news from the EUV ERC

Volume 5 Issue 1

May, 2013

NSF ERC
for
EUV
Science
and
Technology

Inside This Issue

EUV
An NSF Engineering Research Center

The EUV ERC Receives an Extension from the NSF through June, 2014

Typically, Engineering Research Centers have a ten-year cooperative agreement with the NSF. At the end of the ten-year contract, a Center graduates to *independent* status. These ten years of support and guidance from the NSF provide a solid foundation for the Center to continue as an established, effective driver of technology advancement. A measure of the success of the 27-year old ERC program is that 82% of the graduated Centers are still functioning. The EUV ERC's graduation from the NSF program was originally scheduled for October 1, 2013.

In May of this year, the Center was granted a 9 month extension, beyond its planned graduation date in order to extend collaboration and outreach programs. But the most compelling justification for this extension was that the Center has recently moved into new labs at the University of Colorado in Boulder and is in the process of building a new facility for labs at Colorado State University in Fort Collins. Extra time is needed to carefully and deliberately build up these labs. This action by the NSF will extend our Engineering Research Center status through June 30th, 2014 as opposed to the original graduation date of October 1st, 2013.

Above, new 4,600 square foot laboratory under construction at CSU. Right, interior view.

Left, new JILA X-wing where two new 800 sq. ft., ultrastable, state-of-the-art labs are now used for testbed applications.

New Members Join the EUV ERC and its Industrial Advisory Board

Alpine Research Optics

Alpine Research Optics is a leading manufacturer of high performance and high precision laser optics. ARO supplies catalog and custom OEM optics, focusing on high damage threshold thin film coatings and tight tolerance substrates. We support a wide range of applications in areas including Semiconductor, Research & Development, Medical Instrumentation, Energy Research and Micromachining. We are located in Boulder, Colorado, in an area well-known for innovation and excellence in photonics.

Katie White, Courtney Green and Fangfang Shen of Alpine Research Optics at the Center's Annual Retreat in early December at the Tamasag Conference Center north of Fort Collins.

ARO
ALPINE RESEARCH OPTICS

Applied Nanotools

Applied Nanotools is a nanotechnology SME based in Edmonton, Canada that specializes in fabrication of membrane-based optical chips for X-ray and EUV applications. Our products include high-resolution Fresnel zone plates for X-ray focusing and several X-ray and EUV mask technologies that include nano-gratings and calibration standards.

Applied Nanotools also provides state-of-the-art micro and nano-fabrication services to enable fast prototyping and testing of various custom nanotechnology projects. This includes the NanoSOI Process Technology (via CMC Microsystems) for fabricating NEMS and nano-photonic devices.

Mirwais Aktary, President

Ashok Masilamani, CTO and Executive Director

ANT APPLIED NANOTOOLS INC.

CLEO 2013
June 9—14, 2013
San Jose Convention Center

MONDAY, JUNE 10, 2013
12:30 PM - 4:30 PM; TBA Short Course Room #4
SC398. Tabletop Coherent Light Sources for Nano and Atto Science
Instructor(s): Margaret Murnane (University of Colorado at Boulder)
CM3N. Attosecond & XUV Metrology
1:30 PM - 3:30 PM; 14 Salon IV (Marriott San Jose)
2:45 PM - 3:00 PM
CM3N.3. Keyhole Coherent Diffraction Imaging of an Extended Transparent Sample Using Curved Multilayer Mirrors
Matthew Seaberg; Bosheng Zhang; Justin Shaw; Dennis F. Gardner; daniel adams; Margaret M. Murnane; Henry Kapteyn
3:00 PM - 3:15 PM
CM3N.4. Imaging by Integrating Stitched Spectrograms
daniel adams; Carson Teale; Daniel Kane; Margaret M. Murnane; Henry Kapteyn

TUESDAY, JUNE 11, 2013
JTu3B. Advances in Extreme UV Science and Applications I
4:30 PM - 6:30 PM; 02 Executive Ballroom 210B (San Jose Convention Center)
5:00 PM - 5:30 PM
JTu3B.2. High Average Power, 100 Hz Repetition Rate, Table-top EUV/Soft X-ray Lasers
Brendan A. Reagan; Keith Wernsing; Cory Baumgarten; Leon Durivage; Mark A. Berrill; Federico Furch; Alden Curtis; Chase Salsbury; Brad Luther; Dinesh Patel; Carmen S. Menoni; Jorge Rocca
6:00 PM - 6:30 PM
JTu3B.4. Probing of Atomic and Molecular Dynamics with Attosecond EUV Pulses
Stephen R. Leone

WEDNESDAY, JUNE 12, 2013
W1D. Advances in Extreme UV Science and Applications II
10:30 AM - 12:30 PM; 04 Executive Ballroom 210D (San Jose Convention Center)

JW1D. Advances in Extreme UV Science and Applications II
10:30 AM - 12:30 PM; 04 Executive Ballroom 210D (San Jose Convention Center)
12:15 PM - 12:30 PM
JW1D.5. Soft X-Ray Image Plane Holographic Microscopy
Jaroslav Nejdl; Isela Howlett; David Carlton; Weilun Chao; Erik H. Anderson; Mario Marconi; Jorge Rocca; Carmen S. Menoni
JW2A. POSTER SESSION II: Energy, Sensing, and Nonlinear Optics
1:30 PM - 3:30 PM; 17 Exhibit Hall (San Jose Convention Center)
1:30 PM - 3:30 PM
JW2A.54. Spontaneous and induced optical absorption in ultra-low loss amorphous Ta2O5 and SiO2 dielectric thin films, Ashot Markosyan; Roger Route; Martin Fejer; Dinesh Patel; Carmen Menoni

THURSDAY, JUNE 13, 2013

CTh1H. Ultrafast Laser Sources I
8:00 AM - 10:00 AM; 08 Executive Ballroom 210E (San Jose Convention Center)
8:00 AM - 10:00 AM
CTh1H.1. Atomic Inner-Shell X-Ray Lasers pumped by XFEL sources
Nina Rohringer; Clemens Weninger; MIchael Purvis; Duncan Ryan; Gregory Brown; Felicie Albert; James Dunn; Alexander Graf; Stefan Hau-Riege; John Bozek; Christoph Bostedt; Richard London; Jorge Rocca

