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Structural characterization and lifetime stability of Mo/Y extreme ultraviolet multilayer mirrors

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Abstract

We observe a dramatic dependence of the extreme ultraviolet (EUV) reflectivity of Mo/Y multilayers on the oxygen content of yttrium. This is explained by a change in microstructure, increase in roughness of the Y layers and not by an increase in absorption due to oxygen in Y layers. We find best reflectivity of 38.4% is achieved with an oxygen content of 25%, which reduces to 32.6% and 29.6% for multilayers manufactured from oxygen free yttrium and 39%-oxygen yttrium, respectively. These results highlight the importance of experimentally determined optical constants as well as interface roughness in multilayer calculations.

In addition, lifetime stability of Mo/Y multilayers with different capping layers was monitored for one year. The molybdenum- and palladium-capped samples exhibited low surface roughness and about 4% relative reflectivity loss in one year. The relative reflectivity loss on yttrium-capped sample (yttrium with 39% oxygen) was about 8%. However, the reflectivity loss in all three capping layers occurred within the first 100 days after the deposition and the reflectivity remained stable afterwards.

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1. Introduction

Mo/Y is known as the best performing multilayer mirror at wavelengths shorter than the silicon *L* absorption edge (12.4 nm) where well known Mo/Si multilayers can no longer operate. Owing to its outstanding reflectance at around 9.4 nm, Mo/Y multilayer is selected as one of the coatings for the Atmospheric Imaging Assembly (AIA) telescopes on board the upcoming Solar Dynamic Observatory (SDO) Mission.[1] The Atmospheric Imaging Assembly is composed of four science telescopes. These telescopes will image the solar atmosphere in multiple wavelengths, including the Fe XVIII emission line at 9.392 nm, simultaneously to link the solar atmospheric changes to surface and interior changes.

Contrary to extensive studies of Mo/Si multilayers, not much research has been done on Mo/Y multilayers. The maximum achievable reflectance of Mo/Y multilayers reported by Montcalm *et al.* was 21.3%, 34.7%, and 46.1% at wavelengths of 7.9 nm, 9.7 nm, and 11.4 nm, respectively.[2] Later work by Sae-Lao *et al.* on the coating of a diffraction grating with Mo/Y multilayer, reported the reflectance of 34.6 % at 9.2 nm.[3] These results are encouraging, but the reflectance of 34.7% at 9.7 nm, for example, is only 77% of the ideal reflectance calculated using the most up to date optical constants of molybdenum[4] and yttrium.[5] Parameters such as interface roughness/interdiffusion and surface roughness/oxidation were frequently used in the modeling of experimental reflectance data, but no work has been done to examine the real cause of this discrepancy. A better understanding of Mo/Y structural properties may offer the answers and methods leading to improved reflectance which is closer to the ideal reflectance value.

In addition to understanding the microstructure of the as-deposited Mo/Y multilayers, the knowledge about their long-term stability is critically important for their use in spaceflight instruments. The study by Montcalm *et al.* showed approximately 10% relative loss in reflectance within one week after deposition.[2] Because the multilayers were stored in air, the reflectance loss was believed to be attributed to surface contamination and/or oxidation. The reflectance loss was more dramatic in the multilayers terminated with yttrium, leading to a conclusion that molybdenum was a better capping material than yttrium. However, his measurement was performed seven days after the deposition which was too short to truly test the lifetime of Mo/Y multilayers. Hence further studies are required to validate their long term reflectance and structural stability. Moreover, multilayers used on spaceflight instruments require a protection layer that can prevent the reflectance drop due to surface oxidation and contamination.

In this work, the structural characterization and lifetime stability of Mo/Y multilayers are reported. Due to difficulty in obtaining high purity yttrium target for this study, Mo/Y multilayers were fabricated using three different yttrium targets quoted for 99.9% purities from three manufacturers: ACI Alloys (*A*), Plasmaterial Inc. (*B*), and Research and PVD Materials Corp. (*C*). The same molybdenum target quoted for 99.999% purity from Angstrom Science Inc. was used for all multilayers. The purity of yttrium targets and their deposited films were verified using Rutherford Backscattering (RBS) method. The structures of Mo/Y multilayers were studied in detail using small- and large-angle x-ray diffraction (XRD), transmission electron microscopy (TEM), and atomic force microscopy (AFM). These techniques enabled correlation of the multilayer

microstructure with the EUV normal-incidence reflectance results. Lifetime stability of Mo/Y multilayers with molybdenum, yttrium, and palladium capping layers was investigated. Palladium was added to capping materials because it has good optical contrast with yttrium and does not tarnish in air.[6]

2. Multilayer Fabrication

Mo/Y multilayers were fabricated using an ultra high vacuum magnetron-sputtering deposition system. The base pressure in this cryogenic-pumped system was $2x10^{-9}$ Torr prior to deposition. An ultra-high purity argon gas was used at a constant pressure of 2.0 mTorr during deposition. The operating powers for molybdenum and yttrium were regulated at 50 W. Substrates of 1cm x 1cm in size were cut from a polished single-crystal Si (100) wafer. Typical multilayers consisted of 100 Mo/Y bilayers where the first layer was yttrium and the last layer was molybdenum. All multilayers were designed to reflect at a wavelength of 9.4 nm and were labeled with *A*, *B*, or *C* corresponding to different yttrium targets from three manufacturers.

To obtain wavelength calibration for each target, a set of multilayers of various thickness combinations was deposited on a silicon wafer substrate. XRD measurements were performed with a copper K_a (0.15406 nm) source to determine the multilayer periods. The period thickness (Λ) was calculated based on the modified Bragg's equation[6] using the measured angles of the mth-order (m = 1, 2,…, 6) diffraction peaks. With known deposition times and period thicknesses, the deposition rates of molybdenum and yttrium were determined from the slope of thickness versus time. Due to interface formation, a parameter $\Delta\Lambda$ was included in a two-layer model, $\Lambda = d_{Si} + d_{Mo} + \Delta\Lambda$, where a positive $\Delta\Lambda$ value means expansion and a negative $\Delta\Lambda$ means contraction of the interlayer

thickness. In Mo/Y multilayers, the $\Delta\Lambda$ values were always negative and less than 0.1 nm, suggesting a small multilayer period contraction.

For the capping layer study, Mo/Y multilayers with molybdenum, yttrium, and palladium capping layers were compared. The capping layer thicknesses for molybdenum and yttrium were the same as molybdenum and yttrium thicknesses within the multilayer. A series of multilayer samples was made to find the optimum palladium thickness where only the capping layer thicknesses were varied from 2 nm to 6 nm.

