Recent Developments in EUV Reflectometry at the Advanced Light Source

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ABSTRACT

In order to satisfy the metrology requirements of multilayer coatings for EUVL optics and masks, improvements have been made to the reflectometry beamline at the Advanced Light Source. The precision in determining multilayer peak reflectance and wavelength has been improved by reducing the measurement noise. The peak reflectance of a typical Mo/Si multilayer can now be measured with a precision of 0.08% rms (relative) and the centroid wavelength with a precision of 0.007% rms. It has now been possible to determine the contribution of scattered light to the spectral purity. Under the typical measurement conditions the scattered light accounts for about 1.3% of the incident beam. With an appropriate slit it is possible to reduce the scattered light to 0.25%. By correcting for the remaining scattered light, it is estimated that a reflectance accuracy of 0.1% (absolute) is obtained for a typical Mo/Si multilayer.

Keywords: EUV lithography, reflectometry, metrology, multilayer reflectivity

1. INTRODUCTION

The reflectometry and scattering beamline (6.3.2) at the Advanced Light Source (ALS) in Berkeley[1] has served as an important resource for the US EUV Lithography program. The feedback provided by wavelength measurements of the multilayer-coated optics, with a precision of 0.02% rms, have enabled coatings with the uniformity required for the engineering test stand[2] (ETS). Efforts to improve the reflectivity of the coatings have relied on the ability to perform peak reflectance measurements with a precision of 0.2% rms and accuracy of 1%. As the technology matures, the tolerances on the coatings will naturally become tighter and consequently so will the requirements for the measurement precision and accuracy. In a continuing effort to refine the measurement capability at the ALS, improvements have been implemented and the current status is discussed here.

The main source of noise affecting the reflectance precision was found to be due to the analog-to-digital converter (ADC). Improvements in the control software have allowed a significant reduction in the ADC noise. With this improvement it is estimated that a reflectance precision of 0.08% rms is now achieved which is limited by the detector non-uniformity.

Perhaps the most important factor in determining the reflectance accuracy is the spectral purity of the incoming light. The presence of undesired wavelengths, which are poorly reflected by the multilayer, causes the measured peak reflectance to be smaller than the true reflectivity. A triple-mirror "order suppressor" was incorporated in the beamline design to reduce higher order light. With the order suppressor and either a Si or Be filter the contribution from higher order light was reduced to less that 0.1%. However, light scattered by the grating or mirrors is spread over a range of wavelengths and is difficult to quantify. In recent years, as more has been learned about the scattered light, it has now become possible to measure this contribution as well.

Measurements of the spectral contamination due to scattered light were performed using a second grating to disperse the light coming from the beamline monochromator. By using an analyzer grating which itself has low scatter it has been possible to quantify the amount of scattered light and to measure it's spectral and spatial distribution. From these measurements it is estimated that scattered light accounts for about 1.3% of the measured signal with the beamline configured for wavelengths around 13 nm. It has also been found that the spatial distribution of the scattered light in the reflectometer is more extended than the monochromatic light. This allows for the effective suppression of the scattered light using an appropriately chosen slit. Using the additional slit it is possible to reduce the contribution from scattered light to 0.25%.

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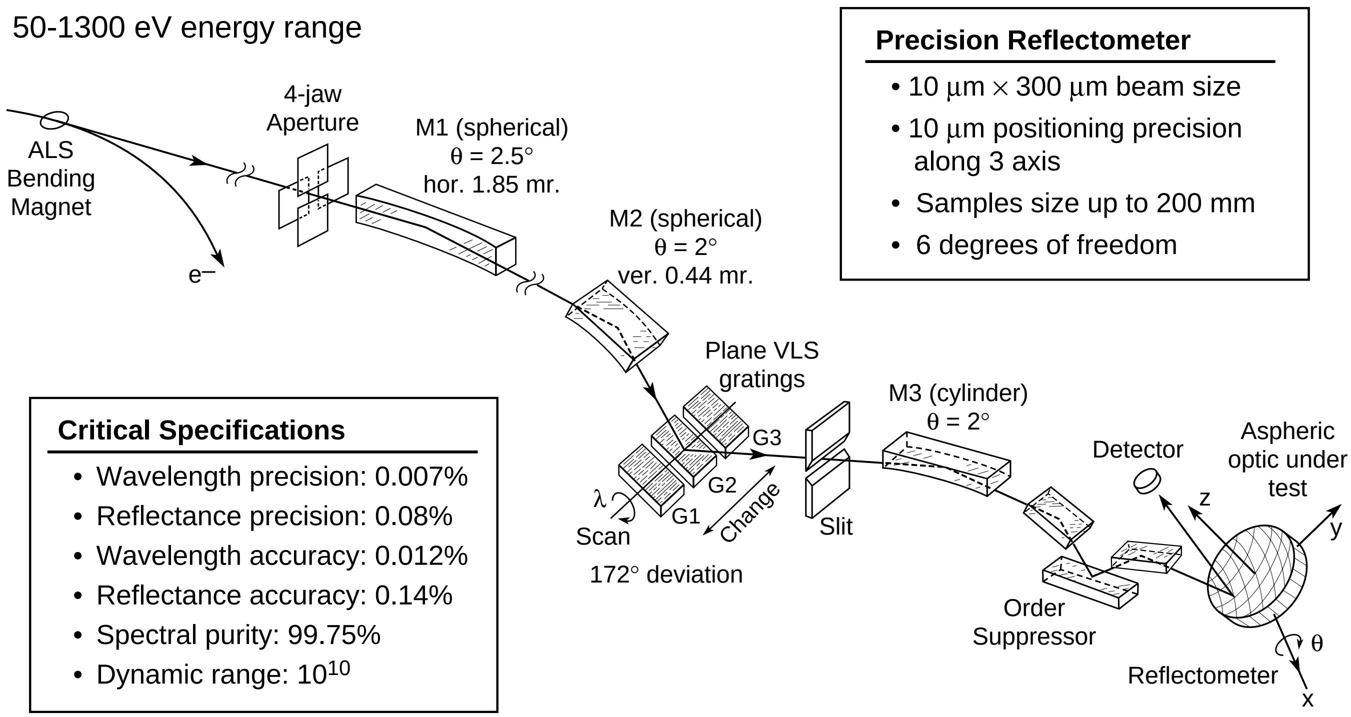

