Sample Research Project Descriptions

The 10-week summer program will be centered on engaging students in exciting research projects. Interns will be assigned specific research projects based on interest, level of prior preparation and challenge, and fit with faculty and graduate mentor research. The projects will allow interns to familiarize themselves with advanced research that builds on concepts they may already be familiar with and to introduce them to new concepts in lasers, optical techniques, and EUV technology. The projects reflect the varied and complementary expertise of the Center faculty and are listed below.

<u>High-Resolution Imaging of Plasmas used for EUV lithography</u> (CSU Prof. Jorge Rocca)

The REU students will use a unique compact EUV laser developed at CSU to image the laser-created plasmas used in EUV lithography. The printing of the most advanced computer chips using EUV lithography requires the generation of high average power of EUV light at a wavelength of 13.5 nm. This light is produced by irradiating micro-droplets of tin with infrared laser pulses. Imaging with an EUV laser will allow researchers to gather information, such as the distribution of neutral atoms and low charge species, that cannot be obtained with longer wavelength probes. A unique compact EUV will be used by the students to generate EUV shadowgrams (Fig. 1) of the tin targets and rapidly evolving tin plasmas with nanosecond time resolution. This is a highly inter-disciplinary project that will expose students to diverse areas of science and engineering, including optics, lasers, nanomaterials, and image processing. Students will learn about the engineering and operation of EUV lasers, EUV imaging, plasma diagnostics and image processing.

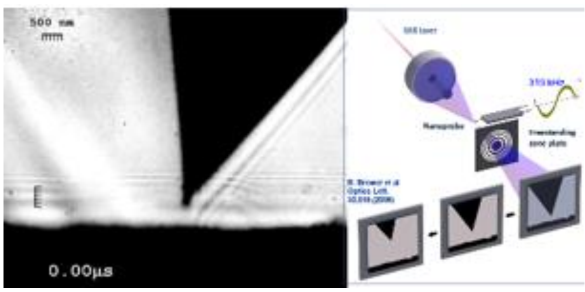

Fig. 1: Single shot EUV shadowgraphy image of needle oscillating at 319 MHz and imaging set-up.

Project learning objective: Learn the fundamentals of imaging with EUV light and apply them to image the laser-created plasmas for semiconductor lithography. The student will become proficient in EUV science and technology producing images using an EUV laser.

<u>Interaction of Ultra-Intense Femtosecond Laser Pulses with Nanostructures: Generation of X-Ray and Gamma Ray Radiation for High Resolution Tomography of Dense Objects</u> (CSU Prof. Reed Hollinger)

The REU students will experiment with the interaction of ultra-intense, ultrafast laser pulses with arrays of aligned nanostructures and optimize it for the generation of high energy photons to be able to acquire high resolution 3-D images of dense objects (Fig. 2). Nanowire arrays irradiated by laser pulses of ultra-high intensity can very efficiently absorb the laser light and convert it into intense picosecond flashes of high energy photons. CSU is fully equipped to conduct these experiments: it has one of the most powerful lasers in the world (ALEPH, 850 TW), a facility to grow nanowire arrays, and all the equipment necessary to perform high resolution x-ray tomography.

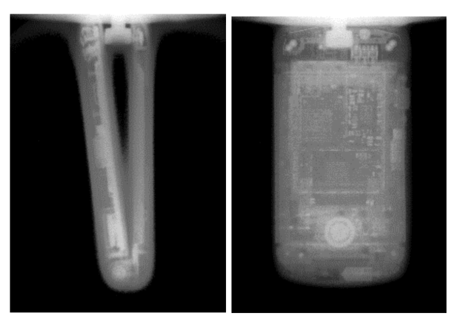
Fig. 2: X-ray radiograph of cell phone acquired with photons produced by CSU's ALEPH laser.

Project learning objective: Students will learn about molecular photodynamics and the production of X-rays by the process of high harmonic generation.

<u>Attosecond Molecular Photophysics by EUV Light Spectroscopy</u> (UCB Prof. Stephen Leone)

The photochemistry of complex molecules is a highly investigated field of study, in which processes such as ring opening, singlet-to-triplet transfer, and radical formation are ubiquitous. In this platform, small molecules are excited with a strong field at 800 nm wavelength or with ultraviolet pulses, and EUV attosecond pulses are used to probe the changes in orbital structure around carbon atoms in the molecule. An example is the Jahn-Teller distortion of methane cation (Fig. 3), in which it is found that upon abrupt ionization of methane a rapid geometry change occurs with concurrent coherent scissoring vibrational motion that is rapidly damped. The timescales for the dynamics are directly obtained in the few-femtosecond time domain. Students will learn about EUV spectroscopy, bond breaking, simulation of spectra, differential absorption, and molecular photophysics. Combining data analysis with simulation and global fitting provides important mathematical concepts for future careers.