3. Multilayer Characterization

3.1 Absolute EUV Reflectance

The EUV reflectance was measured using the reflectometer at the Advanced Light Source beamline 6.3.2 at Lawrence Berkeley National Laboratory. A detailed description of this beamline can be found elsewhere.[8] The normal-incidence (3° off normal) reflectance obtained from three representative samples *A*, *B*, and *C* was 32.6% at 9.27 nm, 38.4% at 9.48 nm, and 29.6% at 9.46, respectively (Fig.1). Slight differences in the peak wavelengths of these three multilayers are mainly due to the accuracy of the deposition rate calibrations. However, the significant differences in the reflectance of the three multilayers could not be explained by their slightly different wavelengths. Since all three multilayers were fabricated using the same design parameters and the same deposition conditions, the most likely cause for the reflectance differences is the purity of yttrium targets.

3.2 Rutherford Backscattering (RBS)

To verify the aforementioned hypothesis regarding the quality of these yttrium targets, RBS measurements were performed on three magnetron-sputtered yttrium films

from targets *A*, *B*, and C. The films were bombarded with 2.3 MeV He^{++} ions and the energies of the backscattered ions related to the depth and the mass of the target atoms were measured. The RBS results revealed <3 %, 25 ± 3 % and 39 ± 3 % atomic oxygen content in the yttrium films from targets *A*, *B*, and *C*, respectively. Since all three films were deposited under the same conditions and were kept in air for several days before characterization, it was concluded that the amount of oxygen present in the yttrium films from targets *B* and *C* was originally incorporated in the targets and was not a result of film oxidation during or after the deposition. The high amount of oxygen assimilated in the *B* and *C* targets may be explained by the vacuum hot pressing method applied in the target fabrication. This method is not as efficient to remove oxygen as the vacuum arc melting method applied in the fabrication of target *A*. In addition to oxygen, it was found that argon, tantalum, and tungsten in a total amount of less than 1% were present in all three yttrium films. The presence of argon was attributed to the argon processing gas used during the deposition. The presence of tantalum and tungsten was attributed to the target fabrication processes. The yttrium film densities were determined to be 4.430 g/cm^3, 4.402 g/cm^3, and 4.088 (with ± 0.18 g/cm^3 accuracy) for samples that were fabricated from targets *A*, *B*, and C, respectively.

Based on yttrium compositions and densities obtained by the RBS measurements, the new EUV/x-ray optical constants for each yttrium target and the predicted EUV reflectance for multilayers *A*, *B*, and C were calculated with IMD.[9] The following structure parameters optimized for a Mo/Y multilayer with 9.4 nm peak reflectivity were applied: the period thickness Λ = 4.78 nm, the number of bilayers N = 100, and the thickness ratio of the absorber layer (molybdenum) to the period thickness Γ = 0.425. The

calculated reflectance is plotted in Fig. 2. These theoretical calculations predict that the multilayer with more oxygen should have lower reflectance than the one with less oxygen, as would be expected due to increasing absorption with oxygen content. However, instead of a trend of increasing reflectance in the order *C*, *B*, *A* as predicted by theory, our measurements showed an increasing trend in the following order: *C*, *A*, *B* (See Fig. 1). It should be noted that the reflectance of sample *B* is in fact the highest reflectance obtained to date from a Mo/Y multilayer for the wavelength around 9.4 nm. The highest reflectance multilayer, sample *B* which contains 25% of oxygen, indicates that oxygen contamination is not the only quality factor for the reflectance performance of Mo/Y multilayers and characterization with other methods is needed to further investigate this issue.

3.3 X-Ray Diffraction (XRD)

The small-angle XRD spectra of the representative multilayers *A*, *B*, and *C* were measured and plotted in Fig. 3. All three samples exhibit a high-quality multilayer structure. A series of strong diffraction peaks indicates sharp interfaces between molybdenum and yttrium, in good agreement with a small interface contraction mentioned previously (See Section 2). The periods of multilayers *A*, *B*, and *C* were determined to be 4.72 nm, 4.83 nm, and 4.85 nm, respectively.

It is evident that the different amounts of oxygen present in the yttrium layers affect the reflectance performance of Mo/Y multilayers differently. At low incident angles, prior to the first order Bragg peak, the x-ray beam penetrates only a few topmost layers of the multilayer. The XRD reflectance in *A* (< 3% oxygen) is higher than in *B* (25% oxygen) and that of *B* is higher than in *C* (39% oxygen) which is in good agreement

with their optical properties. At high incident angles, where x-rays penetrate deeper into the sample, it appears that some structural modification occurred during the multilayer growth process so the overall reflectance performance of these samples follows the same trend (C, A, B) obtained at EUV wavelengths, as was discussed in Section 3.1.

Since we already excluded any substantial interdiffusion on interfaces, the only other parameter left that could affect the reflectance is the interface roughness. To study the interface roughness, rocking scans were performed on each sample around the first and the second order Bragg peaks by fixing the detector at an angle $2\theta = 2\theta_{Bragg}$ and scanning the sample angle θ symmetrically around θ_{Bragg}. The rocking curves can provide useful information about interface roughness. As can be seen in Fig. 4, scattering due to roughness is present in all samples according to substantial scattered intensities around their specular peaks. The scattered intensity of sample *B* is lower than in *A* and that of *A* is lower than in *C* for both first and second order Bragg peak. The rocking scan results show a trend of an increase in roughness in the order: *B*, *A*, *C*, which is consistent with the EUV reflectance results.

To determine the roughness values, we fitted the XRD spectra of three representative multilayers using the Levenberg-Marquardt (MINPACK-1) fitting algorithm[9] available within IMD. The surface roughness and interface roughness (both Mo-on-Y and Y-on-Mo interfaces) of each multilayer were allowed to vary independently because a reasonably good fit could never be achieved when these parameters were set equally. Fig. 5 shows the best fits with the fitted parameters summarized in Table 1. The trend of an increase in surface/interface roughness in the order: *B*, *A*, *C* is in good agreement with the trend of an increase in scattering previously

obtained from the rocking scans. Other fitted parameters such as Λ and Γ, were also similar to the designed values.

The structure parameters determined through the XRD fits of the three representative Mo/Y multilayers were used to calculate their respective EUV reflectance. Fig 6 shows a comparison between the re-calculated EUV reflectance with the measured values of multilayer *A*, *B*, and *C*. The plot in linear scale shows the agreement between the measured and calculated peak reflectance values. As shown, the calculated reflectance of samples B and C is 10% and 13% lower as compared to experimental data, while the calculated value for sample A is 7% higher than the measured value. The most probable cause for these differences could be the errors in the RBS compositions and densities where 0% (4.43 g/cm^3), 25% (4.402 g/cm^3) and 39% (4.088 g/cm^3) were assumed in the reflectance calculations for the oxygen content (density) of the yttrium films of target A, B, and C, respectively. The plot in log scale shows that using these fitting parameters for oxygen, we get very good agreement for all the oscillations in the measurements. Based on fitted parameters in Table 1, we conclude that Mo/Y multilayers made out of an yttrium target with 25% atomic oxygen content has sharper, smoother surface/interfaces, and higher reflectance, as compared to multilayers made out of pure or highly oxidized yttrium targets.

