the present EUV efforts?

Probably, given the investment and progress. Changes in semiconductor and other materials processing industries will allow more differentiation.

Processing at Smaller Geometries Demands Metrology and Imaging Capabilities

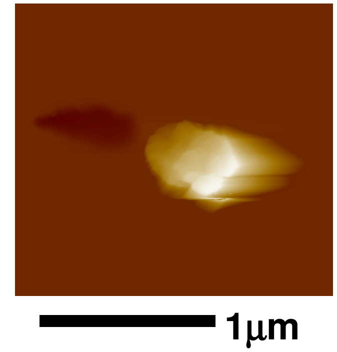
- Defect inspection for masks and wafers.
- Process development and control.
- Circuit debug and critical timing and power localities.

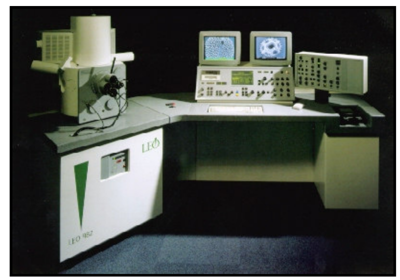
Defect Map Allows Correlation of Defects to Other Tools



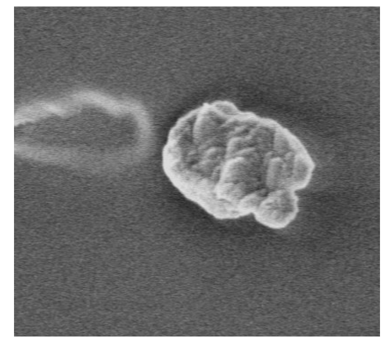
Defect map
of mask blank

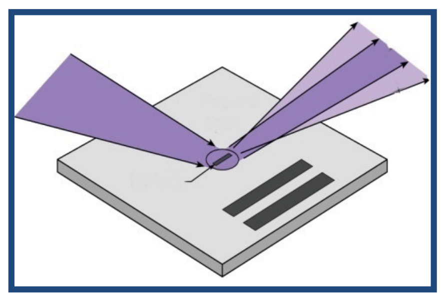
AFM



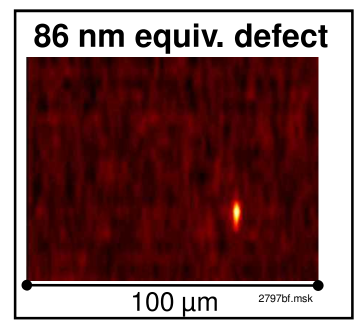


SEM

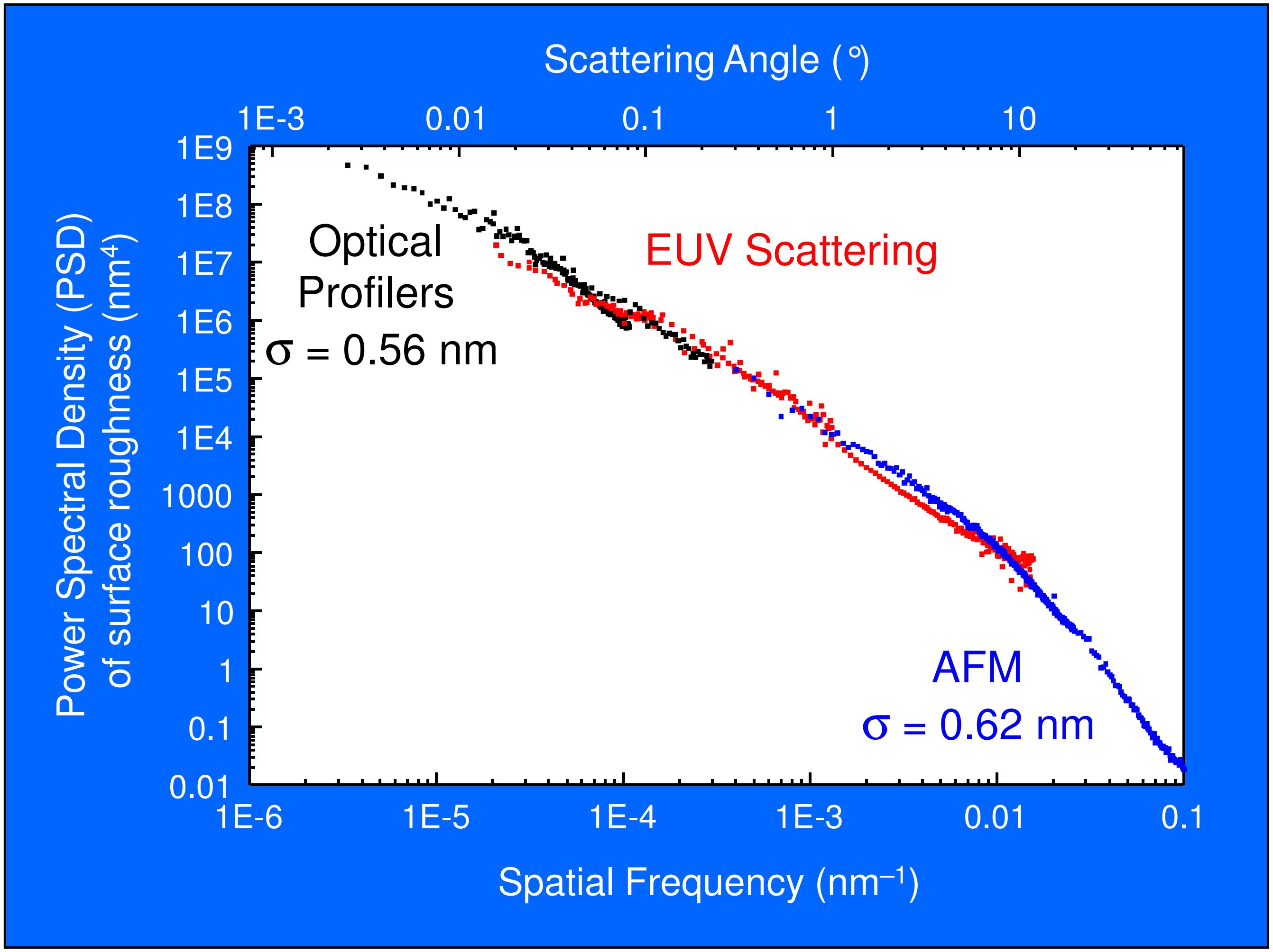




EUV Scatter



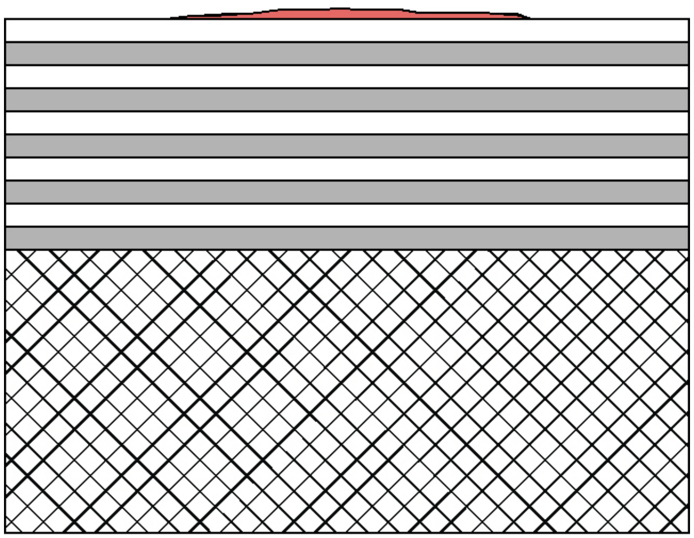
At-Wavelength EUV Scattering Correlates Well with Commonly Available Tools



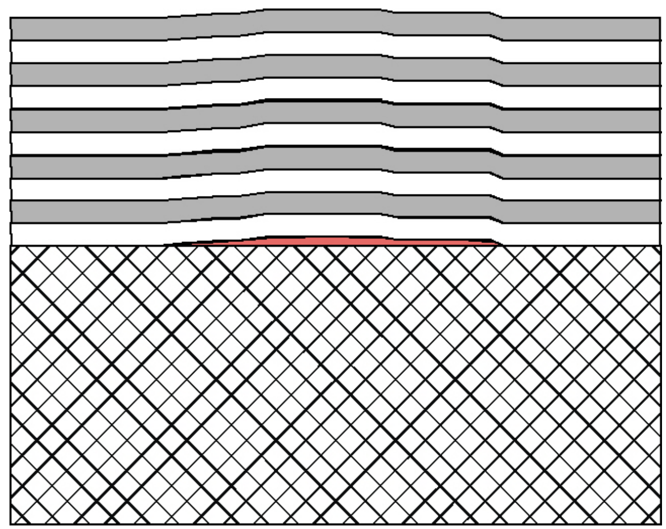
E.Gullikson (CXRO/LBNL)
ALS Beamline 6.3.2

