Construction of an extreme ultraviolet polarimeter based on high-order harmonic generation

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ABSTRACT

We report on the development of a polarimeter for characterizing reflective surfaces throughout the extreme ultraviolet (EUV). The instrument relies on laser high-order harmonics generated in helium, neon, or argon gas. The 800 nm laser generates a discrete comb of odd harmonics up to order 100 (wavelengths from 8-62 nm). The flux of EUV light is a couple orders of magnitude less than a synchrotron source but 30,000 times greater than a plasma source currently in operation at BYU. The polarimeter determines the reflectance from surfaces as a function of incident angle, linear light polarization orientation, and wavelength. The instrument uses a wave plate in the laser beam to control the orientation of the harmonic polarization (linear, same as laser). After reflecting from the sample, the harmonic beams are dispersed by a grating and focused onto a micro-channel plate coupled to a phosphor screen. We have demonstrated the feasibility of this project with a simple prototype instrument, which measured the reflectance of samples from 30 nm to 62 nm. The prototype demonstrated that sensitivity is sufficient for measuring reflectances as low as 0.5% for both s- and p-polarized light. The full instrument employs extensive scanning mobility as opposed to the fixed angle and fixed wavelength range of our earlier prototype. An advantage of employing harmonics as a source for EUV polarimetry is that a wide range of wavelengths can be measured simultaneously. This project represents an authentic 'work-horse' application for high-order harmonics, as opposed to merely demonstrating proof of concept.

Keywords: Extreme ultraviolet, polarimetry, high-order harmonics

1. INTRODUCTION

Incomplete information on the index of refraction for coating materials presents a challenge in producing optics such as mirror coatings for use in the extreme ultraviolet (EUV). Many research groups, including ours at Brigham Young University (BYU), are currently doing research on the design and fabrication of multilayer mirrors for the EUV. The EUV research group at BYU produced mirror coatings that were used on the IMAGE satellite which was launched March 25, 2000[1]. This instrument took the first series of pictures of the Earth's magnetosphere at 41 eV as part of a comprehensive multi-spectral imaging of the near space around the Earth. The mirror coatings used in this satellite needed high reflectance (greater than 20%) at 30.4 nm, 14-degrees from normal and low reflectance (less than 2%) at 58.4 nm. The design work was hampered by the fact that the index of refraction for several of the coating materials differed significantly from published values, forcing re-measurement of these values themselves. Because optical properties are intertwined with surface characteristics and thin-film preparation procedures, the most feasible way to obtain reliable measurements of optical constants of thin-film materials in the EUV is to have a polarimeter co-located with sample preparation and characterization instruments. This would enable a much faster turn-around time than is currently possible with visits to a synchrotron source, some distance away. High harmonics represent an affordable and compact source of EUV light, ideal for doing polarimetry measurements in the 10 to 100 nanometer wavelength range. In this project, we pioneer a new table-top (as opposed to synchrotron-based) EUV reflectivity characterization instrument. With it, we will work to obtain more reliable data for the measured optical constants of important EUV materials. The expansion (and verification) of the optical constant database will benefit many scientific activities worldwide for a variety of terrestrial and space applications, including projection EUV lithography.

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2. BACKGROUND

High harmonics provide an excellent source of polarized, directional, and focusable EUV light. The harmonics form a comb of frequencies throughout the EUV, ranging from about 8 to 62 nm. The odd harmonics of the 800 nm laser light can be generated up to the 100th order and beyond[2 3 4].

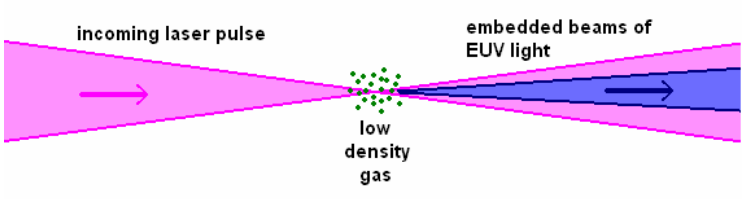


Figure 1: High harmonic beams generated by a laser focused into low-density gas.

