CXRO
THE CENTER FOR
X-RAY OPTICS
LAWRENCE BERKELEY
NATIONAL LABORATORY

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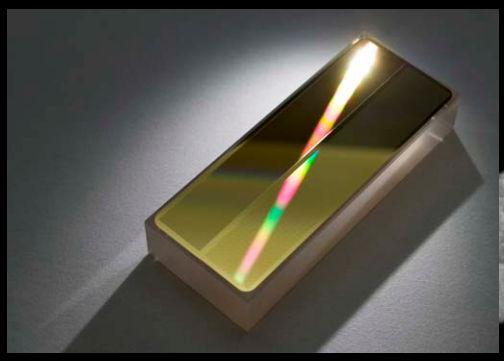
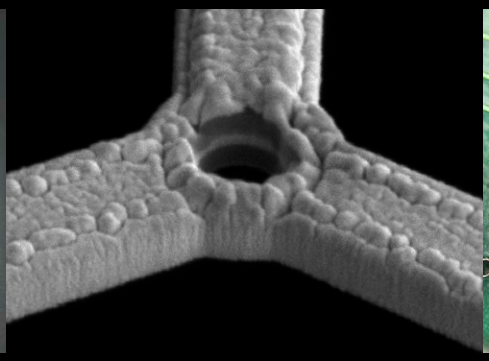
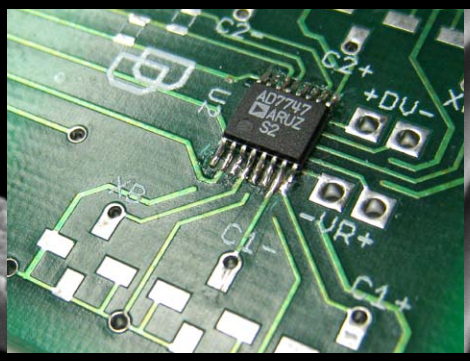
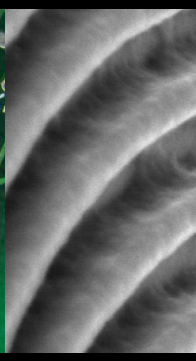
Nanotechnology enabling Nanoscience



The Center for X-Ray Optics is a one-of-a-kind facility with over 25 years experience providing short-wavelength optical solutions. From instrument development to world-leading scientific discovery, our vertically integrated structure allows us to tackle a full spectrum of research. The work performed by Center scientists and collaborators is concentrated in six focus areas.

Soft x-ray microscopy drives research in nanoscience fields, such as nanoscale magnetism, materials and environmental science, and energy-related research.

Extreme ultraviolet (EUV) lithography creates tiny circuit patterns for the next generation of computer chips. We operate the world's highest resolution EUV lithography tool and EUV mask-imaging microscope. CXRO serves as the semiconductor industry's premier center for advanced research into the manufacturing technology of the future.

Optical coatings are key to high efficiency short wavelength optical systems. Our flexible magnetron coating system and world-standard reflectometry beamline deliver superior specialized optics and calibrations for EUV, x-ray and broadband attosecond optics.

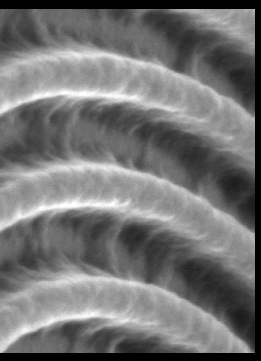
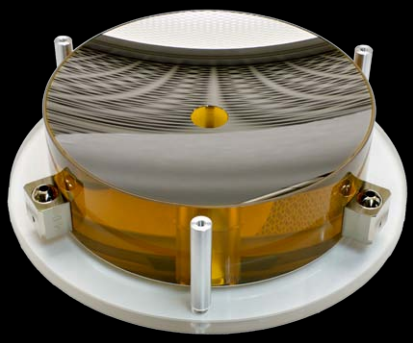
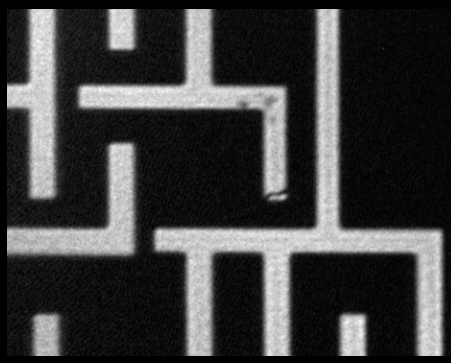
Nanofabrication of x-ray lenses and diffractive optical elements is the specialty of CXRO's Nanowriter electron-beam lithography tool. Our Nanowriter team supplies diffractive lenses and nanostructures for beamlines and light sources around the world.

Wavefront and coherence control are essential elements of nanofocusing and brightness preservation. CXRO research in these areas includes Fourier synthesis illuminators, holographic coherence control, and 50-picometer-accuracy wavefront metrology.

CXRO's precision engineering team is in high demand supporting nearly every aspect of our scientific mission. This resident expertise in mechanical, vacuum, electronic, and computer engineering enables CXRO to rapidly develop and implement one of a kind, complex instruments for both internal and external customers. From nanopositioning actuators to complete experimental systems, CXRO engineers work closely with scientists to develop the tools of world-class research.

