NIST efforts in extreme-ultraviolet metrology

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ABSTRACT

For several decades, the National Institute of Standards and Technology (NIST) has actively supported metrology programs for extreme ultraviolet (EUV) lithography. We will describe our existing programs in optics lifetime, reflectometry, and radiometry. Recent developments include developing quantitative models for both carbonization and oxidation of optics under UV illumination and use of a cryogenic radiometer to calibrate transfer-standard detectors from 4 nm to 400 nm. We describe two programs currently in planning. The first of these is development of a method to calibrate high-power pulsed radiation detectors using a calorimeter. Our current primary standard detectors for 13 nm are based on synchrotron radiation with incident powers of a few microwatts or less. EUV production tools need to measure pulse trains with many hundreds of watts of average power. We will begin this work on our existing low-power detector-calibration facility and use higher-power beamlines with overlapping power ranges and the linearity of synchrotron radiance with stored beam current to extend the calibrations to higher powers. Second, we present a Mueller matrix ellipsometry and scatterometry system covering the far-to-extreme ultraviolet spectral range. This system is expected to achieve the requisite variable polarization and diattenuation control with an entirely reflective optical system. By extending scatterometry to short wavelengths, we intend to demonstrate improved sensitivity and accuracy of parameter retrieval from microfabricated devices. These programs complement NIST's existing far- and extreme-ultraviolet radiometry and metrology programs and expand our support for critical semiconductor manufacturing.

Keywords: Extreme ultraviolet; reflectometry; radiometry; scatterometry; spectroscopic ellipsometry

1. INTRODUCTION

Since the early 1990's, NIST's Synchrotron Ultraviolet Radiation Facility (SURF III) has provided EUV measurements to customers in both the EUV lithography (EUVL) and astronomy communities. SURF III is an ideal source for the measurements presented here, with a peak output near the 13.5 nm wavelength of EUVL,[1] providing a stable platform for both source- and detector-based radiometry. Furthermore, with a key focus on industry-driven EUVL measurements, NIST has proven to be an agile resource for the community providing new and enhanced services at the request of the community[2]. Services including radiometric and reflectance measurements from mature programs are complemented by optics lifetime testing, and photoresist evaluation programs formed as direct responses to EUVL industry stake holders' requests. Current and future activities discussed below illustrate how NIST is and will continue to provide essential services to users of EUV radiation, including nascent efforts at NIST in EUV-based metrology of patterned wafers. SURF III's facilities are currently undergoing renovation to provide enhanced environmental control and electrical power to further optimize the stability and reliability of the SURF III and its beamlines.

2. CURRENT ACTIVITIES

2.1 Radiometry

Ultraviolet radiometry is one of the most mature services provided at SURF III. The majority of the radiometry is detector-based with working standards referenced to an absolute cryogenic radiometer (ACR).[34] The ACR is an electrical-substitution device. The difference in the power to maintain a constant temperature in a cavity is measured when

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International Conference on Extreme Ultraviolet Lithography 2023, edited by Patrick P. Naulleau,
Paolo A. Gargini, Toshiro Itani, Kurt G. Ronse, Proc. of SPIE Vol. 12750,
127500F · © 2023 SPIE · 0277-786X · doi: 10.1117/12.2686832

illuminated and dark. Bracketed measurements are made of the power measured in the ACR and photocurrent measured in a transfer-standard photodiode, yielding the absolute responsivity of the photodiode.

Radiometry measurements are made primarily on Beamline 3. This beamline was originally Beamline X24C on the x-ray ring at the National Synchrotron Light Source (NSLS) at Brookhaven National Laboratory.[5] It features a novel design that allows coverage of a very broad wavelength range with near-ideal conditions. When NSLS was decommissioned, NSLS II management determined that the resolution requirements of Beamline X24C were not appropriate for the upgraded NSLS II. The beamline was moved to Gaithersburg, MD and installed as Beamline 3 on SURF III. Radiation from SURF III is collected by an off-axis parabolic mirror that directs the light to a pair of optical components, usually a grating and a plane mirror. Each of these components rotates and translates so that they can operate at continuous angles of incidence between grazing- and normal-incidence. There are three gratings with ruling densities of (150 mm^{-1}, 600 mm^{-1}, and 2400 mm^{-1}). The optics are scanned in a way that allows the gratings to operate on-blaze for nearly all the wavelengths between 3 nm and 500 nm.

The sample chamber is normally fitted with one or two working-standard photodiodes and up to two detectors under test. The working standards are calibrated periodically using an ACR. The beamline can also be fitted with a variety of endstations to provide users with a platform to perform measurements with monochromatized UV radiation that is referenced to calibrated working standards. Endstations include a reflectometer and the upcoming scatterometry facility described in Section 3.