Mask Blank Defects Can be on the Substrate or Within the Stack

Amplitude Defect

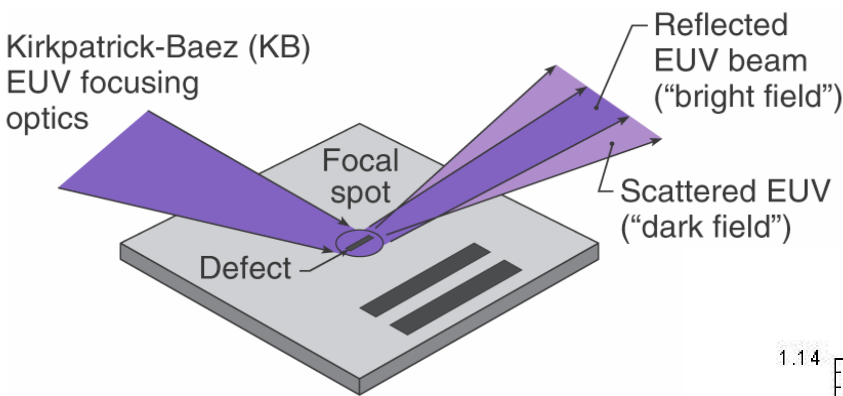


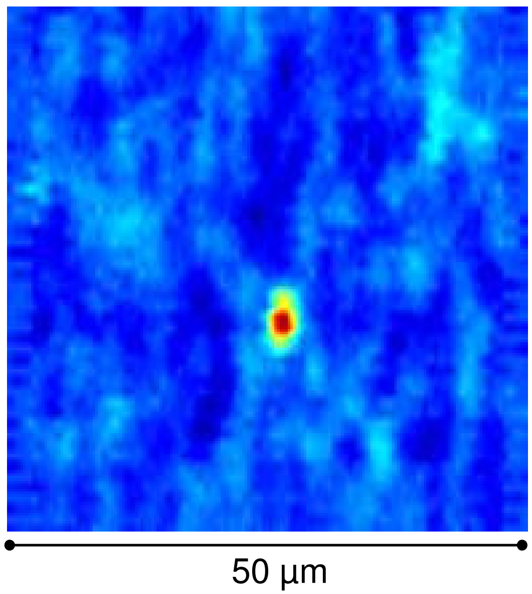
Phase Defect

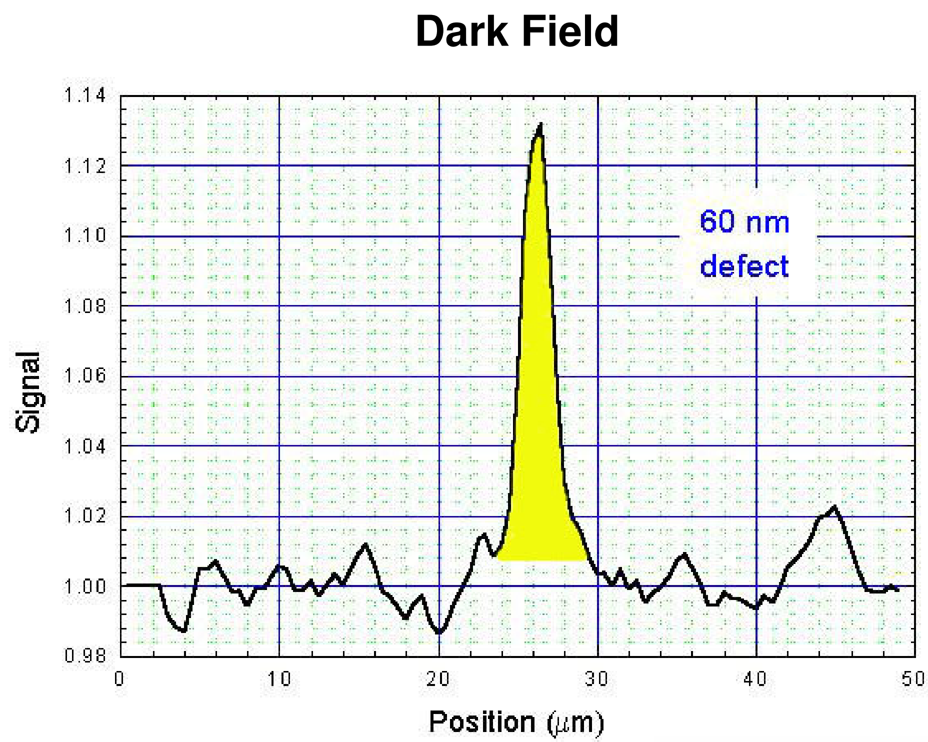


At-Wavelength Mask Blank Defect Inspection

- At-wavelength response to phase and opaque defects
- Correlation with conventional inspection tools





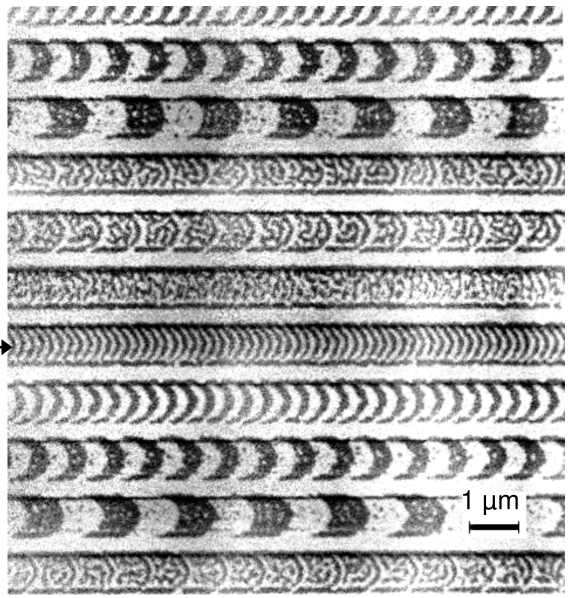


 Courtesy of Moonsuk Yi, LBL and J. Bokor, UCB/LBL.

Applications of Soft X-Ray Microscopy

Magnetic Recording Materials

100 nm lines & spaces

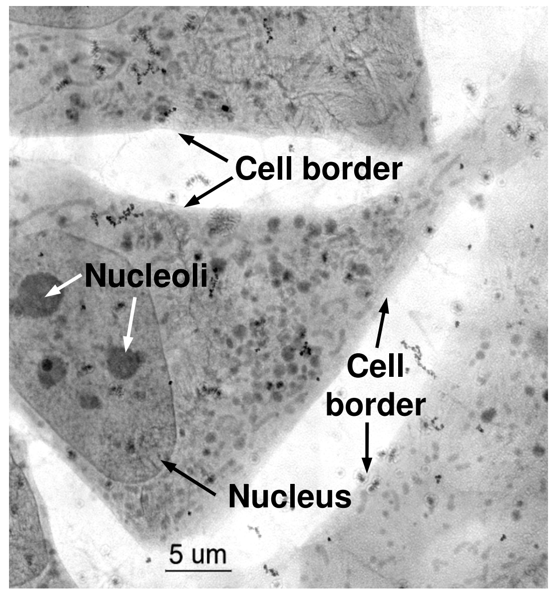


Fe L_3 @ 707.5 eV

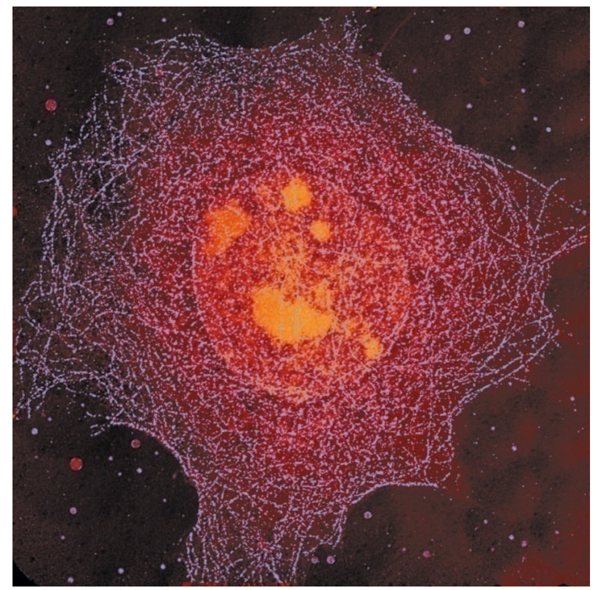
FeTbCo Multilayer
with Al Capping Layer

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

Cryo Microscopy for the Life Sciences



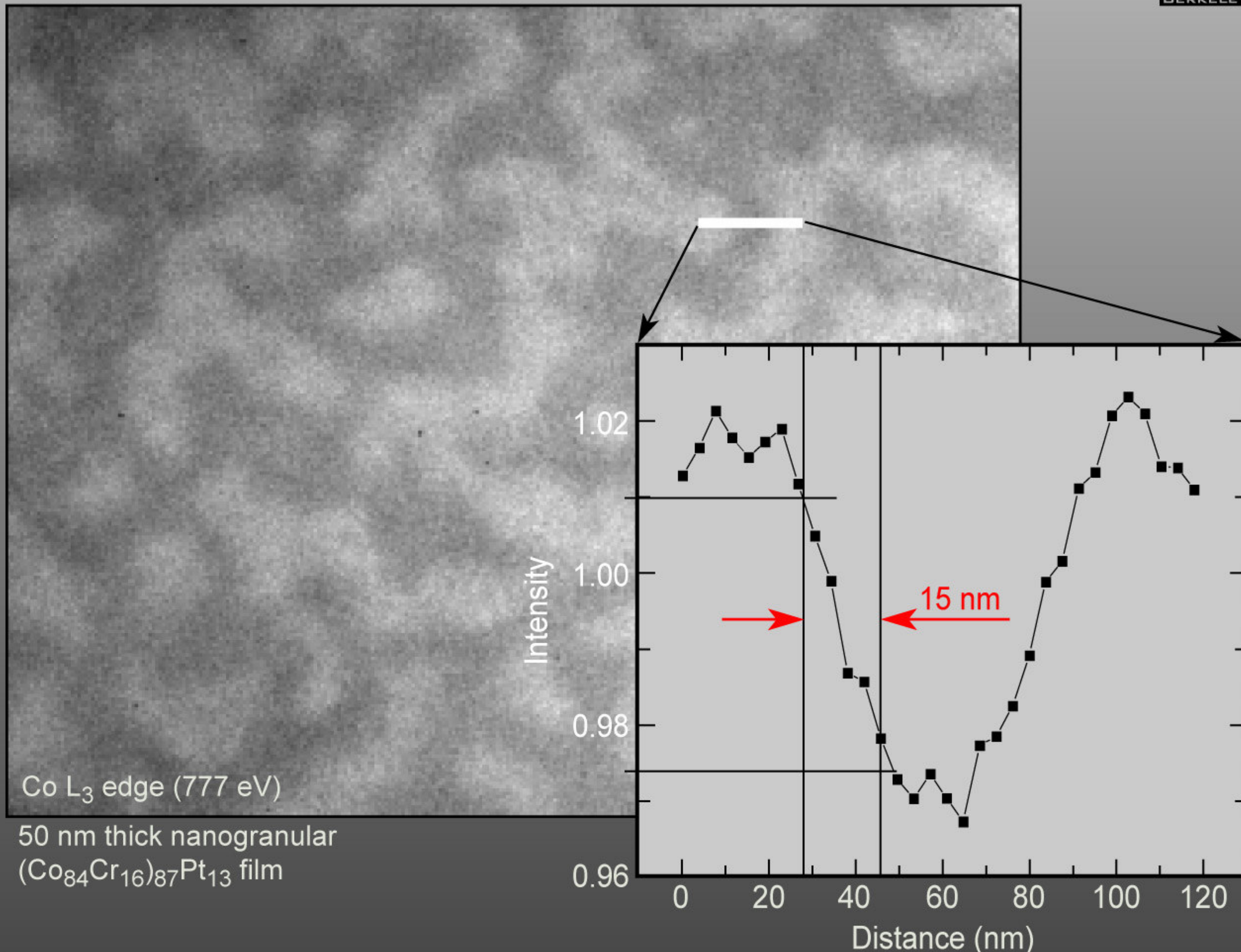
Cryo X-Ray Microscopy
of 3T3 Fibroblast Cells



Protein Labeled
Microtubule Network

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

Magnetic Imaging at Fundamental Length Scales

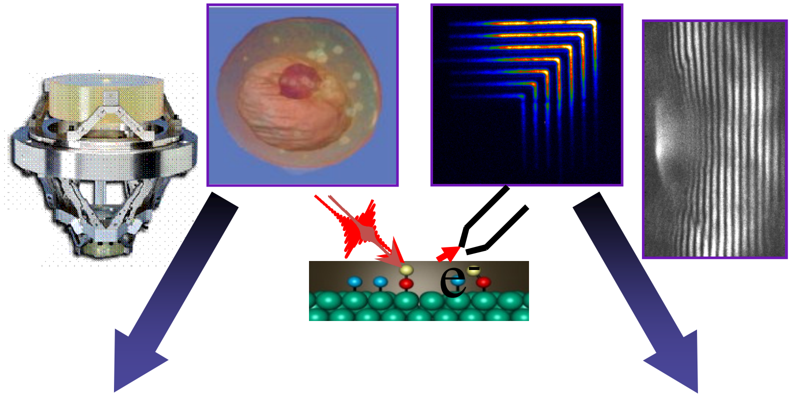


50 nm thick nanogranular
$(Co_{84}Cr_{16})_{87}Pt_{13}$ film

Courtesy of P. Fischer, et al.