Patrick Naulleau
CXRO Interim Director

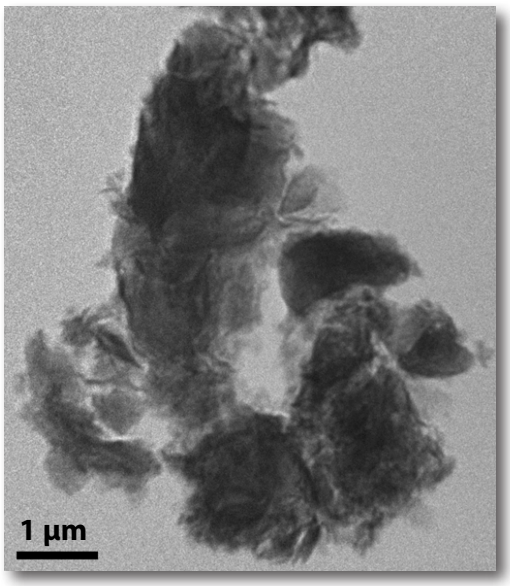
nanoscience


creating nanotechnology

XM-1, a Soft X-Ray Full-Field Zoneplate Microscope

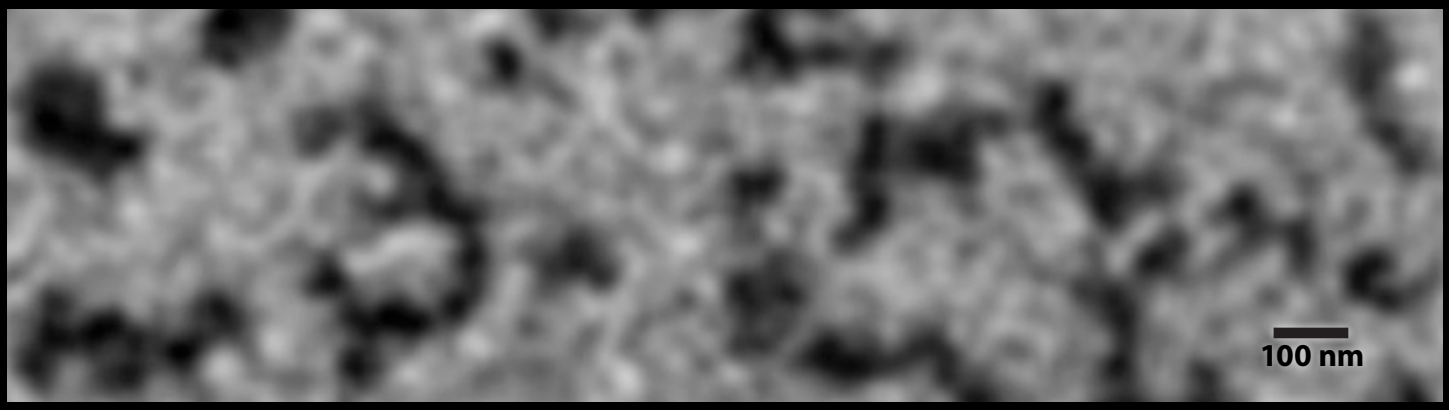
Imaging the world of nanoscale interactions



XM-1 is a world-leading soft x-ray microscope that has defined the leading edge in its field for over 16 years. Every day, it serves scientists from many disciplines. Biologists seeking to understand the life cycle of malaria, earth scientists working to sequester carbon, materials scientists seeking better concrete to strengthen dams and highways, and the leading hard drive manufacturers creating ever-denser memory, all bring their samples to XM-1 to unlock the nanoscale properties that are challenging or impossible to see in other ways.

*"**To understand magnetic materials,** one has to look at the dynamics of their nanoscale spin structures. Soft x-ray microscopy uniquely resolves material properties with high spatial and temporal resolution.*

Peter Fischer
XM-1 Principal Investigator



(above) Magnetic domain structure of an amorphous nanogranular CoCrPt thin film, used in high density magnetic memory. (upper left) XM-1 images of an aqueous sample of montmorillonite particles with hematite colloids. Stereo imaging revealed the spatial arrangement of the hematite particles.

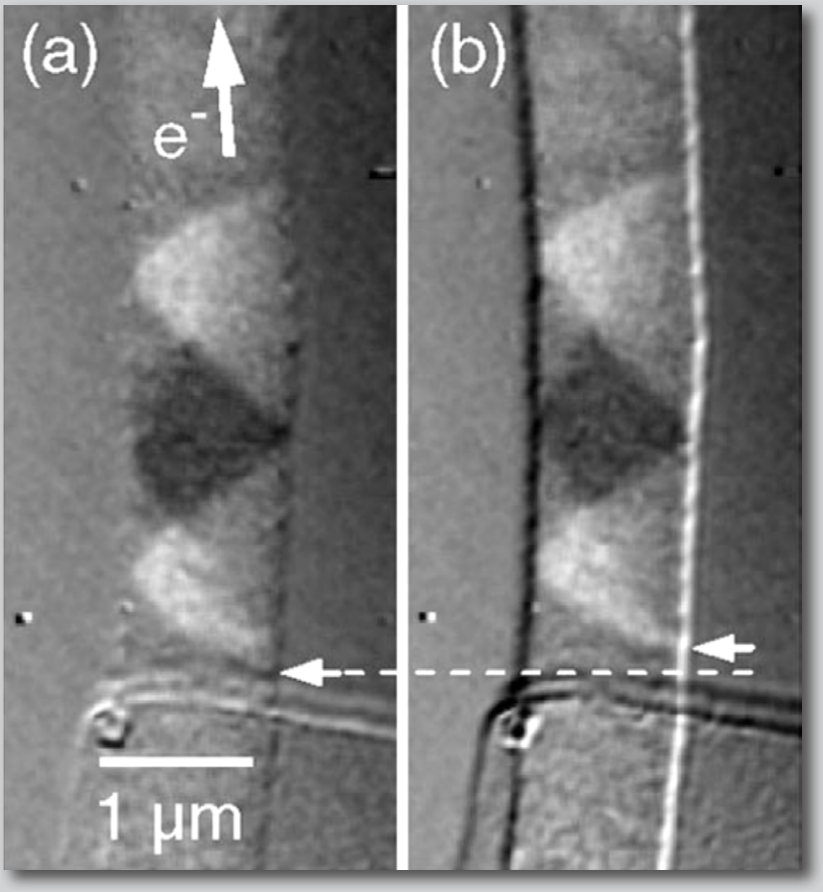
cxro.lbl.gov/XM1

Magnetic Soft X-Ray Microscopy: *Nanomagnetism*

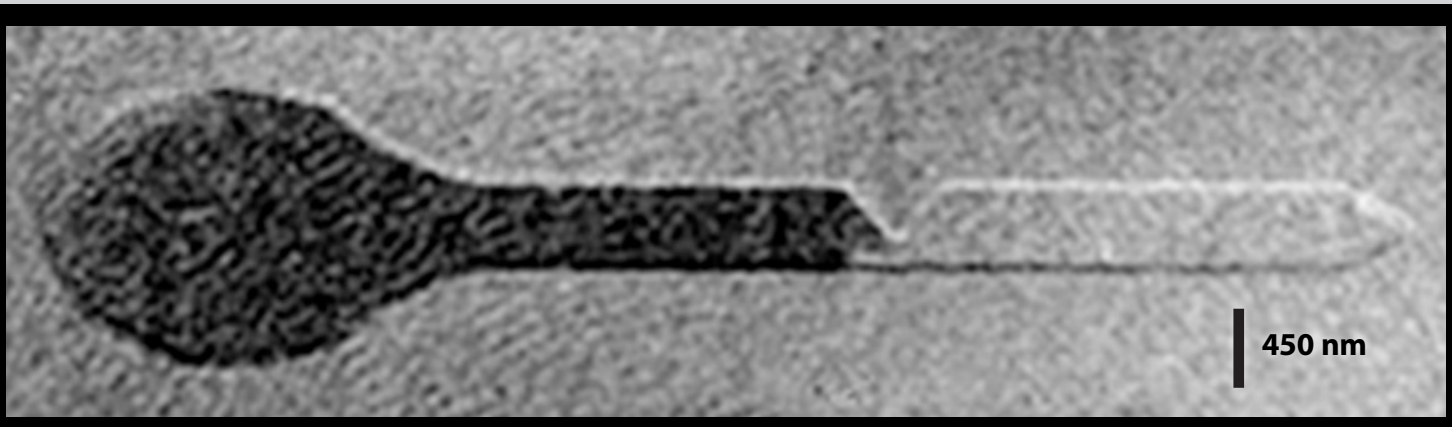
High resolution imaging of nanoscale magnetic structures