FRIDAY, JUNE 14, 2013

QF1C. XUV & X-ray Sources Based on High-harmonic Generation
8:00 AM - 10:00 AM; 04 Executive Ballroom 210D (San Jose Convention Center)
9:45 AM - 10:00 AM
QF1C.8. Single-Shot Wavefront Measurement of an Injection-Seeded Table-Top Soft X-Ray Laser
Shoujun Wang; Lu Li; Yong Wang; Eduardo Oliva; Liang Yin; Brad Luther; Gilles Maynard; D. Ros; Philippe Zeitoun; Jorge Rocca

New technology produces record-high average power soft x-ray laser beams on a table-top

The generation of pencil-like beams of soft x-ray laser light on a table-top has the potential to transform numerous applications in science and technology. Bright soft x-ray laser beams can be generated by heating materials to extreme temperatures similar to those encountered on the surface of the sun by irradiation with an intense optical laser pulse. In spite of significant progress that has greatly reduced the size of plasma-based soft x-ray lasers, their repetition rate has remained limited to a few pulses per second, which restricts their average power limiting their use in applications. This limitation originates in the excessive heat produced by the flashlamps used to drive the optical-wavelength solid state lasers used to heat the plasmas. To overcome this barrier, researchers from the NSF center for Extreme Ultraviolet Science and Technology at Colorado State University have developed a new type of efficient high power ultrashort pulse solid state laser driven entirely by laser diodes that produces high energy infrared laser pulses of picosecond duration at an unprecedented repetition rate of 100 Hz. Using this new technology a compact laser operating at wavelengths 50 times shorter than visible light at record breaking 100 shots per second has been demonstrated to produce record high average power. These results open new applications in science and technology requiring a high average flux of coherent soft wavelength laser radiation, such as the defect tolerant printing of nano-structures.

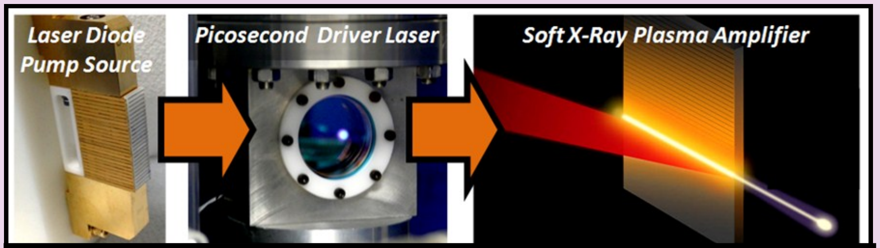


Figure. Conceptual diagram of the high average power soft x-ray laser. Laser diodes efficiently pump a solid state laser that generates high energy optical laser pulses at 100 Hz repetition rate. The optical laser pulses are focused into narrow line on a solid target, where they rapidly heat the material to create a hot dense plasma with condition for soft x-ray amplification. Amplification of spontaneously emitted radiation in the narrow plasma column creates intense soft x-ray laser pulses of picosecond duration**.** The compact high repetition rate, high energy pump laser fits on a single optical table.

Holographic nano-scale movies recorded with "flash" extreme ultraviolet laser illumination

Nanotechnology and nanoscience will greatly benefit from the implementation of alternative high spatial and temporal resolution imaging schemes capable of producing holographic movies of rapidly moving nano-scale objects. Research conducted at the Colorado State University laboratories of the NSF Center for Extreme Ultraviolet Science and Technology has demonstrated a compact table top holographic microscope with the capability to record movies with ultra-high spatial and temporal resolution. The system is based on a holographic setup, in which the coherent illumination of an object by bright table-top extreme ultraviolet (EUV) laser pulses allow holographic images to be obtained with nano-scale spatial resolution. The high photon flux delivered by the EUV laser allows for the recording holograms with a single laser shot in a CCD camera that can be quickly processed to render images of small fast moving objects.

This capability to record holograms with a single laser shot allowed us to record a sequence of flash images and compose a "movie" of the dynamics of a set of nano-pillars (15 micrometers long, 330 nanometers width) oscillating at a frequency of one million times per second. This new imaging system allows the recording of fast evolving nano-scale phenomena with high resolution in a set up that fits in a small table. This time-resolved EUV holography technique complements traditional high resolution imaging systems (TEM, SEM) with the advantage of recording sequences of time-resolved images of rapidly evolving phenomena.

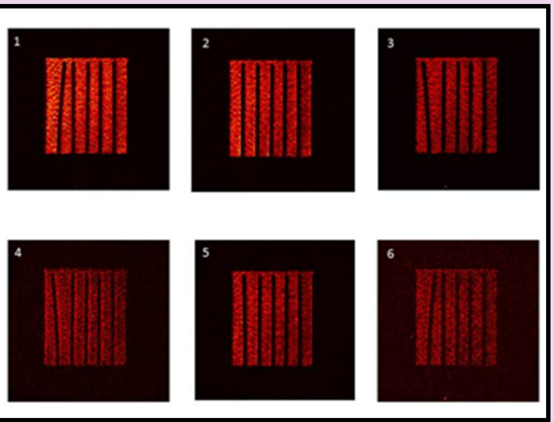


Figure Sequence of a "flash" EUV holograms of oscillating nanopillars. The images can be composed in a "movie" of the oscillating pillars that is available in http://www.engr.colostate.edu/~marconi/. The dotted white line is superimposed at a fixed position to help distinguish the different positions of the pillar.