As depicted in Figure 1, harmonics are generated when a short-pulse laser is focused to create high intensities (approximately 10^{15} W/cm^2) in a gas such as argon, neon, or helium. The laser pulse causes a strongly non-linear interaction between the electric field of the laser and the individual atoms in the gas, generating harmonics that are coherent with the incident beam. Many harmonic frequencies (including EUV) simultaneously emerge from the focus in a collimated beam, which is embedded in the residual laser beam. This includes harmonics with wavelengths in the neighborhood of 13 nm (the 61st harmonic), a wavelength that is important to the EUV lithography community. The harmonics take on the same linear polarization as the incident laser light[5]. The polarimeter will utilize the high harmonics to study polarization-dependent reflectivity of optical materials throughout the EUV. Figure 2 shows a schematic of the setup for recent experiments performed in our group. This setup was used to produce the high harmonics seen in Figure 3. 800 nm, 35 fs, 105 mJ laser pulses are focused to produce intensities of approximately 10^{15} W/cm^2 inside a cell of helium, neon, or argon gas. The high harmonics are detected using a grazing-incidence tungsten-coated grating, which disperses and focuses the different harmonic orders onto a microchannel plate (MCP) coupled to a phosphorus screen.

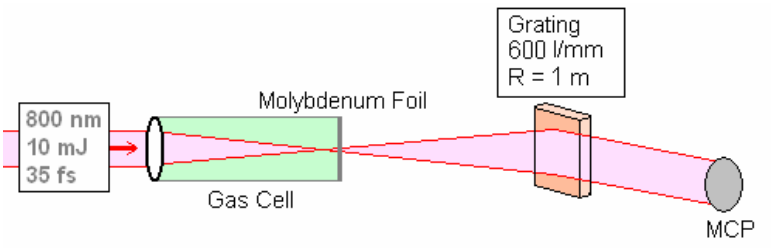


Figure 2: Setup to produce high harmonics.

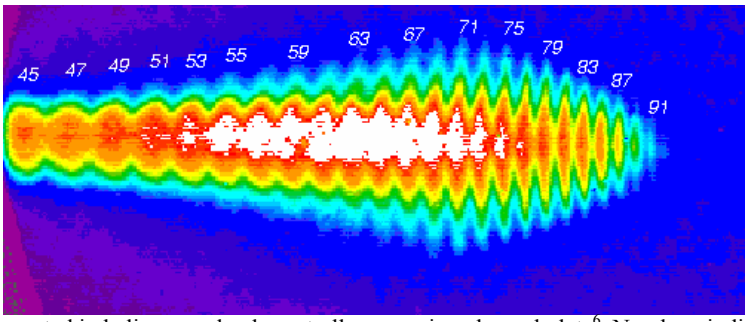


Figure 3: Harmonics generated in helium resolved spectrally on a microchannel plate[6]. Numbers indicate the order of each harmonic.

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3. SPECIFICATIONS FOR HIGH HARMONICS AS AN EUV SOURCE

The technical specifications of high harmonics are still a topic of active research. A summary of the specifications of the system developed at BYU are summarized in Table 1. Also listed are specifications of Beamline 6.3.2 at the Advanced Light Source[7], a beamline commonly used for EUV optics testing, and specifications for a hollow cathode plasma source currently in operation at BYU.

Table 1: Specifications of high harmonic generation as a source of EUV light compared to two commonly used sources, beamline 6.3.2 at the Advanced Light Source and a hollow cathode source currently in operation at BYU.

	High Harmonic Generation at BYU	Beamline 6.3.2 at the Advanced Light Source	Hollow Cathode Plasma Souce at BYU
Energy	20-155 eV (8-62 nm), quantized as 1.55q where q is a positive odd integer (roughly every 3 eV)	50-1300 eV (1-25 nm) continuous.	Various atomic and ionic emission lines from 10-177 eV (7-121.6 nm). Comprises approximately 150 lines.
Flux	$6x10^8$ photons/sec @100 eV (measured)	10^{11} photons/sec @100 eV (calculated)	$2x10^3$ photons/sec @41 eV (measured)
Spectral Resolution ($E/\Delta E$)	>50	7000	>500
Polarization	Rotatable linear polarization, same as laser.	90% s-polarized, 10% p-polarized	Unpolarized
Angular Resolution	0.06º	~0.02º	0.08º
Detectors	Microchannel plate (MCP)	Photodiode, channeltron, CCD	Channeltron
Spot Size at Sample	1000 x 1000 μm	10 x 300 μm	5000 x 5000 μm