Figure 1. *Optical layout and critical specifications of the reflectometry and scattering beamline at the ALS,*

By correcting for the remaining scattered light a reflectance accuracy of 0.1% (absolute) is now possible for a typical Mo/Si multilayer reflectance measurement. Previous reflectance measurements made with the beamline are estimated to be reduced by 0.6 - 0.7% (absolute) from the true reflectance for a typical Mo/Si multilayer. For example, a measured reflectance of 67.0% would become 67.7% when corrected for the spectral purity. This affects the calculation of system throughput by a larger factor. For a 9-multilayer mirror optical system the throughput should be increased by 10%.

2. METROLOGY REQUIREMENTS

In general, the precision and accuracy of a measurement should be significantly better than the fabrication tolerance of the quantity being measured. For imaging optics the tolerance for the d-spacing uniformity is critical. The tolerance is driven by the need to preserve the figure of the optical surface being coated. For the ETS optics[3] the tolerance of the figure of each mirror is 0.25 nm rms. The multilayer coating is allowed a fraction of the figure tolerance. The coatings for the ETS projection optics were allowed 0.1 nm of added figure error. In order to meet this requirement, the measurement precision of the multilayer thickness should be approximately half of this or 0.02% if the coating thickness is 280nm. This was satisfied with the previously achieved wavelength precision of 0.02%. The required wavelength precision for beta-tool optics and beyond will need to tighten in proportion to the figure tolerance on the mirrors, see table 1. The required wavelength accuracy is determined by the mask requirements described below.

In the case of a mask, a non-uniform illumination will result in undesired variations in the size of printed features. Similarly, variations in the multilayer d-spacing or reflectivity across the mask will produce the same detrimental effects as a non-uniform illumination. Thus the requirements for the mask are determined by the illumination uniformity error budget. For the ETS, the portion of the uniformity budget[4] allocated to the multilayer coating on the mask is 1% (3σ). It is assumed that this is equally divided between uniformity of the peak reflectance and multilayer d-spacing. Assuming that the measurement needs to by twice as good as the tolerance in the coating, the required reflectance precision is 0.12% (rms). The wavelength tolerance is determined from the wavelength mismatch between the mask and optical system, which leads to the allowed variation in throughput. The tolerance on the mask wavelength is further split between the mean wavelength averaged over the surface, which determines the required accuracy, and non-uniformity in the wavelength over the mask surface, which sets the measurement precision.

	ETS	*Beta-tool*	*Ultimate*
Optics			
Multilayer Tolerance	0.1 nm	0.05 nm	0.025 nm
Wavelength Precision	0.02%	0.01%	0.005%
Wavelength Accuracy	0.03%	0.03%	0.02%
Mask			
Illumination Uniformity (3σ)	1%	1%	0.5%
Wavelength Precision	0.03%	0.03%	0.02%
Wavelength Accuracy	0.03%	0.03%	0.02%
Reflectance Precision (relative)	0.12%	0.12%	0.06%

Table 1. *The requirements for reflectometry measurements are taken to be one half of the tolerance on the multilayer coating. All quantities are given as relative rms error except the illumination uniformity. The requirements for the imaging optics are based on the added figure error budget for the multilayer coatings as shown. Requirements for the mask are based on the illumination uniformity error budget of 1% (3σ) for the ETS and beta-tool masks and 0.5% (3σ) as the ultimate requirement.*

3. MEASUREMENT PRECISION

The precision quantifies the random errors and can be determined by repeating the same measurement. An important source of random error is the noise in the measurement of the photodiode current used to monitor the power of the incident and reflected beams. The main noise source was determined to be the analog to digital converter (ADC) used to digitize the voltage from the current-to-voltage amplifier. A significant improvement in the ADC noise was achieved by rewriting the control software to average 50 ADC readings for each measurement. The ADC noise was reduced from 2 mV (rms) to 0.3 mV (rms) with a negligible increase in the measurement time. With this improvement, the precision of reflectance and full width half max (FWHM) centroid wavelength was determined by performing repeated measurements on the same multilayer mirror (M4-991130A2). The results are shown in figures 2 and 3 for measurements performed over six days. The sample was removed and realigned each day. With the reduction in ADC noise, the peak reflectance is repeatable with a standard deviation of 0.02% absolute or 0.03% relative. The FWHM centroid wavelength is repeatable to 0.0001 nm rms for measurements performed on the same day. There is a difference of approximately 0.001 nm between measurements performed on different days. This is mainly due to the uncertainty in the sample alignment and corresponds to an angular error of 0.05 degrees for the measurements performed at 5 degrees from normal incidence.