Figure 1 shows a recent measurement of the responsivity of three reference photodiodes. These measurements were made at wavelengths longer than 100 nm using an ACR. 1 mm thick filters of MgF_2 and fused silica suppressed high diffraction orders. The MgF2 has a short-wavelength limit of about 110 nm, while the fused silica is about 150 nm, which is why the fused silica data begin at longer wavelengths. As can be seen, the data transition smoothly between the two sets of measurements.

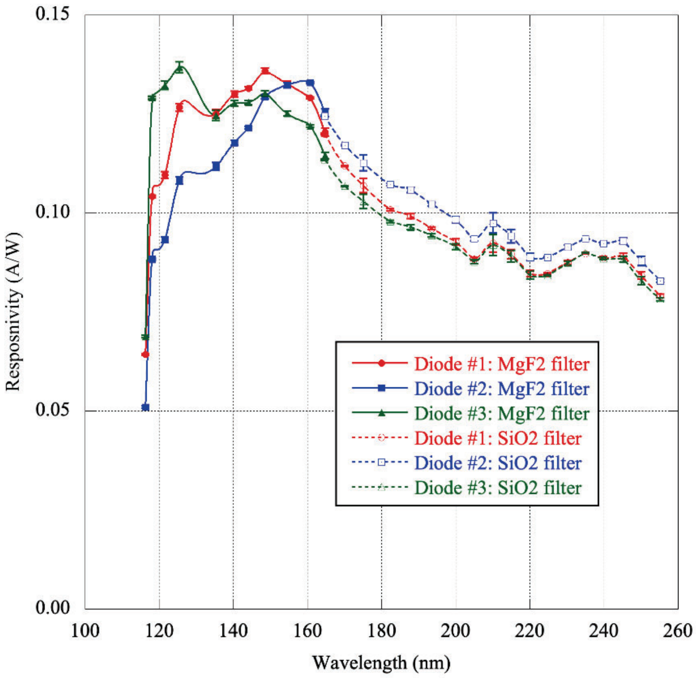

Figure 1. Responsivity of three photodiodes recently measured using an absolute cryogenic radiometer. Measurements were made with a MgF_2 filter (solid markers and lines) and a fused silica filter (open markers, dashed lines).

2.2 Reflectometry

The NIST EUV Reflectometry Facility is housed on a dedicated SURF III beamline (Beamline 7). The varied-line-spacing grating-based monochromator[6] was designed and constructed in the early 1990's. This monochromator has a wavelength range of 7 nm to 35 nm and is well suited for measurements of both EUVL and EUV astronomical components and instruments. The sample chamber, designed to precisely position optics up to 35 cm in diameter and 40 kg in mass, was installed in 2000. The chamber was updated to allow optics up to 45 cm in diameter. It now has six axes of sample motion and three of detector motion, allowing out-of-plane measurements of optics with slopes up to 40°. The beamline is well-suited for a variety of measurements, including reflectance, transmittance, and diffraction efficiency. Near 13.5 nm the system provides reflectance measurements with 0.35% (combined standard uncertainty with coverage factor of k=1) reflectance uncertainty and wavelength uncertainty better than 10 pm.[7]

Figure 2 shows the results of one measurement of a large collector optic. This optic has a slope greater than we can account for with our yaw axis, thus measurements at larger radii could not be done with an in-plane reflection. However, reflectance measurements were conducted so that the polarization at each measurement location matched the polarization of the customers intended light source. The decrease in peak reflectance at larger radii in the figure is not due to degradation in the coating, but to the polarization and the larger angle of incidence at outer radii.

Similar to Beamline 3, Beamline 7 can be outfitted with external endstations to allow for a full instrument system to be measured versus calibrated working standards. Measurements have been conducted previously on fully assembled EUVL source calibration systems to provide calibrations referenced to ACR-calibrated working standards. This beamline is slated for upgrading presently to provide enhanced spectral resolution, wavelength uncertainty, sample manipulation, and overall reliability and measurement efficiency.

2.3 Optics lifetime testing

Beamlines 1 and 8 of SURF III contain three EUV-optics lifetime testing stations. The two are largely identical. Each of these consists of a single focusing Mo/Si multilayer mirror operating at 10° normal angle of incidence. They intercept about 20 mrad of the SURF III irradiance and image the light from the electron beam at about 0.2x magnification. Astigmatic best focus is slightly less than 1 mm on each beamline. The primary difference between the two is that Beamline 8 has an ultrahigh-vacuum endstation, while Beamline 1a is high-vacuum. The sample chamber of each is isolated from the upstream beamline with a thin-film filter or window captured in the gate of a gate valve.[8] Using filtered valves allows the introduction of contaminants such as water or organics into the sample chamber while avoiding contamination of the beamline's upstream optics or the electron storage ring. Contaminant pressures can be introduced in a range of 10^{-10} mbar and 0.1 mbar on Beamline 8 and 10^{-8} mbar and 0.1 mbar on Beamline 1a.