More XRD measurements were performed at larger incident angles to search for any other changes in crystalline structure or composition that could affect the roughness in these multilayers. Large-angle XRD scans were done with and without the sample so that any diffraction peaks due to the experimental setup can be identified and disregarded. Fig. 7 shows a comparison of the large-angle XRD spectra of the *A*, *B*, and *C* samples

over the angular range of $2\theta = 10^\circ$ to 100°. Several broad peaks of polycrystalline materials were detected. To index all the peaks, we surveyed all possible diffracting planes of yttrium, molybdenum, and their oxides based on the powder diffraction (PDF) data. This method includes all the diffraction peaks from a powder specimen. Since crystallites are randomly oriented in a powder specimen, the maximum intensities are expected from the Y (101) and Mo (110). The crystalline peak at $2\theta = 31.19^\circ$ in sample *A* which corresponds to Y (002) implies that the high purity yttrium film is strongly textured. The peak at $2\theta = 32.35^\circ$ in sample *B* corresponds to Y (101). The unknown peak at $2\theta = 30.78^\circ$ in sample *C* does not belong to crystalline yttrium, molybdenum, or any of their known compounds. Other peaks observed in all three samples correspond to molybdenum, e.g. Mo (110) at $2\theta = 40.52^\circ$, Mo (200) at $2\theta = 58.61^\circ$, Mo (211) at $2\theta = 73.68^\circ$, and Mo (220) at $2\theta = 87.59^\circ$. It is possible that the unidentified peak in sample *C* at $2\theta = 30.78^\circ$ is yttrium that was shifted toward lower angle. This line shift may be due to either a uniform strain created by sufficiently high amount of oxygen atoms (39%), which results in larger *d*-spacing (*d* increase from 0.276 nm for $2\theta = 32.35^\circ$ to 0.292 nm for $2\theta = 30.78^\circ$), or due to Y_2O_3 formation. For the latter reason, the change in the peak position to $2\theta = 30.78^\circ$ in sample *C* could be a result of overlapping peaks of Y_2O_3 (222) at $2\theta = 29.15^\circ$ and Y (101) at $2\theta = 32.35^\circ$.

To estimate the minimum grain sizes of yttrium and molybdenum in the multilayer growth direction, we measured the peak widths and calculated the sizes based on the Scherrer formula, $t = \frac{0.9\,l}{b\cos q_B}$, where t is the particle size in a direction perpendicular to the plane of Bragg reflection, b is the peak width measured in radians (in

terms of 2θ) at the half of the maximum intensity, and q_B is the Bragg peak angle. Using the above equation, the yttrium grain sizes are approximately 2.4±0.5 nm in all three samples. The grain size seems to be correlated with the yttrium layer thickness of about 2.8 nm and it is likely that this is the main constraint of yttrium crystallite size in the multilayer growth direction. If yttrium in sample *C* is a combination of yttrium and yttrium oxide, it would be impossible to distinguish them since their grain sizes would still be the same in this direction. For the case of molybdenum, the highest peak intensities were always obtained from Mo (220) in these samples. Therefore molybdenum in all three samples is strongly textured. The grain size of molybdenum crystallites was estimated using the peak widths of Mo (200) because these peaks were clearly resolved in every sample. The broadening effect due to the XRD instrument is also smaller at lower incident angles. The average grain size is about 1.6±0.5 nm in all three samples where the molybdenum nominal layer thickness is 2.0 nm.

These results suggest that having oxygen in the yttrium layer might affect the orientation of yttrium crystallites, but does not significantly change the crystallite sizes of either yttrium or molybdenum in the multilayer growth direction. Without oxygen, the yttrium crystallites are strongly textured (as in *A*) and the Mo-Y interfaces seem to be rougher than the interfaces with randomly oriented yttrium crystals (as in *B*). The 25% atomic oxygen content seems to be insufficient for yttrium to form an oxide, but rather improves the crystalline structure and results in high EUV reflectance (38.4%) that was measured for sample *B*. However, when the oxygen concentration is as high as in sample *C* (39% oxygen), the yttrium microstructure changes either due to increase in yttrium *d*-spacing or due to Y_2O_3 formation. Both scenarios lead to an increase in interface

roughness of the multilayer, consistent with the lower EUV reflectance (29.6%) that was measured for sample *C*.

3.4 Transmission Electron Microscopy

High resolution TEM is a standard imaging technique used to check the quality of multilayers and their interfaces. Further structural characterization of Mo/Y samples *A* and *C* was conducted with TEM to obtain additional evidence of the layer structures. High resolution TEM images of the Mo/Y cross section are shown in Fig. 8 for samples *A* (< 3% oxygen) and *C* (39% oxygen). In general, relatively sharp interfaces (no intermixing layer at the molybdenum and yttrium interfaces) could be observed in both samples. This is consistent with the phase diagram data of the Mo-Y system that shows no mixture phase of these two materials at any temperature and a positive enthalpy of mixing[10] (ΔH = +35 kJ/mole in Mo/Y system). A major difference observed between these images is that yttrium grains in sample *A* are much smaller than those in sample *C*, in the direction normal to the multilayer growth direction. The presence of a high amount of oxygen (39%) in the yttrium target *C* is correlated with the formation of large crystallites in the direction perpendicular to the multilayer growth while the interfaces in sample *A* appear smoother.

4. Lifetime Stability of Mo/Y Multilayers with Various Capping Layers

Mo/Y multilayers with molybdenum, yttrium, and palladium capping layers were studied. Mo/Y multilayers discussed in this section utilize only the yttrium target *C* (39% oxygen). For the case of molybdenum and yttrium, the capping layer thicknesses were fixed to 2.1 nm for molybdenum and 2.7 nm for yttrium, the same thickness as the thickness of these two elements within the multilayer. For palladium, however, a set of

samples was made in which the palladium thicknesses varied from 2 nm to 6 nm. Fig. 9 shows the measured EUV reflectance as a function of palladium thickness. Superimposed is the calculated EUV reflectance. Based on these results, we chose to study the stability of the 5-nm-thick palladium capping layer as it exhibited the highest EUV reflectance.

Surface roughness of the capping layer does not significantly affect the Mo/Y multilayer reflectance. Nevertheless, investigation of the capping layer surface may reveal information regarding the quality of the coverage and degree of protection that the capping material offers to the multilayer structure underneath. The surface roughness of the molybdenum-, yttrium-, and palladium-capped multilayers and also of a typical bare, superpolished silicon substrate (used to deposit all three multilayers) was analyzed with AFM. A typical Si (100) substrate has high frequency roughness of about 0.1 nm rms. The surface roughness of the molybdenum-, yttrium-, and palladium-capped multilayers was 0.17 nm, 0.46 nm, and 0.18 nm, respectively, with an accuracy of ± 0.02 nm. Assuming that the roughness of the Mo/Y multilayer underneath the capping layer was the same in all three samples, the yttrium capping layer is much rougher than the molybdenum and palladium capping layers.