Discoveries in nanoscale magnetics have contributed to increasing storage density in computers: from megabytes to gigabytes to terabytes per square inch during the last decade. Unfortunately current magnetic storage technologies are reaching their physical limitations because the size of a single bit is now measured on the scale of atoms. To cope with the demand for higher density and speed, researchers are exploring a fundamentally different approach called spin-electronics (spintronics).

Researchers exploring novel mechanisms to control spins use XM-1 to see magnetic nanostructures, their fast spin dynamics, and their elemental composition with resolution down to 10 nanometers and 70 picosecond time scales.



Imaging domain walls with a spatial resolution of 25 nm, before (left) and after (right) the injection of a short 1-ns current pulse. The domain wall advances at 110 meters per second, in agreement with theoretical estimates.



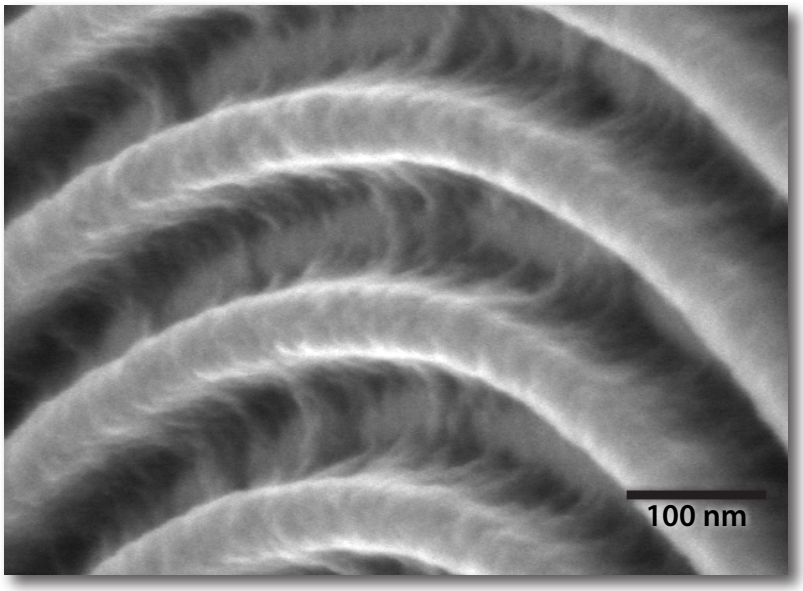
The pinning of a magnetic domain wall at an artificial notch is a basic process for novel storage media devices.

This research is sponsored by The U.S. Department of Energy.

cxro.lbl.gov/nanomagnetism

The SEMATECH Berkeley Micro-field Exposure Tool (MET)

The world's highest resolution projection lithography tool



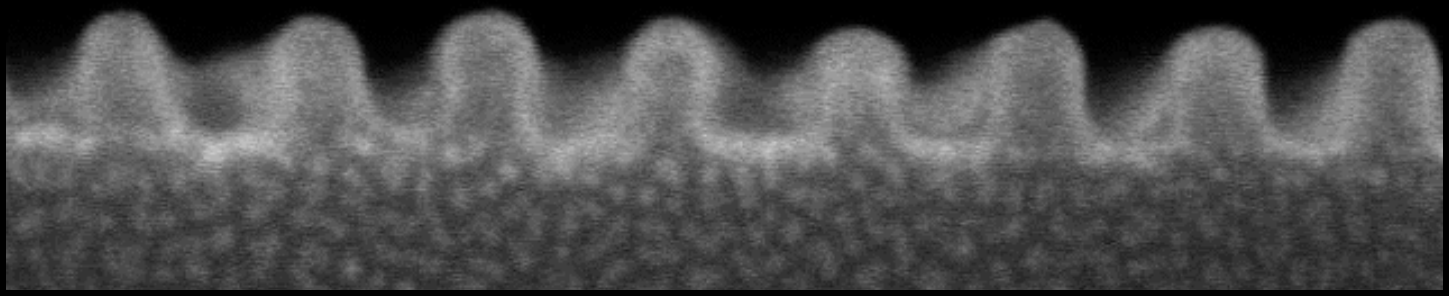
The explosion in computing power over the past 50 years has come from the semiconductor industry's ability to shrink the cost and size of circuit patterns using a process called photolithography. To keep this trend going, the industry is moving to extreme ultraviolet (EUV) lithography: using short wavelength, ultraviolet light. The MET's unique capabilities allow it to reach 16-nm patterning and below, *today*, giving researchers a clear and unparalleled view into the future of photolithography.

> ***For a new lithography technology to be successful,*** *the supporting ecosystem must be developed years in advance. The MET is used by researchers from around the world for early learning in key areas such as resists, processing, and masks.*

Patrick Naulleau
MET Principal Investigator

Simultaneously meeting resolution and line-edge roughness (LER) requirements is one of the biggest challenges facing EUV resists. (Below) 20-nm lines and spaces printed on the MET. (Above) Curved 100-nm features reveal the three-dimensional details of line roughness.

