Title
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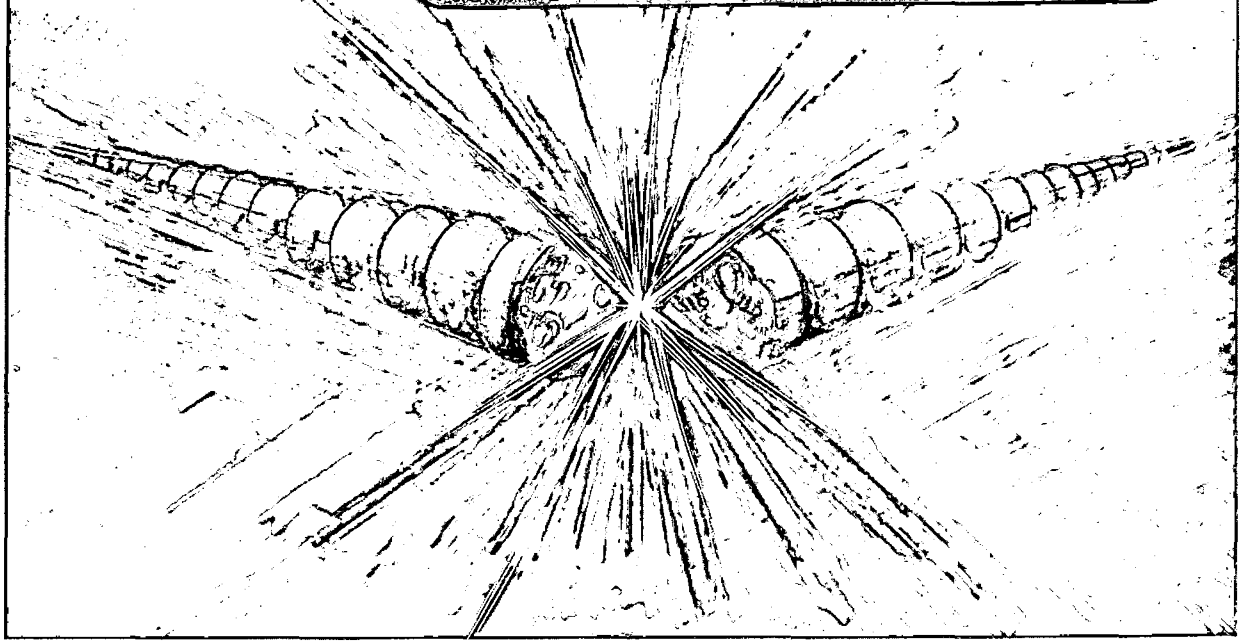

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MULTILAYER REFLECTORS FOR THE EXTREME ULTRAVIOLET SPECTRAL REGION

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ABSTRACT

Reflectivity data from Al-Nb multilayers in the 300-450 Å wavelength range at angles 20-50 deg from normal incidence are presented. Constructive interference between the 10 layer-pairs of this structure is observed. Multilayers deposited on a super-polished optical flat had a much higher reflectivity than those deposited on Si (111) wafers. Annealing multilayers on Si at 330 °C for 3 hr further reduced their reflectivity. Measured peak reflectivities for the multilayer on the super-polished optical flat are 17% and less depending on the angle of incidence. The measured reflectivity is not more than half of that calculated using a model assuming sharp interfaces between elemental materials. The resolution of this device, $\lambda/\Delta\lambda \approx$ 6-7, is in good agreement with the calculated values.

Introduction

The spectral region from 500 to 100 Å, referred to here as the extreme ultra-violet (EUV), is characterized by low normal incidence reflectivities. Normal incidence reflectivities of even the best reflectors in this region, e.g., Re, Os, Ir, Pt, Ag, Au and SiC, drop to values of the order of a few percent in the EUV. This has, until recently, excluded normal and near-normal incidence optical elements from EUV optical designs.

Periodic multilayer interference structures can provide enhanced normal incidence reflectivities and at the same time act as low resolution dispersing elements in the EUV. These optical devices will find applications in synchrotrons, free-electron lasers, laser produced plasmas, astronomy and other areas.