Bright, Coherent, Ultrafast keV X-rays from Tabletop Femtosecond Lasers

2010 marked the 50th anniversary of the first demonstration of the laser, a device that has huge benefit to society. However, the same revolution that happened for visible light sources is only now happening for X-rays. X-rays can penetrate thick samples, image small objects, and have the added advantage of elemental and chemical specificity by employing characteristic elemental X-ray absorption edges. These unique advantages spurred the development of large-scale X-ray free-electron lasers based on accelerator physics, as well as high harmonic generation (HHG) driven by tabletop femtosecond lasers. The HHG process represents nonlinear optics at an extreme. When driven non-perturbatively by an intense femtosecond laser field, atoms radiate like microscopic antenna, emitting high order harmonics of the fundamental laser. However, until recently, bright HHG beams were limited to the extreme ultraviolet (EUV) region of the spectrum (< 150eV), where efficient frequency upconversion is possible using widely available Ti:Sapphire lasers. However, many inner-shell absorption edges in advanced magnetic and catalytic materials (Fe, Co, Ni, Cu) lie at photon energies nearing 1 keV, providing a strong motivation to extend HHG to higher photon energies and correspondingly shorter wavelengths.

Fortunately, a remarkable recent breakthrough demonstrated that high harmonic upconversion can support a record > 5000 order nonlinear process, and most importantly, can be implemented in a phase matched geometry. This advance takes nonlinear optics to an extreme not considered possible until now. By focusing mid-infrared (3.9 µm) femtosecond laser pulses into a high pressure (> 40 atmospheres) gas-filled waveguide, the HHG process can be fully phase matched, where all the atoms in the gas emit X-rays that interfere constructively. The resultant high harmonic beams emerge as a coherent X-ray “white light” supercontinuum that spans from the UV to the keV region of the spectrum, corresponding to wavelengths < 7.7Å. This demonstration represents a laser-like, coherent, tabletop, version of the Roentgen X-ray tube in the soft X-ray region. Moreover, calculations show that the keV-bandwidth coherent supercontinuum has a well behaved chirp that could support a single-X-ray-cycle 2.5 attosecond pulse duration. This advance was made possible through a collaboration of an international team from the University of Colorado Boulder, Technical University Vienna, Cornell University, and University of Salamanca.

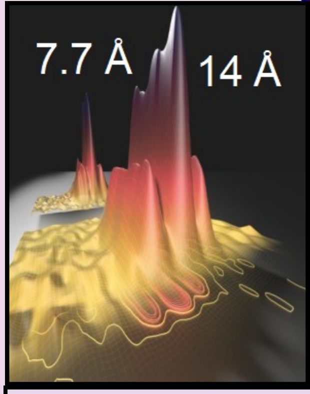


Figure Experimental Young’s Double Slit interference patterns, showing that the high harmonic keV X-rays beams are fully spatially coherent. Two patterns are shown, using X-ray supercontinua with wavelengths at 7.7 and 14 Å.

Looking to the future, because X-ray wavelengths are > 1000 times shorter than visible light and penetrate materials, these coherent HHG X-ray beams promise revolutionary new capabilities for understanding and controlling how the nanoworld works on its fundamental time and length scales. This understanding is needed to design and optimize next-generation electronics, data and energy storage devices, and medical diagnostics. Moreover, the limits of HHG are not yet known: it may be possible to extend HHG to hard X-ray wavelengths. Finally, the unique ability of these broad bandwidth, ultrafast X-rays to probe function at multiple atomic sites simultaneously is already uncovering new understanding of how electrons, spins, phonons and photons behave at the spatio-temporal limits relevant to function.

Tabletop Nanoscale Coherent Imaging using High Harmonic EUV Beams

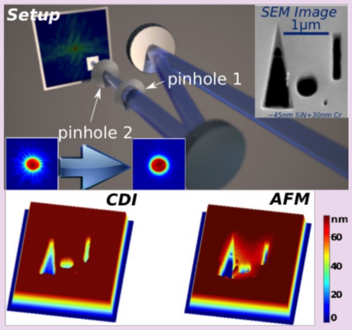


Figure Top – Tabletop CDI geometry, showing object illuminated by coherent high harmonic EUV beam, as well as an SEM image of the sample. Bottom – Comparison between CDI and AFM images.

Microscopy is a critical enabling tool for visualizing the nano-world. By virtue of its short wavelength, soft x-ray microscopy enables element-specific, nanometer-scale imaging of whole unstained cells, magnetic permalloy wires, internal structures in nanocrystals, and magnetic domains in thin film samples. However, to date most x-ray microscopes used large synchrotron facilities. A collaboration between JILA, UCLA, Berkeley, CSU and SLAC dramatically improved the spatial resolution of tabletop soft x-ray microscopes, to ≈ 22nm, while also demonstrating 3D imaging capability.

The team used bright high-harmonic beams at wavelengths of 13-30nm to illuminate various samples (see Fig.). The scatter pattern (diffracted light) from the object is collected on an x-ray CCD camera. Provided that the region illuminated by the x-ray beam is oversampled and the sample or illuminating beam is finite, the image can be reconstructed using iterative phase retrieval algorithms. Moreover, because scattered light from very high angles can be collected, it also encodes information about the sides of the sample. This 3D imaging modality, termed ankylography, enables 3D structure determination from a single 2D exposure. Finally, more recent work demonstrated tabletop full field EUV imaging both in transmission and in reflection modes, with image quality better than advanced atomic force microscopy (AFM, see Fig.).

This coherent Coherent Diffraction Imaging (CDI) EUV microscope provides high spatial and temporal resolution (≈ 10fs), inherent elemental contrast of x-rays, label-free imaging, the ability to image thick samples, and full field imaging in an extended depth-of-field geometry that is relatively insensitive to vibrations —all in a tabletop-scale apparatus. Moreover, advances in high harmonic sources have already generated soft x-ray beams at wavelengths (1 – 6nm) relevant to biological and materials imaging. These advances will make it possible not only to substantially increase the variety of objects that can be imaged, but also to obtain much higher spatial resolution (<10nm), essentially creating a super-resolution microscope that can image thick samples in 3D.