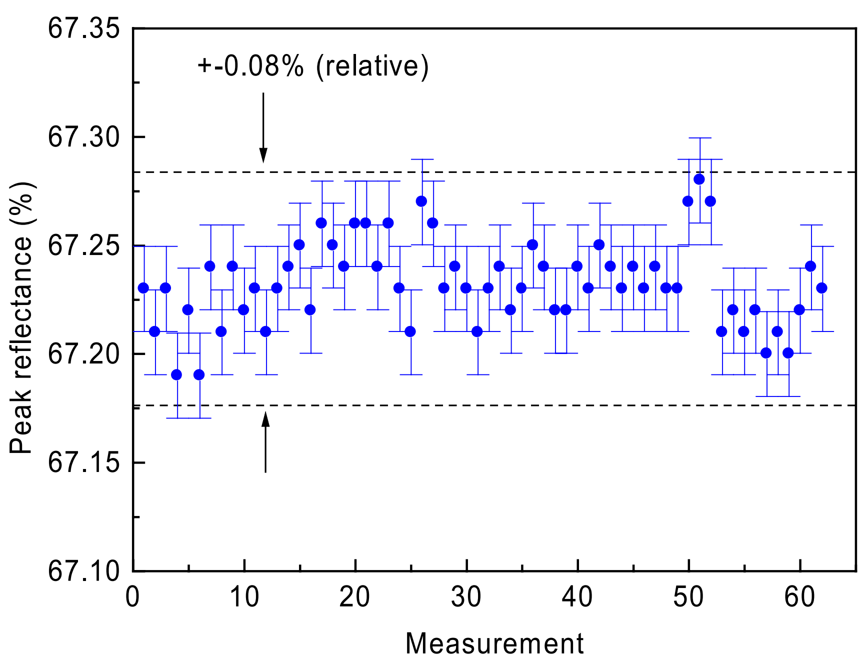

Figure 2. *Repeated measurements of the peak reflectance of the same multilayer were made over 6 days. The sample was removed and realigned each day. The rms variation of the measurements is 0.03% rms (relative) as indicated by the error bars on each point. In general, the precision is estimated to be 0.08% (relative) due to the possibility of larger errors in sample alignment coupled with the non-uniform response of the photodiode.*

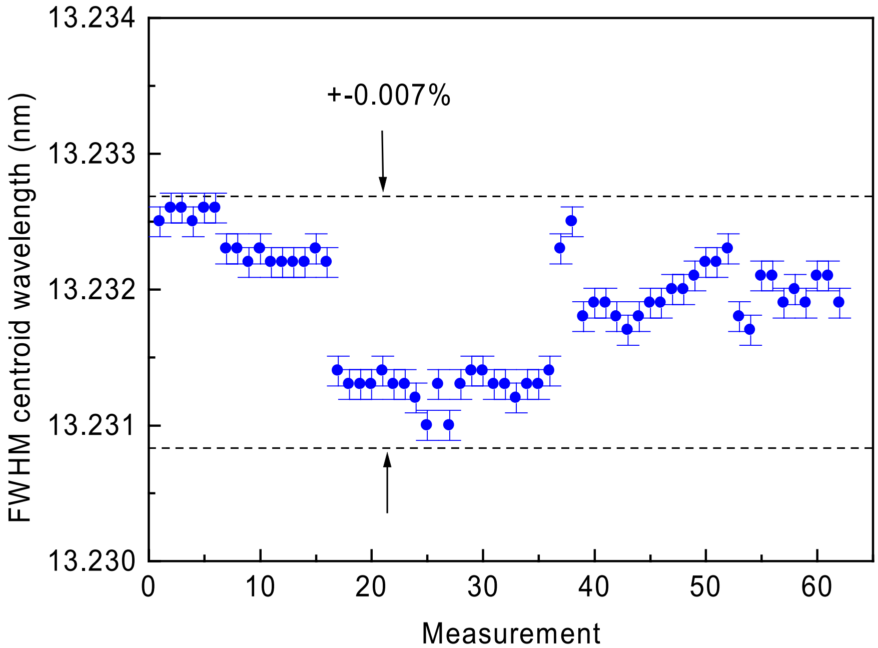

Figure 3. *Measurements of the centroid wavelength of the same multilayer were made over 6 days. The rms variation on any given day is 0.0008% (0.00011 nm) and is indicated by the error bars on each point. Between days there is a larger, up to 0.007% or 0.001 nm, difference in centroid wavelength attributed to the uncertainty in determining the angle of incidence. This corresponds to an angular error of 0.05 deg at 5 degrees from normal incidence where these measurements were performed.*

Fluctuations of the incident EUV power can also produce random errors in the reflectance. The slow decay of the flux due to the finite lifetime of the ALS electron beam is taken into account by normalizing each measurement to the ALS beam current. However, there are variations in the incident power which occur for other reasons such as beam motion or thermal effects in the beamline optics. The beamline optics were designed to minimize the dependence of the flux on variations in the ALS electron beam position. For example, the monochromator is designed to operate without an entrance slit[1].

