Extreme-ultraviolet thin-film interference in an Al-Mg-Al multiple-layer transmission filter

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Thin-film interference has been observed in the transmittance of a filter consisting of 263.5-nm-thick magnesium with a 32.2-nm-thick aluminum layer on each side. The transmittance, measured by synchrotron radiation, has an oscillatory behavior in the 25–70-nm wavelength range. On the basis of the calculation of the transmittance, the oscillatory behavior results from interference associated with the relatively transmissive magnesium and aluminum layers and the reflection from the oxidized aluminum surface layers. The bandpass performance of magnesium and aluminum layers deposited on a silicon photodiode detector is presented. © 2002 Optical Society of America

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1. Introduction

Transmission filters consisting of a thin metal layer or other materials are commonly used in the x-ray and extreme-ultraviolet (EUV) wavelength regions for the purpose of transmitting a desired bandpass and attenuating out-of-band radiation.[1] Such filters can also be used to provide differential pumping to isolate an ultrahigh vacuum region from a region with poor vacuum or contamination sources. The thin filter is usually mounted on a wire mesh support and is otherwise unbacked and free standing.

Bandpass filter layers have been applied directly to the surfaces of silicon photodiode detectors (from International Radiation Detectors Inc.) and characterized by synchrotron radiation.[2] The underlying detector provides support for the thin filter and prevents oxidation and contamination of the lower surface of the filter. Filters consisting of multiple layers of different materials were evaluated in the EUV and soft x-ray regions. The transmittances of the layer materials determined the overall transmittance of the multiple-layer filter and the responsivity of the filtered detector.

When the free-standing filters were evaluated in the EUV wavelength region by synchrotron radiation, it was noticed that the transmittance of an Al-Mg-Al multiple-layer filter had an oscillatory behavior as a function of wavelength. Similar oscillations in the transmittances of thin free-standing aluminum and indium filters were observed by Hunter *et al.*[3,4] The Al-Mg-Al filter was fabricated by Luxel Corporation[5] and consisted of the following three layers: 32.2-nm-thick aluminum, 263.5-nm-thick magnesium, and 32.2-nm-thick aluminum. The purpose of the filter was to transmit wavelengths in a bandpass longer than the Mg L_{III} edge at 24.8 nm and to block far-ultraviolet and visible wavelengths. The thin aluminum layers provided protection against oxidation of the magnesium filter material.

The purpose of this paper is to understand the observed oscillations in the transmittance of the Al-Mg-Al filter and to predict the performance of this filter when deposited on a photodiode. On the basis of the calculation of the propagation of EUV radiation through the various filter layers, it is shown that the oscillations in the transmittance result from the interference of the waves partially reflected by the oxidized aluminum surface layers.

2. Filter Transmittance

The filter transmittance measurements were performed at the U.S. Naval Research Laboratory beamline X24C at the National Synchrotron Light Source at Brookhaven National Laboratory. A monochromator provided dispersed x-ray and EUV radiation with a resolving power of 600.[6,7] A thin free-standing beamline filter was inserted into the radiation beam to attenuate the higher harmonic radiation from the monochromator while passing the desired

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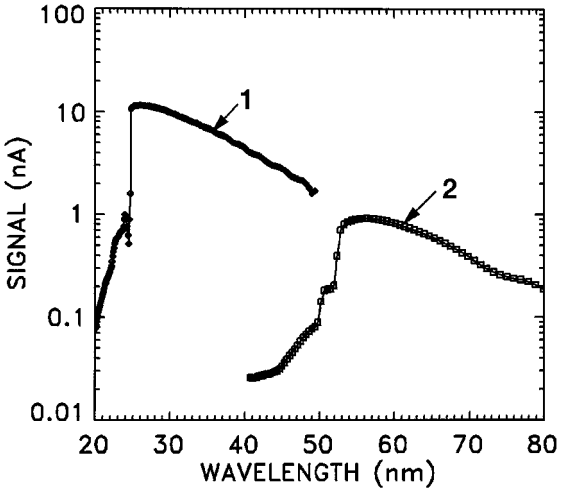

Fig. 1. Detector current generated by the synchrotron radiation beam passing through the Al-Mg-Al beamline filter (curve 1) and the Sn beamline filter (curve 2).