Source stability is a critical issue in order to obtain accurate and repeatable reflectance and transmittance data. Unfortunately, because of considerable amplification, small fluctuations in the laser cause large fluctuations in generated harmonics. By averaging data where the laser is within a specific power range, we expect to be able to obtain stability on the order of 1%. Using this method forces us to give up some flux, but we are certain it will work. Another method we will test for accuracy and repeatability is binning the data so that reflectivity from samples can be calculated repeatedly from data falling within a variety of laser energy bins and the averaging the results, rather than discarding data that lies outside of a predetermined narrow energy range.

4. PROTOTYPE EXPERIMENT

We recently constructed a simple prototype instrument at BYU to make polarization-sensitive reflectometry measurements in the EUV[8]. The instrument utilized laser-generated high harmonics as a source of spatially coherent polarized EUV light. Figure 4 shows a schematic of the prototype instrument.

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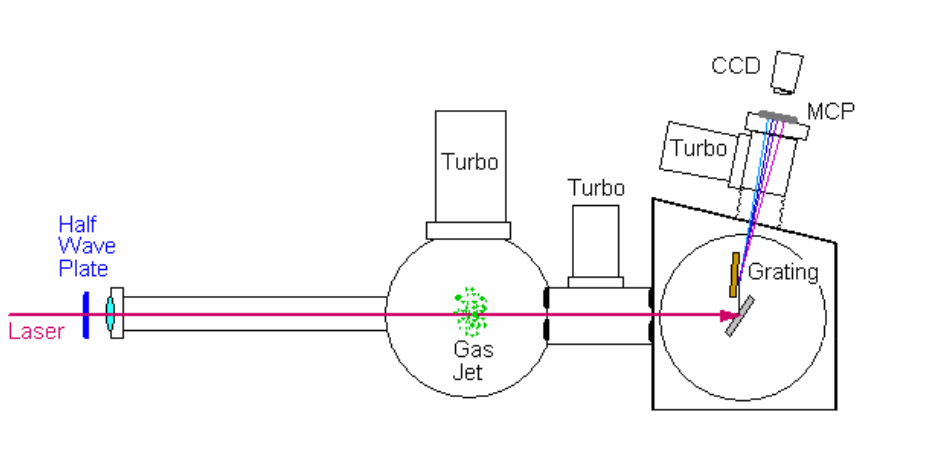


Figure 4: Prototype polarimeter (top view)[8].

The high harmonics for this prototype experiment were created in argon gas inside the first chamber. A half wave plate in the laser beam controlled the orientation of the harmonic polarization. Three turbo pumps provided differential pumping to maintain low pressure in the detection chamber. The incident angle on the sample was fixed at 45 degrees. The harmonic beams proceeded to a tungsten-coated 600 l/mm grating (2º blaze) with a 1 m radius of curvature. They were diffracted and focused by this grating onto an MCP coupled to a phosphor screen. Figure 5 shows the harmonics at the MCP as observed by a CCD camera after being reflected from two silicon wafers (with different oxide thickness). Figure 6 shows a comparison between the s and p reflected high-harmonic light from the two surfaces.