Rational for Center Vision: Until recently applications requiring bright EUV light had to be taken to large “light factories”

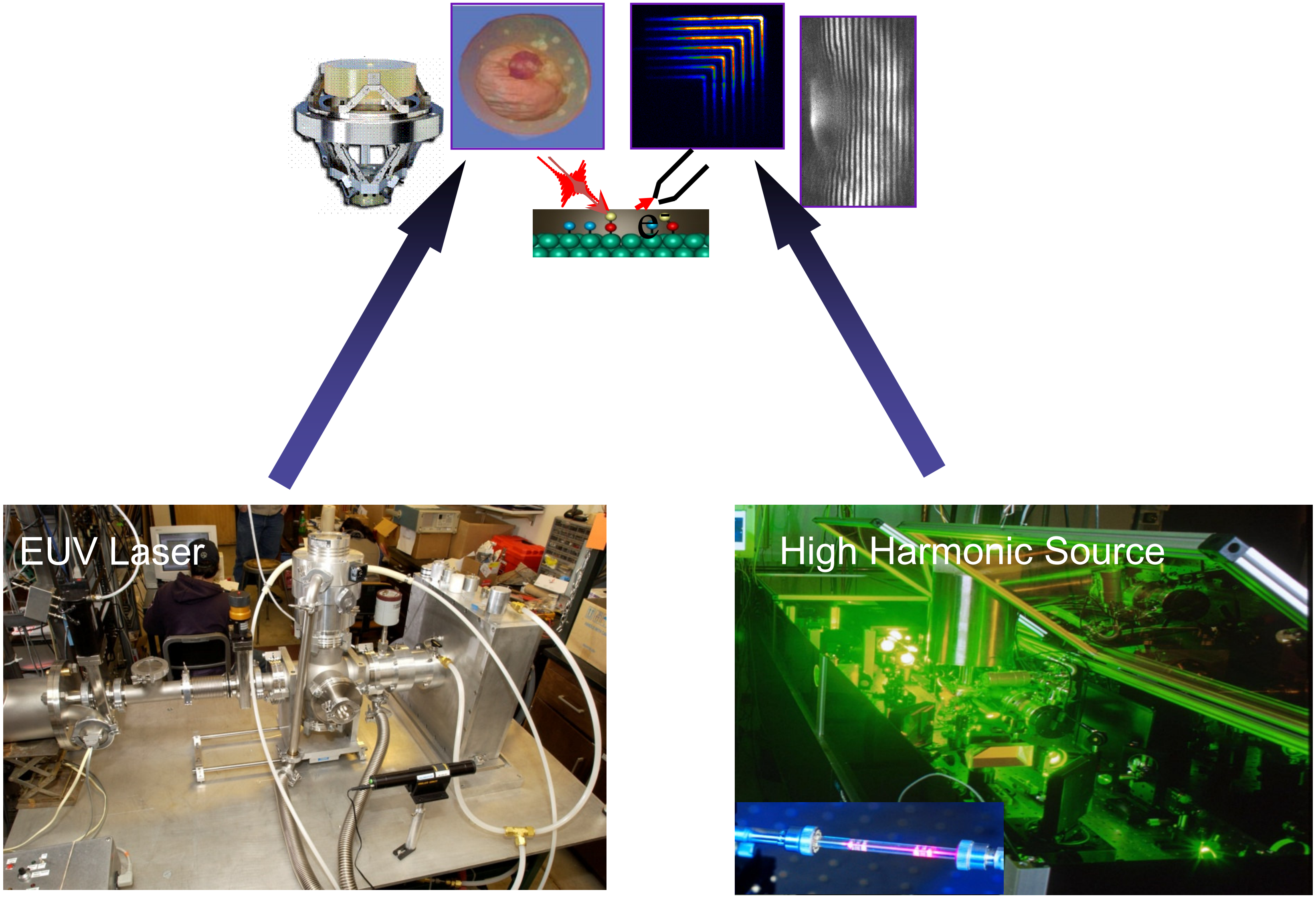
EUV
An NSF Engineering Research Center



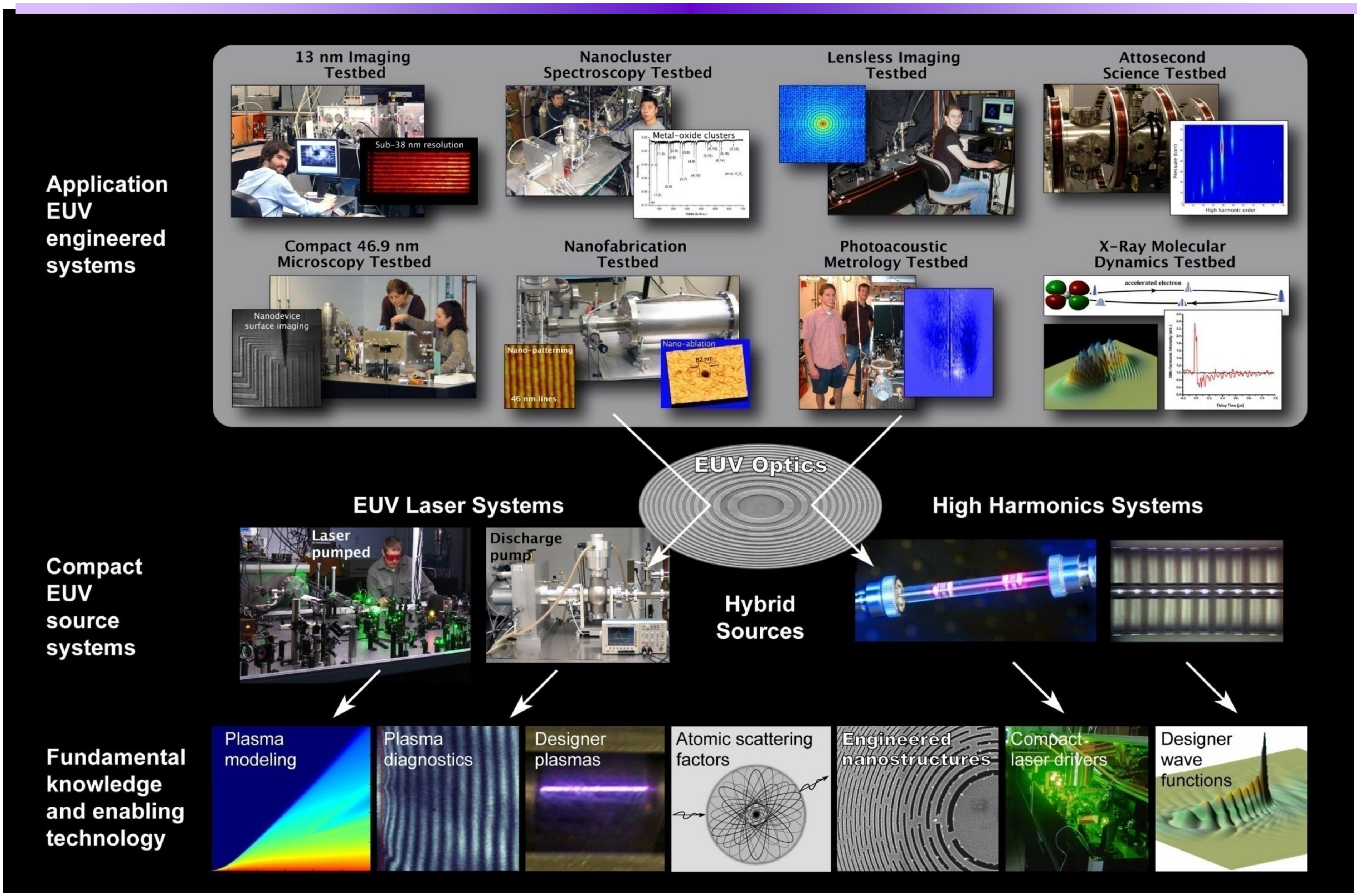
Synchrotron Light Source

Free Electron Laser

Center Vision: take the source to the application



Research Map for EUV ERC

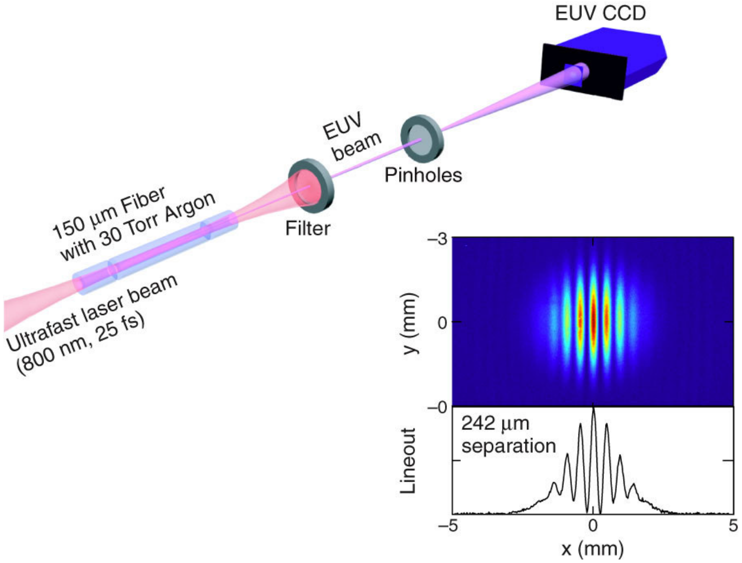


Development of compact coherent EUV sources with significantly improved capability

Two Complimentary Approaches

High Harmonics
- Very High Repetition Rate 1-100 kHz
- Femtosecond pulse width
- Low Pulse Energy nJ
- Moderate Monochromaticity $\lambda/\Delta\lambda \sim 100$
- High Spatial Coherence
- Highly Tunable

EUV Lasers
- Lower Repetition Rate 1-100 Hz
- Picosecond-nanosecond pulse width
- High Pulse Energy 100 nJ-1mJ
- High Monochromaticity $\lambda/\Delta\lambda \sim 10^4$
- High/moderate Spatial Coherence
- Tunability limited to line selection



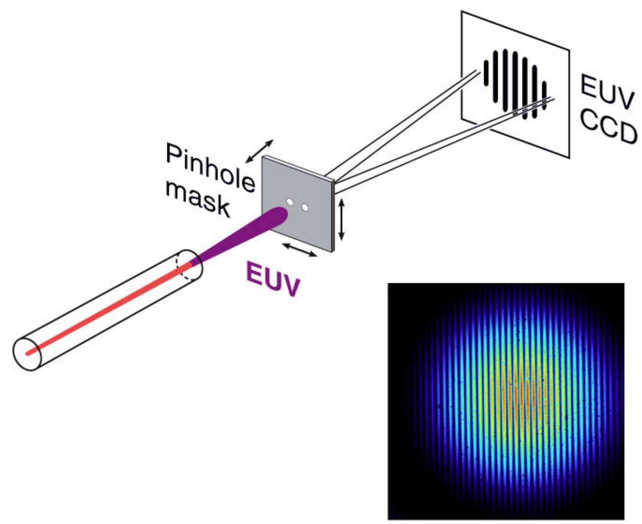
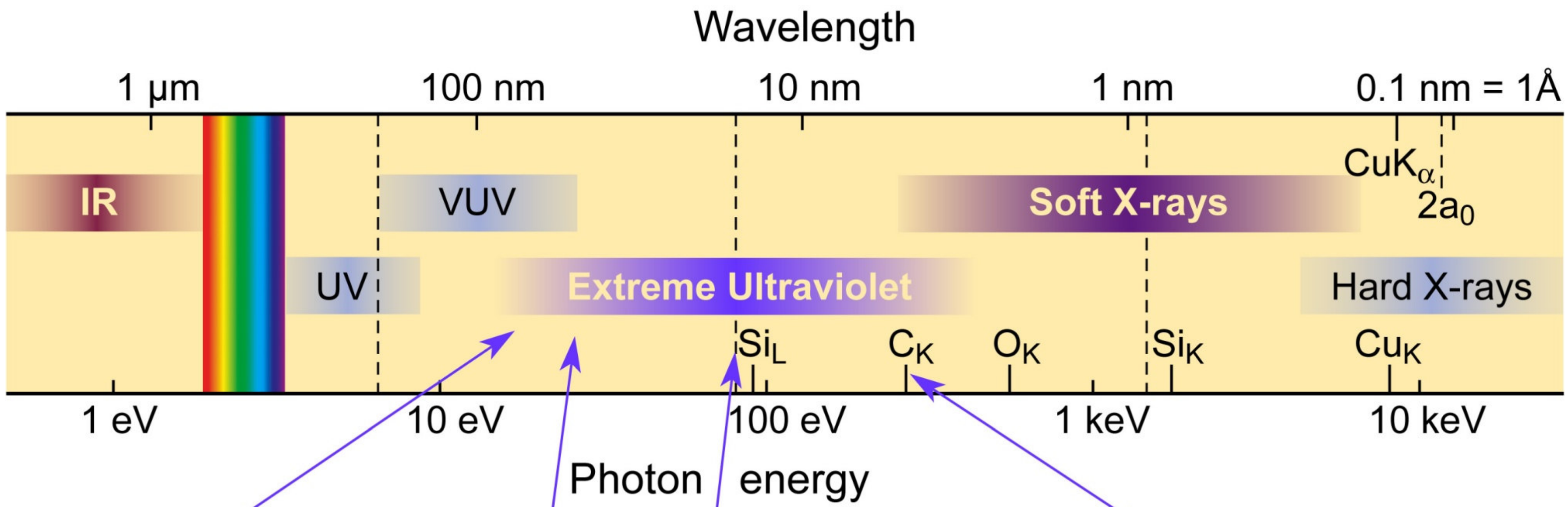