EUV bandpass of interest. The beam was incident on a silicon photodiode detector, type AXUV-100G from International Radiation Detectors Inc., and the detector current was measured by a precision electrometer (Keithley Model 617).

The detector currents in the 20–80-nm wavelength range are shown in Fig. 1. For 20–50-nm wavelengths, an Al-Mg-Al beamline filter with layer thicknesses of 32.2, 263.5, and 32.2 nm, respectively, was utilized (curve 1 in Fig. 1). The Mg L_{III} absorption edge at 24.8 nm is present. The layer thicknesses were known from the filter material deposition process and the mass per area of the filter. For 40–80-nm wavelengths, a 109-nm-thick Sn beamline filter was utilized (curve 2 in Fig. 1), and the Sn N_V absorption edge at 51.9 nm is present. Both filters were fabricated by Luxel Corporation.[5]

The transmittance of a second Al-Mg-Al filter (also with layer thicknesses 32.2, 263.5, and 32.2 nm) was determined by measurement of the ratio of the detector currents with and without the second Al-Mg-Al filter in the beam. The results are shown in Fig. 2(a). The transmittance of the Al-Mg-Al filter in the 23–40-nm wavelength range was determined by use of the Al-Mg-Al beamline filter to attenuate higher harmonic radiation from the monochromator. The transmittance of the Al-Mg-Al filter in the 40–70-nm wavelength range was determined by use of the Sn beamline filter to attenuate higher harmonics.

As shown in Fig. 2(a), the transmittance of the Al-Mg-Al filter has an interesting oscillatory behavior that increases in amplitude and period with increasing wavelength. In contrast, the transmittance of a 160-nm-thick Ti filter shown in Fig. 2(b), measured by the same procedure, has no oscillatory behavior. This suggests that the oscillations in the Al-Mg-Al transmittance are associated with the multiple-layer nature of the Al-Mg-Al filter. The titanium absorption edge at a 38-nm wavelength results from absorption of the type $3p$-$3d$ and has been observed in the neighboring transition metal scandium.[8]

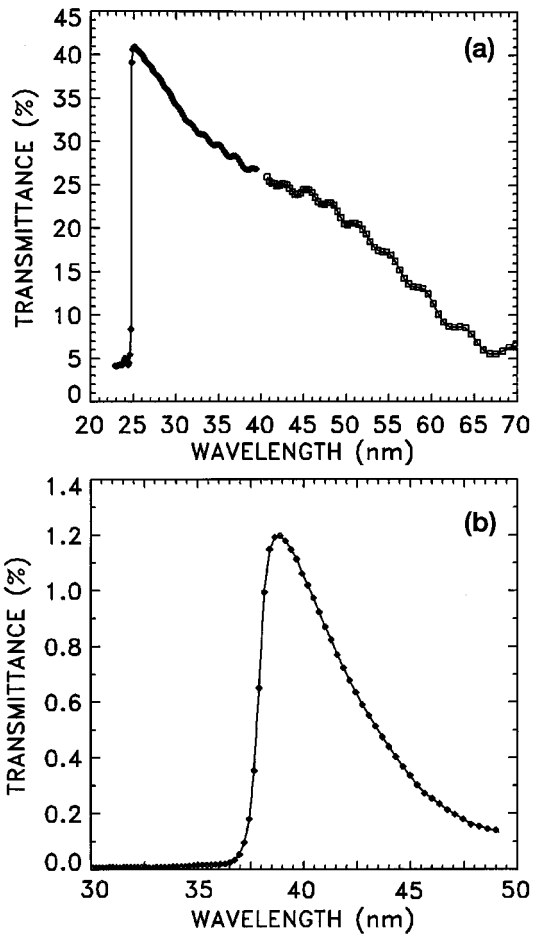

Fig. 2. Measured transmittances of (a) the Al-Mg-Al filter and (b) the Ti filter.

The transmittance of the Al-Mg-Al filter was calculated by means of accounting for the electromagnetic wave transmitted and reflected at each layer interface and the attenuation of the wave in each layer by use of the formalism of Ref. 9. The assumed layers were Al_2O_3, Al, Mg, Al, and Al_2O_3 with thicknesses of 7.5, 24.7, 263.5, 24.7, and 7.5 nm, respectively. Thus the aluminum on either side of the magnesium was assumed to be oxidized with a typical surface oxide thickness of 7.5 nm.[10] The optical constants were derived from the following sources and bulk material densities: Al_2O_3 (Ref. 11, 3.99 g/cm^3), Al (Ref. 12, 2.70 g/cm^3), and Mg (Refs. 13 and 14, 1.74 g/cm^3).