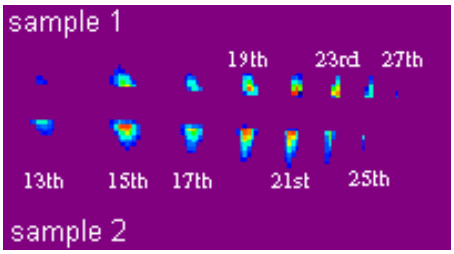


Figure 5: Harmonics reflected from two different samples

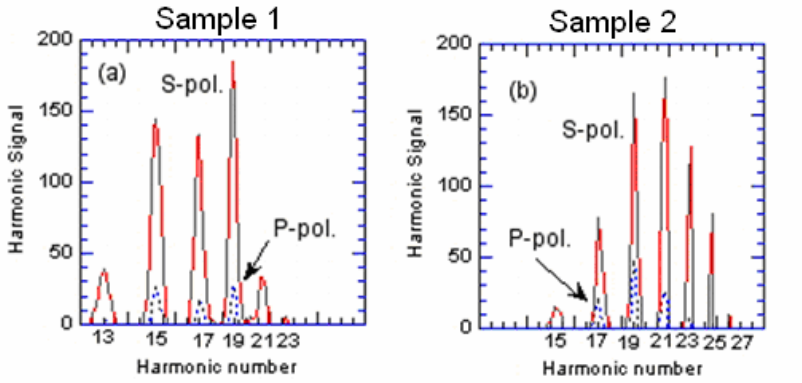


Figure 6: S-polarized vs. p-polarized high harmonics reflected from two silicon wafers with different oxide thicknesses.

The two surfaces show significant differences in reflectivity, presumably owing to their different oxide layer thicknesses. The prototype work determined that the grazing incidence tungsten-coated grating reflects very nearly equal percentages

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of s and p-polarized light (in this wavelength range). These measurements also show that the source will have sufficient brightness to measure reflectances as low as 0.5%.

5. INSTRUMENT

We are currently constructing a full-scale polarimeter instrument at BYU based on the prototype which will allow researchers to characterize optical surfaces in the EUV on a routine basis. To our knowledge, this will be the first time that high harmonics have been employed in a 'work-horse' setting, as opposed to merely demonstrating proof of concept. The full instrument will determine the reflectance from samples as a function of incident angle, light polarization orientation, and wavelength (associated with a discrete comb of odd harmonics of 800 nm, up to order ~100). An attractive advantage is the ability to measure reflectances from a wide comb of wavelengths simultaneously. The full-scale instrument will employ extensive scanning mobility (rather than the fixed angle and fixed wavelength range of the prototype). Our experience with the prototype gives us confidence that the full instrument shown in Figure 7 will work.

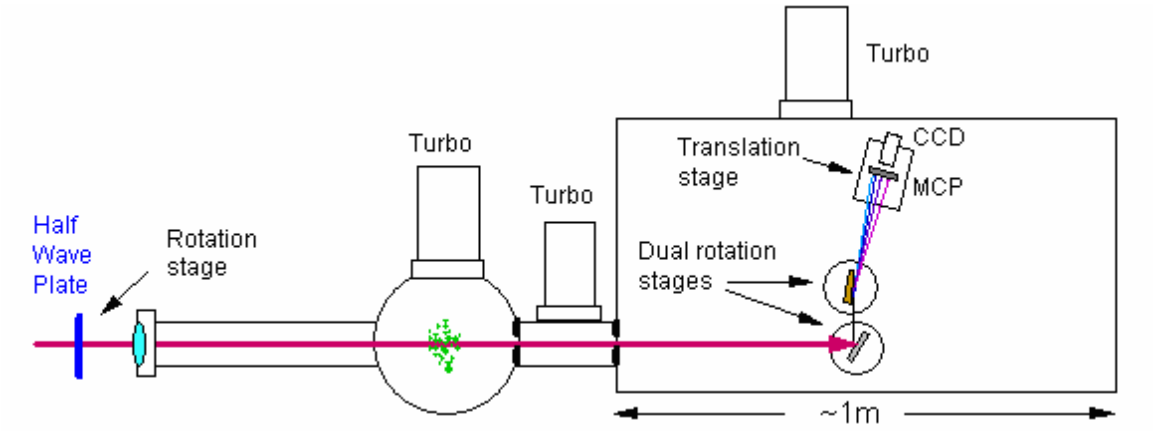


Figure 7: The full-scale polarimeter.

The new instrument employs an automated positioning system (see Figure 8). The sample will sit above two concentric rotation stages. One will vary the incident angle of the harmonic light on the sample. The other will swing the entire detection system (grating and x-ray CCD) through twice that angle. A second pair of rotation stages will sit beneath the grating - one to adjust the grating angle and the other to separately adjust the angle of the detector arm. A linear translation stage will be used beneath the CCD to bring the detector to the focal point of the harmonic orders of interest.