Table-top EUV Sources



46.9 nm EUV laser
(26.4 eV)
3 mW, 1 ns @ 5 Hz
Laptop
$\lambda/\Delta\lambda = 10^4$
Full spatial coherence
7×10^{14} ph/s

30 nm EUV HHG
(n = 27, 42 eV)
2 µW, 10 fs @ 1 kHz
Optical table
$\lambda/\Delta\lambda \sim 10^2$
Full spatial coherence
3×10^{11} ph/s

13.2 nm EUV laser
(93.9 eV)
1 µW, 4 ps @ 5 Hz
Optical table
$\lambda/\Delta\lambda = 10^4$
Full spatial coherence
7×10^{10} ph/s

4.4 nm SXR HHG
(n = 181, 280 eV)
½ nW, 10 fs @ 1 kHz
Optical table
$\lambda/\Delta\lambda = 10^1$
Full spatial coherence
1×10^7 ph/s

Ch01_F01_March07.ai

Coherent hard x-rays using x-ray lasers?

EUV
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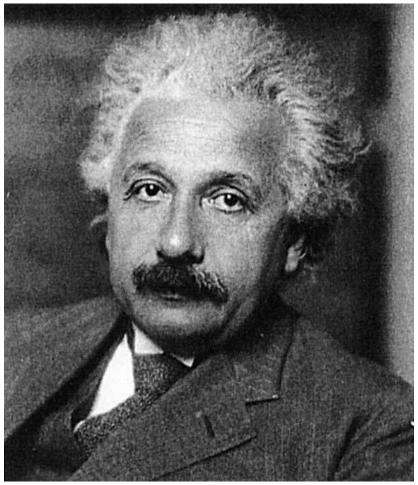


Spontaneous emission

Stimulated emission

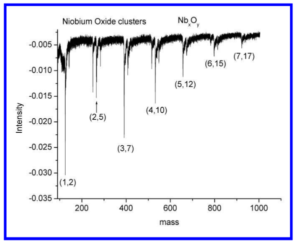
$$\frac{A_{21}}{B_{21}} = \frac{8\pi h\nu^3}{c^3} \propto \nu^3$$

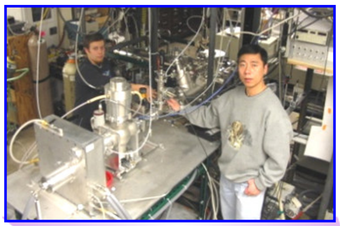
$$Power \propto \left(\frac{1}{\sigma_g}\right)\left(\frac{1}{\tau}\right)(h\nu) \propto \frac{1}{\lambda^5}$$

- 1 µm -> 1 mW
- 1 nm -> TW
- 1 Å -> 1 PW

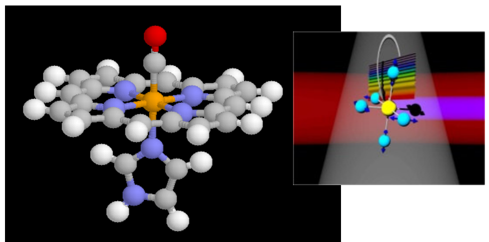
EUV Spectroscopy - Unique Scientific and Technological Frontiers

I. Cluster spectroscopy
- Understand surface reactions
-Basic science, catalysis
-CSU

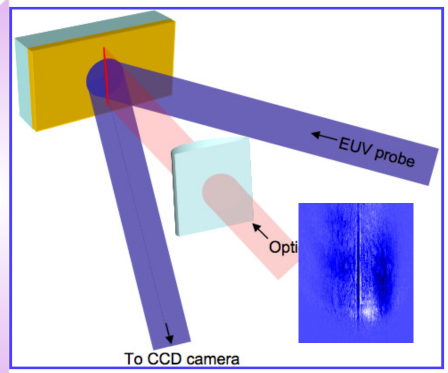




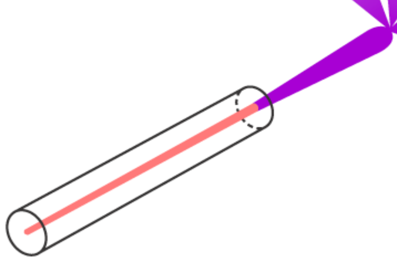
II. Ultrafast molecular dynamics
- Gas phase and surfaces
- Understand chemical reactions
- Basic science, catalysis, drugs, bio

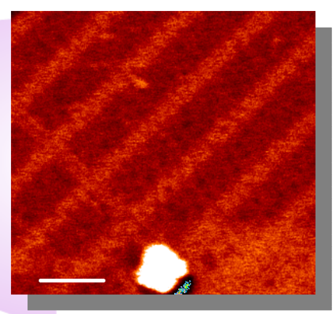


II. Ultrafast electron dynamics
- Gas phase and surfaces
- Understand complex electron correlations
- Basic science, catalysis, imaging



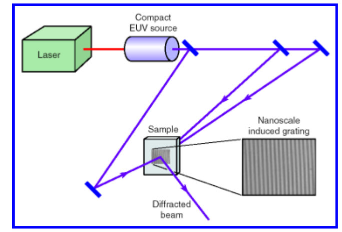
III. Nanothermal metrology
- Nanoscale materials
- Understand heat transport on nanoscale lengths; characterize thin films and interfaces
- Basic science, materials metrology, thermal management

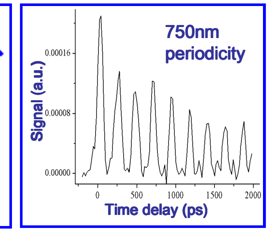


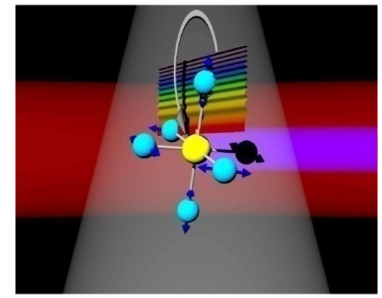


IV. Spectromicroscopy
- Nanoscale materials, interfaces
- Understand nanoscale materials
- Basic science, materials and photoresist metrology
- UC Berkeley

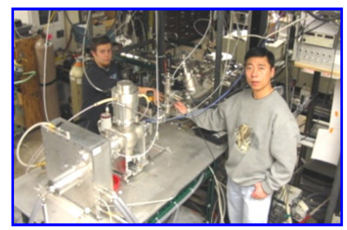
Coherent Spectroscopy and Imaging

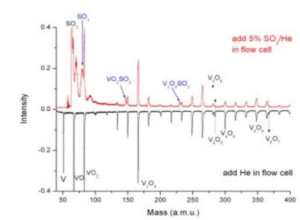




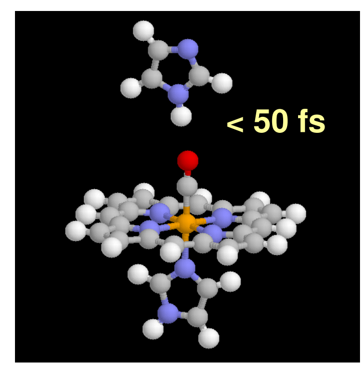


- *High Harmonic sources*
  - Photoacoustics probed with EUV light
  - Nanothermal heat flow
  - Lensless coherent imaging
  - Ultrafast dynamics on catalytic surfaces
  - Ultrafast molecular dynamics
  - COLTRIMS reaction microscope: “radiation femtochemistry”





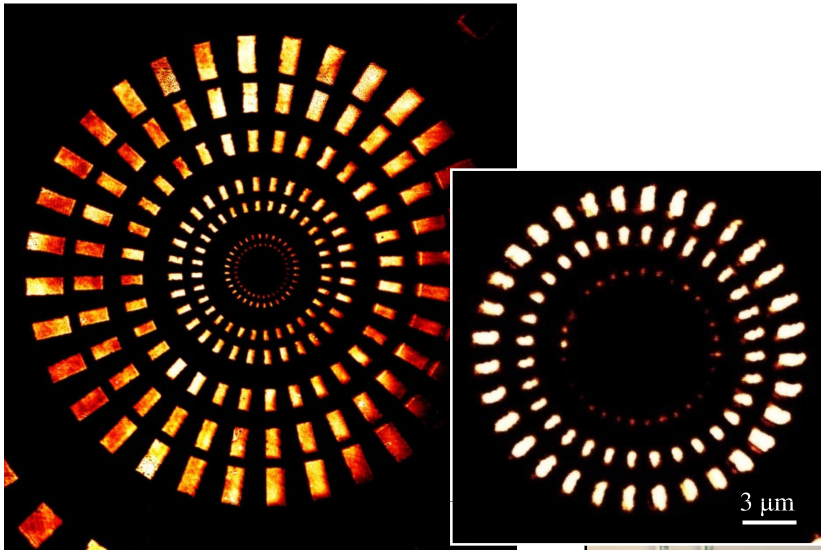
- *Capillary Discharge sources*
  - Spectroscopy of nanoclusters using EUV ionization
  - Nanoimaging, nanopatterning, nanoablation



- *Synchrotron sources*
  - Metrology at the ALS
  - EUV spectromicroscopy of photoresists