The calculated and measured transmittances of the Al-Mg-Al filter are compared in Fig. 3. Because there are no free parameters in the calculation, the agreement is considered to be good. The amplitude and period of the oscillations increase with wavelength, and the wavelengths of the calculated and measured extrema coincide. The calculated amplitudes tend to be larger than measured, and this probably results from the assumption that the layer interfaces are discrete whereas in reality the optical constants vary continuously across the layer interfaces.

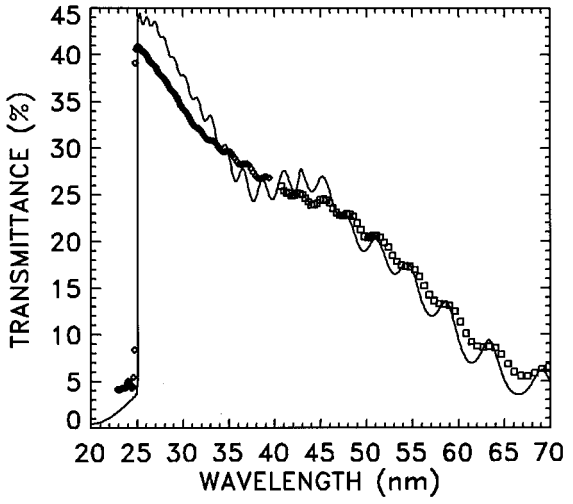

Fig. 3. Comparison of the measured transmittance (data points) and the calculated transmittance (curve) of the Al-Mg-Al filter.

The calculated absorptance, reflectance, and transmittance of the Al-Mg-Al filter are shown in Fig. 4(a). The values of absorptance and reflectance tend to increase, and the transmittance tends to decrease with wavelength. The assumed layer thicknesses are Al_2O_3 (7.5 nm), Al (24.7 nm), Mg (263.5 nm), Al (24.7 nm), and Al_2O_3 (7.5 nm). The variations in the absorptance, reflectance, and transmittance with changes in the assumed magnesium thickness, at an incident wavelength of 50 nm and for fixed Al_2O_3 (7.5-nm) and Al (24.7-nm) thicknesses, are shown in Fig. 4(b). The oscillatory behavior is present even for the smallest magnesium thickness. This suggests that the oscillations are primarily associated with reflections from the aluminum layers on each side of the magnesium layer. The magnesium functions as a spacer layer between the partially reflecting aluminum layers. The transmittance shown in Fig. 4(b) tends to increase with decreasing magnesium thickness because of reduced absorption in the magnesium spacer layer.

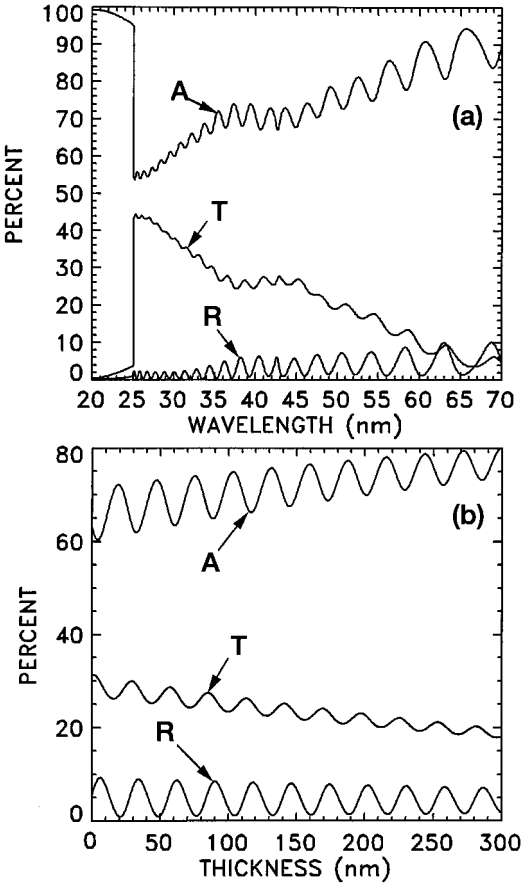

Fig. 4. (a) Calculated absorptance A, transmittance T, and reflectance R of the Al-Mg-Al filter. (b) The calculated values as functions of the Mg thickness and for 50-nm wavelength incident radiation.

