A simple null-field ellipsometric imaging system (NEIS) for \textit{in situ} monitoring of EUV-induced deposition on EUV optics

Rashi Garg\(^1\), Nadir Faradzhev\(^2\), Shannon Hill\(^3\), Lee Richter\(^3\), P. S. Shaw\(^3\), R. Vest\(^3\), and T.B. Lucatorto\(^3\)

\(^1\)College of Nanoscale Science and Engineering, University at Albany, NY 12203
\(^2\)Rutgers, The State University of New Jersey, Piscataway, NJ 08854
\(^3\)National Institute of Standards and Technology, Gaithersburg, MD 20899

1. \textbf{ABSTRACT}

We describe a null-field ellipsometric imaging system (NEIS) that provides for the real-time imaging of carbon deposition profiles on extreme-ultraviolet (EUV) optics in a vacuum system. NEIS has been demonstrated at NIST on a small chamber that is used for EUV optics lifetime testing. The system provides images of carbon deposition spots with sub-nanometer resolution thickness measurements that maintain good agreement with those from \textit{ex-situ} spectral ellipsometry (SE) and x-ray photoelectron spectroscopy (XPS). The system will be implemented on several synchrotron beamlines for real-time monitoring of carbon film growth on optics during EUV irradiation.

KEYWORDS: EUV, null-field ellipsometry, imaging, optics, contamination

2. \textbf{INTRODUCTION}

In pre-production extreme-ultraviolet (EUV) lithography systems, carbon contamination of the illumination and projection optics is one of the primary sources of throughput loss. To address the problem of such EUV-induced contamination, a program was established at the Synchrotron Ultraviolet Radiation Facility (SURF III) of the National Institute of Standards and Technology (NIST) to measure the contamination rates and scaling behavior of various organic species that are likely to be found in the vacuum environment of an EUV lithography tool\(^1\). Previously, samples were exposed to a defined dose of EUV in fixed partial pressures of various admitted gases and then removed from the vacuum for \textit{ex-situ} characterization with x-ray photoelectron spectroscopy (XPS) and spectroscopic ellipsometry (SE). This approach has worked well for studies of pressure and intensity scaling. However, the speed and breadth of experiments would be greatly improved with \textit{in-situ} analysis, allowing real-time study of optic contamination and avoiding the possible influences of exposure to air before \textit{ex-situ} analysis. Furthermore, since the intensity distribution of the EUV radiation on the sample is known, an \textit{in-situ} imaging system with sufficient (lateral) spatial resolution would permit simultaneous studies of the pressure, dose, and intensity scaling of optic contamination. To this end, we have recently constructed an \textit{in-situ} imaging system to monitor carbon growth in real time based on single-wavelength null-field ellipsometry\(^2\).

3. \textbf{IMPLEMENTATION OF NULL-FIELD IMAGING ELLIPSOMETRY}

Ellipsometry has long been used as a non-destructive optical method for determining film thickness and optical properties with submonolayer sensitivity and a high absolute accuracy\(^3\). In a standard ellipsometric measurement, the incident and reflected beams are assumed to be completely polarized and the ratio \(\rho\) of the field reflection coefficient \(r\) for \(p\) (electric field in the plane of incidence) or \(s\) (electric field perpendicular to the plane of incidence) is determined:

\[
\rho = \rho_1 + i\rho_2 = \frac{r_p}{r_s} = \frac{\text{Tan}[\Psi]}{\text{Cos}[\Delta]}
\]

where the magnitude and phase of \(\rho\) is often described in terms of the angles \(\Psi\) and \(\Delta\). Because it is a ratiometric technique, ellipsometry is very precise. In general, the physical parameters of the system (film thickness, dielectric functions, etc.) are determined by forward simulation of the experimental parameters \(\Psi\) and \(\Delta\) from data collected over a suitable spectral range. The technique of using data taken over an interval of wavelengths to characterize the films is
called spectroscopic ellipsometry (SE). Images of thin film structures could be obtained with SE either by rastering a continuous series of spot measurements or by the use of a detector that images a given area of the sample.

A common design of for an ellipsometer is the polarizer-compensator-sample-analyzer (PCSA) configuration in which the incident beam is placed into a specific polarization state by a polarizer and compensator (quarter wave plate). The beam is then reflected from the sample surface and the reflected beam is passed through the analyzer element onto a detector. The NEIS uses this configuration with the detector being a CCD camera that allows for the imaging of the sample.