Thrust 2: Imaging, Patterning and Metrology

Ne-like Ar, 3p-3s, λ = 46.9 nm
plasma discharge laser

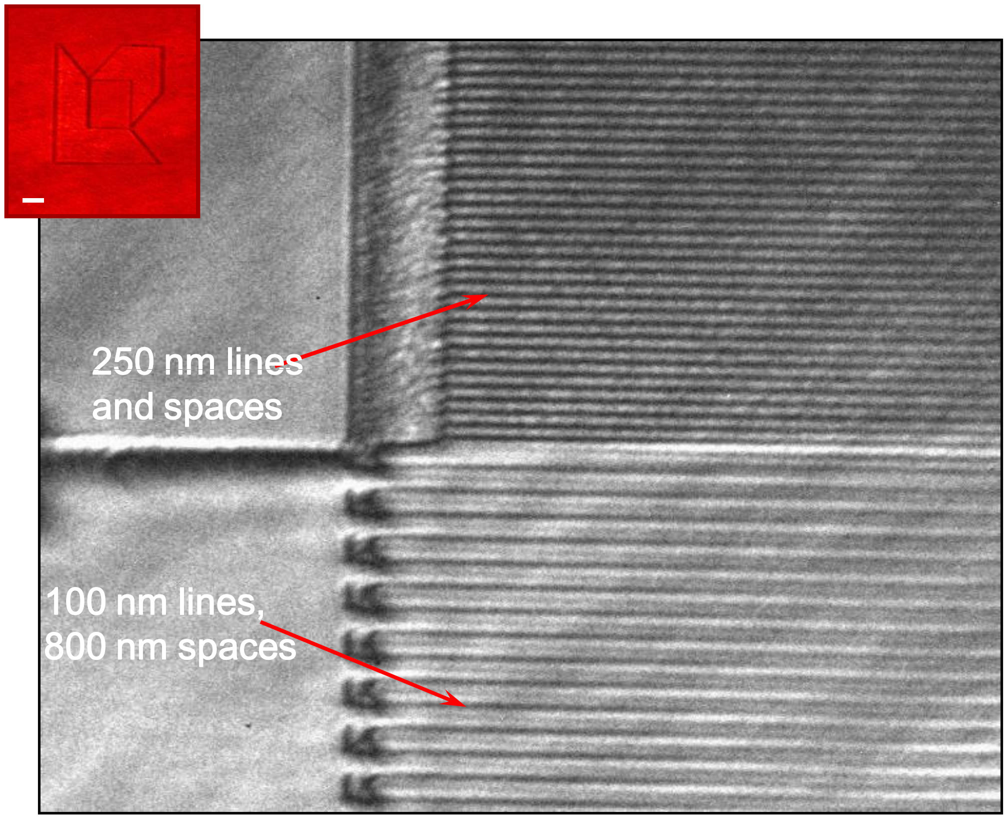


100 nm innermost features
λ = 46.9 nm, 3 Hz
20 sec. exposure

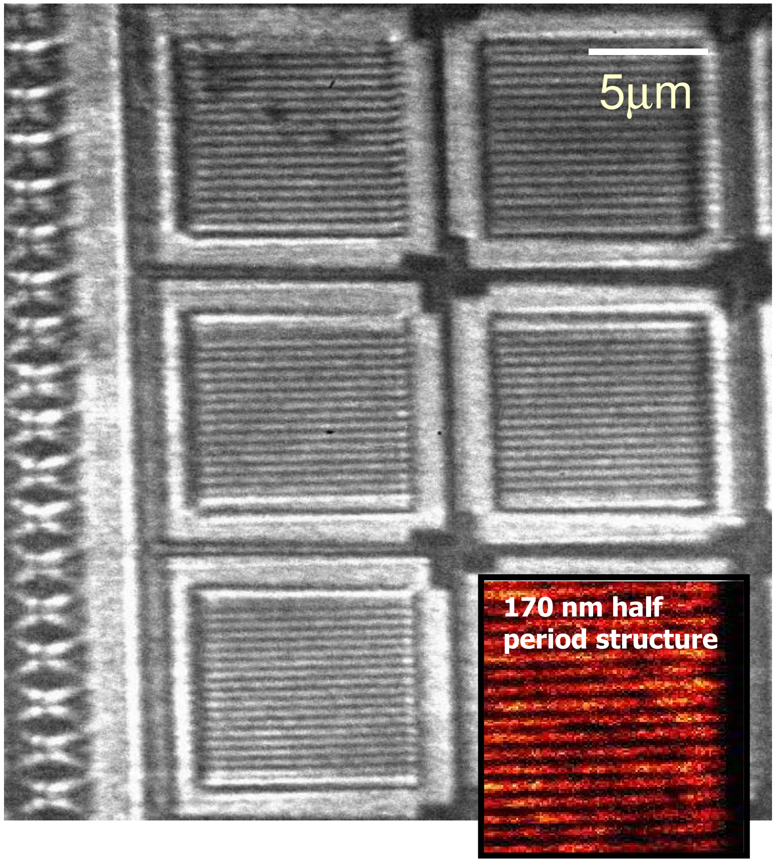
Graduate student Courtney Brewer and undergraduate Abbie Tippie (CSU)

Reflection mode imaging using the 46.9 nm microscope using a Δr = 200 nm objective zone plate

EUV Image of polysilicon lines on Silicon



EUV Image of metal pattern on Silicon

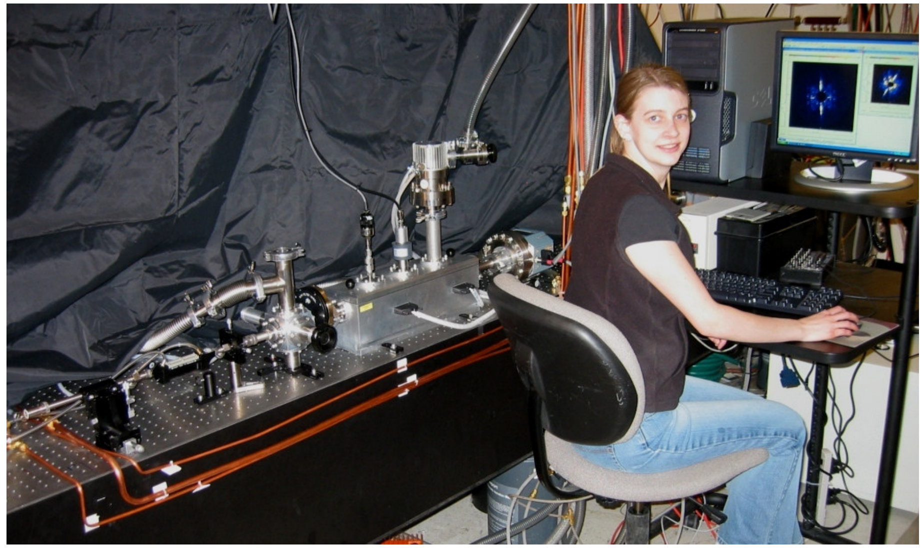


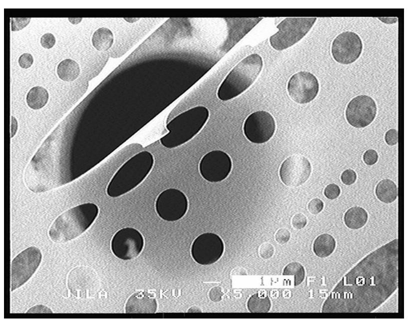
Exposure time: 20 sec @ 3Hz - Spatial resolution: ~150 nm

Lensless Coherent Imaging

Coherent EUV beam

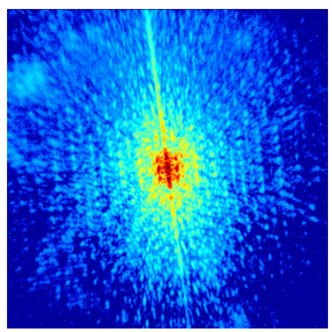
QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.





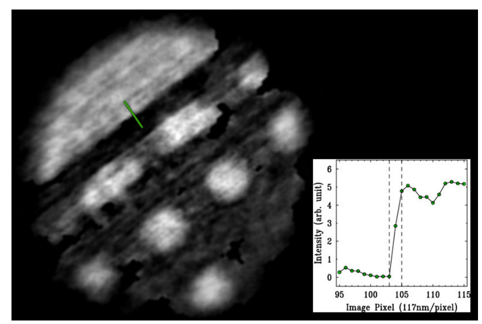
QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

Test objects



QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

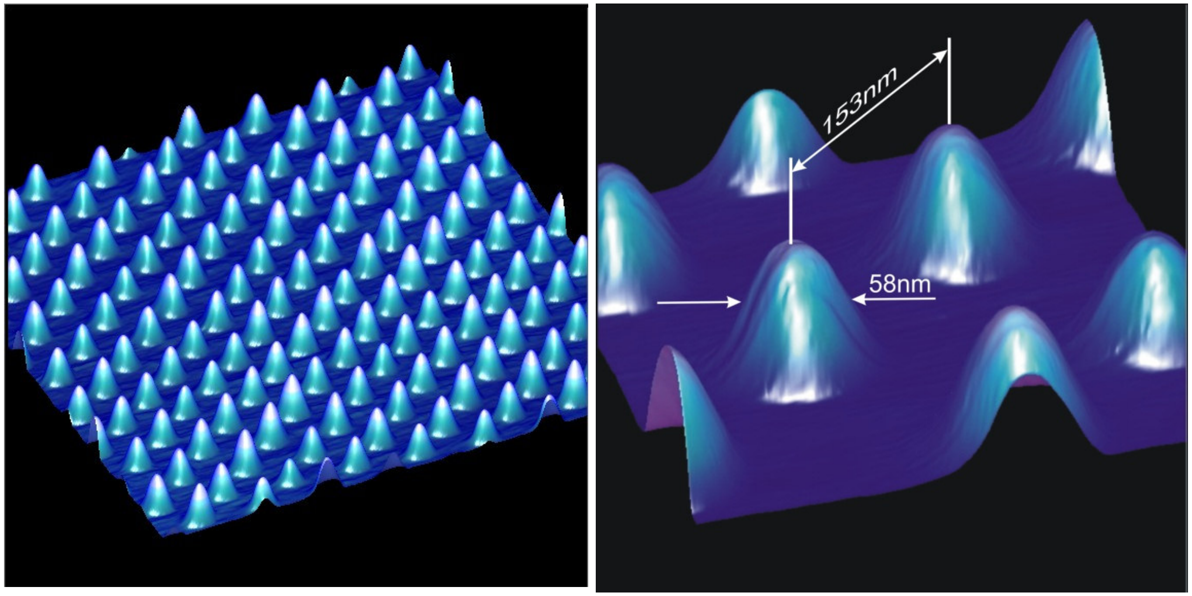
Diffraction patterns



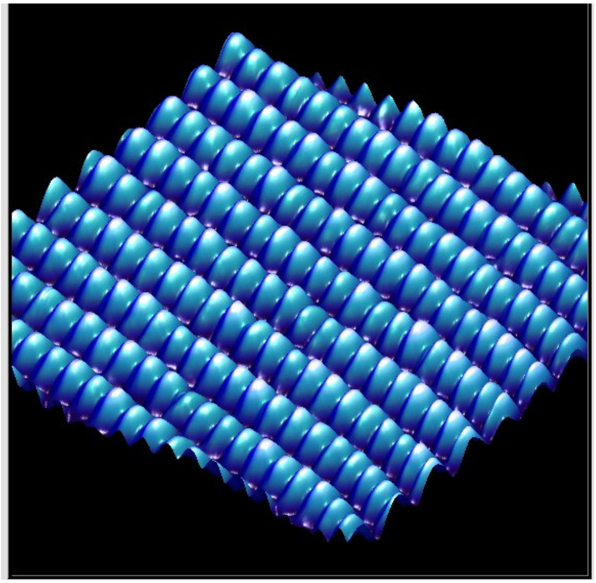
Reconstructed image ***(200nm resolution)***

Features 60 nm in diameter with different geometries are printed in PMMA by using multiple exposures