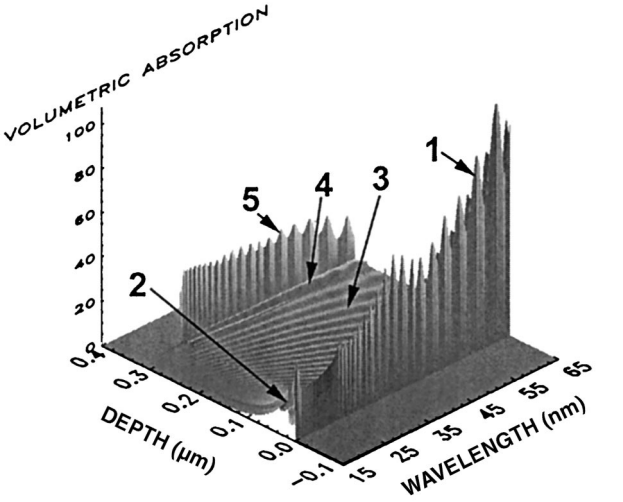

Fig. 5. Calculated volumetric absorption (in units of μm^{-1}) of the Al-Mg-Al filter as a function of the incident wavelength and the depth into the filter layers: 1, Al_2O_3; 2, Al; 3, Mg; 4, Al; and 5, Al_2O_3.

The volumetric absorption is defined as the absorbed energy per unit volume in the filter material divided by the energy incident on the surface of the filter per unit area. The volumetric absorption was calculated by the formalism of Refs. 15 and 16. The volumetric absorption (in units of μm^{-1}) as a function of the depth into the Al-Mg-Al filter and the incident wavelength is shown in Fig. 5. The numbered layers in Fig. 5 are 1, Al_2O_3 (7.5 nm); 2, Al (24.7 nm); 3, Mg (263.5 nm); 4, Al (24.7 nm); and 5, Al_2O_3 (7.5 nm). The radiation is initially incident on layer 1.

Summing the volumetric absorption over the thickness of each filter layer, the absorptance in each layer was calculated as shown in Fig. 6. The absorptance is typically high in magnesium at wavelengths below the Mg L_{III} absorption edge at 24.8 nm and in aluminum and aluminum oxide below the Al L_{III} edge at 17.0 nm.

As can be seen in Fig. 5, the volumetric absorption in the Al_2O_3 surface layers is large owing to the relatively large attenuation coefficient in aluminum oxide, more than ten times higher than in aluminum. The contrast in the optical constants between aluminum oxide and the underlying aluminum, and the

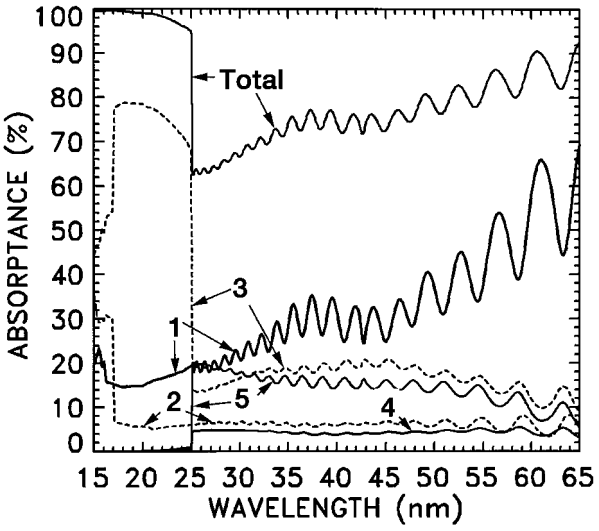

Fig. 6. Calculated absorptance of the Al-Mg-Al filter layers: 1, Al_2O_2; 2, Al; 3, Mg; 4, Al; and 5, Al_2O_3.