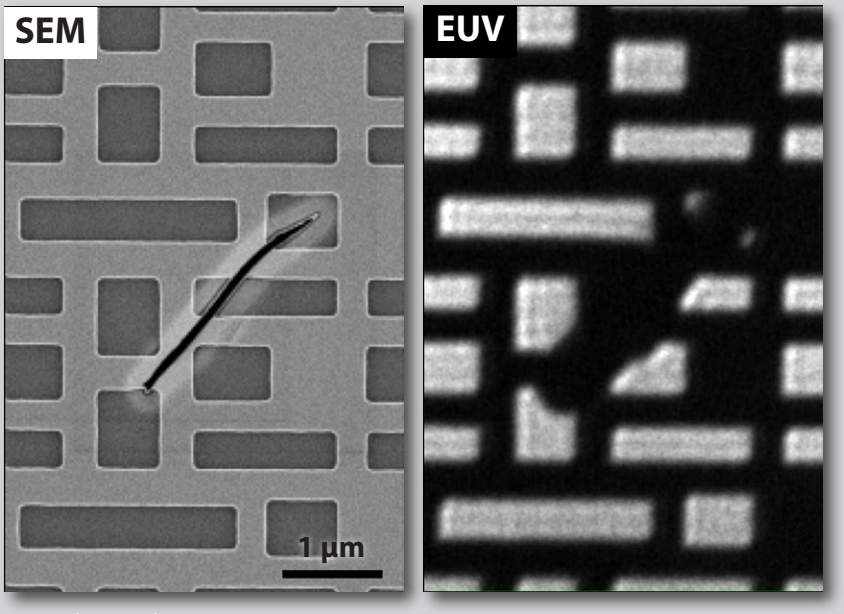
This research is sponsored by SEMATECH



cxro.lbl.gov/MET

The SEMATECH Berkeley Actinic Inspection Tool (AIT)

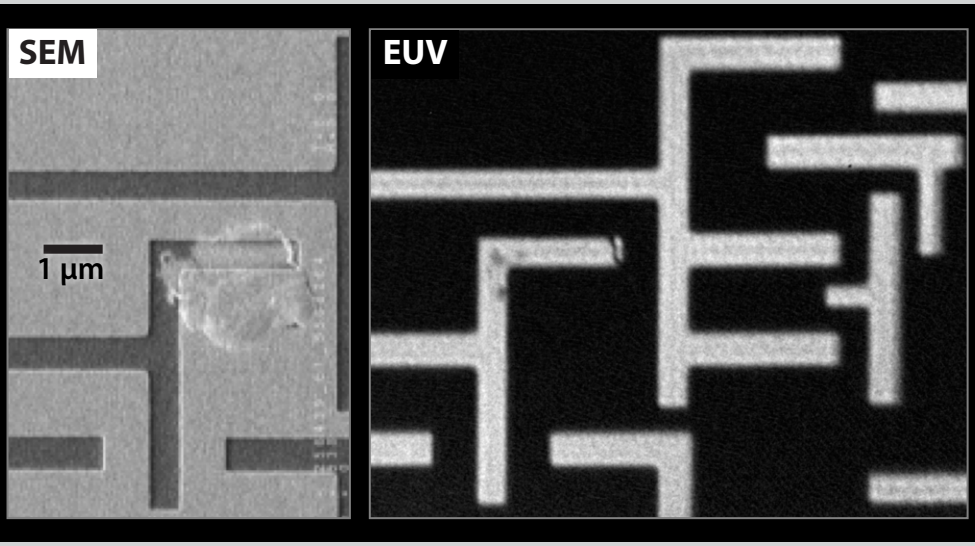
A worldwide unique EUV microscope for mask imaging



Masks carry the pattern that becomes the circuit layout on a chip. Years ahead of commercial EUV mask imaging tools, the AIT detects defects and characterizes masks using EUV light. The AIT is the world's first zoneplate microscope with an array of interchangeable, high-magnification lenses—made by CXRO's Nanowriter. Only EUV-light microscopy can predict how the defects will print in an EUV lithography tool.

In lithography, a single defect ruins the pattern. *Our daily work with the AIT answers the semiconductor industry's most pressing mask R&D questions. We study the unique EUV response to defects, mask architectures, and defect repair strategies.*

Kenneth Goldberg
AIT Principal Investigator



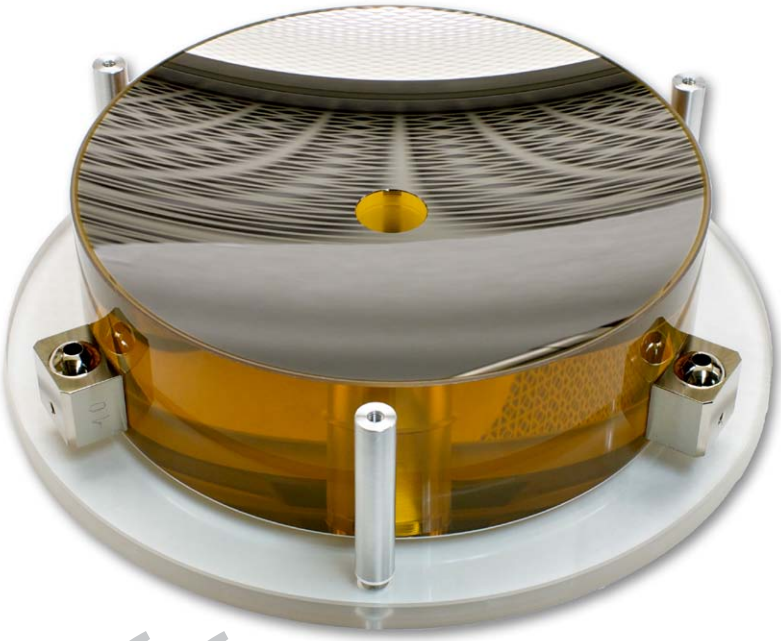
Some mask defects are barely detectable using the most advanced commercial tools. While other defects that are opaque to other light wavelengths and to electron-beam microscopy can actually be transparent to EUV light.

This research is sponsored by SEMATECH

cxro.lbl.gov/AIT

The CXRO Reflectometer

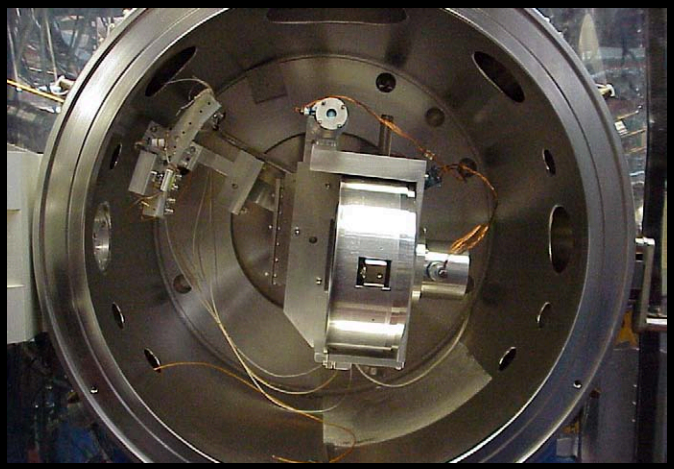
The world standard for EUV and x-ray reflectance measurements



Advanced tools for EUV and soft x-ray science rely on accurate mirror metrology to perform at their peak. The CXRO Reflectometer serves as a worldwide reference standard. Its high accuracy and unrivaled precision enable it to characterize the fundamental optical properties of materials, the quality of optical elements, the resolution of grating spectrometers, the scattering properties of ultra-smooth surfaces, and the efficiency of detectors, at EUV and soft x-ray wavelengths.

