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# An assessment of yttrium optical constants in the EUV using Mo/Y multilayers designed as linear polarizers

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## ABSTRACT

We have produced and characterized Mo/Y multilayers designed as linear-polarizers for use near  $\lambda \sim 8$  nm. By depositing these films directly onto silicon photodiodes, we are able to measure both reflectance and transmittance in the EUV using synchrotron radiation. These measurements have been used to access the accuracy of yttrium optical constants in this wavelength range. We describe our experimental results and discuss the prospects for the future development of efficient EUV polarization elements.

## 1. INTRODUCTION

Mo/Y multilayers having high reflectance at normal incidence have been developed recently in the 8-12 nm wavelength region.<sup>1,2</sup> An important application of these coatings is in solar imaging and polarimetry at 9.4 nm where line emission of Fe XVIII is observed.<sup>3</sup> Our research is directed therefore at the production of Mo/Y multilayers, for use as reflectors as well as for efficient polarizing elements in the EUV.

The design of such multilayers in this wavelength range relies on the accuracy of the optical constants of the constituent materials (i.e. molybdenum and yttrium). While there is now good agreement in the measured optical constants for molybdenum,<sup>4,5</sup> the optical constants of yttrium have only recently been measured.<sup>6</sup> Part of our research is thus focused on an assessment of yttrium EUV optical constants.

To this end, we have produced prototype Mo/Y linear polarizers that operate in the EUV region, and by depositing these films directly onto silicon photodiodes, we have measured the reflectance and transmittance as a function of both wavelength and angle. Comparison of the measured to the calculated response allows us to investigate the accuracy of the yttrium optical constants.

## 2. MO/Y MULTILAYERS AS POLARIZATION ELEMENTS

Polarimetry may be the key to the puzzling questions about solar magnetic fields and solar heating. This technique requires two major optical elements, a linear-polarizer and a phase retarder. A linear-polarizer is a device that produces linearly polarized light, independent of the polarization state of the incident light. A retarder is a device that produces a specific phase shift between the two orthogonal components of the incident electric field. As shown in Fig. 1 for an ideal polarimetry setup, the incident beam is allowed to propagate to a rotating phase retarder followed by a rotating linear polarizer and a silicon photodiode detector. The Stokes parameters ( $S$ ), which describe the polarization state of the incident beam, and the polarization characteristics of the phase retarder, can be determined based on the measured intensity as a function of the azimuth rotation angles  $\chi$  (for phase retarder) and  $\eta$  (for linear polarizer). Detailed analysis of this technique can be found elsewhere.<sup>8-9</sup> Phase retarders and linear polarizers are widely available in the visible, but until now these elements are difficult if not impossible to produce in the EUV wavelength region. Our interest is, therefore, to develop these polarization elements based on the principle of high reflectance multilayer mirrors.

A multilayer mirror consists of a periodic stack of alternating layers of two materials with different refractive indices. The peak wavelength ( $\lambda$ ) depends on the multilayer period or bilayer thickness ( $\Lambda$ ), and the incident angle according to the Bragg equation. The multilayer response can be further optimized by adjusting the relative layer thickness ratio  $\Gamma$  (defined as the thickness of the absorber layer divided by the period), and by adjusting the number of bilayers  $N$ . To maximize the polarization effect, the multilayer period must be chosen so that the peak wavelength is

tuned for the Brewster angle. At this incident angle, only the electric field vibrating normal to the plane of incidence (s-polarized light) is reflected while the electric field vibrating parallel to the plane of incidence (p-polarized light) is mostly absorbed and/or transmitted. For a perfect linear-polarizer, the p-polarized reflected beam ( $R_p$ ) should vanish, and the polarization ( $P$ ) defined as  $(R_s - R_p) / (R_s + R_p)$  is equal to one (100%). Complementary, the opposite

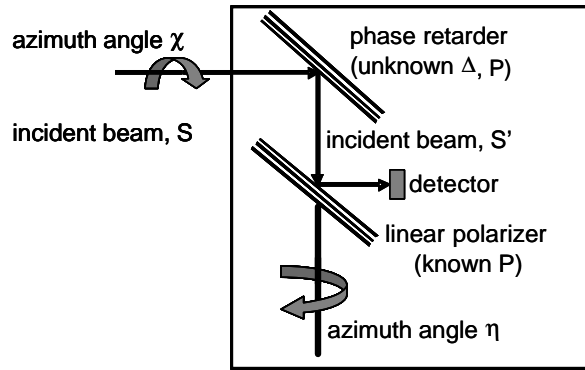


Figure 1. Ideal polarimetry setup with a rotating phase retarder of unknown polarization ( $P$ ) and retardation ( $\Delta$ ) and a rotating linear-polarizer of known polarization. Both polarization elements are shown for operation in reflection.

polarization effect is enhanced in transmission resulting in high  $T_p$  and low  $T_s$ . Therefore, multilayer linear-polarizers can be operated in either reflection or transmission, depending on the preferred geometry of the optical systems.