An important feature of the harmonics is that they can have an arbitrary polarization, dictated by the polarization of the input laser beam. The polarization can be rotated using a wave plate in the laser beam before the harmonics are generated. The orientation of the wave plate will be controlled by yet another automated rotation stage. All rotation and translation stages, together with the readout of the measured signal and real-time laser characteristics will be managed by a single computer running LabView.

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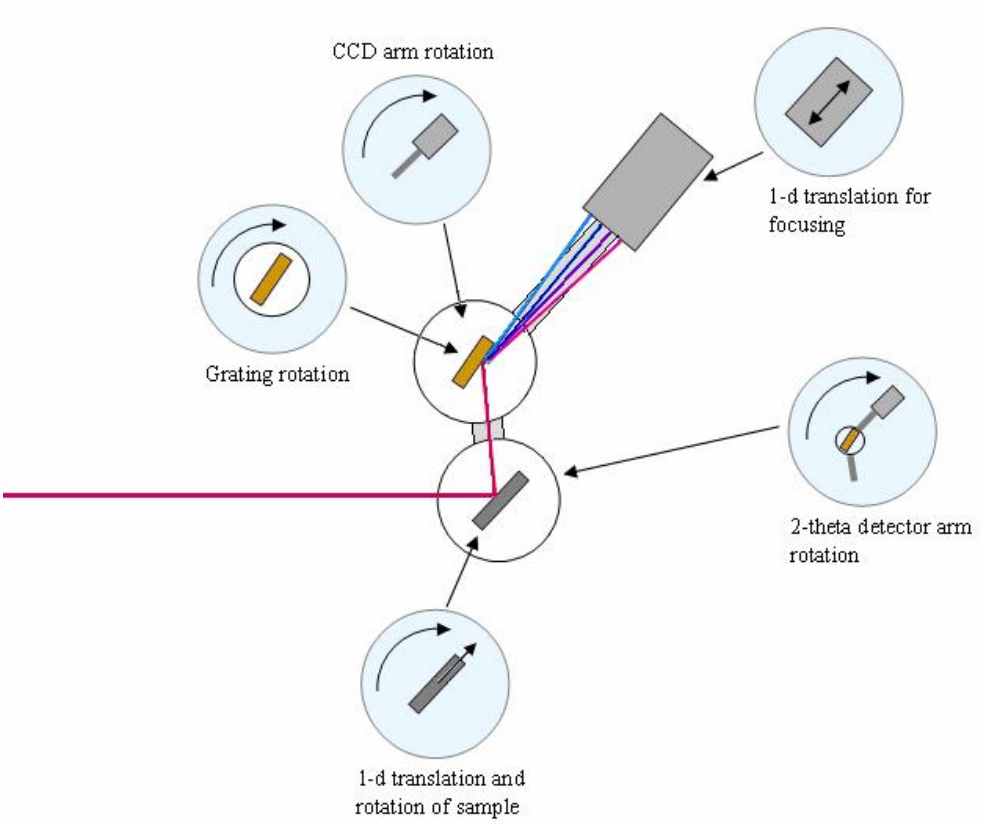


Figure 8: Polarimeter positioning system.

6. CONCLUSION

This project promises a useful research tool to the EUV thin-film researchers at BYU. An EUV polarimeter co-located with sample preparation and characterization instruments will allow for sensitive determination of optical constants with fast turn-around and time sensitive measurements not possible with a remote synchrotron source. Our prototype instrument demonstrated the feasibility of this instrument and showed that we can measure reflectances as low as 0.5%. High harmonics as a source of EUV light constitute a broad range of wavelengths from 8 nm to 62 nm with a flux a factor of 200 times below that available at Beamline 6.3.2 at the Advanced Light Source, but a factor of 30,000 times brighter than a plasma source currently used at BYU. The spectral resolution is not as sharp as that from either a synchrotron or a line source, but it is good enough to resolve many features in optical constant data. The well-controlled polarization and the ability to measure reflectances simultaneously over a wide comb of wavelengths are clear advantages.

ACKNOWLEDGEMENTS

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