> ***Mirrors and detectors are the foundation of soft x-ray science.*** *We routinely measure the reflectivity and scattering properties of the most advanced x-ray and EUV optics in the world.*

Eric Gullikson
CXRO Reflectometer Principal Investigator



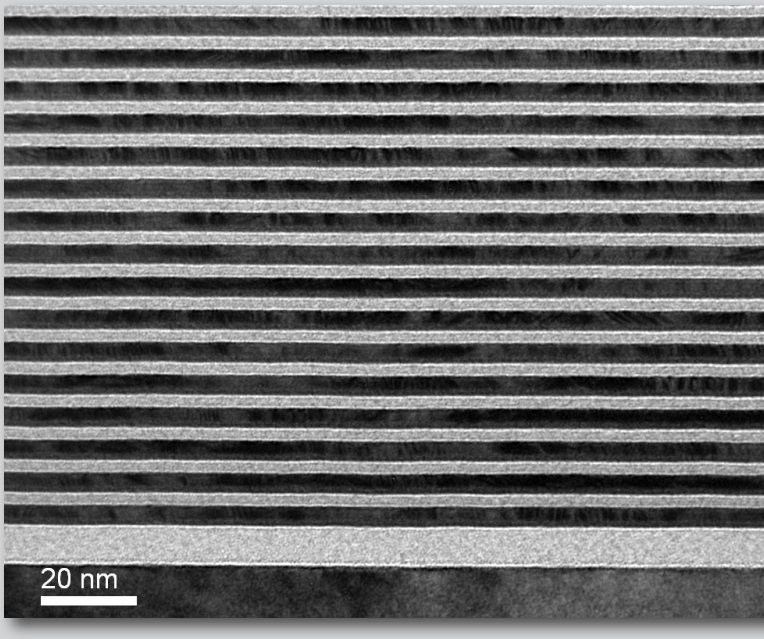
(far left) CXRO Reflectometer's monochromator grating. (left) The reflectometer's vaccum chamber. (upper left) The MET's secondary mirror.

cxro.lbl.gov/reflectometer

Multilayer Mirrors and Custom Optical Coatings

Developing advanced reflective coatings for temporal and spatial control of short-wavelength and attosecond light

X-rays and EUV light are absorbed by nearly every material, making traditional (glass lens) refractive optics impossible to use. Mirrors used to reflect, bend and focus short-wavelength light need special multilayer coatings with layers that are only a few atoms thick. CXRO is a world leader in the development of state of the art x-ray coating and testing, creating novel structures for use in EUV lithography, attosecond science, broadband applications, and synchrotron beamlines.



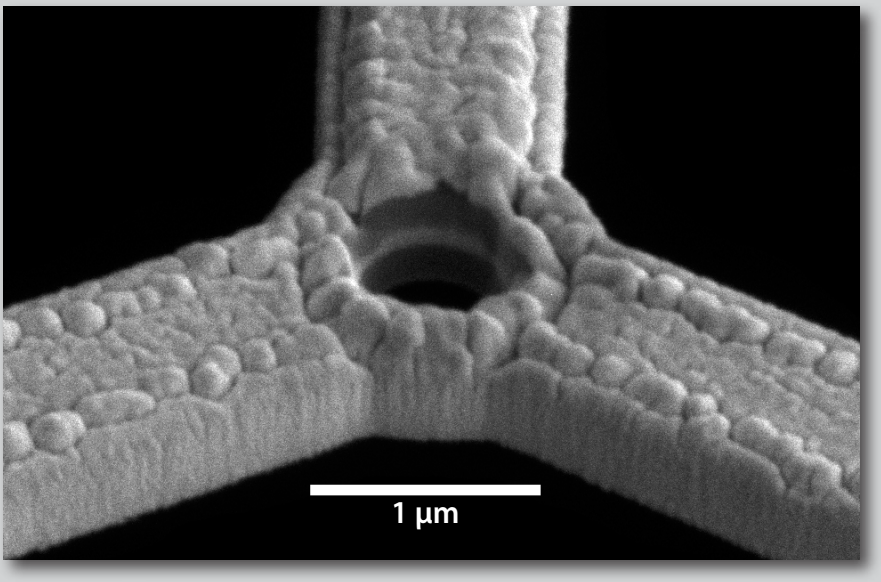
By tailoring the layer thicknesses, the reflectivity and optical properties can be customized for many applications. In order to work with high efficiency, and maintain the correct phase of the reflected light, layer thicknesses have to be controlled to a level smaller than the width of a single atom.

Transmission electron microscope (TEM) cross sections (upper right) of a Mo/Si multilayer coating, and (above) an aperiodic multilayer designed for broadband reflectivity. Layers are a few nm thick.