Characterization of Vibrational Coherences by Core-Level High Harmonic Transient Absorption

The vibrational coherence produced by strong-field ionization in the ${}^{1}\Sigma_{g}^{+}$ ground state of Br_2 is characterized by femtosecond high-harmonic transient absorption spectroscopy. Probing the Br $3d_{5/2,3/2} \rightarrow \sigma^{*}$ core transitions at 64-72 eV, the coherent vibrational amplitude is observed in time by a significant shift of the Br 3d core level transition energy with bond length, 0.07 $\frac{\text{eV}}{\text{pm}}$, to higher energies at shorter bond lengths. The initial launch point of the coherent vibrational amplitude is observed on the outer turning point and the coherence has the expected period of 104 fs for the predominant $\nu_0\nu_1$ quantum beat. The coherence in Br_2 is formed by localized ionization that occurs at bond lengths shorter than the equilibrium geometry around the minimum ionization energy in accordance with Ammosov-Delone-Krainov theory. The results demonstrate the sensitivity of core level transient absorption spectroscopy to internuclear separation and provide a general means to analyze the quantum beats of vibrational coherences and their formation directly.

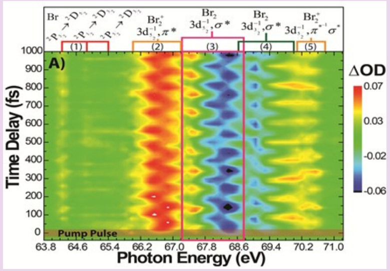


Figure Comparison of experimental data and theoretical simulation of the core-level transient absorption signal of strong-field ionized Br_2. A) False color map of the experimental absorption signal in time using an ionizing 800 nm pump field of (shown at t = 0 in transparent red). The ground state coherence is observed to launch on the outer turning point of the potential with a period of 104 fs by the transitions bracketed (3) and (4), labeled by the final state electronic configuration. The coherence of the ion is observed through transitions (2) and (5), with a 94 fs period. Atomic Br transitions are labeled ().

Acoustic Nanometrology using High Harmonic EUV Beams

Nanofabrication technologies now make it possible to deposit single-atomic-layer films and pattern nanometer scale structures. However, our ability to precisely characterize the mechanical properties of structured systems at sub-100nm dimensions remains limited. In addition to enabling the design, manufacture and process control of nanoscale devices, precise characterization of ultrathin films and nanostructures is necessary for understanding how the elastic properties change in scaling from bulk material to monolayers, for example, or how heat transport is modified by non-diffusive transport.

Currently, elastic characterization of thin films relies mostly on nano-indentation measurements. While providing a measurement localized to the region directly compressed by the atomic force microscope tip, this is a destructive measurement which is greatly influenced by the substrate beneath the thin film of interest – particularly as the film thickness shrinks. Various models can be used to try to account for the substrate contribution, and thus extract the ‘real’ film characteristics. However, these approaches still rely on fairly thick films (>100nm) or knowledge of some of the material properties – such as the Poisson’s ratio for the film and substrate. Non-contact acoustic methods such as picosecond ultrasonics using visible light has long been used for longitudinal acoustic wave (LAW) measurements of thin films. However, these are limited by the wavelength of visible light, to film thicknesses >600nm.

In a collaboration between JILA, Berkeley, Intel and Western Digital Hitachi, we showed that photoacoustic nanometrology using coherent EUV beams is a unique and powerful tool for probing ultrathin films with a wide range of mechanical properties and thicknesses well under 100nm. In this technique (see Fig.), short wavelength acoustic waves are generated through laser excitation of a nano-patterned metallic grating, and then probed by diffracting coherent EUV beams from the dynamic surface deformation. Both longitudinal and surface acoustic waves within thin films and metallic nanostructures can be observed using EUV light as a phase-sensitive probe. Simultaneous measurement of both the longitudinal and transverse surface wave velocities yields both the Young’s modulus and Poisson’s ratio of films of thicknesses <50nm for the first time. The Figure shows an ability to characterize acoustic waves with penetration depth ≈ 10nm, demonstrating an ability to make possible precise mechanical characterization of nanostructured systems. In the future, shorter wavelength (1-10nm) high harmonic beams can extend this approach for extracting nano-mechanical properties at even sub-10nm length scales.

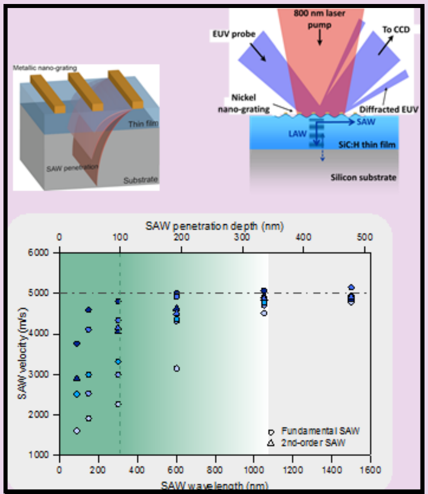


Figure Top left - Surface acoustic waves penetrate into the material over a depth equal to a fraction of their wavelength. Top right – Setup for laser excitation of a nano-grating, that launches transverse and longitudinal acoustic waves, that can be detected using EUV HHG beams. Bottom – Series of measurements using different gratings and film thickness and material, demonstrating an ability to extract the mechanical properties of ≈10nm films.

Visualizing the composition of nano-scale objects in three-dimensions with an extreme ultraviolet laser

Microscopes allow one to 'see' the shape and morphology of objects but are incapable to assess chemical composition. If there were an imaging system with the capability to probe at the nanoscale chemical composition of single cells or microorganism, revolutionary insight would be gained on the on the biochemistry of these complex systems. Towards this goal, researchers of the NSF Center for Extreme Ultraviolet Science and Technology at Colorado State University have combined extreme ultraviolet laser ablation and mass spectrometry to demonstrate for the first time a microscope that maps chemical composition in 3-dimensions with nano-scale resolution and high sensitivity. A focused extreme ultraviolet laser is used to ablate extremely small holes on a solid sample and the ablated material is analyzed by mass spectrometry. The figure shows the composition map of a heterogeneous sample containing gold pillars grown onto a indium-tin-oxide covered glass substrate and immersed in photoresist (Figure a). The composition map shows the distribution of each of the materials obtained from the analysis of consecutive single-shot ablation events (Figure b). The technique has been demonstrated to map composition with 140 nm lateral, and 50 depth resolution. The method has achieved atto-mole detection sensitivity of intact organic molecules with mass up to ~ 400 atomic mass units. These proof-of-principle experiments are paving the way to obtain 3D composition images of nanostructures and biological samples objects with nanometer-scale spatial resolution.