The EUV reflectance of these various capped Mo/Y multilayers was measured repeatedly over a period of one year. All the multilayers were kept in plastic containers and in air at room temperature. Since the multilayer periods and their initial reflectance values were not exactly the same, the measured reflectance at any given time was normalized to its initial value for comparison purposes. The normalized reflectance plotted as a function of time is shown in Fig. 10 for three representative samples. As shown, all three multilayers had a significant reflectance drop in the first three months

after deposition, followed by an extended period of time where the reflectance remained stable. Small shifts (less than 0.1 nm) of the reflectance peaks toward shorter wavelengths were observed in the first three months after deposition indicating further period contraction in these samples. However, the wavelength shifts of less than 0.1 nm were too small to be measured in the XRD spectra. After the first three months, the wavelength remained constant while the reflectance continued to decrease as a function of time. Molybdenum appears to be the best capping material among the three materials studied, with a reflectance drop of only 2.3% relative to its initial value in the first three months. The reflectance results in one year old samples confirmed that molybdenum- and palladium-capped samples were stable and that their loss in reflectance decreased less than the reflectance of the yttrium-capped sample. It should be emphasized once again that the yttrium capping material in this study came from target *C* (39% oxygen), which, as has been discussed in Section 3.4, formed a rough layer with large crystallites. Therefore the poor performance of yttrium target *C* in the capping layer study could be attributed to the presence of oxygen or coverage problem. A simple explanation for the loss in reflectance (Fig. 10) could be the following: in the case of molybdenum-capped sample, the molybdenum layer was mostly oxidized by the time the first measurement was done. No large reflectance loss could occur due to oxidation of the yttrium layer underneath since that layer already consisted of yttrium oxide. In the case of oxidized yttrium capping layer, the oxygen probably diffused through the yttrium oxide along the grain boundaries until it reached the molybdenum layer. The reflectance loss was mainly associated with the oxidation of the molybdenum layer underneath. The small reflectance loss in palladium-capped sample could be explained with palladium being a noble metal

that formed a thin and stable oxide on it surface. As was demonstrated in Section 3.2, yttrium films made from pure yttrium target (target *A*) do not oxidize readily in air. Thus pure yttrium could be a successful capping material for Mo/Y multilayers and should be the topic of further investigations.

5. Conclusions

Mo/Y multilayers were fabricated with an ultrahigh vacuum deposition system using three different yttrium targets which had < 3%, 25%, and 39% atomic oxygen in their yttrium layers. The highest multilayer reflectance of 38.4% at 9.48 nm was achieved with the yttrium target with 25% oxygen. Scattering measurements suggest that this multilayer has lower interface roughness than the samples with < 3%- and 39% atomic oxygen. Without oxygen, the yttrium crystallites are strongly textured and the interfaces are rougher than the randomly oriented yttrium crystals with 25% oxygen content. The 25% atomic oxygen content is insufficient for yttrium to form an oxide, but too much oxygen (e.g. 39%) can result in an increase of *d*-spacing or a formation of Y_2O_3. The crystallite size of yttrium or molybdenum is similar in all three samples in the multilayer growth direction. However, the sample with the highest amount of oxygen (39%) exhibits large yttrium crystallite size in the direction perpendicular to the multilayer growth as observed in TEM images. The increase in crystallite size, increase in *d*-spacing, or formation of Y_2O_3, all results in an increase of interface roughness and loss in EUV reflectance. To further optimize the Mo/Y reflectance, better understanding of the relationship between oxygen content and multilayer structural properties is needed.

Lifetime stability of Mo/Y multilayers fabricated from yttrium target *C* (39% oxygen) and capped with molybdenum, oxidized yttrium (39% oxygen), and palladium

was monitored for up to one year. All samples experience some reflectance drop in the first three months after the deposition due to the surface contamination/oxidation. Their reflectance peaks were also shifted toward shorter wavelengths due to multilayer contraction. The reflectivity seems to stabilize after about 100 days after deposition in all three cases. The molybdenum- and palladium-capped samples exhibit the best performance with low surface roughness and approximately 4% relative loss in reflectance after one year. The oxidized yttrium-capped sample (39% oxygen) performed poorer with 8% relative loss in reflectance in one year, most likely due to the oxidation of molybdenum layer underneath yttrium. Since pure yttrium films seem to be oxidation resistant, yttrium should be explored further as a candidate for a capping layer.

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Table 1. Fitted parameters for the XRD data of the three representative Mo/Y multilayers *A* (< 3 % oxygen), *B* (25% oxygen), and *C* (39% oxygen).

Multilayer	Λ (nm)	Γ	$\sigma_{surface}$ (nm)	$\sigma_{Mo\text{-}on\text{-}Y}$ (nm)	$\sigma_{Y\text{-}on\text{-}Mo}$ (nm)
A	4.73	0.45	0.55	0.30	0.62
B	4.85	0.48	0.54	0.24	0.25
C	4.85	0.46	0.92	0.31	0.65