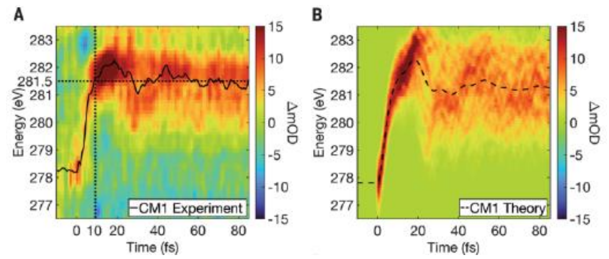

Fig. 3: (A) Experimental X-ray absorption signal from the C 1s orbital in methane cation to the vacant sigma CH bonding orbital, showing the rapid shift as the molecular geometry changes, and concurrent ringing of the scissoring vibrational mode. (B) Theoretical calculation of multiple trajectories of the same abrupt geometry change. CM indicates the first central moment of the spectral changes.

Project Learning Objective: Students will learn about molecular photodynamics and the production of X-rays by the process of high harmonic generation.

<u>Attosecond Carrier Relaxation and Coherent Phonon Dynamics via X-Ray Spectroscopy</u> (UCB Prof. Stephen Leone)

REU students will participate in understanding atomic motion in solids, which is of interest for several areas of materials science, including photocatalysis and phase-change materials via x-ray spectroscopy. Following excitation by the broadband pump pulse, the Peierl's distortion in a solid (a periodic distortion of the lattice in a one-dimensional crystal) such as antimony (Sb) is lifted, allowing for the well-reported coherent phonon motion to take place. The temporal resolution of attosecond pulses allows this oscillation to be traced from the earliest timescales following excitation (Fig. 4), which offers the opportunity to understand how initial and thermalized distributions of carriers interact to influence the overall lattice motion. The clear oscillations in the transient absorption signal are related to both the excited carrier population and to the motion of the lattice, which can be separated with suitable mathematical decomposition. Students learn about solid state dynamics from electronic carrier interactions, lattice motions, lasers and attosecond pulse generation, as well as important mathematical analysis methods.

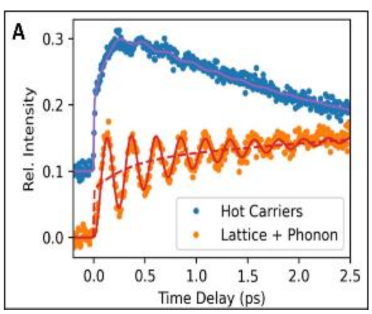

Fig. 4: Singular value decomposition of principal components of transient Sb signal. Blue curve corresponds to the signal attributed to carriers excited by the pump, with a decay related to the thermal relaxation and recombination of carriers. Orange curve describes the lattice temperature and position (phonon).

Project Learning Objective: Students will learn about the physics of coherent lattice motion and thermalization of carriers, as well as alignment and operation of intense ultrafast lasers.

Design, Fabrication and Diagnostics of interference Coatings for High Intensity Lasers (CSU Prof. Carmen Menoni)

In the most advanced high intensity lasers multilayer dielectric coatings (Fig. 5) play a very important role in maximizing laser output power and pulse energy operation. In this project REU students will be involved in the design, growth, and characterization of interference coatings for near infrared ultra-high intensity lasers that are used as drivers to generate intense beams of soft and hard x-rays. These advanced thin film structures consist of stacks of thin layers of transparent amorphous oxides that are deposited by ion beam sputtering. The REU student will participate in the design of these structures, in their synthesis, and in their optical characterization to determine their absorption loss at near infrared wavelengths and their stress. The REU student will participate in experiments that will test the resistance of the coatings to laser damage.

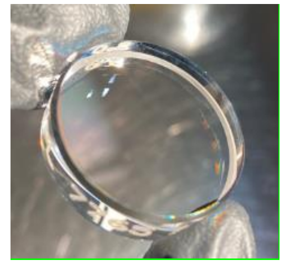

Fig. 5: Multilayer mirror consisting of a stack of GeTiO and SiO_2 layers, designed for high reflectivity at 1064 nm wavelength.