Typically a significant amount of phase retardation occurs only near the Brewster angle. Approximately 0 degree and 180 degree phase differences between the s-polarized and p-polarized components are expected near normal- and grazing-incidence, respectively. The 180 degree phase retardation is ideal for use as a half-wave plate, a device that can be used to rotate the polarization plane of linearly polarized light about the incident beam axis. However, it is generally preferable to use a so-called quarter-wave plate, which gives a 90 degree phase difference, to facilitate the characterization of circularly-polarized light. Based on the available optical constants of molybdenum and yttrium, the maximum phase retardation expected for Mo/Y multilayers is much less than 45 degree in both reflection and transmission at 9.4 nm. However, the accuracy of this calculation and the performance of Mo/Y multilayers as phase retarders have not yet been determined experimentally.

### 3. EXPERIMENT

Mo/Y multilayers were fabricated by dc-magnetron sputtering at Lawrence Livermore National Laboratory, and at Columbia University. For the case of linear polarizers, the coatings were designed with peak response at 8.2 nm (where  $\Lambda = 6.0$  nm,  $\Gamma = 0.47$ , and  $N = 75$ ) instead of 9.4 nm to determine the polarization limit at short wavelengths where reflectance closer to the theoretical maximum is rather difficult to achieve. The deposited layer thicknesses were determined by X-ray reflectometry using Cu-K $\alpha$  radiation. The multilayers were deposited directly onto silicon photodiodes. In this way, the transmittance and reflectance of the films can be characterized simultaneously (by measuring both the transmitted beam intensity with the underlying photodiode and the reflected beam intensity with a separate detector) without requiring the production of fragile freestanding flat samples. The multilayer-coated photodiode, if optimized as a linear polarizer operating in transmission, conveniently serves as a compact analyzer (combination of linear polarizer and detector).

The multilayers were characterized using the Naval Research Laboratory beamline X24C at the National Synchrotron Light Source at Brookhaven National Laboratory. The dual-element monochromator, comprising a gold coated mirror and a 600 l/mm grating, provides an EUV beam with spectral resolution of approximately 400. A boron filter was used to reduce higher harmonic contamination; the boron  $K$  edge was used to calibrate the wavelength scale in the 8 nm range. Since the incident beam is not perfectly polarized in the horizontal plane, the degree of linear

polarization (90%) independently determined from a polarization study at 13.5 nm was assumed throughout the wavelength range explored in this work.<sup>10</sup> The reflectometer at this beamline can be rotated 90 degree about the beam

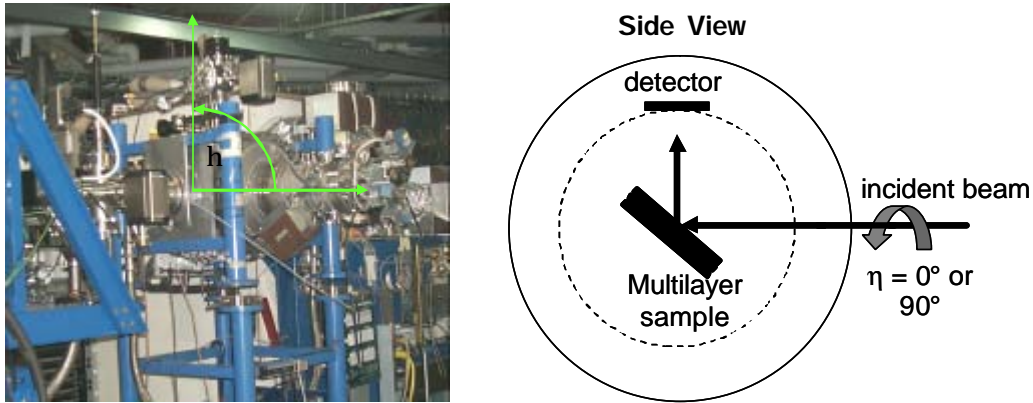


Figure 2. Layout of the reflectometer at the National Synchrotron Light Source beamline X24C for multilayer calibration in s-polarization ( $\eta = 90^\circ$ ) and p-polarization ( $\eta = 0^\circ$ ).

axis, and the reflectance and transmittance of each multilayer can be characterized in both s-polarization and p-polarization configurations (See Fig 2). To obtain the phase information of multilayers optimized as phase retarders, it will be necessary to modify the reflectometer so that a rotating phase retarder can be inserted before a rotating linear-polarizer, as illustrated in Fig. 1. This upgrade of the reflectometer is still underway. The remaining discussion is therefore limited to the performance of Mo/Y multilayer linear-polarizers.