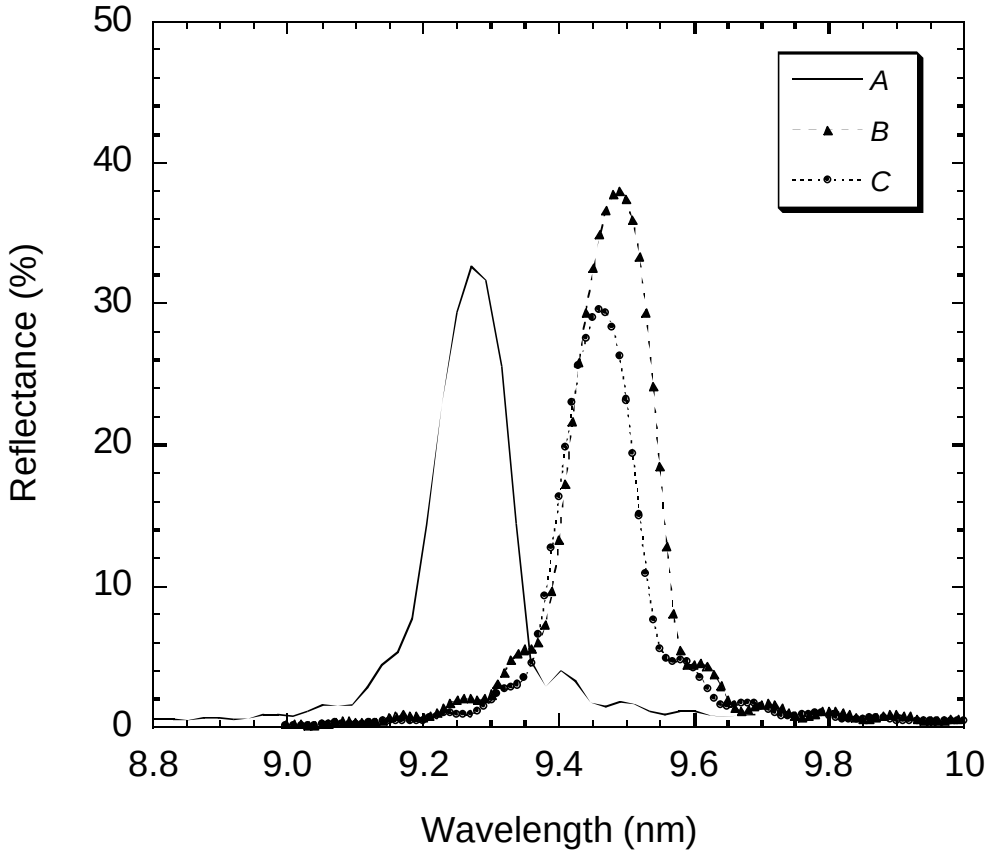

Figure 1. EUV reflectance of three representative multilayers *A*, *B*, and *C*, which were fabricated from the yttrium targets of ACI Alloys, Plasmaterial Inc., and Research and PVD Materials Corp., respectively. The reflectance measurements were performed at 3° normal-incidence angle.

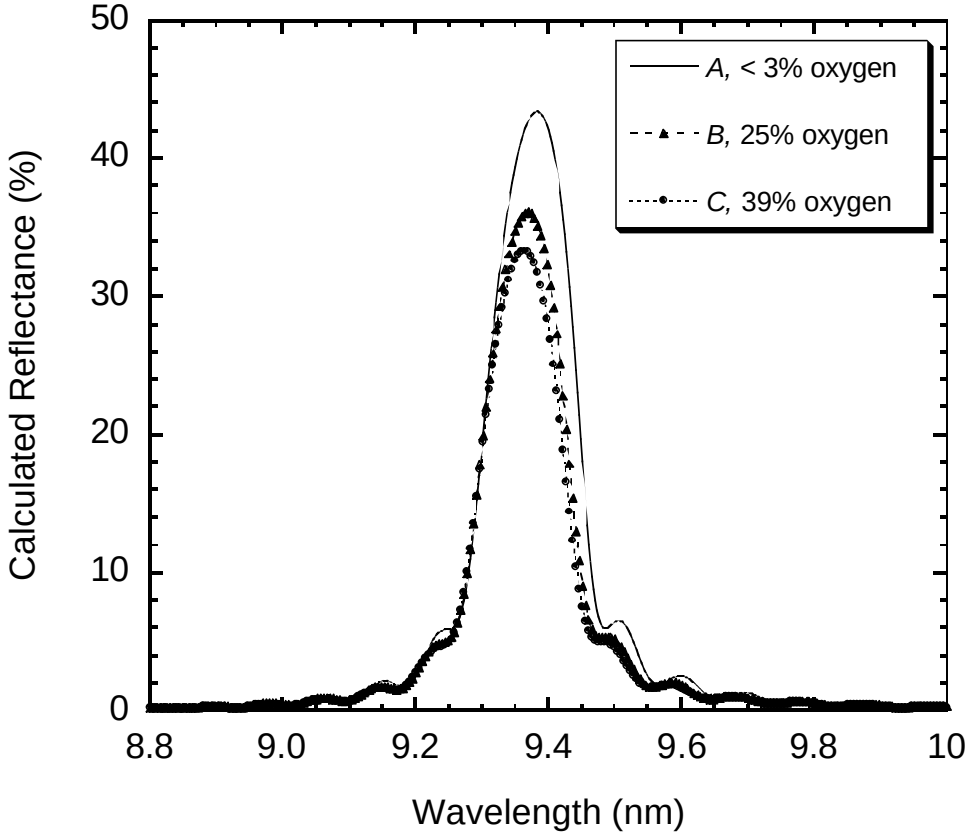

Figure 2. The calculated EUV reflectance of three Mo/Y multilayers *A*, *B*, and *C*, which have < 3%, 25%, and 39% atomic oxygen in their yttrium layers.

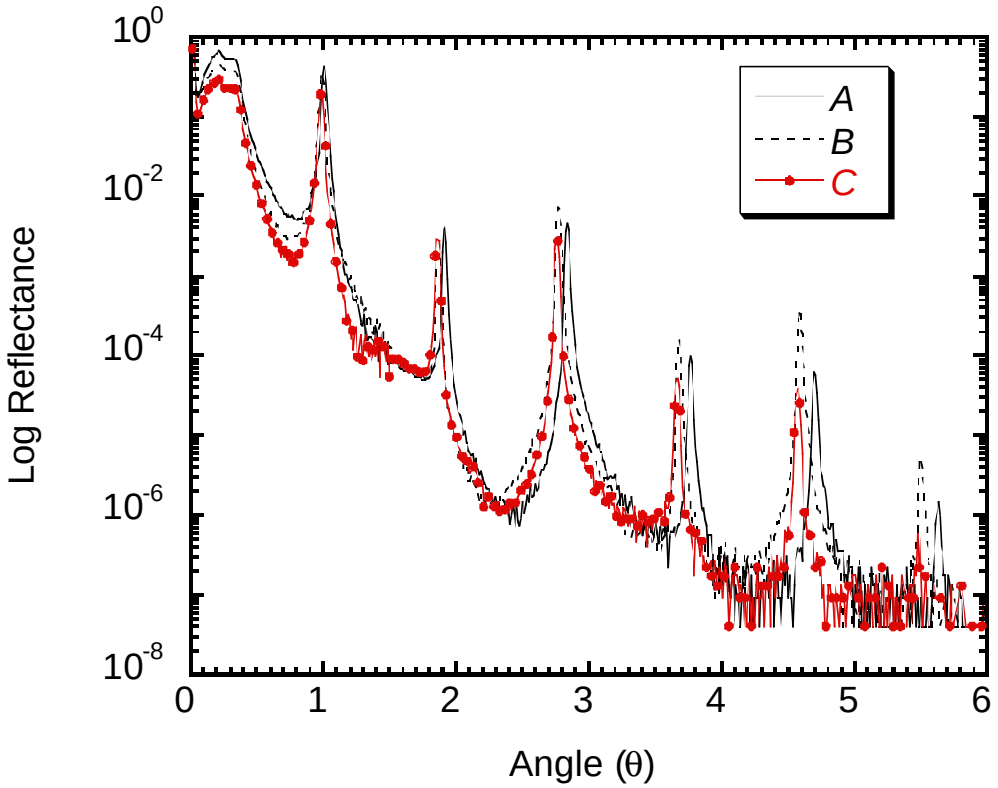

Figure 3. Measured XRD of three representative Mo/Y multilayers *A* (< 3% oxygen), *B* (25% oxygen), and *C* (39% oxygen) showing up to the 6th order Bragg reflection.