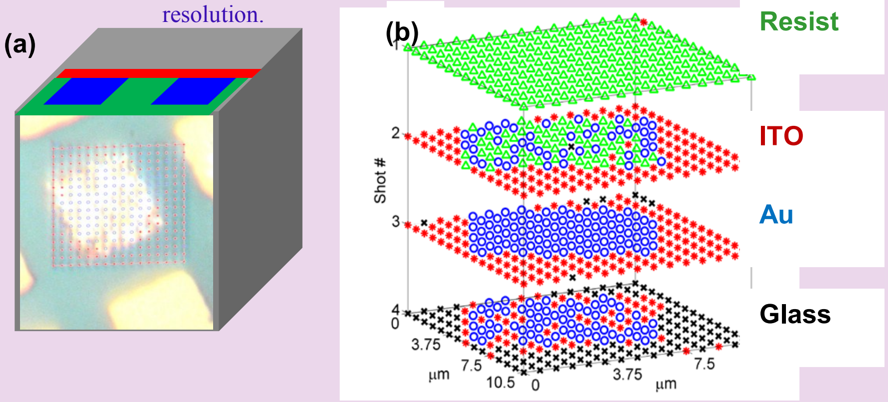


Figure 3D composition imaging by extreme ultraviolet laser ablation mass spectrometry. (a) Sample consisted of 8 mm wide Au pillars 30 nm thick fabricated onto a indium tin oxide layer (ITO) 20 nm thick deposited onto a glass substrate. A polymer resist layer 50 nm thick planarized the sample. (b) Composition map obtained from the analysis of mass spectra from four consecutive single-shot laser ablation events at each of the 16x16 grid of probed sites. The ion image plots the distribution resist, ITO, Au and glass versus laser shot number.

Extreme Ultraviolet image-plane holographic microscopy

The images captured with a conventional microscope are a magnified map of the absorption or reflection contrast in the object. Important information is lost because phase is not recorded, which makes it difficult or impossible to obtain images from objects that have low absorption. Through the use of an imaging geometry that combines a reference wave that interferes with the object wave at the image plane, it is possible to capture, with a microscope, broad area images from which the amplitude and phase image-plane holographic microscopy is particularly attractive when using extreme ultraviolet and soft x-ray illumination that strives for absorption contrast when the wavelength of the illumination is far from specific absorption edges.

In a first demonstration of image-plane holographic microscopy at extreme ultraviolet (EUV) wavelengths, Center researchers used a microscope geometry that incorporates two special lenses that use diffraction to generate the reference and object beams required to create broad area holograms at the image plane. Analysis of holograms from an object consisting of periodic elbow patterns fabricated on Si that have low absorption contrast (<30%) at l=46.9 nm, the wavelength of the illuminating laser, results in amplitude and phase images with a spatial resolution of ~ 100 nm. These capabilities make it possible to reconstruct the 3D morphology of nanostructures. The set-up is wavelength scalable to obtain images with further improved spatial resolution. The only requirement for the implementation of this imaging configuration is to use illumination that has a high degree of spatial and temporal coherence.

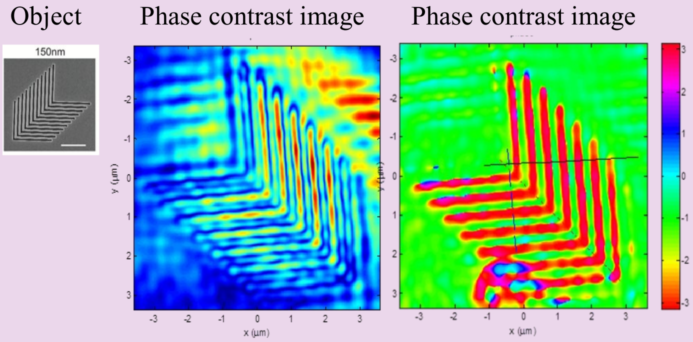


Figure Image-plane-holography microscopy allows the reconstruction of absorption and phase contrast images from a weakly absorbing object. The object consists of a Si elbow pattern fabricated onto a Si_3N_4 membrane. The absorption contrast between the Si and the membrane is 30% which is reflected in the absorption contrast image. The phase variation in the phase contrast image is (2.3±0.3) rad. This phase shift accurately measures that expected from the 100 nm thick Si lines.

Utilizing Transient EUV Absorption on Studying Charge Carrier Dynamics

The development of new photovoltaic and photocatalytic devices requires an understanding of how semiconductor material interacts with light and how the photo-generated charge carriers undergo relaxation. The excited state character of a-Fe_2O_3 after 400 nm excitation is studied by transient extreme ultraviolet (EUV) absorption spectroscopy which probes the optical transitions from atomic core orbitals to conduction band. Following excitation, a transient signal appears near the iron $M_{2,3}$ absorption edge at 56 eV. The initial rise is characteristic of an 84 fs instrument response time, followed by a 284 ± 20 fs decay to a long-lived excited state. Charge transfer multiplet theory models the initial excited state spectra for the two possible a-Fe_2O_3 bandgap excitation pathways: a ligand-to-metal charge transfer (LMCT) and an iron d-to-d spin flip transition. The experimental data resembles the red-shifted simulation result for a LMCT excited state. The 284 ± 20 fs relaxation could be intraband hot electron decay or charge trapping process. The elemental and oxidation-state specificities are demonstrated for EUV transient absorption. Combined with low femtoseconds temporal resolution, this technique will be expanded to study ultrafast charge carrier dynamics in multicomponent nanoscale systems.