The design considerations which led to the Al-Nb combination for our initial investigations of the 300-450 Å reflectivity of multilayers are somewhat different than those of previous efforts in this wavelength range [1-5]. Published values of the optical constants δ and β (where the complex refractive index $\hat{n} = 1 - \delta - i\beta$) in this region [6] were assumed to adequately describe the optical behavior of the very thin layers which make up the multilayers, and are shown in Fig. 1. High absorption is a fundamental problem in designing multilayers in this region, limiting the number of layers which can contribute to constructive interference. Aluminium is a good material for the low absorption layers, providing that it can be layered without significant oxidation, because its L edges are at slightly higher energies than those of interest. Instead of choosing one of the high Z, high reflectivity materials above for the high absorption layers, it was noted that the reflectivity at each interface depends strongly on the difference in δ and β for the materials on each side of the interface. Niobium was chosen as an element whose optical constants, both δ and β, contrast greatly compared to those of Al. Over most of the 300-450 Å range δ for Al is positive, while δ for Nb is negative, yeilding substantial constrast. There is also much contrast in β, although the absorption of Nb in this region is not as great as that of the high Z, high reflectivity elements mentioned above, so that more layers contribute to the interference than would be the case had one of these other elements been used as the high absorption material.

Experimental

Al-Nb multilayers were fabricated by magnetron sputtering onto substrates rotating at constant velocity under elemental sources. The base pressure before and after sputtering was 5x10-7 torr, and 2.25 microns of purified Ar was the sputtering gas. Two different types of substrates were coated during the same deposition: a super-polished optical flat and semiconductor grade, high conductivity Si (111) wafers. The optical flat substrate was prepared by washing in hot detergent, rinsing in deionized water and degreasing in isopropyl alcohol vapor, while the Si wafers were deposited upon as received. Approximately 900 Å of Al was deposited first, then ten layer-pairs consisting of about 230 Å of Al and 46 Å of Nb were deposited, with Nb as the last layer. The Al layers were exposed to the ambient Ar sputtering gas for about 45 seconds before being overcoated with the Nb layers, thus minimizing time for possible oxidation.

One sample on a Si substrate was annealed in a vacuum of 6x10-7 torr at 330 °C for 3 hr.

One sample on a Si substrate was characterized by Rutherford backscattering spectroscopy (RBS) using 1.8 MeV He ions at various angles of incidence.

Reflectivity measurements were made at SURF, National Bureau of Standards. A toroidal grating monochromator provided monochromatic radiation to the sample which was mounted on a 2-axis goniometer positioned on the Rowland circle of the monochromator. The measurements were made in a symmetric Bragg geometry with the sample and windowless photodiode detector rotating in the vertical plane, corresponding primarily to s-polarization. The precise mixture of s- and p-polarization, resulting from the finite angular acceptance of the apparatus, was not measured. The presence or absence of an Al filter in the incident beam had little effect on the reflectivities, so that harmonics and stray light were not a significant problem. The data presented here were taken with no Al filter installed.

Results and Discussion

The EUV reflectivity of these Al-Nb multilayers was found to depend strongly on the substrate and on annealing. Figure 2 shows the measured reflectivity vs. wavelength for three multilayers taken with the incident and reflected beams 30 deg from normal incidence. A reflectivity peak is seen for the samples on the optical flat and on Si, at roughly 410 Å and 370 Å respectively. These peaks are at different wavelengths because the structures have slightly different d-spacings resulting from different substrate-target distances. The multilayer on the super-polished optical flat shows a much stronger interference peak than the multilayer on Si. The specific mechanism yielding these different reflectivities with substrate are unknown, though presumably result either from different roughness of the different substrates or from a different growth morphology of the underlying Al layer on the different substrates. The annealed sample on Si shows no indication of constructive interference, so that substantial changes take place in these structures under these moderate heating conditions. These changes have not yet been studied in detail, but may result from the formation of one of several stable Al-Nb intermetallic compounds [7].

Figure 3 shows the reflectivity from the sample on an optical flat measured as a function of wavelength at a series of angles ranging from 20 to 50 deg from normal incidence. Data points at each angle are connected by lines in the figure. A peak in the reflectivity is observed at each angle. The changing wavelength of the reflectivity peak with angle is in accord with Bragg's law (including refraction), showing that the peaks do result from constructive interference from the different layers of this structure.