#### 4. RESULTS

The reflectance and transmittance of a representative Mo/Y multilayer were measured as a function of wavelength at various incident angles ranging from 5 degree to 50 degree from normal using s-polarized and p-polarized synchrotron radiation. The results, after correcting for the degree of linear polarization of the incident beam, are shown in Fig. 3. In reflection,  $R_s$  and  $R_p$  are approximately identical near normal incidence. The peak wavelengths shift towards shorter wavelengths as the incidence angle increases. The polarization increases as the Brewster angle is approached: at 45 degree we measure  $R_s = 29.37\%$  and  $R_p = 0.75\%$ . The maximum polarization for this Mo/Y multilayer operating in reflection was thus determined to be  $P = 95\%$  at  $\lambda = 8.25$  nm.

In transmission we measure  $T_s = 1.35\%$  and  $T_p = 7.56\%$  at 45 degree. As a result, we determine a maximum polarization of  $P = 70\%$  at  $\lambda = 8.19$  nm. This value is probably too low for practical use as a linear polarizer. It may be possible to improve the polarization in transmission by increasing the number of bilayers, thus increasing  $R_s$  and reducing  $T_s$ .<sup>11</sup> Nevertheless, this increase in polarization comes at the expense of a decrease in efficiency.

In order to investigate the accuracy of the yttrium optical constants available in the literature, fits to the measured reflectance and transmittance data were calculated using molybdenum optical constants from CXRO, and yttrium optical constants from both Sae-Lao *et al.* and CXRO. Only the period  $\Lambda$  and the thickness ratio  $\Gamma$  were allowed to vary in the model. The best-fit values obtained using both yttrium optical constants were found to be the same:  $\Lambda = 5.935$  nm and  $\Gamma = 0.47$ . However, the peak reflectance predicted from both yttrium data sets was always higher than the measured values (See Figure 4). We found that equally good improvements to the fits could be obtained with either set of yttrium optical constants by adjusting fit parameters describing the surface roughness, surface contamination, and interface imperfections. The main difference between the two fits is that the CXRO data requires larger interface widths relative to the Sae-Lao *et al.* values, reflecting the smaller extinction coefficient values in the CXRO data set. There is no method to verify the absolute accuracy of these surface/interface parameters thus far.

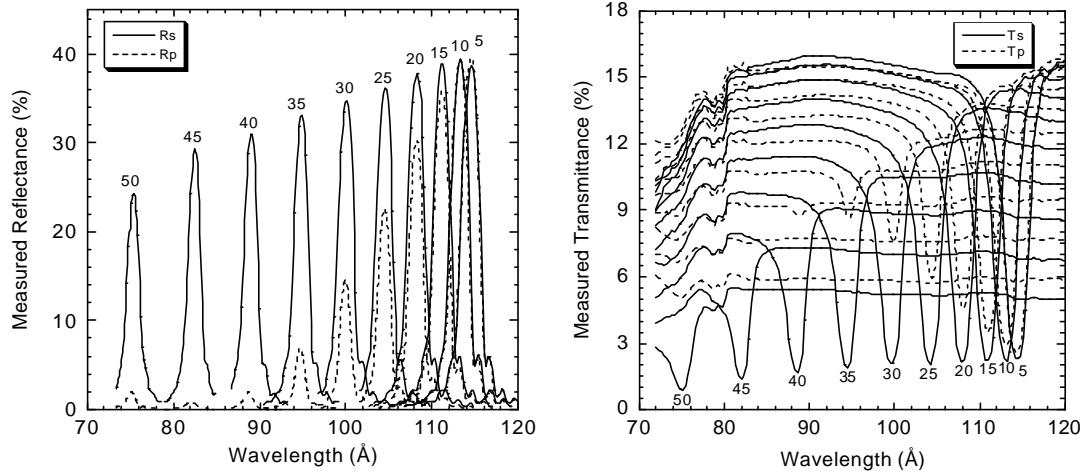


Figure 3. The measured reflectance and transmittance of the Mo/Y multilayer linear-polarizer at incident angles ranging from 5 degree to 50 degree from normal.