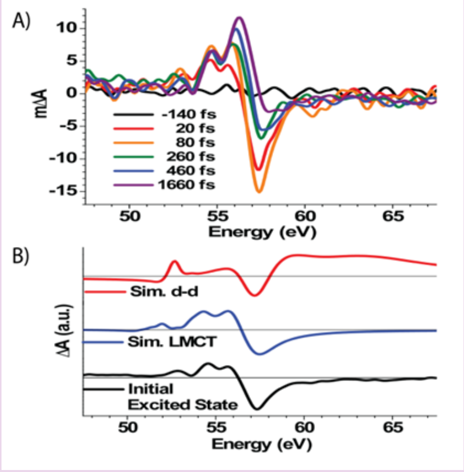


Figure A) Transient EUV absorption spectra of a-Fe_2O_3 at different pump-probe delay times. B) Comparison of the spectra of simulated d-d excited state, simulated LMCT state, and experimental data (top to bottom).

New Engineered Microscope System has an Impact on the Integrated Circuit Industry

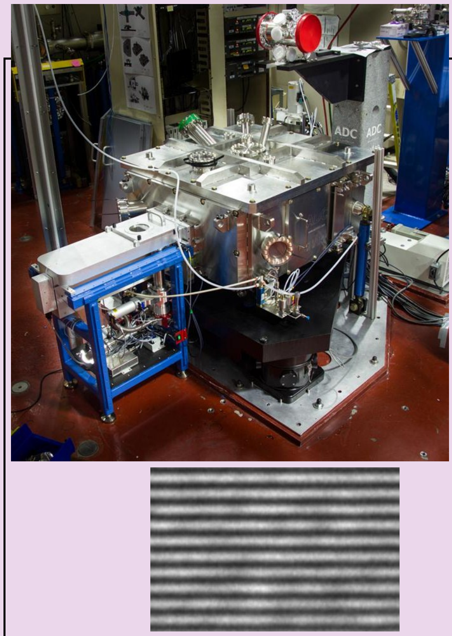


Figure (top) SEMATECH High-NA Actinic Reticle review Project (SHARP) system at LBNL. (bottom) 14-nm half-itch node features (55-nm on the mask) imaged with a 0.42 numerical aperture (4x) zoneplate. These were the smallest features available on the test mask.

A newly developed Extreme Ultraviolet (EUV) mask microscope for the integrated circuit lithography process is affecting current and future generations of product with its capability reaching the 8 nanometers (nm) half pitch node. Masks are a critical component in the manufacturing process used to produce both the current and future generations of complex microprocessors, the heart of electronic devices ranging from smartphones to high end computers. Use of a microscope for mask inspection becomes very challenging when the features are in the range of 20 nm or below.

The SEMATECH High-Numerical Aperture (NA) Actinic Reticle review Project (SHARP) represents a significant advance over its predecessor, the SEMATECH Berkeley Actinic Inspection Tool (AIT), which was decommissioned in September 2012. SHARP utilizes several advanced technologies to achieve its design goals: including the first Fourier-synthesis illuminator on a zoneplate microscope, EUV MEMS mirrors, and high-efficiency freestanding zoneplate lenses with numerical aperture values up to 0.625 (4×).

In its first week of operation, SHARP demonstrated approximately 150 times higher light throughput than AIT and a spatial resolution down to 14-nm half-pitch node on a 4x EUV mask and limited by availability of features on the mask. SHARP has hundreds of selectable high-resolution zoneplate lenses and computer controlled coherence making it extremely flexible giving EUV lithography researchers a window on several generations of future mask technology.

Capturing Nanoscale Spintronics using High Harmonic EUV Beams

Strong magnets exist only because all the spins in a magnet, each of which is like a very small bar magnet with a north and south pole, are lined up to point in the same direction. Although magnetism has been studied for over 2000 years, it is still an incompletely understood phenomenon. The fundamental length and time scales for magnetic phenomena are nanometers (nm) and femtoseconds (fs). However, a comprehensive microscopic model of how spins, electrons, photons and phonons interact does not yet exist. Moreover, many technology experts believe that next-generation computer disk drives will use optically-assisted magnetic recording to store more data more efficiently, and with faster access. However, many questions remain about how the delivery of optical energy can be optimized for maximum drive performance.

Using the world's fastest light source – bursts of laser-like X-ray beams -- scientists at JILA and NIST, with collaborators from Germany and Sweden, were able to simultaneously capture the behavior of different microscopic bar magnets in important magnetic alloys and multilayers of iron and nickel. This new capability allowed them to make a series of surprising discoveries about the fastest processes in magnetic materials. First, they found that spins on different atoms behave differently just after being exposed to laser light (in the first few quadrillionths of a second which is the first 10 femtoseconds). The iron spins react slightly faster to light than do the nickel spins, suggesting that the iron spins "see" light much more readily than the nickel spins. Until now, it was assumed that all the spins in a strong magnet behaved in the same way. Second, in more recent work, they observed giant, ultrafast, laser-generated spin-currents in magnetic multilayers – that can even increase the magnetization of a material to above its normal maximum value. These findings shed light on a rich variety of new physics at play in femtosecond magnetization dynamics of technologically important magnetic alloys and multilayer systems, uncovering which interactions are important to include in theories. This information could lead to faster and "smarter" computers because it suggests that hard drives could be engineered to enhance the delivery of the optical energy to the spin system.

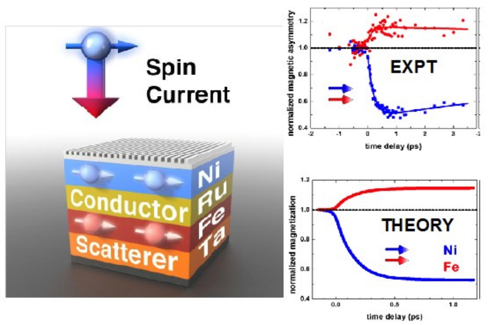
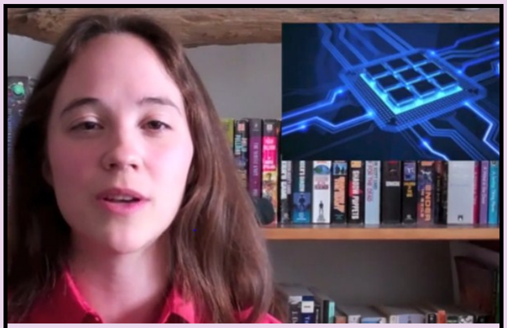


Figure After exciting the top Ni layer with a fs laser pulse, an intense spin-current propagates into the buried Fe layer at ballistic velocities. This giant spin-current transiently enhances the Fe magnetization by 20% above the normal peak value.