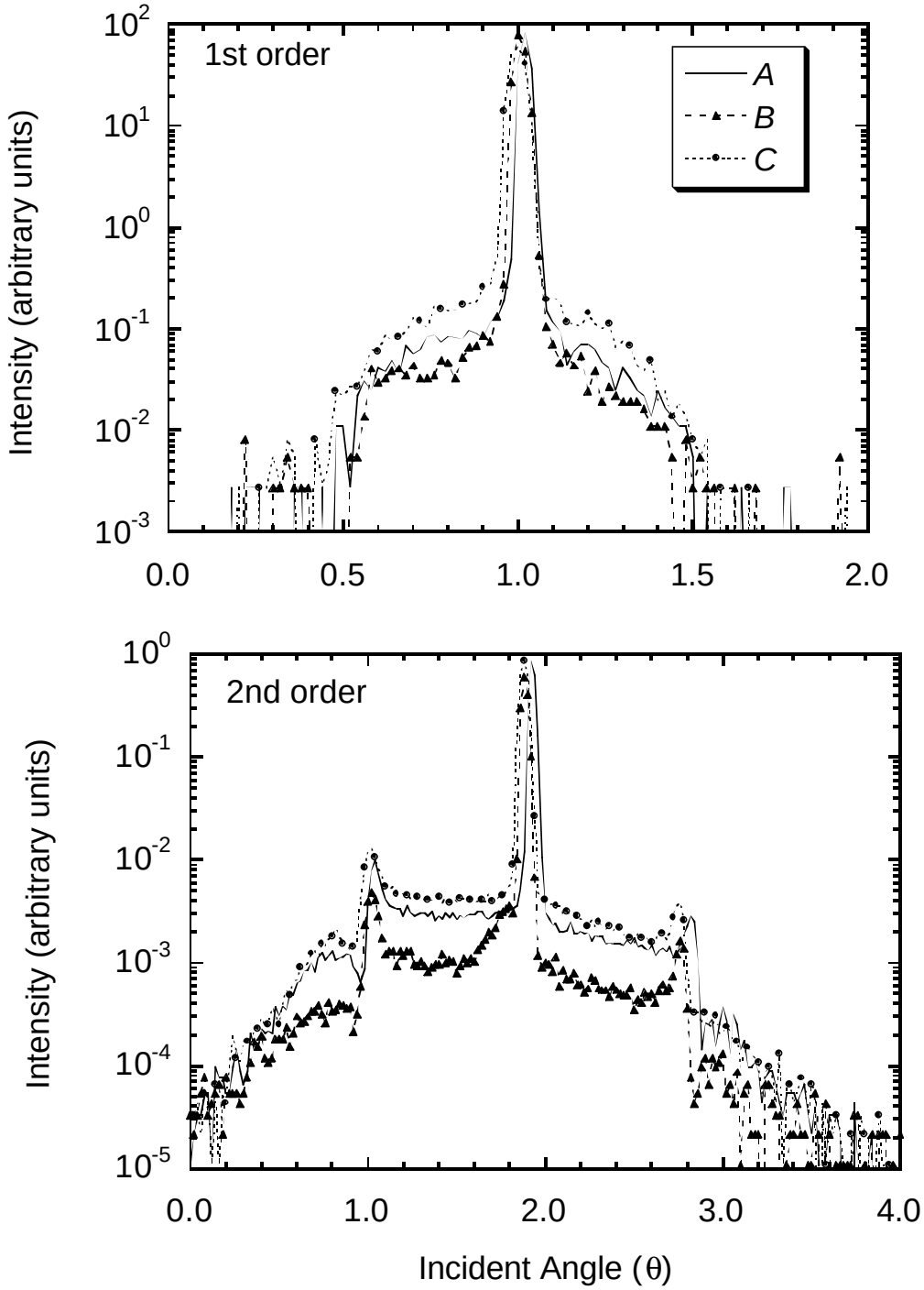

Figure 4. First- (top) and second-order (bottom) rocking curves of multilayers *A* (< 3% oxygen), *B* (25% oxygen), and *C* (39% oxygen). The intensities away from the Bragg peaks drop rapidly because the input beam or the detector was shadowed by the sample.

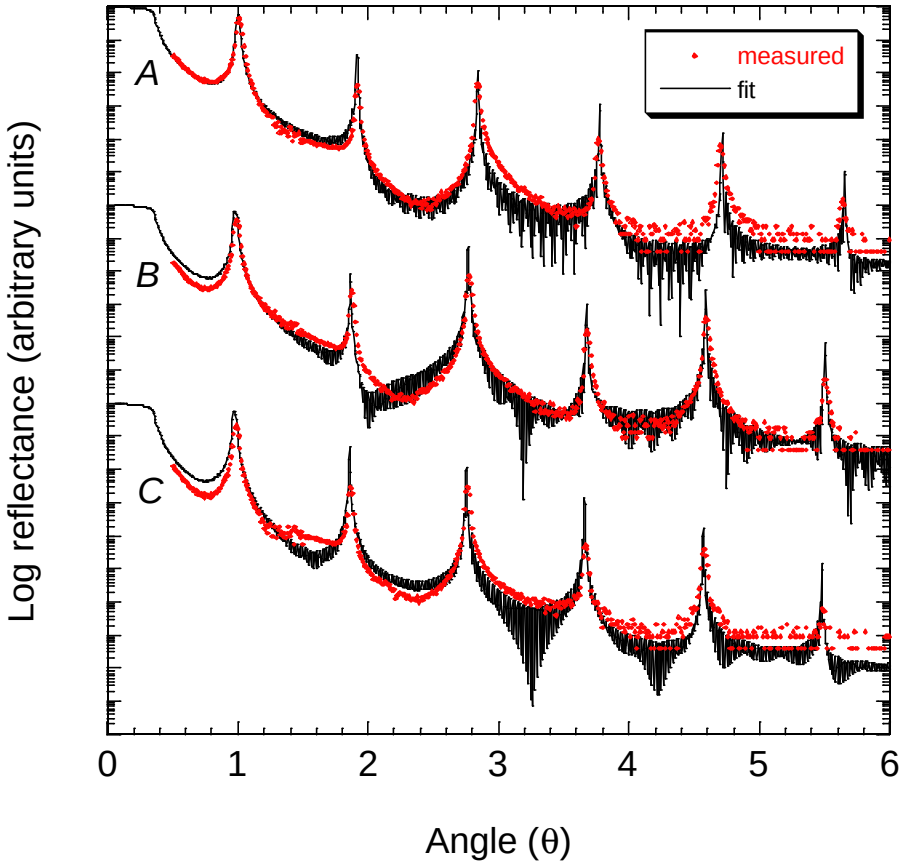

Figure 5. The best fits (line) to the XRD data (symbol) of multilayer *A* (< 3% oxygen), *B* (25% oxygen), and *C* (39% oxygen). The yttrium optical constants at copper K_a energy were adjusted according to the yttrium compositions and densities obtained from the RBS measurements.