In a null field imaging system such as NEIS, one uses the capability of a PCSA instrument to set the intensity coming from a part of the field of view to zero. This is accomplished by adjusting the polarizer/compensator pair so that the polarization state of the impinging beam has a phase difference between the p and s polarizations that is the negative of the $\Delta$ in the selected region, a setting that makes the reflected beam linearly polarized, and then adjusting the analyzer to block this linearly polarized beam. Thus, the selected part of the sample with this particular $\Delta$ will appear black, and other parts of the sample where there has been a change in $\Delta$ due to a change in thickness or optical properties will show up with an intensity that is proportional to the difference in $\Delta$ squared, to first order.$^2$

We implemented a single wavelength NEIS based on a 635 nm laser source. In single wavelength ellipsometry, one can only measure two parameters ($\Psi$ and $\Delta$). This is enough to determine the pseudo dielectric function of a substrate. However, for a thin film with unknown index ($n$ & $k$) and thickness, the physical problem is underdetermined. In principle, if it is known that $k$ is zero, then both $n$ and $t$ can be determined. Extensive studies of the dielectric function of carbonatious deposits have been performed in the context of diamond-like coatings.$^4$ A Tauc-Lorentz dielectric function has been found to well represent the absorption of the $\pi-\pi^*$ transitions. The fundamental gap (and thus absorption at 635 nm) can vary significantly with the nature of the film. We have chosen to calibrate the dielectric functions of both substrate and deposit with ex-situ spectroscopic ellipsometry that provides greater precision than the current NEIS system.

We obtained the pseudo optical constants of substrates from the SE measurements by inverting psi and del from unexposed regions. The substrate was a trilayer thin film structure of Mo, Si, and TiO$_2$ on a piece of silicon wafer. This tri-layer substrate has the same surface structure as an EUV lithography multilayer mirror but eliminates the resonance effects that complicate EUV-induced damage studies.$^1$ The measurements reflect the combined optical response of the Si wafer, Mo, Si, and TiO$_2$ layers, and adventitious hydrocarbon. Next a Tauc-Lorentz dielectric function was derived for the deposit by fitting the SE data from the peak of multiple deposits simultaneously, in a multi-sample fashion, to a single overlayer of variable thickness on the substrate. We find the fundamental gap to be $\approx$2.0 eV and the index at 635 nm to be $n=2.09 \pm 0.00$.

The derived dielectric function is consistent with hydrogenated amorphous carbon films with moderate sp$^2$ character. The real index of ~ 2 below the gap indicates a density greater than ‘polymeric’ hydrocarbon. Similar SE studies have recently been reported by Chen, et al.$^5$. They obtain a polymer-like ($n$~1.5, weak absorption) deposit. This indicates that care must be taken in the development of the ellipsometric model as the optical properties of the deposit maybe sensitive to deposition conditions.
4. DESCRIPTION OF THE INSTRUMENT

Figure 1 schematically represents the system as constructed on the octagonal vacuum chamber used for NIST optics lifetime testing. A 635 nm diode laser coupled through a single mode fiber to an aspheric lens collimator is the source. Mounted collinearly with the laser source on the input side is a thin film polarizer and a zero-order quarter wave plate with the fast axis aligned at 45° with respect to the plane of incidence. On the analyzer end we have another thin film polarizer and a CCD camera.

To achieve the best nulling results, the extinction ratio of the polarizer must be high. We measured the rejection our polarizers to be on the order of $10^{-5}$. Additionally, since the phase change $\Delta$ at reflection depends on the angle of incidence, the incident light must be very well collimated to null the signal over the illuminated area of the sample, a requirement favoring the choice of the laser and aspheric collimator. The well-collimated laser beam is incident on the sample at an angle of incidence of 68°.

The CCD is a commercially available CMOS device with 1024 by 1280 pixel format and 8-bit pixel depth. The objective lens on the camera demagnifies the image by a factor of approximately 2.1 so the CCD pixel size of 5.2 µm by 5.2 µm corresponds to approximately 11 µm by 11 µm in the object plane. The CCD output is monitored in real-time with frames selected at periodic intervals stored on a computer for subsequent analysis.

5. DEMONSTRATION OF NEIS PERFORMANCE

To demonstrate the performance of the NEIS, we measured the same EUV-induced carbon films used in determining the dielectric function. The results from the small spot SE measurements on that sample are shown in Figure 2. As can be seen, there are nine islands of carbon film with different thicknesses that were grown under a variety of EUV dose and ambient gas conditions. According to this analysis, the peak carbon film heights of the nine islands range from about 0.6 nm to 2.5 nm. Using the dielectric functions derived from the multi-spot analysis, it was calculated that at 68° angle of incidence and a wavelength of 635 nm, the ellipsometric phase shift $\Delta$ upon reflection is 158.84° for the substrate and 156.49° for a 1-nm thick carbon film on the substrate. This leads to a sensitivity of $\Delta$ to carbon thickness of 2.35° / nm of deposited carbon. This sensitivity will be used in the NEIS measurements using a nulling method to obtain the thickness of each carbon film.
Figure 2. a) Spot-scanned SE image of typical EUV test exposures. Image is 16.6 mm x 10.2 mm; Full color range is 2.7 nm. Features near the bottom of the image are artifacts due to scratches from the substrate mount. b) Line scan through the peak of the indicated spot (2) and through the edge (1). Note the change in scale.