Project learning objective*:* Learn fundamentals of optics and apply them for the design of multilayer coatings. The student will become proficient in the design and characterization of thin film coatings and in the optical science that supports it.

Synthesis of Amorphous Oxides and Their Characterization (CSU Prof. Carmen Menoni)

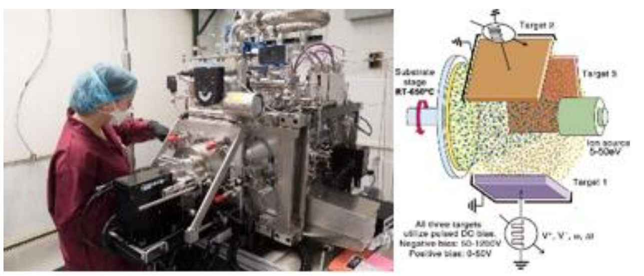

Fig. 6: Bias target deposition system used to deposit mixtures of several oxides to create ternary and quaternary thin films. In this process, metal targets are biased to accelerate Ar ions into the target and sputter the target in a reactive oxygen atmosphere.

Amorphous oxides are broadly used in many technologies including coatings for laser optics. At CSU we have the capability to deposit metal oxide thin films by ion beam sputtering. We can deposit binary, ternary, and quaternary mixtures, for example TiO_2 doped GeO_2 (TiGeO) (Fig. 6). We study the optical, structural, and mechanical properties of the thin films using a variety of techniques with the goal to study how microstructure affects these properties. This project will offer the REU student opportunities to learn how to grow amorphous metal oxide thin films by sputtering. The REU student will learn how to characterize the materials by ellipsometry and spectrophotometry to analyze their optical properties.

Project learning objective*:* Learn fundamentals of vacuum systems, and of physical vapor deposition. Learn how to characterize oxide thin films by optical methods. The student will become proficient in the synthesis of thin films by sputtering and in their characterization.

<u>Light Matter Interactions in Solid-State High Harmonic Generation Spectroscopy</u> (UCB Prof. Michael Zuerch)

Solid-state high harmonic generation (sHHG) is an emerging nonlinear spectroscopy technique based on strong-field interactions in a solid. In sHHG, an ultrafast pulsed driving field (typically mid-infrared, 3-4 µm wavelength) causes electron tunneling from the valence to conduction band in a semiconductor (Fig. 7). The electron then oscillates in the conduction band in concert with the driving field, resulting in harmonic emission within that band (called intraband); the electron can also recombine with the valence band hole resulting in an interband contribution to harmonic emission. The nonlinear outputs are in the visible to near ultraviolet. The resulting harmonic spectrum contains information on the electronic band structure and crystal symmetry of the material. An REU student will participate in sHHG measurements of single-crystal transition metal oxides and metal chalcogenides with the goal of developing a better understanding of how properties of the driving field, such as chirp (e.g. low frequency comes before high frequency in time), as well propagation through bulk materials affect the resulting harmonic spectrum. This project will enable accurate modeling of future sHHG measurements on bulk quantum materials for applications in energy conversion and quantum information. The project will enable the REU student to gain experience in applications of ultrafast lasers and the theory of strong-field light-matter interactions in solids while helping to develop a new and promising spectroscopy technique.

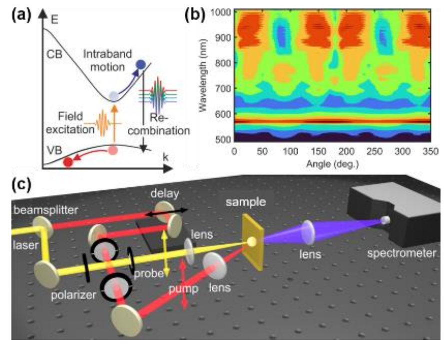

Fig. 7: (a) Schematic mechanism of sHHG showing strong-field electron tunneling, intraband motion, and recombination resulting in emission of high harmonics. (b) Example sHHG anisotropy measurement of (110) oriented ZnTe. (c) Optical layout of the pump-probe sHHG spectrometer.

Project Learning Objective: Students will gain hands-on experience with ultrafast laser applications, deepen their understanding of strong-field light-matter interactions in solids, and contribute to the development of an emerging nonlinear spectroscopy technique by conducting sHHG measurements on single-crystal transition metal oxides and metal chalcogenides.