The focusing multilayer mirror has a reflectance peak at about 13.3 nm but also has >50 % reflectance at wavelengths longer than about 75 nm. The use of a Be or Si filter isolates the EUV peak, while different filters or window materials allow investigations at longer wavelengths. The average peak irradiance in these beamlines is in the few $\mathrm{mW/mm^2}$ range, depending on the filter/window material.

Beamline 1b is a grazing-incidence facility with very high throughput. Originally designed for witness-sample testing of photoresists,[9] the optical element is a Rh-coated toroid operating at 10° grazing angle of incidence. Again, a thin-film filter is mounted in a gate valve to provide some wavelength selection and a vapor seal between the beamline and sample chamber. Due to the high power (0.5 W) incident on the filter, specially designed filters with copper mesh are utilized to dissipate the heat.[10] Different spectra and different power levels can be obtained using filters such as Zr, Si, or Al.

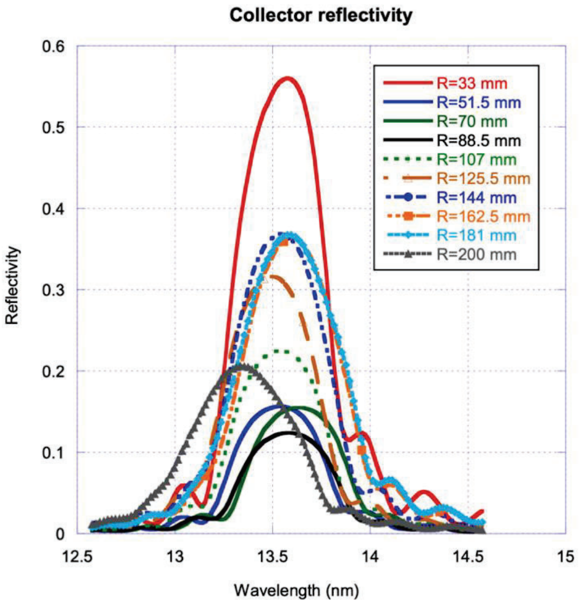

Figure 2. Reflectance of a large optic with 45° polarization at multiple radii indicated in the legend.

3. FUTURE DIRECTIONS

3.1 Source metrology

NIST currently offers high-power calibrations of detectors for pulsed or CW radiation from the IR to deep-UV[11] and lower-power EUV calibrations described above. However, there is no ongoing effort that joins the two, a critical challenge given industry methods for EUVL sources for lithography rely on a CO_2 laser with 10.6 μm wavelength and 50 kHz repetition rate to excite a tin plasma. A small pre-pulse expands a tin droplet to optimize coupling between the laser light and the tin electrons. A large main pulse generates the plasma, which emits over a broad spectrum, including the band near 13.5 nm.

The anticipated source-metrology plan will include metrology for both the CO_2 laser and the EUV source. Development of the latter will largely occur at SURF III. This will need to be done with a bootstrapping process since no beamlines at SURF III can provide the power of an EUVL source. The process will involve finding a power range, likely on Beamline 1b, where calibrated EUV photodiodes and calibrated calorimeters or radiometers for the IR-DUV can both work well. Using data obtained under these conditions will allow us to verify that the instruments behave as expected so that their properties can be extrapolated into the very high powers applicable to EUVL sources. The calibration of a series of these devices has been shown to be accurate over 20 orders of magnitude in power,[12] so this undertaking is not pushing the limits of our understanding.

Quality SI-traceable measurements of both input laser power and source power will add to understanding the conversion process and can direct improved models of the process.

3.2 Scatterometry

Current techniques for rapid chip-inspection metrology, operating between the IR and DUV, will be pushed beyond their limits for future generations of devices such as complementary field-effect transistors.[13] We have launched a program to develop scatterometry in the wavelengths between 10 nm and 150 nm to extend inspection metrology well into the future. Note that "scatterometry" has multiple meanings in the literature depending on the application and wavelength. For the IR to DUV, scatterometry is the spectroscopic ellipsometry of patterned wafers for optics-based detection of smallest, or critical, dimensions (OCD), utilizing the 0th-order and manipulating polarization states to reconstruct the average parametrized geometry. However, "EUV scatterometry" reports have utilized natively polarized light from a synchrotron[14] and a high-harmonic source (HHGs),[15] capturing intensities at multiple diffraction orders to enable parametric reconstruction. This new optical platform will bridge the gap between these two approaches using spectroscopic ellipsometry between about 50 nm and 150 nm while allowing the harnessing of EUV diffraction-based metrology at selectable orthogonal polarizations at shorter wavelengths.