cxro.lbl.gov/coatings

The CXRO Nanowriter

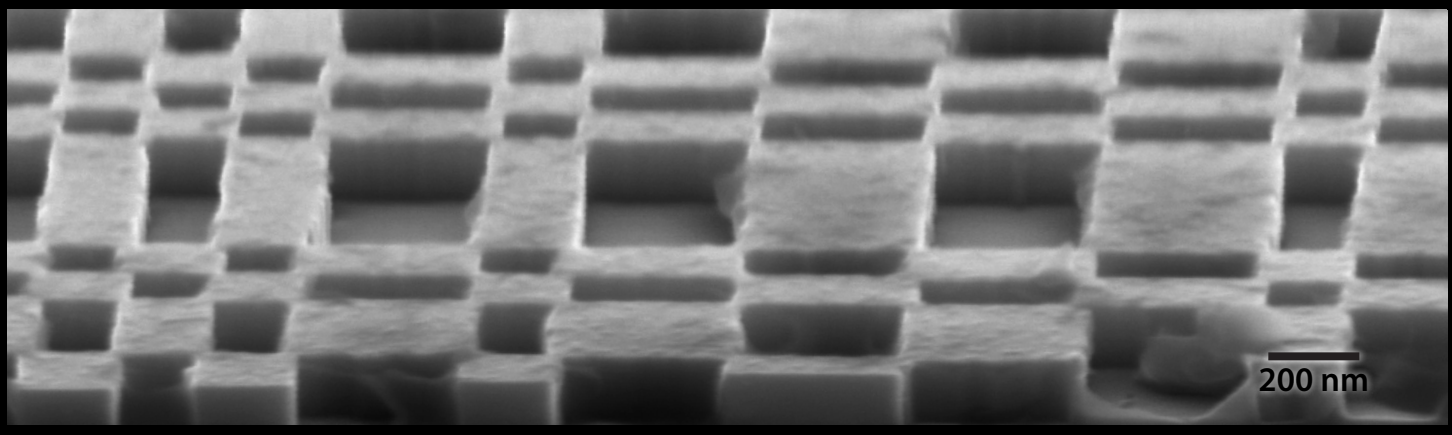
Delivering engineered nanostructures to focus and control light



Many fields of nanoscience rely on the creation of customized, man-made nanostructures. Controlling matter on the length scale of large molecules takes specialized tools and unique expertise, cultivated at CXRO for nearly 20 years. CXRO researchers use an electron-beam lithography tool called *The Nanowriter*. Its high-fidelity, high-resolution patterning capabilities support a broad array of scientific instruments and projects worldwide.

> ***As we scale down the dimensions of structures*** *into the deep sub-micron and nanometer range, many new and exciting properties can be explored, and ultimately engineered into useful systems.*

Erik Anderson
Nanowriter Team Leader



(above) A binary pseudo-random array used in microscope calibration. (upper left) An electron-microscope aberration-correcting *phase plate* for imaging low *Z* materials, like DNA.

cxro.lbl.gov/nanofabrication

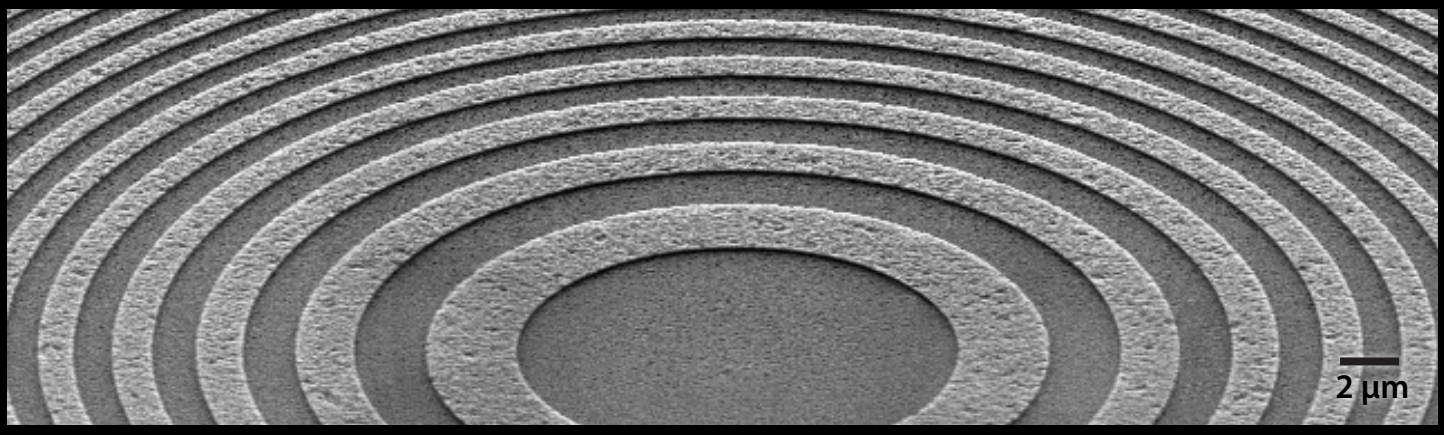
Electron Beam Nanolithography for Zoneplate Fabrication

Diffractive lenses for a new generation of x-ray beamlines

Researchers need specialized EUV and soft x-ray lenses to produce ultra-sharp images with elemental, chemical, and magnetic sensitivity. Since regular lenses cannot be used with short-wavelength light, researchers use zoneplates—tiny holograms that diffract and focus light. CXRO's Nanowriter is the only electron-beam lithography tool customized to shape the curved, continuous patterns of diffractive lenses and optical elements.

This is where different areas of nanoscience and nanotechnology come together. *We use the Nanowriter to make the zoneplates that researchers use to solve Nature's mysteries on the smallest scale. Biologists, chemists, electrical engineers, and material scientists, use CXRO's zoneplates for cutting-edge science.*

Weilun Chao
Nanowriter Team



(above) A classic zone plate structure. (upper right) A *freestanding* zone plate designed for high light-efficiency.

This research is sponsored by The U.S. Department of Energy.

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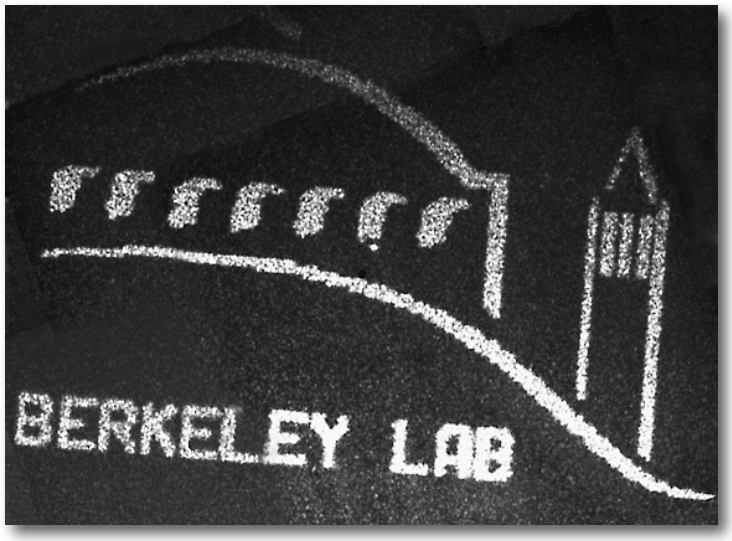
Coherent EUV and Soft X-Ray Optics