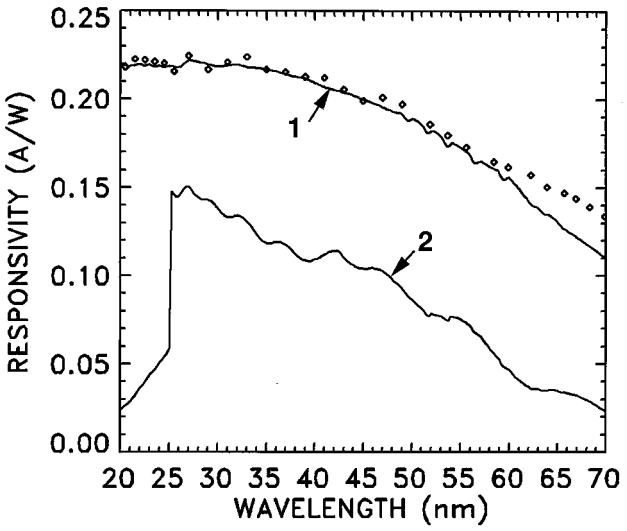

Fig. 7. Measured responsivity of the uncoated silicon photodiode (data points), the calculated responsivity of the uncoated photodiode (curve 1), and the calculated responsivity of the Al-Mg-Al coated photodiode (curve 2).

transmittance in magnesium at wavelengths longer than the Mg L_{III} edge at 24.8 nm, are the primary factors resulting in the thin-film interference effects such as the observed oscillations in the transmittance.

3. Filtered Photodiode Responsivity

Depositing the multiple-layer filter directly on a detector has the advantages of providing support for the thin filter layers and preventing contamination and oxidation of the side of the filter in contact with the underlying detector. Because the filter is not free standing, the filter layers can be made thinner and more transmissive, and this increases the overall responsivity of the detector compared with a free-standing filter and an uncoated detector.

The detector responsivity is defined as the current appearing in the external circuit divided by the incident radiation power. As discussed in Ref. 17, the responsivity is modeled by calculation of the propagation of the electromagnetic wave through the filter and detector layers and the deposition of radiation energy in the detector layers. The deposited radiation energy creates electron–hole pairs, and the conduction electrons are collected and appear as a current in the external circuit.

As an example of the filtered detector performance, consider the responsivity of a silicon photodiode detector with the following filter layer materials and thicknesses: Al_2O_3 (7.5 nm), Al (24.7 nm), Mg (100 nm), Al (24.7 nm), and Al_2O_3 (7.5 nm). The detector is assumed to be of the type AXUV-100G, and the detector layers, thicknesses,[18] and carrier collection efficiencies are SiO_2 (6 nm, 0.15), phosphorus-doped n-type Si (100 nm, 1.0), epitaxial p-type Si (150 nm, 1.0), and Si substrate (1.0). The optical constants for SiO_2 and Si were derived from Refs. 19 and 20, respectively.

The listed carrier collection efficiencies were determined by means of matching the calculated responsivity (curve 1 in Fig. 7) to the measured responsivity[21] of the unfiltered AXUV-100G photodiode (data points in Fig. 7). The 0.15 carrier collection efficiency in the surface SiO_2 layer is the same as determined in the soft x-ray region (1–25 nm) when we use the same responsivity model.[17] The carrier collection efficiencies in the underlying silicon regions are unity. The calculated responsivity of the filtered photodiode is shown by curve 2 in Fig. 7. The filtered photodiode has relatively high responsivity at wavelengths longer than the Mg L_{III} absorption edge at 24.8 nm because of the thin and transmissive filter layers.

The oscillations in the responsivity of the detector with the Al-Mg-Al coating are a result of the interference within the coating. The oscillations are diminished when the oxidized aluminum layer that is in contact with the detector is removed from the coating. In general, the oscillations in the detector responsivity can be used to determine the layer thicknesses if the optical constants are known. Alternately, the optical constants can be determined if the layer thicknesses are known. A related technique was used recently to determine the optical constants of Sc and Ti layers deposited on silicon photodiodes. The Sc and Ti layers were overcoated with a thin silicon layer to protect the transition metal layers from oxidation and contamination.[8,22]

4. Conclusion

When the propagation of EUV radiation was calculated through the layers of a free-standing Al-Mg-Al filter, it was determined that the oscillations observed in the experimental transmittance data resulted from the interference of the waves partially reflected by the oxidized aluminum surface layers. On the basis of the good agreement between the cal-

culated and the observed transmittances, the performance of the filter applied to a photodiode was predicted. The filter on the photodiode provides relatively high responsivity for wavelengths from the Mg L edge at 25 nm to approximately 60 nm and should provide good visible light blocking.

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