Stokes polarimeters in transmitting optical systems are often constructed using polarizers followed by rotating phase retarders. The condition number of the matrix having rows containing the Stokes vectors transmitting through the system is a figure-of-merit for a polarimeter.[16] It can be shown that the optimum polarimeter has a condition number of $\sqrt{3} \approx 1.7$. In the EUV, transmitting optics are not available, and one must employ reflective optics instead. Three- or four-bounce reflective elements[17] can exhibit significant retardance but also exhibit significant diattenuation. Figure 3 shows the calculated condition number for a four-bounce reflective polarization state generator, where the angle of incidence on each reflection varies from $\theta = 75°$ to $85°$, the reflectors are made of silicon, and the initial beam is linearly polarized. The condition number can be kept less than 3 for significant spectral ranges, especially if θ can be varied, suggesting a spectroscopic Mueller matrix ellipsometer[18] can be constructed in the EUV.

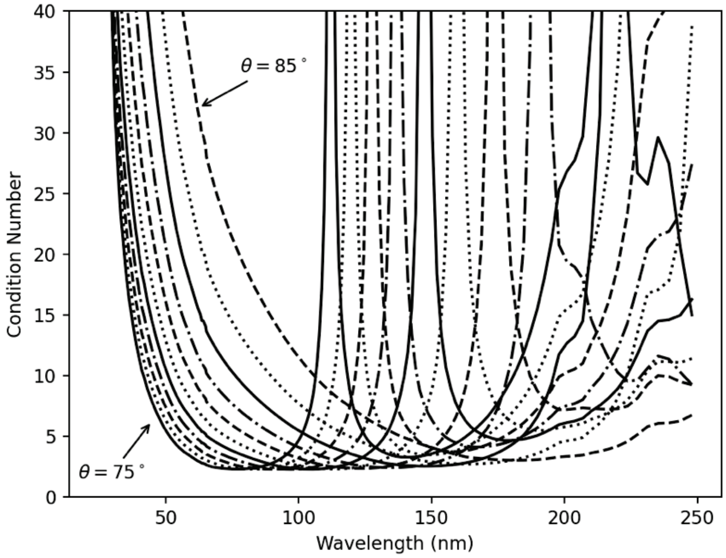

Figure 3. Condition number for a four-bounce reflective polarization state generator, where the angle of incidence on each reflection varies from $\theta = 75°$ to $85°$, the reflectors are made of silicon, and the initial beam is linearly polarized.

A system with four-bounce, rotating polarizing elements operating at 10° grazing angle of incidence for both incident and reflected light has been designed. A four-bounce system is more forgiving for alignment. It also has higher throughput than a three-bounce system because the second mirror in a three-bounce system has an angle of incidence twice that of the end mirrors. A new experimental chamber is large enough to accommodate motion stages to allow both spatial and angular movement of the sample. The polarizers will have sufficient throughput to wavelengths as short as 40 nm.

The endstation will also include more conventional non-polarization-dependent scattering measurements that will allow considerable overlap with the ellipsometer and will allow measurements out to 5 nm wavelength. Whereas the region of 50 nm to 150 nm is very surface sensitive, Si is most transparent in the region around 12.5 nm, which will allow the light to penetrate well into a Si-based device.

Initial development and validation of the instrument will take place on Beamline 3 at SURF III. This will allow us to fine-tune the wavelength to be on either side of an absorption edge, which can flip the contrast among different elements in a device. The instrument will frequently be used at SURF III for purposes such as optical-constants measurements and further instrumental development. An endstation will also be built for use with an EUV high-harmonic generation source. Our ultimate research goal is to build an instrument that demonstrates the feasibility of these techniques for use in a fab facility.

4. CONCLUSION

Along with the suite of beamlines described here, SURF III also has beamlines that can be made available or repurposed for new projects. Beamline 1 has gone through several iterations: endurance testing of mirrors and filters, photoresist outgassing, resist sensitivity measurements, witness-sample testing, and other materials testing. Each of these modifications took place in six months or less. Beamlines 3 and 7, as mentioned, can both be fitted with auxiliary endstations. There are also two beamlines that can be quickly fitted with simple experiments including customer experiment chambers.

Beyond the applications of the SURF III synchrotron mentioned above, the SURF III EUV light source is well positioned for the development of additional EUV metrology needs. Synchrotron light sources are inherently versatile because multiple beamlines, with significantly different application, can be operated at the same time. In addition, the smaller size of SURF III enables NIST to be fast and flexible in our response to industry needs. For example, a kinematic endstation mounting on Beamline-3 allows this beamline to host the ACR scale realization instrument, a reflectometer and photodiode calibration chamber, the scatterometry instrument, and other new endstations as required for future applications. Additionally, Beamline 1 has gone through several iterations: endurance testing of mirrors and filters, photoresist outgassing, resist sensitivity measurements, witness-sample testing, and other materials testing. Each of these modifications took place in six months or less in response to industry needs.

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