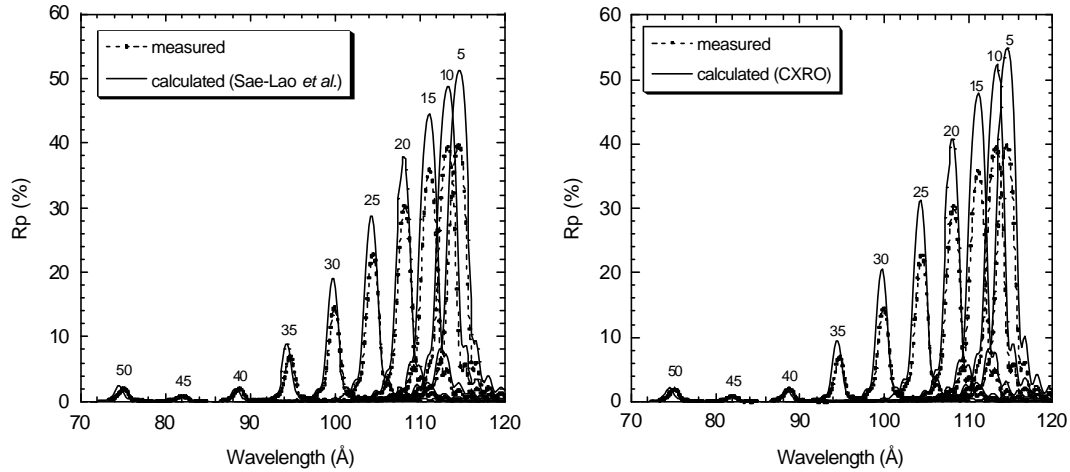


Figure 4. The fits to the measured p-polarized reflectance ( $R_p$ ) of the Mo/Y multilayer linear-polarizer using molybdenum optical constants from CXRO and yttrium optical constants from Sae-Lao *et al.* (left) and CXRO (right).

On the other hand, the fits to the transmittance curves are rather insensitive to surface contamination and interface imperfections. Therefore the transmittance fits can be used to access the accuracy of the optical constants used in the calculations independent of any uncertain multilayer imperfections. As shown in Fig. 5, better agreement is obtained from the fits to the transmission data using the optical constants from Sae-Lao *et al.* The inaccurate degree of polarization of the incident beam adds uncertainty to the measured reflectance and transmittance values, but these systematic errors cannot explain the large differences between the measured and calculated CXRO transmittance values. Furthermore, the fits to the transmission data cannot be improved significantly even by adjusting the interface widths to extreme (and highly improbable) values.

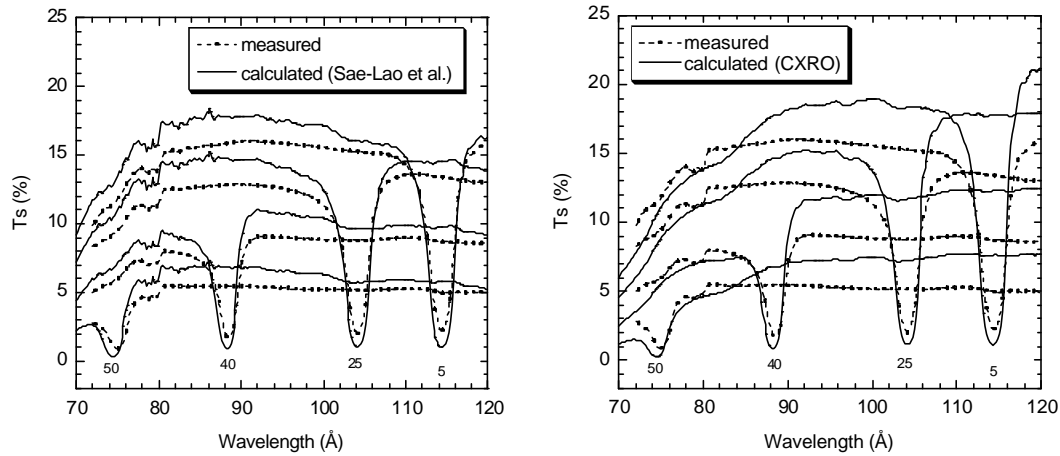


Figure 5. The fits to the measured s-polarized transmittance ( $T_s$ ) of the Mo/Y multilayer linear-polarizer using molybdenum optical constants from CXRO and yttrium optical constants from Sae-Lao *et al.* (left) and CXRO (right). Only the transmittance curves at incident angles of 5 degree, 25 degree, 40 degree, and 50 degree are shown for clarity.

## 5. SUMMARY

We have demonstrated the use of Mo/Y multilayers as linear-polarizers at  $\lambda \sim 8$  nm. The polarization obtained from a Mo/Y multilayer was  $P = 95\%$  in reflection and 70% in transmission. It will be necessary to increase the polarization in transmission of Mo/Y multilayers, in order to produce practical linear-polarizers in this wavelength range operating in transmission mode.

The accuracy of available yttrium optical constants was investigated by attempting to fit the measured reflectance and transmittance of the Mo/Y polarizers with available optical data. Both sets of yttrium optical constants available in the literature accurately predict the peak wavelengths of the Mo/Y multilayers studied here. However, although neither data set can be used to accurately predict the peak reflectance and peak transmittance values simultaneously using a single set of multilayer parameters (nor can this discrepancy be attributed to systematic measurement errors), we find that the data from reference [6] gives somewhat better agreement overall. A planned upgrade to the X24C beamline will allow for the measurement of the reflected and transmitted phases of multilayer polarizing elements. This information thus will help to better assess the accuracy of optical constants.

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