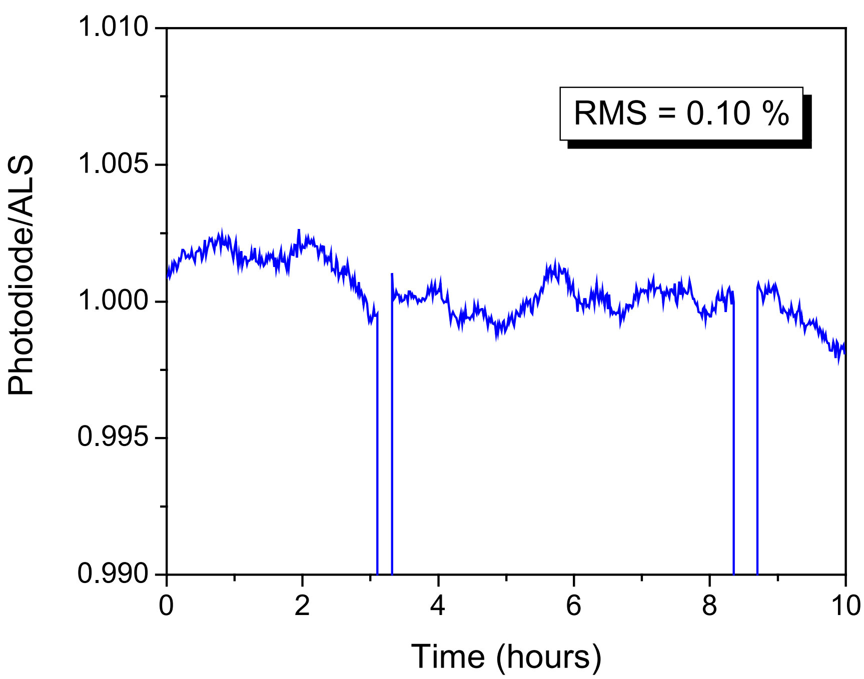

Figure 4. *The stability of the incident power (photodiode current) when normalized to the electron beam current in the ALS storage ring. Variations in the normalized power are reduced to 0.1%.*

In figure 4, the incident 13.4 nm EUV power normalized to the ALS beam current is shown over a ten hour period. The ALS beam was refilled at approximately 6-hour intervals. The incident power after normalizing to the beam current fluctuates by 0.1% rms. The fluctuations occur over a time scale of tens of minute. By performing frequent measurements of the incident power this source of error can be minimized. For example, over a typical 10-minute interval the fluctuation in normalized power shown in figure 4 is less than 0.02%. For a high precision reflectance measurement three scans are performed for each sample: reflected beam-incident beam-reflected beam this measurement sequence typically takes less than 5 minutes.

Another source of random error is related to the non-uniform response of the photodiode. This can lead to an error in the reflectance if the incident and reflected beams do not hit the detector at the same spot. The photodiode that is used for reflectance measurements was selected for its good uniformity. Over the central 7 mm region the rms variation in response is 0.07%. Typical position errors due to sample misalignment are estimated to less than 0.5 mm. This source of error can be as small as 0.03% rms if the most uniform region of the photodiode is used.

4. REFLECTANCE ACCURACY

The absolute accuracy of the reflectivity is determined by systematic errors and is more difficult to establish. By reducing the known systematic errors it was estimated that an absolute accuracy of 1% has been achieved in the past. A comparison with independent measurements at other facilities is a good test of the systematic errors determining the accuracy. Such a comparison[5] was done in 1998 with the reflectometer[6] operated by the PTB at BESSY. The peak reflectance measured at both facilities on the same multilayers agreed to better than 1%. However, there have also been indications of systematic errors in the ALS measurements on the order of a percent. Measurements of multilayer reflectivity using a second multilayer mirror as a band pass filter consistently gave reflectance values about 0.5% (absolute) higher than under the standard conditions. The measurements of spectral purity presented below are consistent with this observation.

The spectral purity of the incident EUV light is believed to be the most significant systematic error determining the reflectance accuracy. Spectral contamination can occur either as higher order light diffracted from the monochromator grating, which occurs at discrete wavelengths $\lambda/2$, $\lambda/3$, etc., or as broadband scattered light. The contamination from higher orders is relatively easy to determine and has been effectively suppressed by using a filter and high-order suppressing mirrors. Scattered light is more difficult to quantify since it is spread over a broad band of wavelengths. New measurements of the spectral purity have been made and are discussed in the following sections.

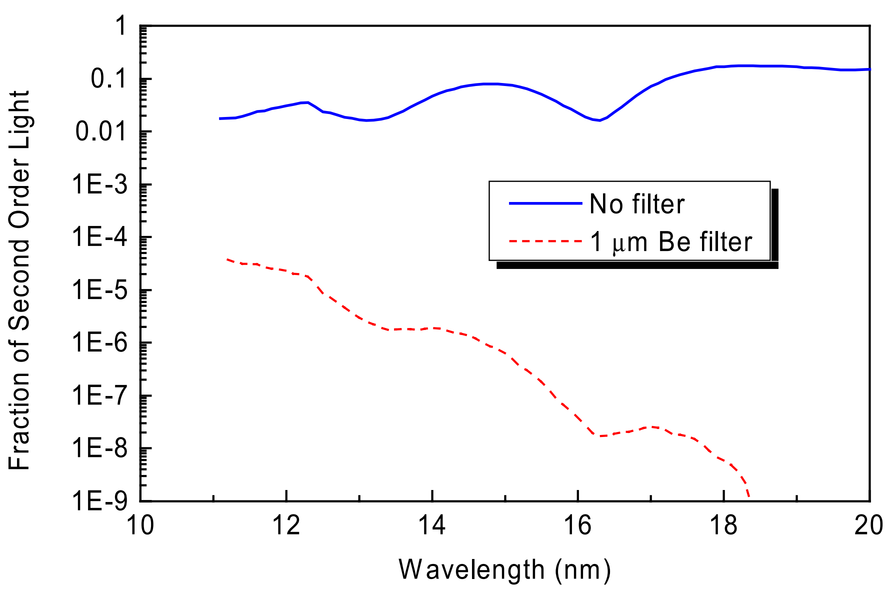

Figure 5. *The relative contribution from second order light. Measurements were performed without a filter using a transmission grating to analyze the beam entering the reflectometer. The second order contribution with the filter (dashed curve) is based on the calculated filter transmission. The second order contribution at 13.4 nm is 2 ppm for the standard Mo/Si measurement using the 1 micron Be filter.*