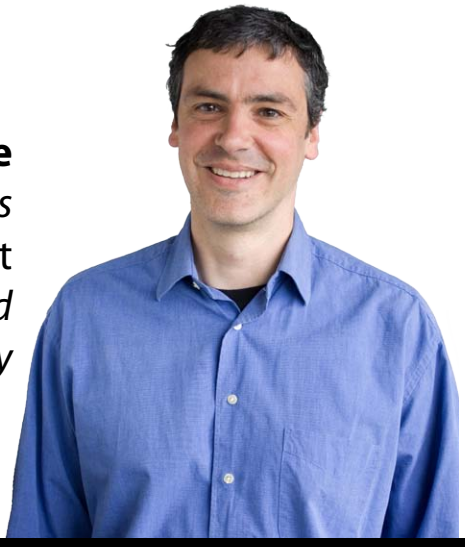
Engineering x-ray coherence for high-resolution imaging

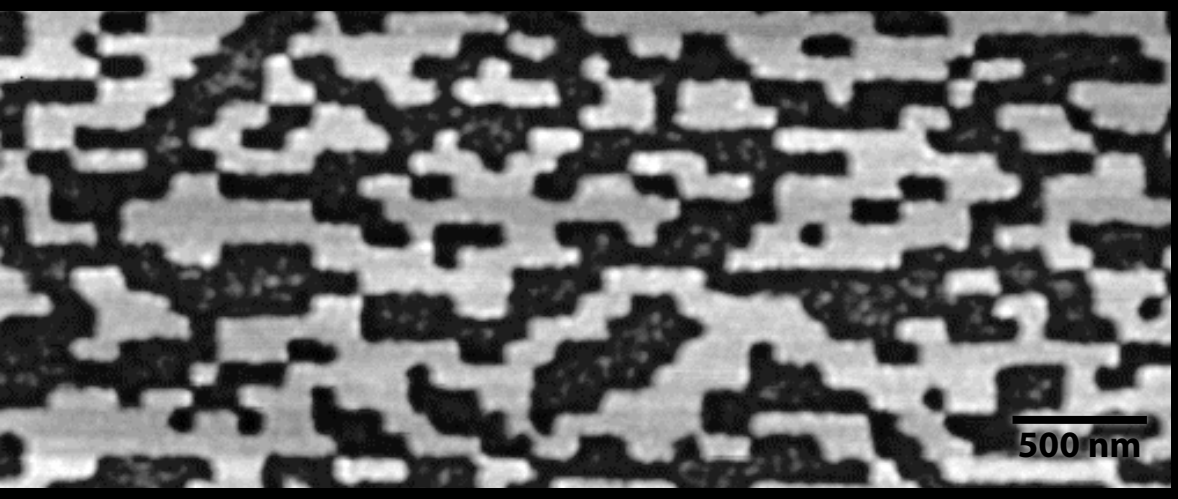


Illumination properties play a critical role in the performance of optical systems. CXRO develops techniques to systematically control spatial and temporal coherence, and improve the illumination uniformity of short wavelength light. These methods include scanning coherence synthesis, diffractive structures designed using phase retrieval methods, and temporal-to-spatial coherence conversion methods.

> ***I am often asked,* 'What is the best coherence state for imaging?'** *Unfortunately the answer is not simple and ranges from* coherent *to* incoherent *depending on the problem at hand. We study and implement new methods to allow researchers to vary coherence to their needs."*

Patrick Naulleau
MET Principal Investigator





(left) detail of an EUV hologram that synthesizes a source with coherence properties matching the LBNL logo. (above left) A holographic image of the logo, created with this hologram.

This research is sponsored by SEMATECH and the U.S. Department of Energy.

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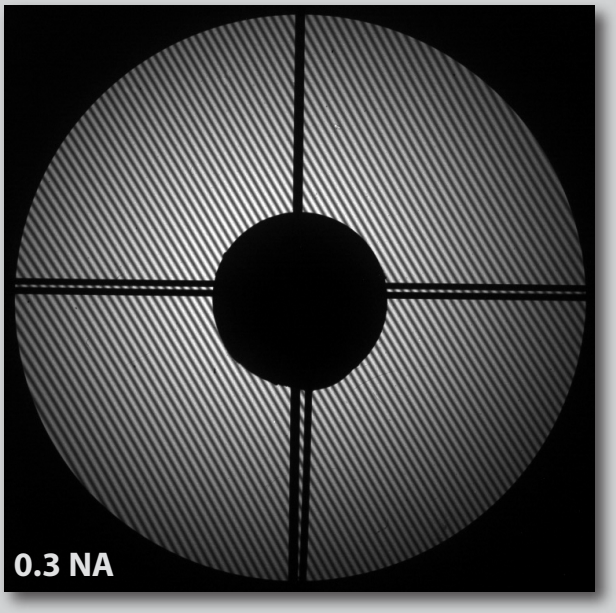
Metrology for Nanofocusing and Brightness Preservation

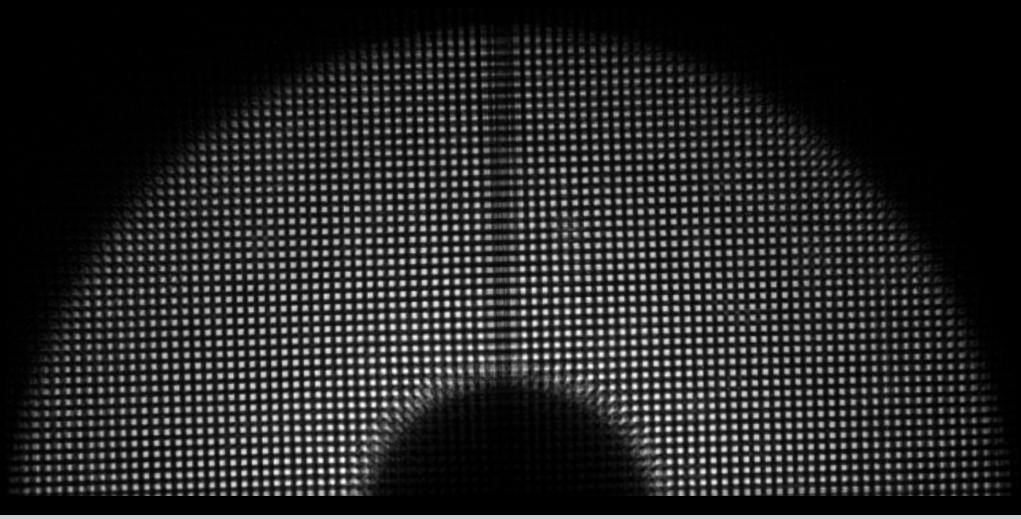
Wavefront control with sub-angstrom sensitivity



New applications with short-wavelength lenses demand the highest quality optics ever made, and the most accurate tests to quantify them. Lens aberrations are measured in fractions of a nanometer. CXRO has pioneered world-leading interferometry and optical testing methods that have been adopted by leading-edge groups worldwide. We are now working to bring these techniques to a new generation of beamlines and lenses.