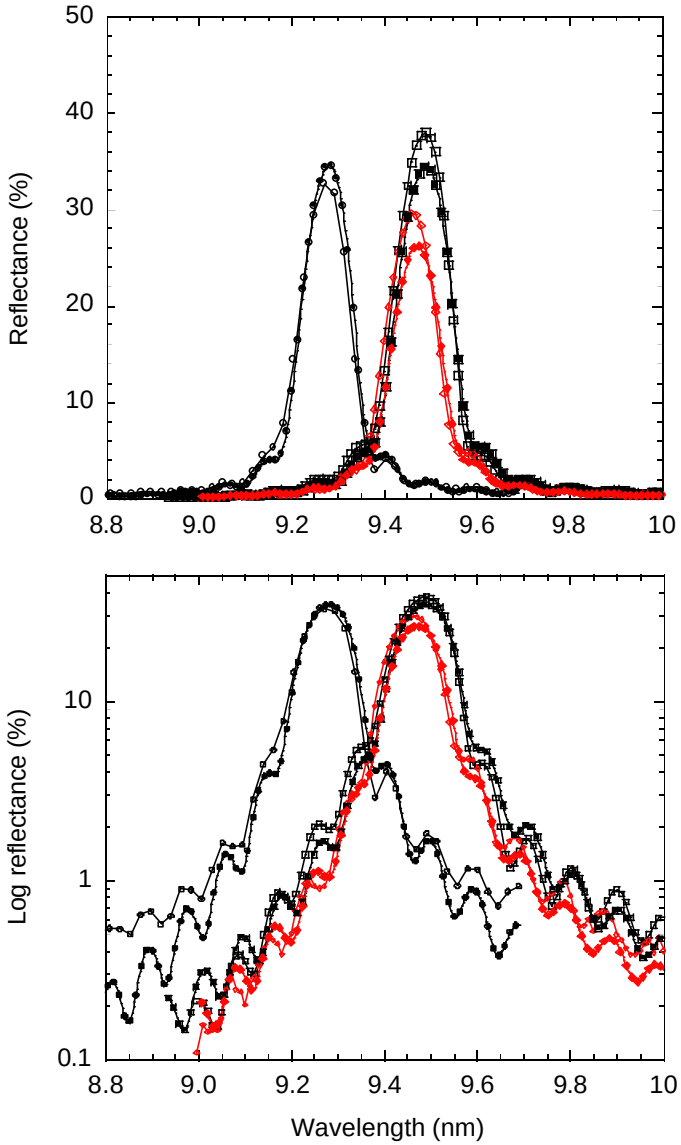

Figure 6. Comparison of measured (open symbol) and calculated (solid symbol) EUV reflectance in linear scale (top) and log scale (bottom) of three representative Mo/Y multilayer samples *A* (circle), *B* (square), and *C* (diamond) using the structure parameters that were determined from the fits to their XRD data.

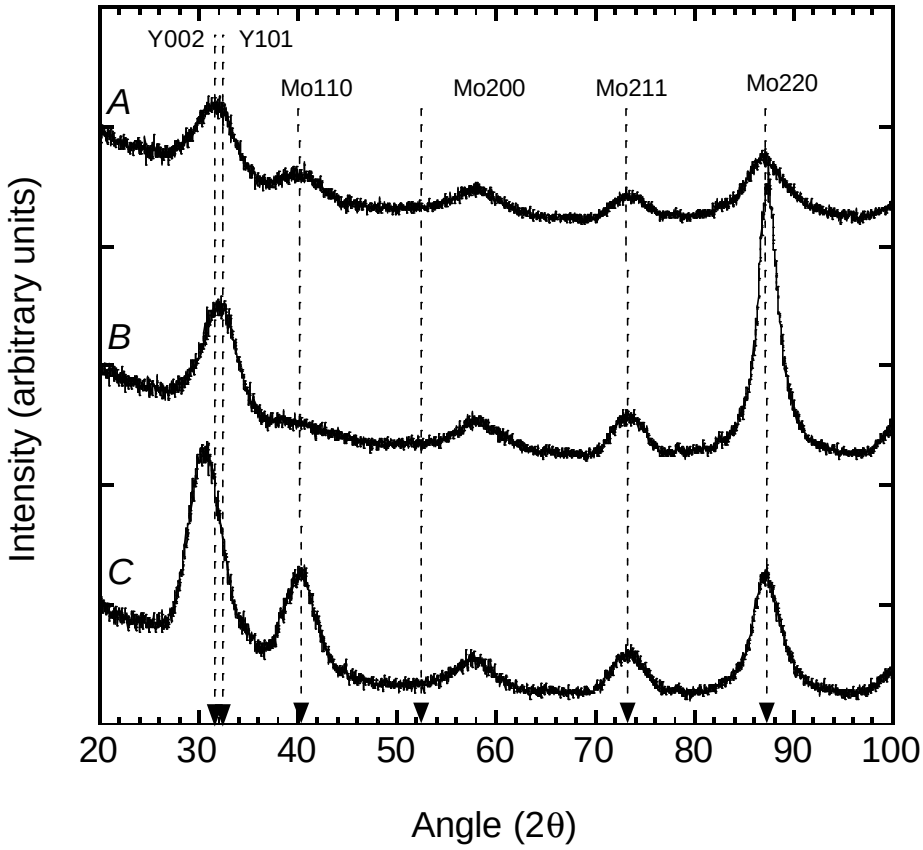

Figure 7. Comparison of large-angle XRD spectra of Mo/Y multilayer samples *A* (< 3% oxygen), *B* (25% oxygen), and *C* (39% oxygen).