In the typical configuration of the beamline for Mo/Si reflectance measurements, a set of higher order suppressing mirrors is used as well as a 1 μm thick Be filter. The contribution from higher order light was measured using a transmission grating mounted in the reflectometer to disperse the incoming beam. Without the Be filter, the second order contribution at λ/2 could be determined, orders higher than the second were undetectable. The fraction of the photodiode current due to the second order light is shown versus wavelength in figure 5. The second order fraction with the Be filter in place was projected from the measurements without the filter using the calculated transmission of a 1 μm thick Be filter. With the filter, the second order contribution is estimated to be 2 ppm. It was not possible to observe the spectrum of any broadband/scattered light with this setup due to the large amount of scattering from the transmission grating.

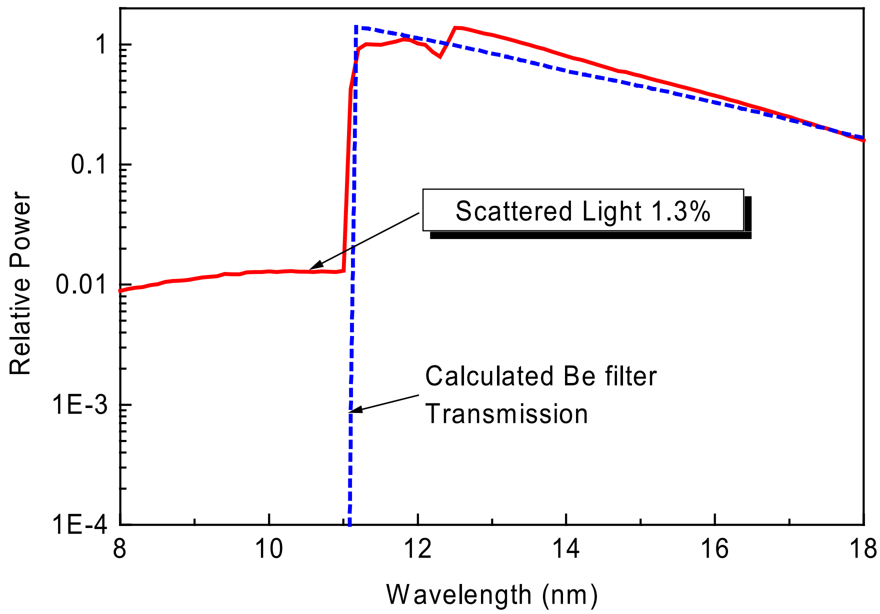

Figure 6. *The measured photocurrent versus wavelength from a photodiode (proportional to the incident power) located in the reflectometer (solid curve). The calculated transmission of the 1 micron Be filter used in the beamline is scaled to the measured power for comparison. For wavelengths below the Be K edge (11.1 nm), where the Be filter transmission drops dramatically, the residual power is an indication of the spectral purity.*

In figure 6, the current on a photodiode is used to measure the EUV power in the reflectometer as a function of monochromator wavelength. As can be seen from the dashed curve, the transmission of the Be filter drops to an extremely small value for wavelengths below the Be K edge at 11.1 nm. (The absence of pinholes in the filter is apparent in the upcoming data.) When the monochromator is set to wavelengths less than 11.1 nm the photodiode current is an indication of the fraction of incident light which occurs at wavelengths where the Be filter transmission is high. Since the contribution from higher order light has been shown to be small, the spectrally impure light must be due to scattered light.

In order to determine the spectrum of scattered light arriving in the reflectometer a high quality ruled 300 l/mm reflection grating was mounted in the sample position and a 0.5-mm slit used on the photodiode detector. By fixing the detector at an angle of 8 degrees and scanning the grating angle, the spectrum of the incident light could be measured. The spectra are shown in figure 7 with the monochromator set for four different wavelengths. The spectra consist of a monochromatic peak on top of a broad band. The width of the peak is determined by the relatively low resolution of the spectrometer (analyzer grating and detector). The broad band portion of the spectrum extends from the Be edge at 11.1-nm to about 16-nm where it is lost in the noise. This shape is due to the transmission of the Be filter as well as the beamline optics. It is most likely that the broad band portion of the spectrum is due to scattering from the monochromator grating, but this remains to be completely understood. As expected, there is no contribution from higher order light within the sensitivity limits of this measurement. The absence of a peak when the monochromator wavelength is set to 11.0 nm is evidence that there are no pinholes in the Be filter. An important and useful observation is that the intensity of the broadband portion of the spectrum is roughly independent of the monochromator wavelength.