*"**For x-ray optics, tiny shape, slope, or position errors** can mean the difference between nano-focusing and major frustration. We develop the high-accuracy methods required to squeeze light into the tightest focused beams, preserving source coherence.*

Kenneth Goldberg
Beamline Optical Metrology Co-Principal Investigator



(upper left) An EUV *null-test* interferogram of the MET lens. This test calibrates the interferometer for sub 100-picometer accuracy. (left) Detail of an EUV wavefront measurement using shearing interferometry.

This research is sponsored by LBNL through an LDRD grant, and by SEMATECH and the EUV LLC

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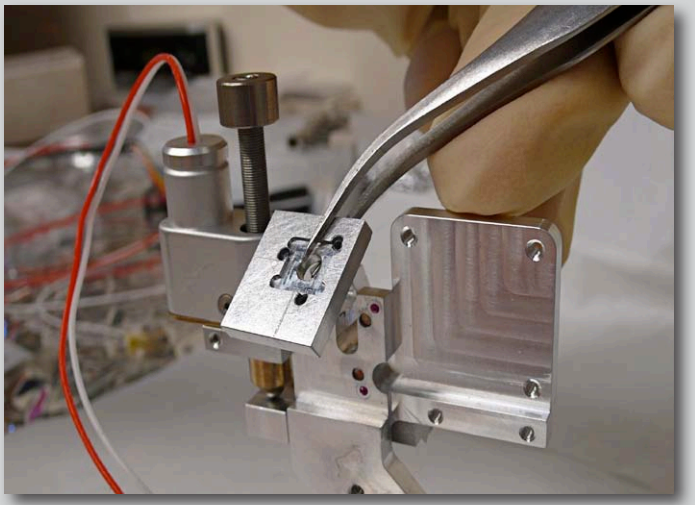
CXRO Precision Engineering

Building the tools of nanoscience

*"**CXRO's engineering team** works together with scientists to create unique, high-performance experimental systems for every project we conduct. From light-source to detector, from project planning to commissioning: we do it all.*

Senajith (Seno) Rekawa
CXRO Chief Engineer

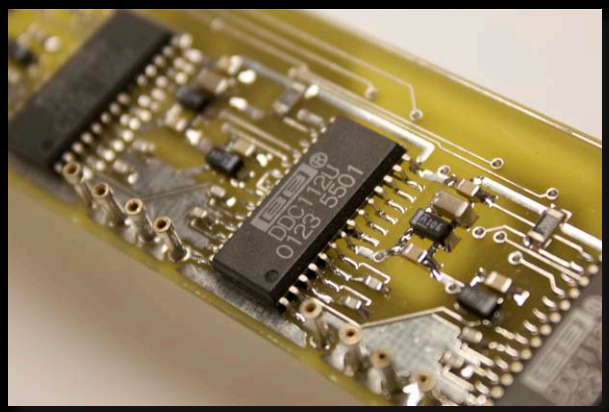
The CXRO Machine Shop in Building 2.



The AIT's kinematic zoneplate holder.

"Our team delivers and supports novel, state-of-the-art, reliable and safe research systems, on time and on budget. We focus on creating tools that work 24/7.

Ron Tackaberry
Computer Support Leader
& CXRO Business Manager



An integrated in-vacuum electronics package for a nanometer height-sensor.

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Recent Highlights

Soft X-Ray Microscopy

Imaging of lateral spin valves with soft x-ray microscopy **[Phys Rev B 80]**

Direct observation of stochastic domain wall depinning in magnetic nanowires **[Phys. Rev. Lett. 102]**

Imaging nanoscale magnetic structures with polarized soft x-ray photons **[IEEE Photonics PP(99)]**

Switchable cell trapping using superparamagnetic beads **[IEEE Magnetics Letters 1]**

EUV Lithography

First demonstration of 20-nm lines space printing using EUV projection lithography tool **[JVSTB 27(6)]**

First demonstration of mask contributors to resist LER **[Appl. Opt. 48]**

Actinic imaging of native and programmed defects on a full-field mask **[SPIE 7636]**

Optical Coatings

Broadband extreme ultraviolet multilayer mirror for super-continuum light at a photon energy of 35–65 eV **[Appl. Opt. 48]**

5000 groove/mm multilayer-coated blazed grating with 33% efficiency in the 3rd order in the EUV wavelength range **[SPIE 7448]**

Nanofabrication

Demonstration of 12-nm-resolution Fresnel zone plate lens based soft x-ray microscopy **[Opt. Exp. 17]**

Coherent Optics

Ultra-high-accuracy optical testing: creating diffraction-limited short-wavelength optical systems **[SPIE 5900]**

A Fourier-synthesis custom-coherence illuminator for EUV microfield lithography **[Appl. Opt. 42]**

Precision Engineering

Design and implementation of a vacuum-compatible laser-based sub-nanometer resolution absolute distance measurement system **[Opt. Eng. 44]**

CXRO's External Partners

Industrial Partners

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Government and University

LBNL Materials Sciences Division ▪ Albany Nanotech LBNL Advanced Light Source Division ▪ IMEC ▪ NIST University of California, Berkeley ▪ Georgia Tech ▪ CEA Leti ASET ▪ IMEL ▪ Lincoln Laboratory ▪ University of Albany Cornell University ▪ University of North Carolina, Charlotte ▪ Institut polytechnique de Grenoble Institute of Microelectronics N.C.S.R. Demokritos

Acknowledgement

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I. Mochi and N. Smith prepare an AIT mirror.

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soft x-ray microscopy • nanomagnetism • nanobiology • extreme ultraviolet lithography • lithographic printing photoresist testing • mask architecture research • mask defect inspection • defect repair • reflectometry • optical constants • scattering • multilayer mirrors • detector calibration • optical coatings • attosecond optics • holographic elements • diffractive optics • Fresnel zoneplate lenses • patterned masks • pinhole spatial filters • interferometry optical testing • wavefront control • coherence control • illuminator design • synchrotron experimental systems beamline optical testing • at-wavelength testing • precision engineering • beamline design • nano-positioning

Generations Ahead

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