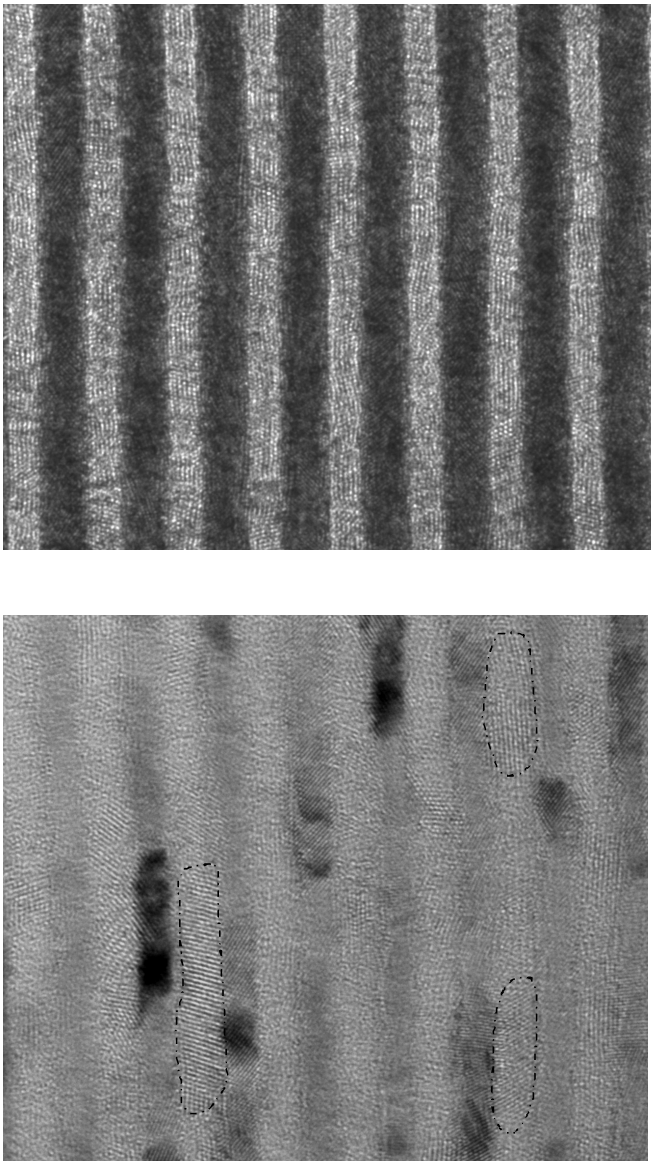

Figure 8. TEM images of (a) Mo/Y sample *A* (< 3% oxygen) and (b) Mo/Y sample *C* (39% oxygen). A thicker sample or higher-*Z* material will scatter more electrons than a thinner sample or lower-*Z* material. Therefore the originally thicker sample *A* has better contrast than sample *C* and the higher *Z* material (molybdenum, *Z* = 42) appears darker than the lighter *Z* material (yttrium, Z = 39). Few examples of large yttrium crystallites in the direction normal to the multilayer growth due to the presence of high amount of oxygen are outline in sample *C*.

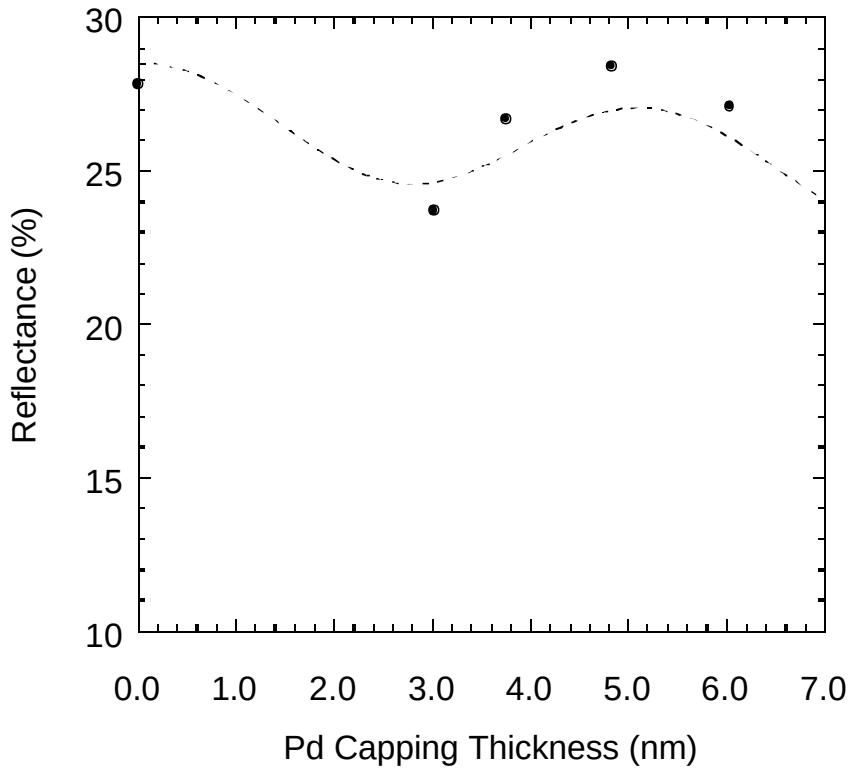

Figure 9. Measured (data points) and calculated (dash line) EUV reflectance as a function of palladium capping thickness from five Mo/Y multilayers. The palladium capping is coated on top of a molybdenum-terminated Mo/Y multilayer.

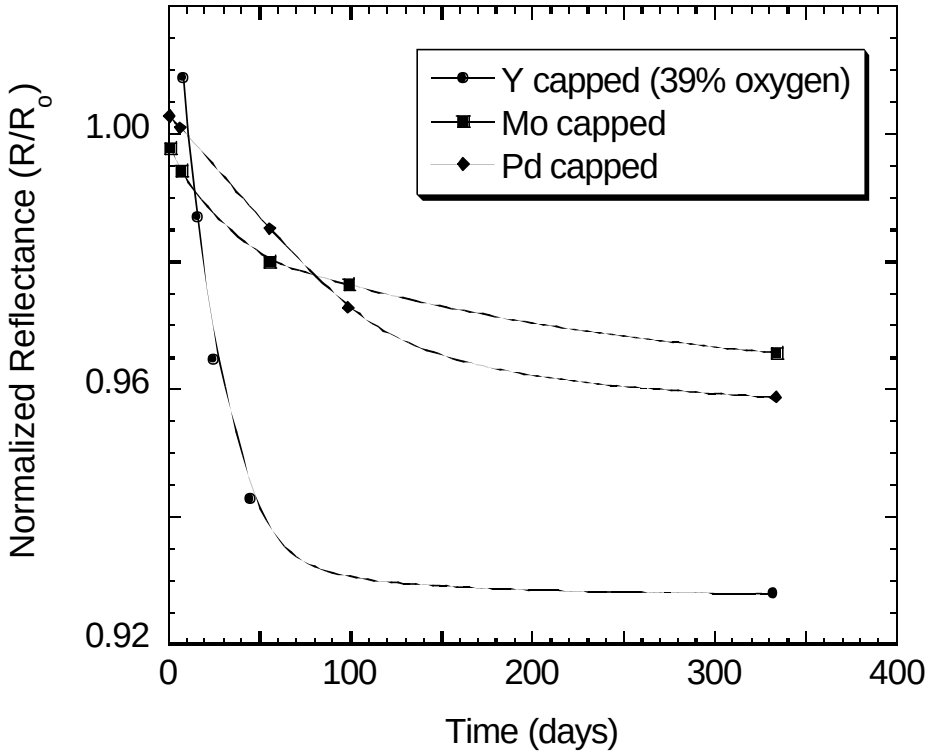

Figure 10. Measured EUV reflectance of molybdenum-, yttrium-, and palladium-capped Mo/Y multilayers (symbols) normalized to the initial value (immediately after deposition) as a function of time for a period of one year. The lines are interpolations of the measured points.