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EUV Ellipsometry on Mo/Si Multilayers

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Abstract. We investigate polarisation properties of a reflective Mo/Si multilayer system in the EUV range using polarized synchrotron radiation at BESSY-II. The characterization involves reflectivity measurements with s- and p-polarized light as a function of the wavelength for three different angles near normal incidence. The phase retardance is determined near normal incidence for one fixed angle of incidence as a function of the wavelength. As an additional spin-off of the polarimetry measurement the Stokes parameters of the beamline could be determined. With the 8-axis UHV-polarimeter we have measured the complex reflection coefficients for the first time and establish this ellipsometry technique as an additional sensitive probe to characterize and model multilayer optical elements.

1. Introduction

High-reflectivity Mo/Si multilayer coatings operating in near-normal incidence geometry are required for the next generation of EUV-lithography at around 13.5 nm. Up to now such optical coatings are only characterized by a "Reflection over the wavelength" or "Reflection over angle" curve. Usually only the reflection in s-polarization geometry is determined.

Necessary for the optical imaging in EUV-lithography is, however, the complete knowledge of the polarization properties, i.e. the change in phase at the interfaces of a multilayer. At present this information is simulated from coating models. In future EUV-systems with a higher angular load on the mirrors due to the increased numerical aperture the phase behavior of s- and p-polarized light becomes more important. This might have a detrimental effect on the contrast of the illuminated structure and a reality check of the multilayer-model becomes necessary for EUV-lithography. Therefore at-wavelength metrology is an indispensable tool for the characterization of high-quality multilayer optical systems [1].

2. Experiment

The ellipsometry measurements were performed with the BESSY soft-x-ray polarimeter [2] that is extended to allow polarimetry measurements with both optical elements in reflection mode. The principle of the polarimeter is based on the independent rotation of two optical elements around the light axis by the angles β and γ while the reflected intensity is recorded by a polarization insensitive detector (GaAs Schottky photo diode). The first optical element is the retarder, which reflects and introduces a phase shift Δ between s- and p-waves upon reflection. It is realized by a Mo/Si multilayer with an angle of incidence $\Theta_{A.}$ The second optical element is the analyzer with an angle of incidence Θ_γ. It is realized by another Mo/Si multilayer with the Bragg angle near the Brewster angle.

The measurements were performed at the plane grating monochromator beamline PGM-1 [3] connected to the APPLE-II type undulator [4] UE56/2 at the BESSY-II storage ring facility. The spectral resolution is 0.1 eV. A grating of 400 l/mm, an aperture of 2×2 mm at 13 m from source and a fix-focus constant of $c_{ff} = 1.4$ were used. The chosen fix-focus constant value operates in high order suppression. A beryllium filter was set into the beam pass to further reduce the higher order distribution of the radiation. All measured signals are normalized to the ring current. Part of the results has been published elsewhere [5].

3. Results and Discussion

Figure 1 shows the reflectivity measurements for the retarder multilayer in the first order of the Bragg peak. Maximum R_s reflectivity of 66.8% was measured at 13.08 nm, maximum R_p reflectivity is 58% at 13.03 nm. The maximum R_s reflectivity decreases, while the maximum reflectivity in p-geometry R_p gets larger with smaller angles of $\Theta_{A.}$ The difference between R_s and R_p decreases going towards normal incidence, i.e. $\Theta_A=0$, as expected from Fresnel equations.

Slight differences between theory [6] and measurement can be seen regarding peak reflectivity and the peak width. Especially the Kiessig Fringes show significant discrepancy with respect to the theoretical modelling.