Nanoscale knowledge: Discovering how small is different

The continual push in the technology world toward smaller, faster, more efficient and more powerful has resulted in amazing progress in the nano-fabrication of ever smaller components. The challenge is that measurement tools have failed to keep up, which makes it very difficult to know how processes we understand at large scales – like heat flow or elasticity – change when the size scale is small. We use nanoscale-wavelength, laser-like extreme ultraviolet light to measure these nanoscale systems directly, characterizing the surprisingly inefficient heat flow away from tiny metal pillars and measuring the elastic properties of films that are a thousand times thinner than human hair. Understanding the behavior of these tiny systems is what we need to propel our future technological development – so we understand not only how to fabricate nanoscale components, but also how they will behave so as to best design and improve them.



Center graduate student, Kathy Hoogeboom-Pot, created a video about her research for an NSF-IGERT competition.

Watch the video at http://posterhall.org/igert2013/posters/375

If you have difficulty locating these publications online, please contact Robert.Bower@colostate.edu

Publications Since Last Newsletter

Publications in Peer-Reviewed Technical Journals

B. A. Reagan, K. A. Wernsing, A. H. Curtis, F. J. Furch, B. M. Luther, D. Patel, C. S. Menoni, J. J. Rocca, “Demonstration of a 100-Hz repetition rate gain-saturated diode-pumped table-top soft x-ray laser,” Optics Letters, **37**, 3624 (2012).

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If you have difficulty locating these publications online, please contact Robert.Bower@colostate.edu

Publications Since Last Newsletter

Publications in Peer-Reviewed Technical Journals (continued)

D. F. Gardner, B. S. Zhang, M. D. Seaberg, L. S. Martin, D. E. Adams, F. Salmassi, E. Gullikson, H. Kapteyn, and M. Murnane, "High numerical aperture reflection mode coherent diffraction microscopy using off-axis apertured illumination," Optics Express **20**(17), 19050 (2012).

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P. W. Wachulak, M. C. Marconi, A. Isoyan, L. Urbanski, A. Bartnik, H. Fiedorowicz, R. A. Bartels, “Aspects of nanometer scale imaging with extreme ultraviolet (EUV) laboratory sources” Invited Paper. Opto-Electronics Review, **20**, 1 (2012).

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C. Teale, D. Adams, M. Murnane, H. Kapteyn, and D. Kane, "Imaging by integrating stitched spectrograms," Opt. Express **21**, 6783 (2013).

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Industrial Advisory Board Meeting
February 28, 2013, San Jose, California

Members of the Center's Industrial Advisory Board joined Center Principal Investigators and staff for a meeting held at the end of the SPIE Advanced Lithography conference in San Jose, California. PIs Margaret Murnane, Patrick Naulleau and Jorge Rocca provided updates on Center research. The Industrial Liaison Officer, Bob Bower, provided attendees with an overview of industry program activities. Much of the latter part of the meeting focused on sustainability planning that will insure the Center is able to continue and grow ERC programs of benefit to industry. The meeting included the annual SWOT analysis. The Center's Executive Committed is sincerely grateful for the IAB's input to this process.

This year's meeting included presentations from the Center's Deputy Director, Margaret Murnane, University of Colorado, Boulder, Patrick Naulleau, Director, CXRO at Berkeley, and the Center Director, Jorge Rocca, Colorado State University.

Research Updates

Progress in the Development of High Harmonic Lasers and Applications
Margaret Murnane
Progress in the Development of EUV Lasers and Applications
Jorge Rocca
Progress in EUV Metrology Systems and Applications
Patrick Naulleau

Retreat Planning

Because there will be no more NSF site visits and because the EUV ERC desires to have a meaningful opportunity for members of the IAB to spend time with Center PIs, researchers, students and staff in a setting that provides opportunity to learn about, discuss and provide feedback on Center research, the EUV ERC is evolving the Center's Annual Retreat to meet these needs. Over the past two years, IAB attendance and participation in the annual retreat has steadily grown. During this IAB meeting, the Center sought feedback from the members regarding the best time and location for the retreat so that more IAB members could attend. It was determined that we will target a time in early to mid Fall and we will hold the retreat in Colorado providing attendees the opportunity to visit the campuses and labs at Colorado State University and the University of Colorado, Boulder.

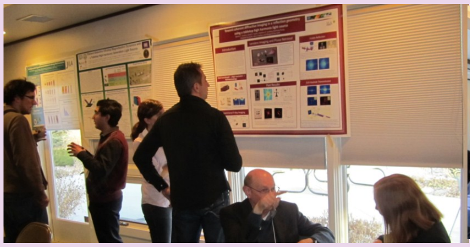
EUV ERC Annual Retreat

December 4th, 2012
Tamasag Conference Center, Bellevue, Colorado

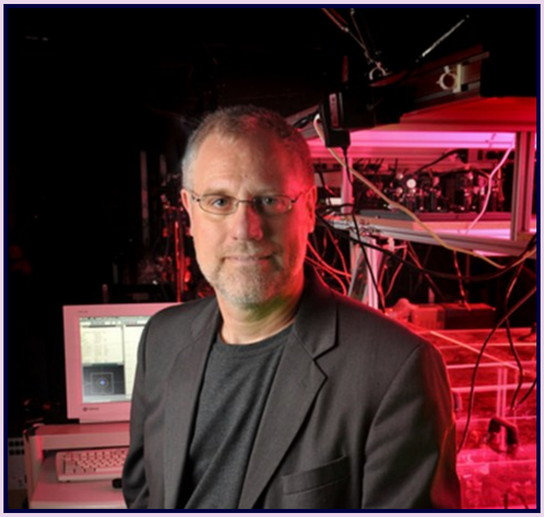
Over the past few years, the EUV ERC has made a special effort to include members of the IAB in the Center's Annual Retreat. Typically held in early January, the retreat has featured research updates, primarily presented by graduate students and postdocs, as well as presentations from content experts outside the Center on topics ranging from IP to patent fillings to talks delivered by local entrepreneurs on "how to start a successful high-tech business". Center members from all three campuses have numerous opportunities to network with people from industry throughout the day and at the evening dinner event. The most recent retreat was held in early December and included over 14 people from industry including guest speaker, Richard Solarz from KLA-Tencor providing insights to our students about their potential career paths and their opportunities in industry. A highlight of the meeting was the student poster session. Breakout meetings were also held for the students as well as a meeting between the IAB members in attendance and the Center's Executive Committee.