60nm Dots printed in PMMA



60nm Elipses printed in PMMA

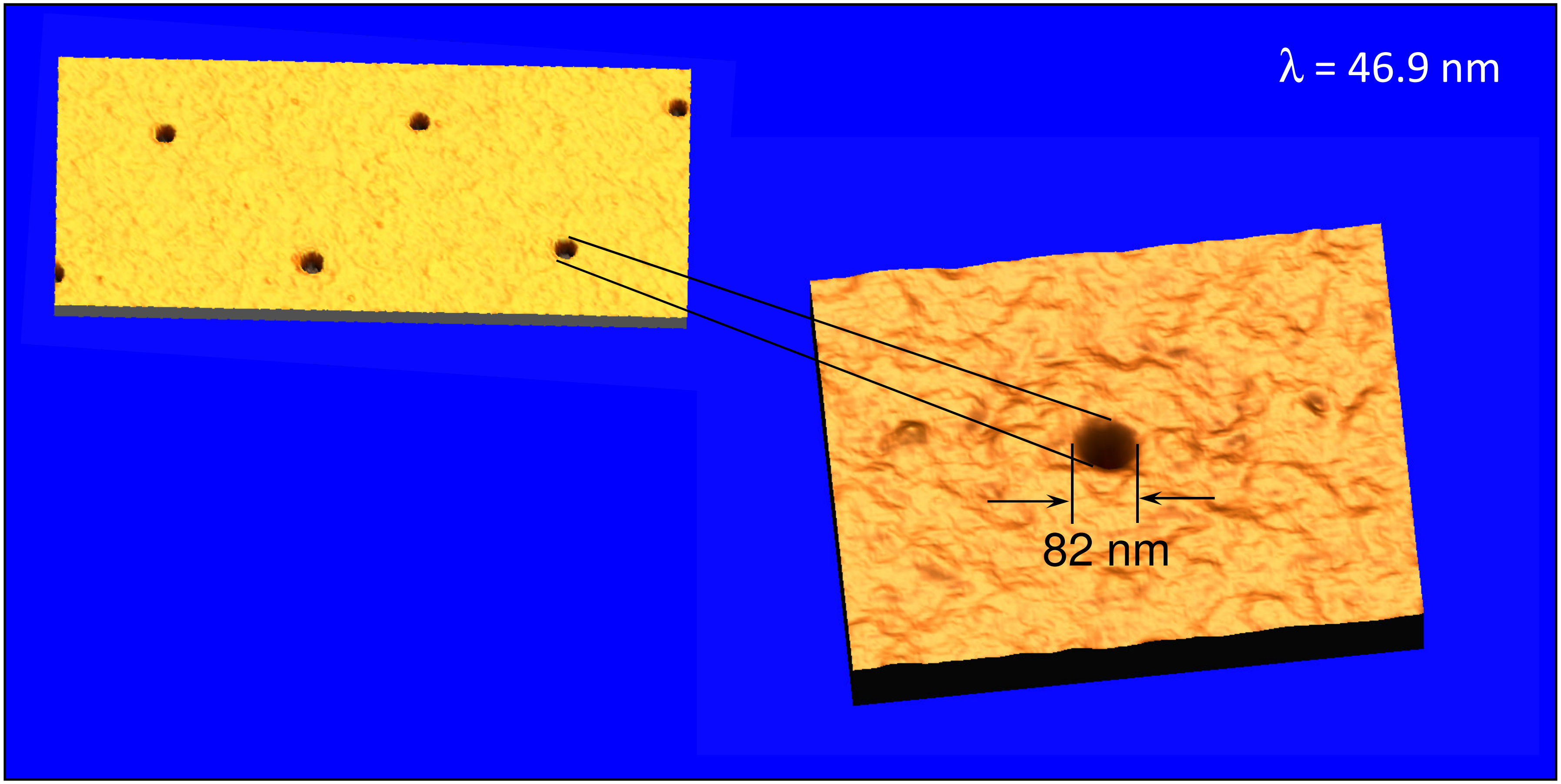


- Pattern geometry is controlled with exposure dose and angle of rotation between successive exposures
- Highly uniform patterns over areas 0.5x0.5 mm^2 are printed
- Nanopillars, nanacontacts can be fabricated with standard methods using these patterns as masks

Applications: nanoscale magnetic structures, plasmonics,…....

Menoni and Marconi, CSU

EUV Laser-based nanoprobe

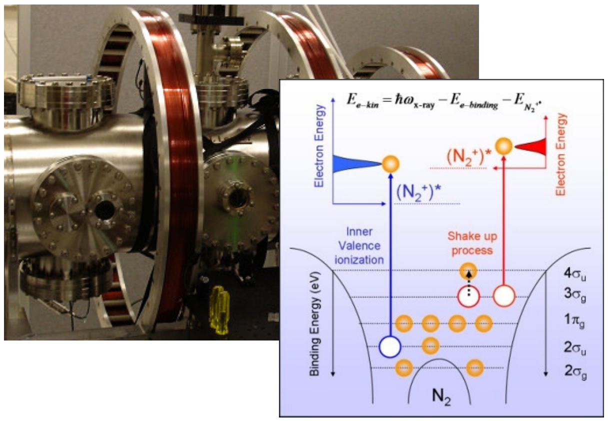


Joint work with JMAR

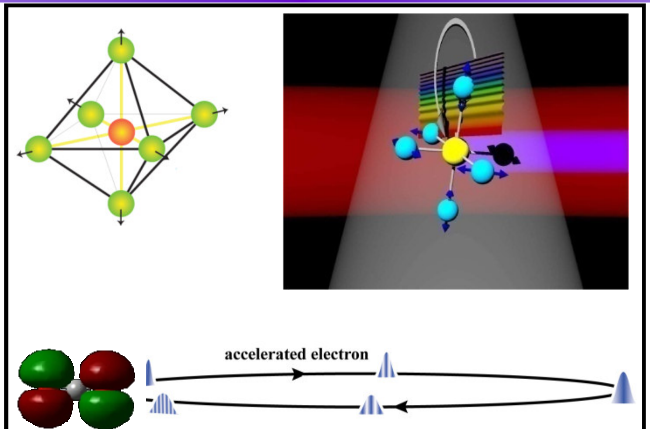
Rocca, Menoni, CSU

Generation and applications of High Harmonic beams

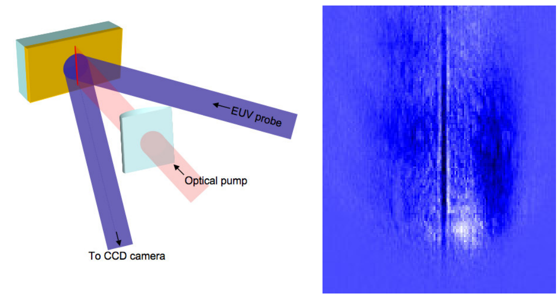
EUV
An NSF Engineering Research Center



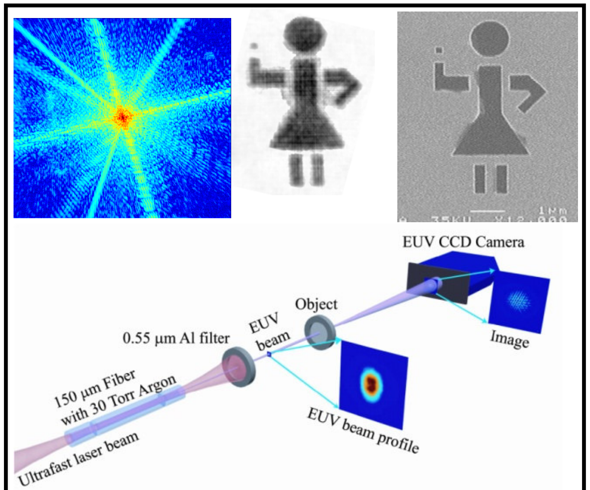
X-ray driven molecular dynamics *(Science to be published)*



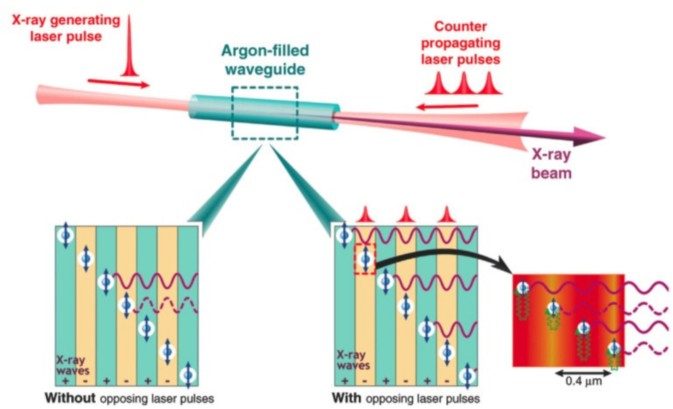
Coherent electron probes of molecules *(PNAS **103**, 13279 (2006))*



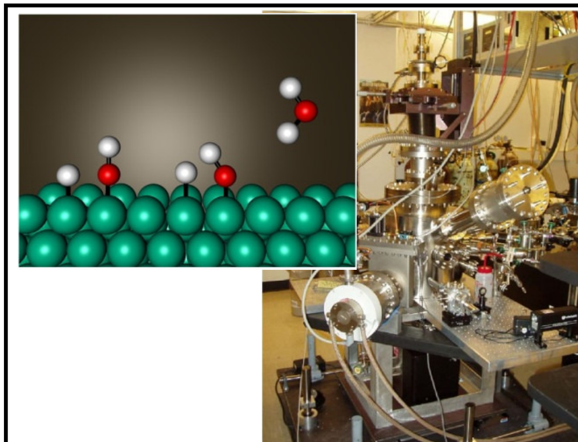
Femtosecond x-ray holography *(Appl. Phys. Lett. (2006); Opt. Lett. (2007))*



Coherent x-ray imaging
(PRL to be published (2007))



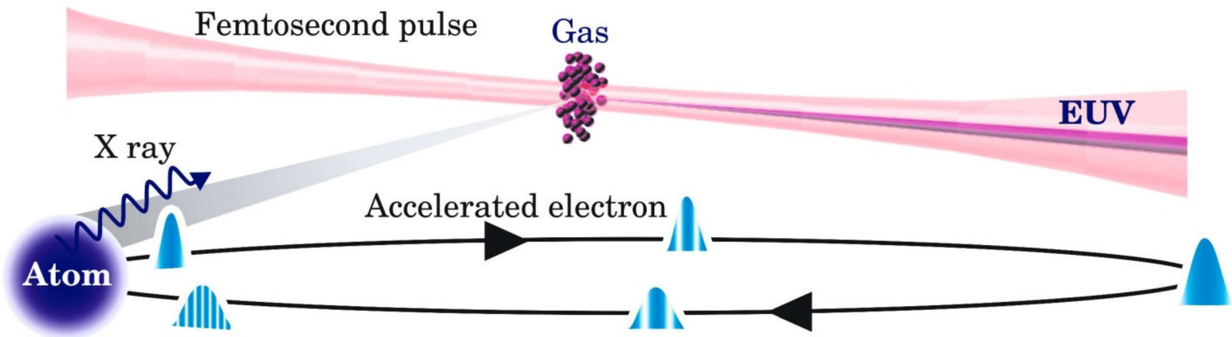
Attosecond nonlinear optics
*(Nature Phys. 3, 270 (2007); PRL **98**, 123904 (2007); Science (Aug 10, 2007))*