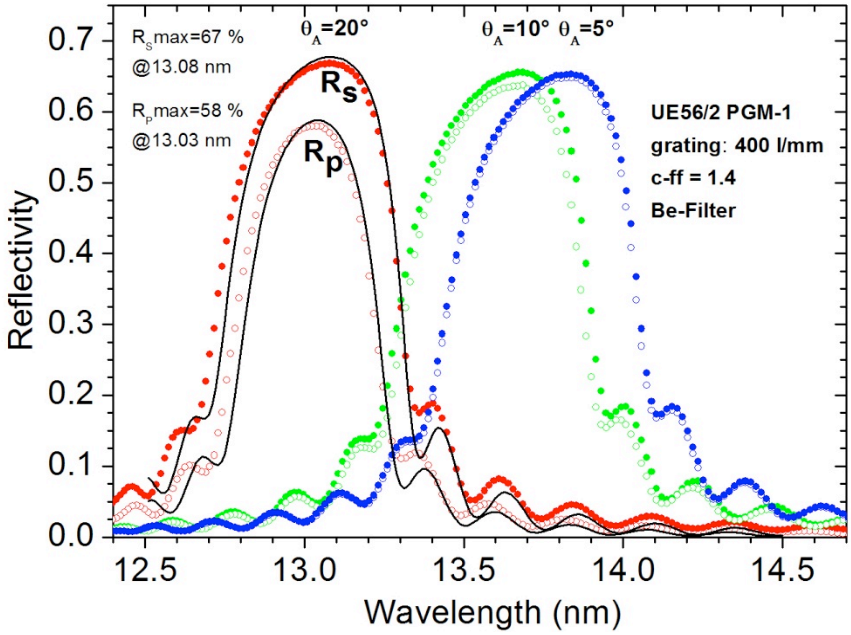

Figure 1. Reflectivity measurements for s- and p-polarized light. The black lines are the theoretical calculations performed at 20° off normal incidence. The incident angle Θ_A, being at 20°, 10° and 5° off normal, was kept fixed while varying the photon energy.

Figure 2 shows the phase retardance Δ as function of the wavelength for the retarder multilayer. The measurements were performed by varying the azimuthal angles β and γ between 0° and 360° for fixed Θ_A=20° and Θ_γ at the relevant Bragg maximum near 45°. The polarization of the radiation was set to right-hand circular polarized light (RCP, σ^-), i.e. the Stokes parameter is S_3=-1 according to our convention [7]. The ratio of R_p/R_s from the reflectivity measurement was set to this fixed value while fitting the polarimetry equation [8]. By that the number of degrees of freedom in the least χ^2-fitting procedure is reduced. This leads to a more reliable result for the fitted phase retardance.

The error bars in Fig. 2 are the 95% block bootstrap confidence intervals. The block bootstrap method is a computational approach that gives measures of uncertainties to sample estimates [9], [10]. The blocks were created by putting eight neighboring measurements according to γ within one block. The reliability of the block bootstrap method has been tested in a simulation.

The maximum phase retardance stays below 0.9 nm. The zero-crossing is at 12.98 nm. The block bootstrap confidence intervals give an accuracy of the phase retardance better than 0.1 nm. Data points taken twice at the same wavelength lie within their corresponding confidence intervals as can be seen exemplary in the gray enlarged area within Fig. 2.

The theoretical phase retardance (black curve) has been calculated on the basis of the same multilayer model as of Fig. 1. Except for the maxima and minima in the range of the Kiessig-fringes the agreement with the experimental data is good.