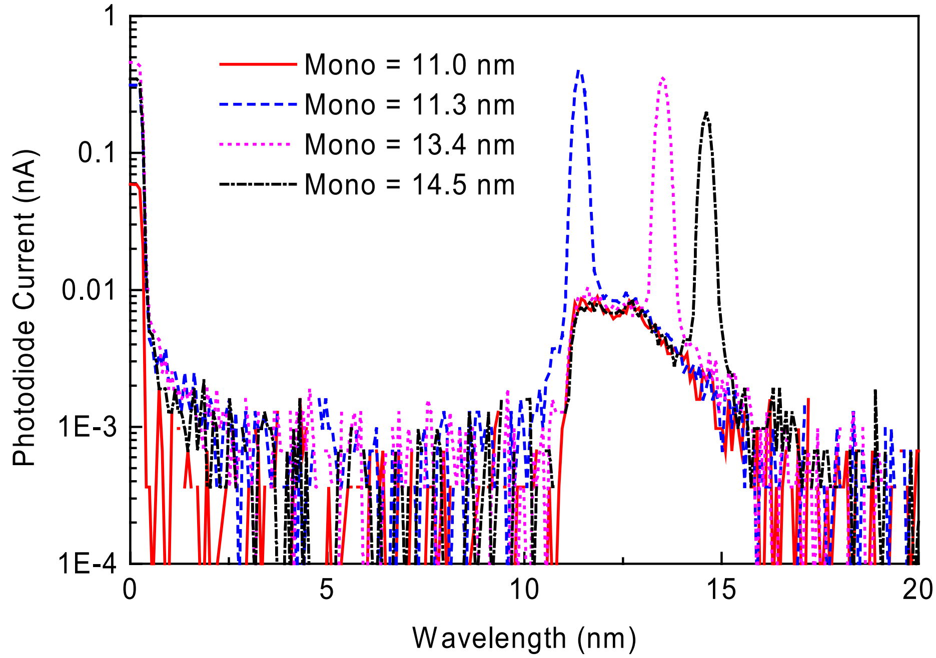

Figure 7. *The spectrum of light entering the reflectometer from the beamline. The spectrum was obtained using an analyzing grating mounted in the reflectometer. Spectra are shown with four settings of the monochromator. A monochromatic peak rides on top of a band of scattered light, which is independent of the monochromator wavelength. With the mono set to 11.0 nm the monochromatic peak is completely attenuated by the Be filter but the band of scattered light is unaffected. As expected no higher order light is observed.*

The effect of the broadband component on a reflectivity measurement can be described as follows. Let the photodiode current be given by

$$i(\lambda) = i_0 \quad I(\lambda,\lambda')d\lambda' \quad \text{where} \qquad I(\lambda,\lambda')d\lambda' = 1$$

With the monochromator set for a wavelength λ, I(λ,λ')dλ' is the contribution to the photocurrent from light with wavelengths between λ' and λ'+dλ' and can be expressed as

$$I(\lambda,\lambda') = (1-f)\delta(\lambda'-\lambda) + f \cdot I_s(\lambda,\lambda') \quad \text{and} \qquad I_s(\lambda,\lambda')d\lambda' = 1$$

The second term is the contribution to the photocurrent from the scattered light. If the broadband contribution is assumed to be independent of the monochromator wavelength λ, the *measured* reflectivity will be given by

$$R_{meas}(\lambda) = \quad R(\lambda')I(\lambda,\lambda')d\lambda' = (1-f)\cdot R(\lambda) + f \cdot \overline{R}\,.$$

Where the second term represents the scattered light which is reflected by the multilayer. The reflectivity of the multilayer averaged over the spectrum of the scattered light is

$$\overline{R} = \quad R(\lambda')I_s(\lambda')d\lambda'\,.$$

The value of the measured reflectivity is reduced by the factor (1-*f*) from the true reflectivity and there is an additional flat background (independent of λ) given by the second term arising from the portion of the broadband spectrum reflected by the multilayer. For a typical Mo/Si multilayer this small DC background is estimated to be about 0.1% absolute.

5. THE SPATIAL DISTRIBUTION OF SCATTERED LIGHT

A surprising finding of these measurements is that the spatial distribution of the broadband portion of the spectrum differs from that of the monochromatic light. The monochromatic EUV light is focussed at the center of the reflectometer in the horizontal plane by the beamline M1 mirror. In this plane, the beam is expected to be a 1:1 image of the ALS source (0.3-mm FWHM). The beam profile was measured by scanning a 0.5-mm slit in the horizontal direction and the current measured on a photodiode fixed on the detector arm behind the slit. With the monochromator set at 11.3 nm a peak is observed on a broad background. The width of the background is limited by the size of the photodiode (10 mm). The background is due to scattering from the beamline mirrors and grating. With the monochromator set to 11.0 nm the monochromatic portion of the spectrum is completely stopped by the Be filter and only light from the broadband portion of the spectrum reaches the reflectometer. As can be seen in figure 8, the spatial distribution of this light is relatively flat with no peak at the focus of M1. This allows for the selective reduction of the broadband light by trimming the wings of the beam in the horizontal plane.

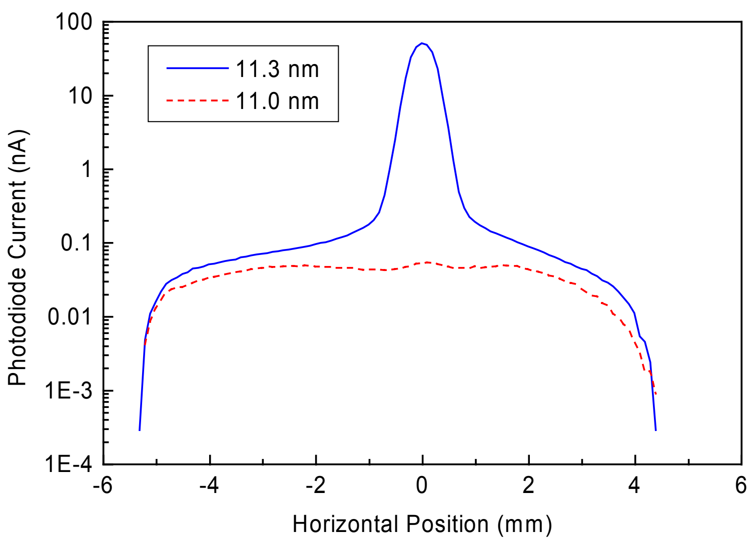

Figure 8. *The spatial distribution of light measured by scanning a 0.5-mm slit though the beam in the reflectometer. In the horizontal plane the light is focused by the M1 mirror of the beamline and should be a 1:1 image of the ALS source. When the monochromator is set to 11.3 nm, a narrow peak is obtained on top of a broad background. With the monochromator set to 11.0 nm the light entering the reflectometer is only the broad spectral band of scattered light, which has a flat distribution.*