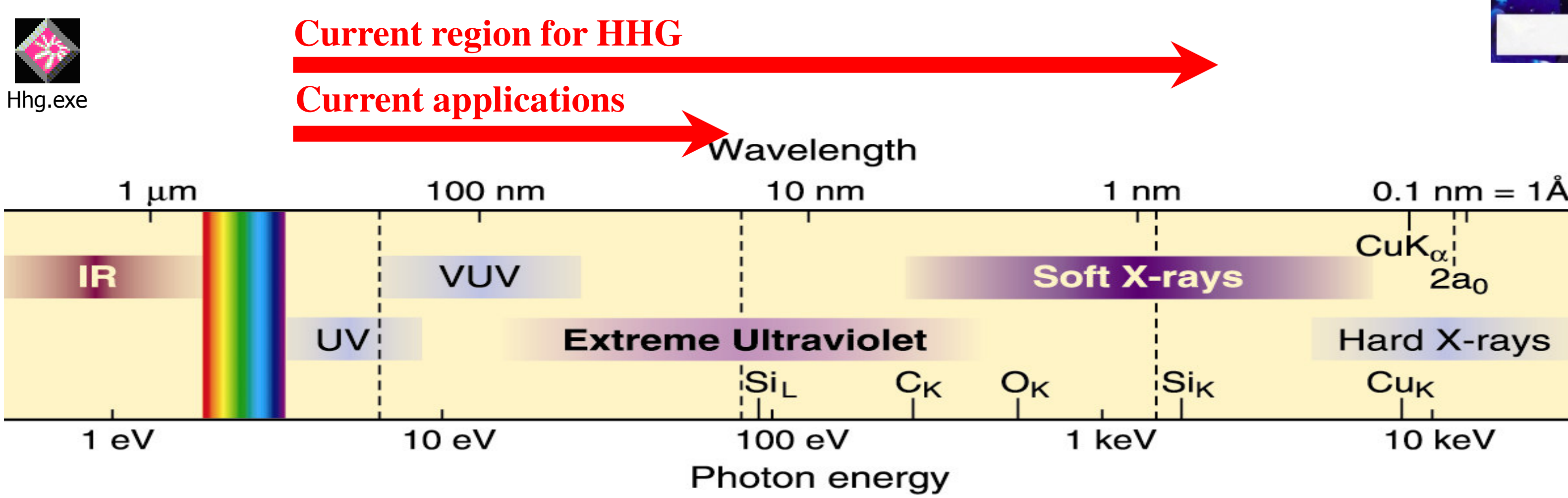


Molecular and electronic dynamics at surfaces
*(PRL **97**, 113604 (2006))*

Coherent x-ray generation using XNLO

- *Coherent* x-rays are generated by focusing an intense laser into a gas
- Broad range of energies generated simultaneously from UV - keV

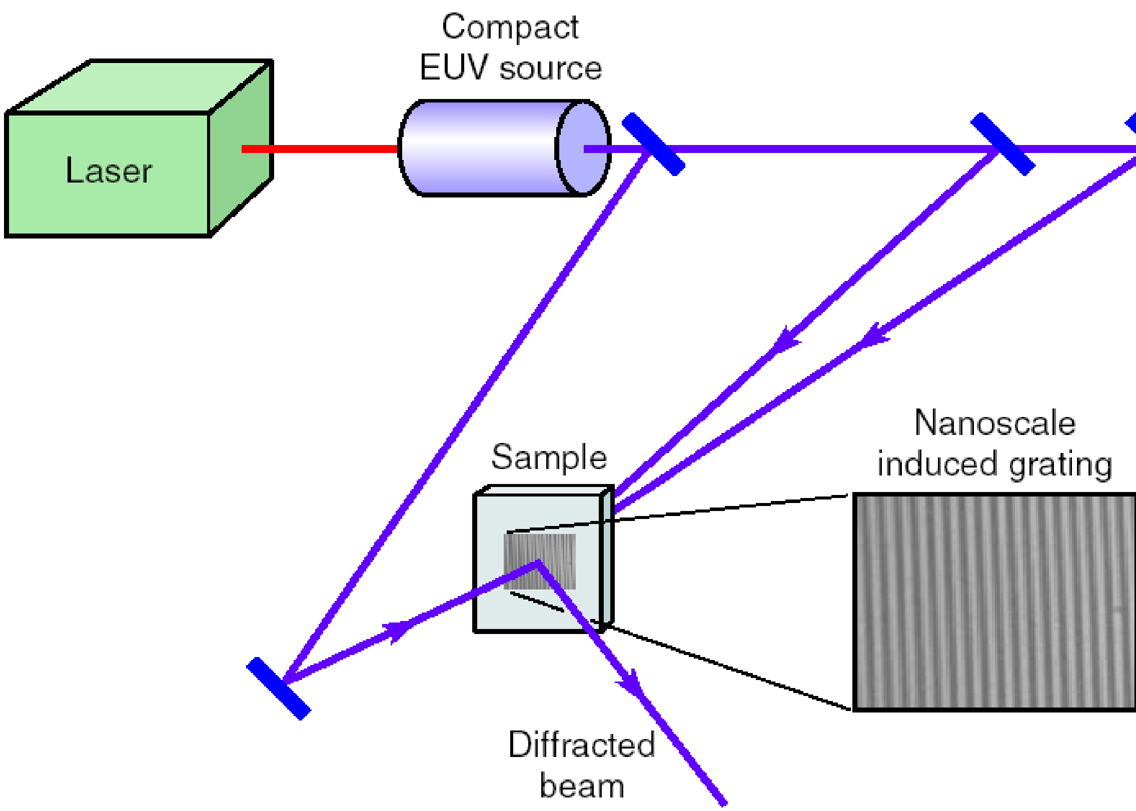


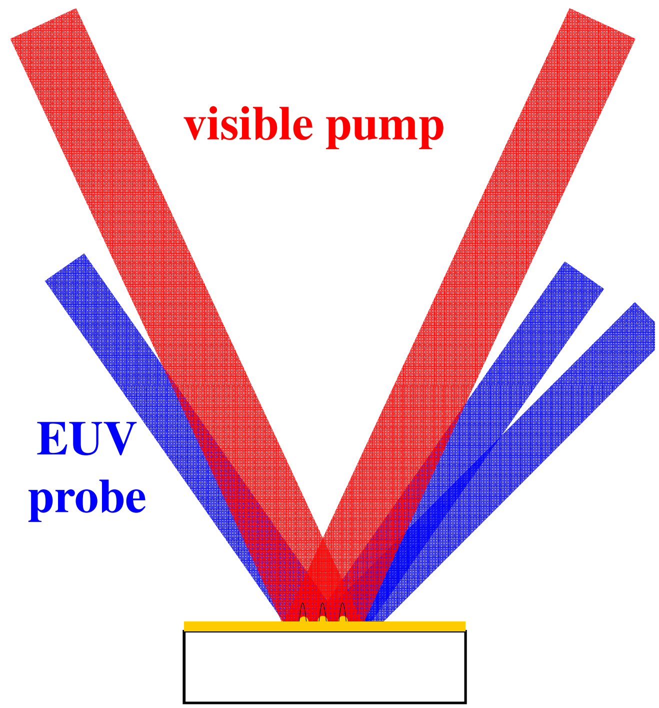


10^{11} ph/sec *10^{10} ph/sec* *10^{7} ph/sec* *100 ph/sec*

Kapteyn and Murnane, CU

Photoacoustic metrology using EUV light

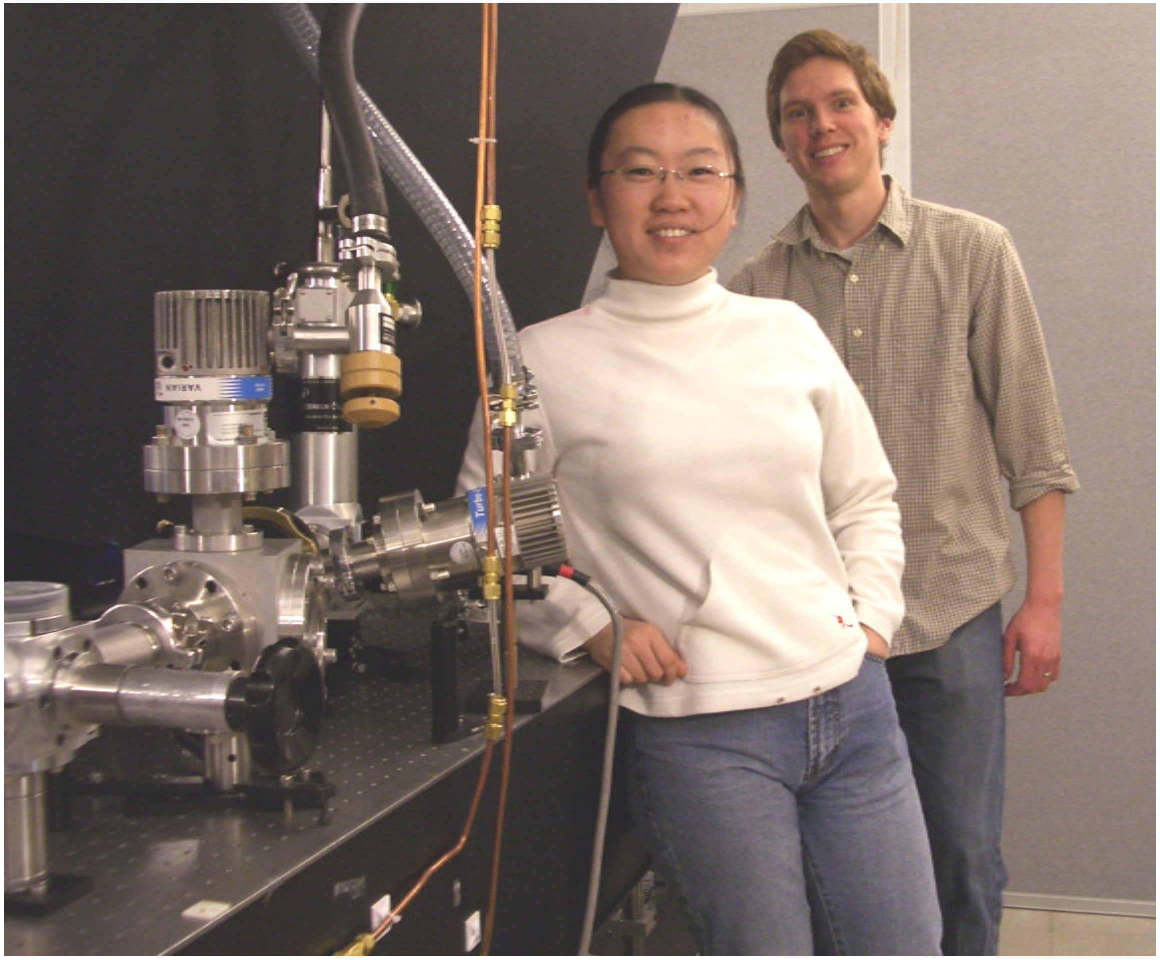




- Nonlinear spectroscopies are powerful probes of materials BUT spatial scale and sensitivity limited by λ
- Use EUV light to measure high-frequency dispersion, thin films, adhesion, intermixing, composites, polymers, liquids
- Collaboration with Keith Nelson, MIT