2013 Retreat Planning

Feedback from the IAB has indicated that we should target a time in early to mid Fall for this year's retreat and we should hold the meeting in Colorado providing attendees the opportunity to visit the campuses and labs at Colorado State University and the University of Colorado, Boulder. We are putting together Fall calendars now and will be seeking IAB input on potential dates. We are planning for an even larger industry turnout for this year's retreat!



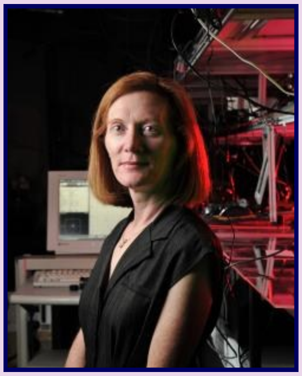
Henry Kapteyn Elected as a Member of the National Academy of Sciences



Henry Kapteyn, a Professor at the University of Colorado and JILA Fellow, who is a Principal Investigator of the NSF Engineering Research Center for Extreme Ultraviolet Science and Technology, was elected to membership in the National Academy of Sciences, the academy announced on April 30, 2013. Kapteyn joins two other faculty members of the EUV ERC ,Margaret Murnane and Steve Leone, as members of the National Academy of Sciences.

Kapteyn's election to the Academy recognizes his pioneering contributions to the development of coherent extreme ultraviolet and x-ray sources and their use in studies of ultrafast dynamic processes in material and chemical systems, nano-scale coherent imaging, and other applications. The new technology makes it possible to generate coherent extreme ultraviolet and soft x-ray bursts of femtosecond and attosecond duration. His election also recognizes his contributions to the development of femtosecond optical laser technology that constitute enabling laser technology utilized worldwide. Through the years and at the Center he has been an inspiring mentor to numerous students.
Additional recognition of Kapteyn's accomplishments include the Ahmed Zewail Award in Ultrafast Science and Technology, the Arthur L Schawlow Prize, the R. W. Wood Prize, and the Willis E. Lamb Award for Laser Science and Quantum Optics. Kapteyn was elected to the American Association for the Advancement of Science in 2007.

Margaret Murnane Elected Honorary Member of the Irish Academy



Margaret Murnane was elected an Honory Member of the Royal Irish Academy in March of 2013. She was nominated for the honor by Professor Eugene Kennedy, MRIA, and Professor Luke Drury, MRIA. Murnane is a Fellow of JILA and a Distinguished Professor in the Departments of Physics and Electrical and Computer Engineering at the University of Colorado, Boulder.

The Royal Irish Academy was founded in 1785 for the advancement of learning and scholarship in Ireland. The Academy's modern mission is faithful to its founding charter. This all-Ireland institution promotes excellence in scholarship, recognizes achievements in learning, and undertakes its own research projects, particularly in areas relating to Ireland and its heritage. The Academy is looking forward to Murnane's participation and involvement in its mission.

Jonathan Grava wins “Value in Action” award at Cymer

Daniel Brown, VP, Technology Development at Cymer, Inc., speaking of two-time “Value in Action” award winner, **Jonathan Grava,** a graduate of the EUV ERC program, stated, "Jonathan is one of our most highly valued system-level EUV experts. He has been instrumental in executing critical demonstrations of advanced technology capability consistently during his period with Cymer, and continues to be an integral and essential contributor in our most demanding product development activities."

EUV ERC Students and Graduates

Three Additional Center Ph.D.s Hired by Cymer

Lukasz Urbanski (right) became the 6th Center student to be hired by Cymer, Inc. Lukasz began working at Cymer on May 6th and has joined other former EUV ERC graduates, Georgiy Vashenko, Peter Langston (below right), Johathan Grava, David Kemp and Mike Purvis (below left). Lukasz, Peter and Mike now hold the position of "Senior Systems Engineer".

Leigh Martin received a 2013 NSF Graduate Fellowship. He is currently affiliated with JILA, University of Colorado, Boulder, and NIST. Leigh also was also recognized as an Outstanding Physics Department Graduate (undergraduate)

Dr. Carlos Hernandez Garcia received a Marie Curie Postdoctoral Fellowship

Jennifer Ellis received a 2013 NSF Graduate Fellowship. She is currently affiliated with JILA, University of Colorado, Boulder, and NIST.

Patrik Grychtol received a 2012 Postdoctoral research fellowship granted by the German science foundation (DFG)

Dr. Wen Li received the Presidential Early Career Award for Scientists and Engineers PECASE

Erik Hosler is graduating with his Ph.D. and will be joining Center member GLOBALFOUNDRIES

Josh Vura-Weis will be joining the faculty at the University of Illinois

The Extreme Ultraviolet (EUV) Engineering Research Center is one of 15 centers established in the United States through the National Science Foundation and supplemented by industry funding. Colorado State University (CSU) is the host institution with partner sites at the University of Colorado (CU), UC Berkeley and Lawrence Berkeley National Laboratory. The Center research mission is the development of compact coherent EUV sources and EUV-engineered systems that provide solutions to challenging scientific and industrial problems, including the development of new tools for nanotechnology and nanoscience. The Center has an important educational mission providing a unique environment for the training of students, young engineers and scientists. An Industry Advisory Board (IAB) with members, ranging from large- to small-capitalized companies, spanning instrumentation, semiconductor, lasers and optics, nanotechnology and the biological and chemical sciences actively participate in early access to technologies, joint research projects, directed research projects and the hiring of the some of the best students in the world in these areas.

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