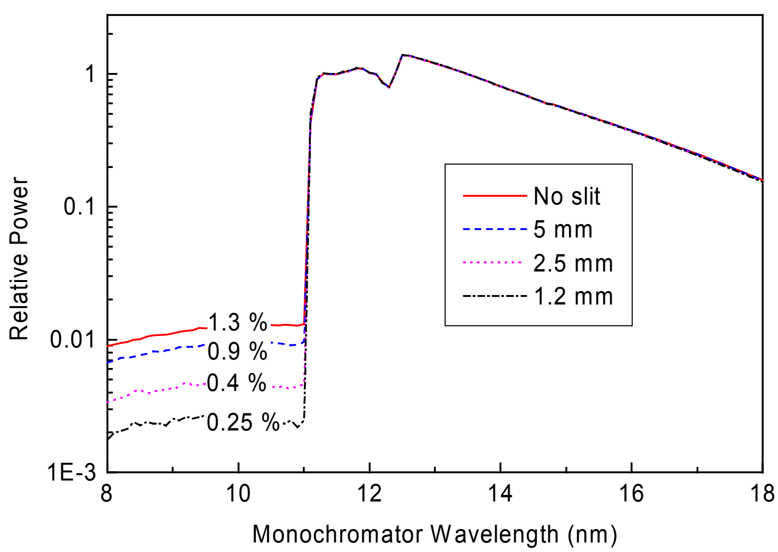

Figure 9. *By inserting a slit just upstream of the reflectometer the scattered light can be suppressed relative to the monochromatic light. The photodiode current at wavelengths below the Be K edge is a measure of the amount of scattered light. The numbers are the relative contribution at 13.4 nm*

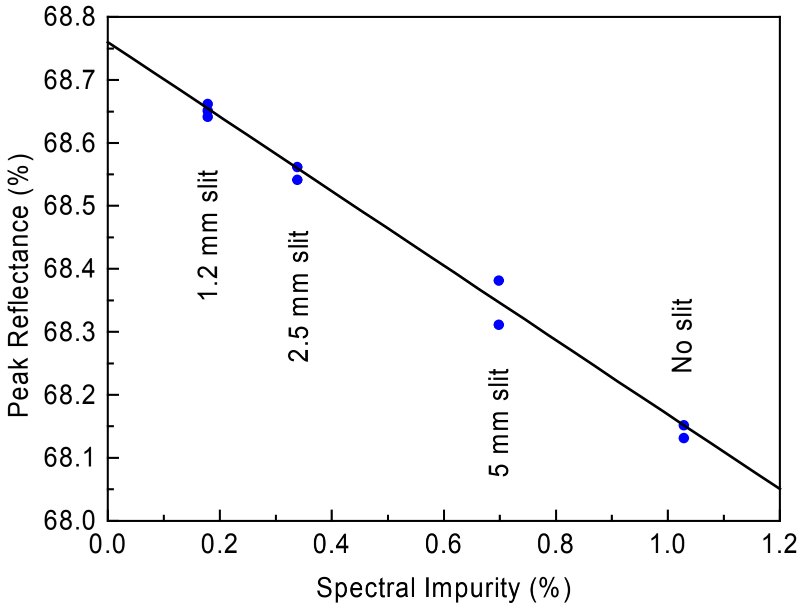

Figure 10. *Measured peak reflectance versus the fraction of the incident light contained in the broadband scattered light. A slit was used just upstream of the reflectometer to reduce the amount of scattered light. The measured peak reflectance without a slit is reduced, by the broadband scattered light, by about 0.6% (absolute). The multilayer was Mo/Si with 60 bilayers and a FWHM centroid wavelength of 12.86 nm.*

The effect of trimming the wings of the beam using a slit can be seen in figure 9. The photodiode current is plotted versus monochromator wavelength and is normalized at a wavelength of 11.3 nm. The fraction of broadband light is measured by the signal when the monochromator is set to wavelengths below 11.1 nm. The fraction of broadband light is reduced from 1.3% with no slit to 0.25% with a 1.2 mm slit.

The multilayer reflectance was measured using the slit to vary the amount of broadband/ scattered light. The measured peak reflectance versus spectral impurity is shown in figure 10. The straight line for each sample is given by