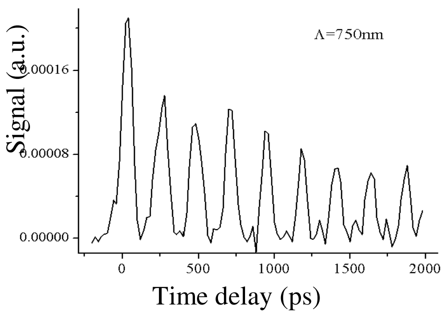
Non-diffusive heat transport

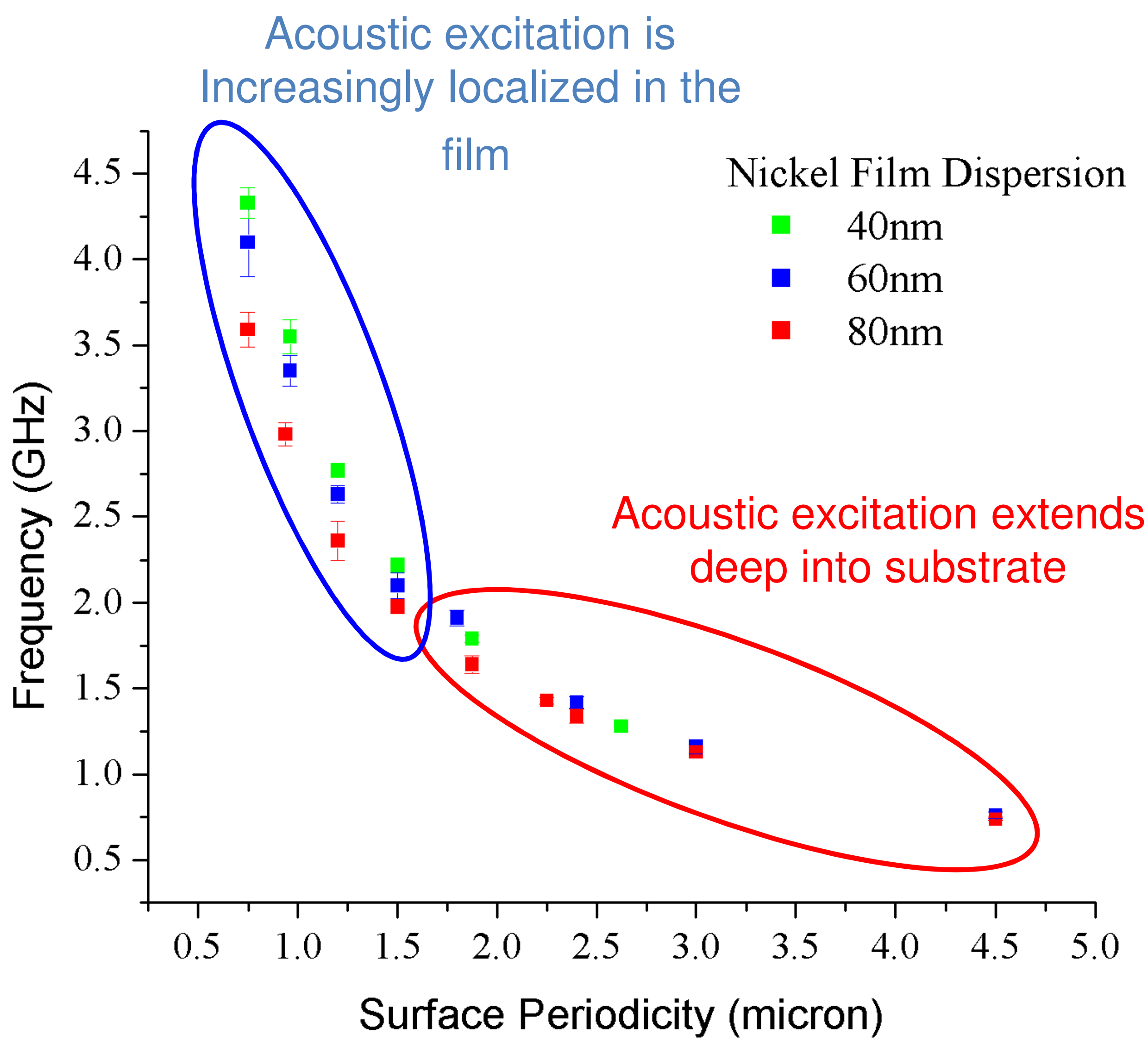
EUV
An NSF Engineering Research Center



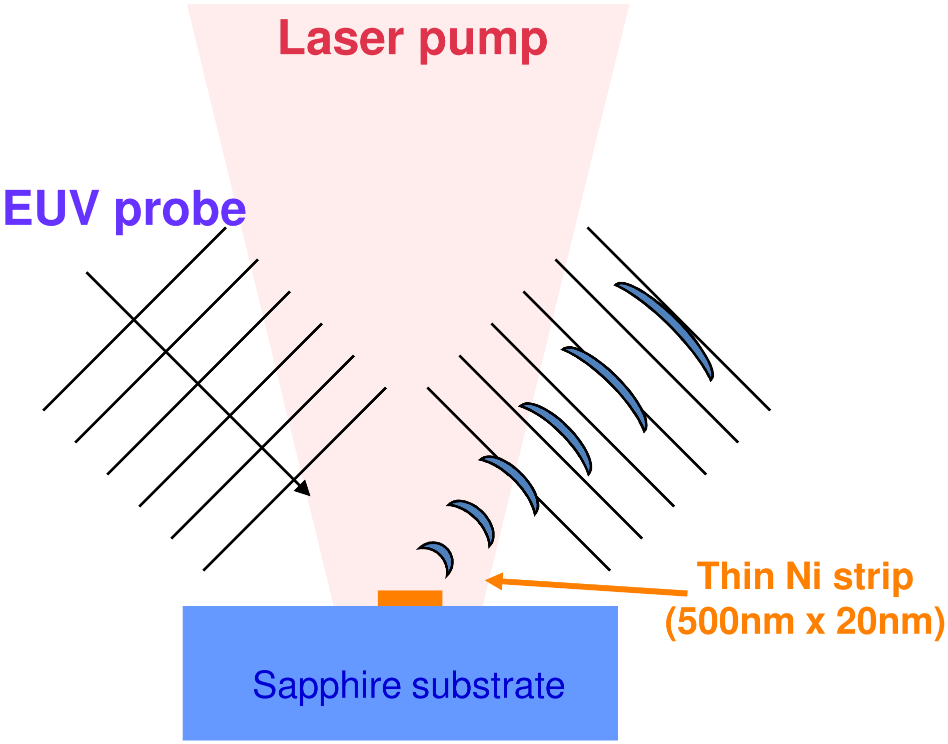
Students Qing Li and Mark Siemens with setup for EUV photoacoustic and nanothermal metrology.

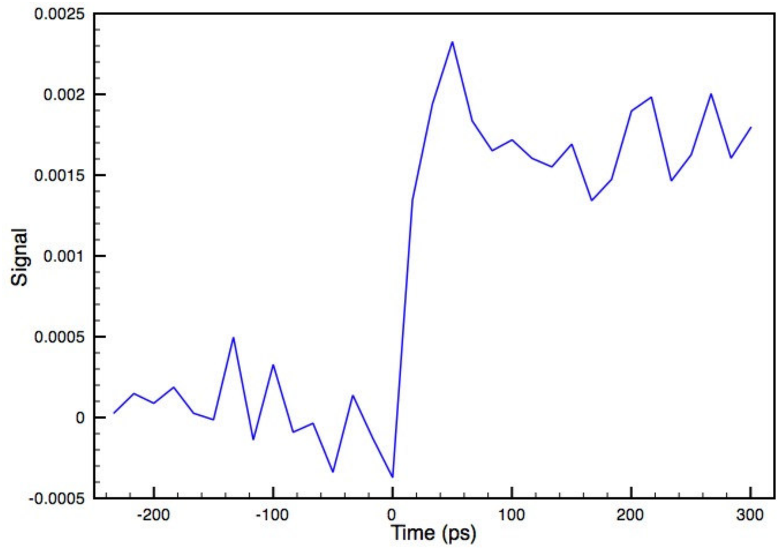
Thin Film Characterization





Non-diffusive heat transport at M/I interface



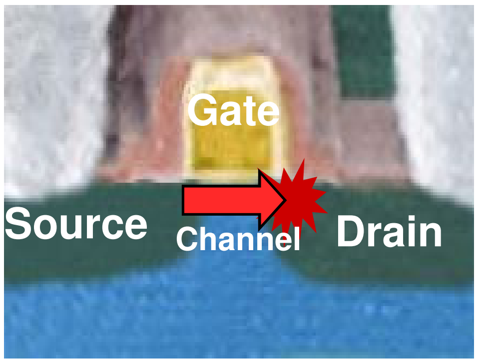


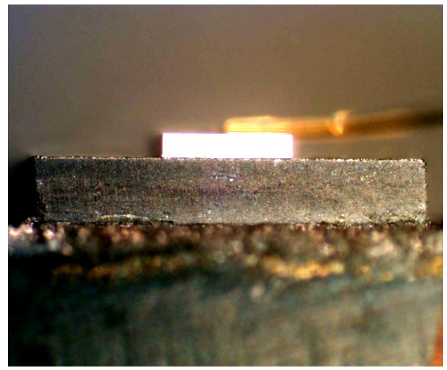
Observed thermal expansion

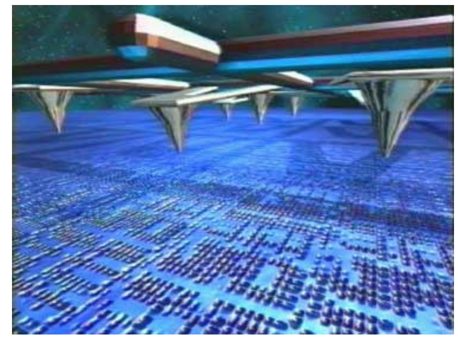
- Understanding heat transport at short length scales is critical for advances in nanoscience and nanotechnology
- Same approach can probe heat transport across metal/insulator boundaries smaller than the phonon mean free path

EUV-probed Heat Transfer in Nanodevices

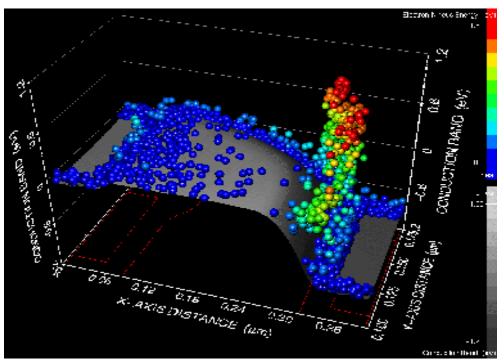
- Ronggui Yang
  - Nanoscale and Ultrafast Thermal Sciences Lab, CU-Boulder)



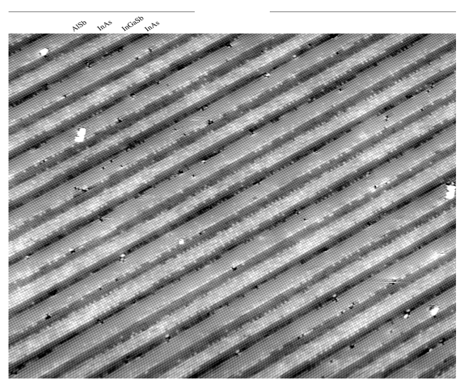




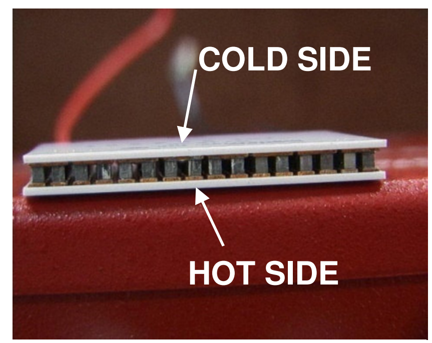
Data Storage (IBM)



MOSFET (IBM)



Laser Diode (S. Pei)



Energy Conversion

Conclusion

- Continued exploration of smaller geometries requires sources, metrology and spectroscopy advances.
- We are at a point where it once again is materials advances that will pave the way to new and exciting products and phenomena.
- In Colorado, we have some of the most advanced research taking place at extending the capabilities to reach, understand and use these materials.