Figure 3 shows a false color rendering of the raw NEIS intensity from a carbon island with peak thickness of about 2.1 nm. To obtain this image, the orientation of the polarizer was adjusted such that the null condition occurred at the bare substrate around the carbon island. As mentioned earlier, the observed intensity profile in the spot is proportional to the square of the carbon thickness.

Figure 3. NEIS image of a carbon contamination spot (1.1 mm x 0.7 mm) on a capped multilayer structure. The value of the carbon thickness determined by using the difference in the values of delta between the substrate and the peak of the carbon deposit was 2.1 nm. This is to be compared to the value of 2.45 nm determined by an SE measurement. The vertical and horizontal line outs are proportional to the intensity forming the image. The thickness in turn is proportional the square root of the intensity.

We characterized the thickness of the center of each carbon island by a nulling method in which one can measure the value of $\rho$ in two locations: a reference location that has no deposited carbon (although there will generally be a native carbon layer, but this is presumed to be reasonably uniform over the sample) and the region with a carbon layer grown by EUV exposure in a contaminating environment. In our apparatus, only the value of $\Delta$ changes appreciably on
reflection, so the signal can be effectively nulled at the reference location and then re-nulled at the contaminated location by changing only the polarizer orientation. The angular change in the polarizer is $\Delta/2$, and the film thickness can then be calculated using the optical constants of the film and substrate. The method has good sensitivity for film thickness and is independent of detector linearity and light intensity fluctuations.

Figure 4 shows the peak thickness of all nine carbon islands measured by SE and the null-method with NEIS. To build a map of carbon thickness on the sample using the null method, one must repeatedly tune the polarizer for each surface location to be studied. This procedure is time-consuming and fails to exploit the inherent parallel data acquisition available from the CCD. Using an off-null method greatly increases the measurement speed by acquiring all the spatially resolved data at one time in the CCD image. The analyzer is set to null the signal from an uncontaminated reference spot. For sufficiently thin films, the thickness $d$ is then linearly proportional the square root of the intensity $I$ recorded by the CCD:

$$d = k\sqrt{I}$$

This approximation is valid if the film thickness less than about 5 nm. Because of the high measurement throughput and ease of this technique, it is preferred for in-situ monitoring of the growth of carbon films during EUV exposure. There are two primary drawbacks to this technique: first, the intensity is directly proportion to laser power and any fluctuation in laser power will induce uncertainty in thickness determination, and, second, the image intensity only provides a relative measurement of thickness. An absolute calibration is required to convert the pixel intensity value to film thickness. For the measurements discussed here, we monitored the laser power and found variation of only a few percent over the time required to measure all nine carbon islands. The required absolute calibration is taken from comparison to the thickness values obtained by SE.

Figure 4. Peak thickness of each carbon island measured by SE and the $\Delta$ measurement from NEIS.

Figure 5 shows the carbon thickness measured by NEIS using both the null and off-null methods as a function of the thickness measured by SE. The lines are a least-square linear fit to each data set. It is remarkable that the best linear fit to these two independent data sets are visually indistinguishable on the plot. For both methods, the standard uncertainty implied by the scatter around the best fit is 0.4 nm. Good agreement with the SE data is indicated by the slope of the best-fit line: $0.9 \pm 0.2$ for both methods; perfect agreement would be indicated by a slope of unity. Using either the null or off-null method, the NEIS provides carbon thickness measurements with a standard uncertainty of 0.4 nm. In our measurements, the median film thickness was 1.9 nm, giving a relative standard uncertainty of about 20%.
Figure 5. The thickness of the carbon film as measured by the NEIS system using the null (red circles) and off-null (blue circles) methods. The uncertainty in the NEIS method is 0.4 nm, and the agreement with the thickness as determined by spectroscopic ellipsometry is excellent. The slope of the best fit lines is 0.9 ± 0.2; perfect agreement is indicated by a slope of unity.

6. SUMMARY

We have demonstrated a simple NEIS system that can be used for the real-time imaging of carbon depositions on EUV optics in a vacuum system. Our measurement results using a test sample showed good spatial resolution with sub-nanometer sensitivity to carbon growth. The uncertainty in film thickness determined by NEIS is 0.4 nm, or about 20% for the films thickness studied here, using ex-situ spectral ellipsometry as a thickness standard. NIST plans to implement NEIS systems to monitor real-time carbon film growth on optics during EUV irradiation as part of our optics lifetime research program.

7. REFERENCES