$$R = R_0(1 - 0.85 f)$$

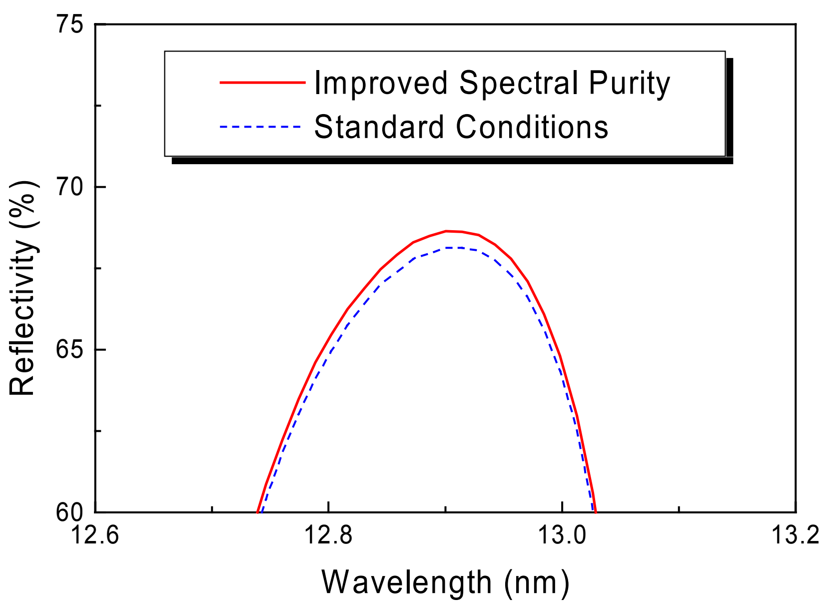

Figure 11. *The measured peak reflectivity increases when the spectral purity is improved by using a slit to block the scattered light.*

where *f* is the fraction of light in the broadband spectrum as deduced from figure 10. The factor of 0.85 appears because some of the scattered light is reflected by the multilayer. The multilayer reflectivity averaged over the spectrum of the scattered light is approximately 15% the multilayer peak reflectance. The multilayer has a peak reflectance of 68.1% with the beamline in the standard configuration. The peak reflectance extrapolated to zero scattered light is 68.7%, an increase of 0.6%. Since the centroid wavelength of this multilayer is 12.86 nm the fraction of scattered light is a little over 1% compared to 1.3% at 13.4 nm. The high precision of the measurements is apparent from the spread in the points in this figure. The ability to extrapolate the peak reflectance to elliminate the effect of spectrally impure light should allow an accuracy which is better than the residual 0.25%. It is estimated that after correction for the spectral purity, an accuracy of 0.1% (absolute) is achievable for the peak reflectivity.

6. CONCLUSION

The main source of noise affecting the reflectance precision was found to be due to the ADC. Improvements in the control software have allowed a factor of 10 reduction in the ADC noise. With the improved ADC noise the wavelength precision is mainly limited by the procedure used to calibrate the monochromator and by errors in the angle of incidence. The monochromator calibration is checked on a daily basis using the absorption edge of the 0.3-micron silicon filter. The wavelength of the Si filter has been calibrated against the line Kr 3d5/2-5p absorption line at 13.595 nm. The error associated with determining the wavelength of the Si edge is 0.0005 nm. The effect of an angular error depends on the angle of incidence. A wavelength error of ±0.0008 nm would result from a ±0.04 degree uncertainly when the measurements are performed at 5 degees from normal incidence. The wavelength accuracy is determined by the uncertainty[7] in the wavelength of the Kr 3d5/2-5p absorption line that is used as the primary standard.

Wavelength	*RMS Uncertainty*	*Error Type*
Measurement Noise	0.0008 %	Random
Calibration Method	0.004 %	Random
Sample Alignment	0.006 %	Random
Precision	0.007 %	
Kr Standard	0.011 %	Systematic
Accuracy	0.011 %	

Table 2. *The relative rms errors associated with the measurement of the FWHM centroid wavelength for a typical Mo/Si multilayer. The measurement noise was determined by repeated measurements without realigning the sample. The error associated with the samples alignment is corresponds to a 0.04 deg uncertainty at 5 degrees from normal incidence.*

Peak Reflectance	*RMS Uncertainty*	*Error Type*
Electronic Noise	0.03 %	Random
Incident Power Stability	0.02 %	Random
Detector Non-uniformity	0.07 %	Random
Precision	0.08 %	
Higher Order Light	0.0002 %	Systematic
Scattered Light	0.25 %	Systematic
Accuracy	0.14 %	

Table 3. *The relative rms errors associated with the measurement of the peak reflectance of a typical Mo/Si multilayer. The measurement noise was determined by repeated measurements without realigning the sample.*

It is estimated that a reflectance precision of 0.08% rms is now achieved which is limited by the detector non-uniformity. This is a substantial improvement from the precision of 0.2% that was achieved in the past. The present level of precision is sufficient to measure reflectance uniformity to the required tolerance for an ETS mask and is approaching the ultimate requirement of 0.06%.

The scattered light contribution to the spectral purity has been measured for the first time. It is found to consist of a broad spectrum roughly independent of the monochromator wavelength. Under the conditions used for the typical multilayer reflectance measurements of the past, with the Be filter, the broadband component of the spectrum accounts for roughly 1.3% of the total photocurrent measured in the incident beam at 13.4 nm. For future reflectivity measurements it will be possible to reduce the amount of broadband scattered light by the use of a slit ahead of the reflectometer and to apply a correction for the remaining spectral impurity.

While it is difficult to prove the accuracy and it is always possible that a systematic error may have been overlooked, it is believed that by reducing and correcting for the scattered light, a reflectance accuracy of 0.1% (absolute) is now possible. Previous reflectance measurements made with the beamline[8] are estimated to be 0.6 - 0.7% lower than the true reflectance for a typical Mo/Si multilayer reflecting near 13.4 nm. For example, a measured reflectance of 67.0% would become 67.7% when corrected for the spectral purity. This affects the calculation of system throughput by a larger factor. For a 9-multilayer mirror optical system throughput estimates should be increased by almost 10% from that calculated based on previous measurements.

7. ACKNOWLEDGEMENTS

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