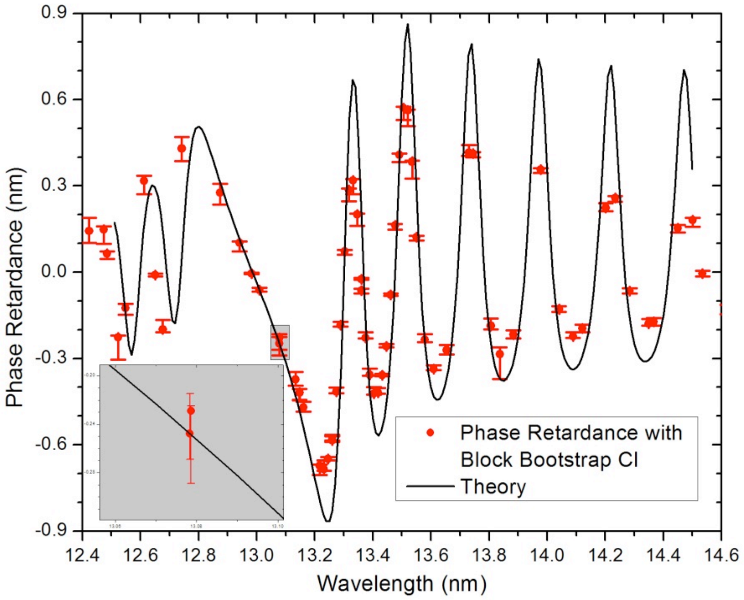

Figure 2. Phase retardance in nm for the retarder Mo/Si multilayer. The grey enlarged area shows two measurements taken at the same wavelength accordingly (phase retardance in radian corresponds to 2π/λ times this value).

As an additional by-product of the polarimetry equation the full characterization of the beamline is accomplished. Figure 3 shows the Stokes parameters of the beamline UE56/2 PGM-1. The proportion of circularly polarized light S_3 decreases going toward longer wavelengths, which is consistent with the undulator settings.

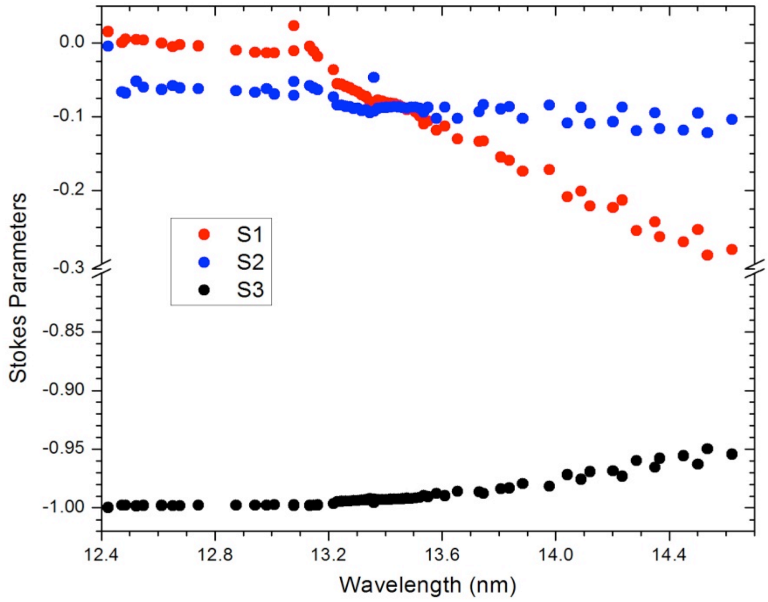

Figure 3. Stokes parameters determined from the polarimetry measurement of the UE56/2 PGM-1 beamline. Reduction is due to tuning range limitation of UE56 in circular mode.

The average Stoke parameter S_3 describing circular polarized light, within the tuning range of UE56 undulator, is -0.9980 with a standard deviation of 0.0005. Going beyond the tuning range, located at 13.05 nm, the linear polarized light contribution increases contrary to the circular mode.

4. Summary

We characterised a Mo/Si multilayer in the EUV range with polarised synchrotron radiation. Differences can be seen comparing the theoretical calculation and the measurement for the reflectivity as well as the phase retardance. The modelling therefore does not describe the multilayers in a satisfactory way.

The ellipsometry technique is an additional sensitive probe to characterize and model multilayer optical elements and enables complete at-wavelength characterization. Measurement of complex reflection coefficient enables a more refined modeling of multilayer, the interdiffusion layers and its interface structure. The direct measurement of the phase retardance enables a comparison to the theory to ensure a low wavefront error and to guarantee proper imaging resolution.

The complete polarization state of the beamline UE56/2 PGM-1 in the EUV range could be determined as an additional benefit from the polarimetry measurement.

5. References

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