The reflectivity data from the sample on the optical flat is compared with calculated performance in Figs. 4 and 5. These calculations [8] are based on a model assuming sharp interfaces between elemental layers described by optical constants taken from ref. [6]. The ratio of the thicknesses of the Al to Nb layers was taken as that determined during characterization for sample preparation, while the values of 230 Å and 46 Å for these respective thicknesses were determined by matching calculated and measured peak positions. Calculations presented here are for the case of complete s-polarization. Figure 4 compares measured with calculated reflectivities for incident and reflected angles 40 deg from normal incidence. The measured peak reflectivity is about 15%, or roughly half of that calculated. The wavelength resolution of this device is $\lambda/\Delta\lambda$ = 6.2 in good agreement with that calculated. Figure 5 shows the trend in the peak reflectivity versus wavelength both measured and calculated for this particular multilayer. The trend with wavelength in the experimental data agrees with the calculation, but experimental values are never more than half of the calculated values. Calculations indicate that the decreasing reflectivities at longer wavelengths (and hence angles closer to normal) can be offset by a design using slightly different thicknesses of Al and Nb layers. Likewise the peak at normal incidence can be shifted to different wavelengths by slight variations of the layer thicknesses.

Several possible sources for the discrepancies between the measured and calculated reflectivities in Figs. 3 and 4 can be suggested. The assumption of complete s-polarization may help to account for the discrepancies for angles away from normal incidence. Due to the finite angular acceptance of the apparatus there is some mixture of polarizations in the experimental data that is not accounted for in the calculation. The assumption of compositionally abrupt and smooth interfaces for the calculation may not be entirely justified, and departures from this assumption would also help to explain the discrepancies. It is also possible that the optical constants used to describe pure Al and Nb may not adequately describe the ultra-thin layers that make up these structures. Partial oxidation of the Al layers would also tend to reduce the measured reflectivity, although this can be ruled out as a significant factor because no signal corresponding to backscattering from oxygen was observed in the RBS results.

Conclusions

Constructive interference between the 10 layer-pairs of an Al-Nb multilayer is observed in the 300-450 Å wavelength region at angles ranging from 20 to 50 deg from normal incidence. Substrates and annealing have a strong effect on the reflectivity of Al-Nb multilayers at these wavelengths, with a super-polished optical flat acting as a better substrate than Si (111) wafers. Annealing a multilayer on Si destroyed its multilayer interference peak. The measured peak reflectivity for the sample on the super-polished flat is no more than half of that calculated using a model assuming sharp interfaces between elemental layers using published values of optical constants. Several possible sources for this discrepancy are suggested. This work demonstrates that Al can be incorporated into multilayer structures by sputtering without significant oxidation. These preliminary results of our investigations, together with those of others, demonstrate that significantly enhanced normal incidence reflectivities in the EUV can be obtained using periodic multilayer structures. Further work is needed to find optimal materials and substrate combinations for specific EUV wavelengths, to understand the materials effects leading to and limiting these optimal designs, and to study the thermal stability of these devices.

Acknowledgements

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FIGURES

Figure 1. Optical constants δ and β, where $\hat{n} = 1 - \delta - i\beta$, for Al and Nb taken from ref. [6] show much contrast over most of the 300 to 450 Å wavelength range. Between 300 and 320 Å most of the contrast is in β.

Figure 2. Reflectivity versus wavelength is shown for three Al-Nb multilayers each taken with the incident and reflected beams at 30 deg from normal incidence. The multilayer on the optical flat shows higher reflectivity than that on a Si wafer, which shows higher reflectivity than an annealed multilayer on Si.

Figure 3. Reflectivity versus wavelength is shown for an Al-Nb multilayer on a super-polished optical flat substrate. The different curves are for different angles from the normal.

Figure 4. Measured and calculated reflectivity versus wavelength for an Al-Nb multilayer at 40 deg is shown here. The calculation assumes sharp interfaces between elemental layers described the optical constants in Fig. 1, and complete s-polarization.

Figure 5. The peak reflectivity of the Al-Nb multilayer on the super-polished optical flat at different angles is compared with that calculated. The trend with wavelength is the same but the measured values are never more than half of those calculated.

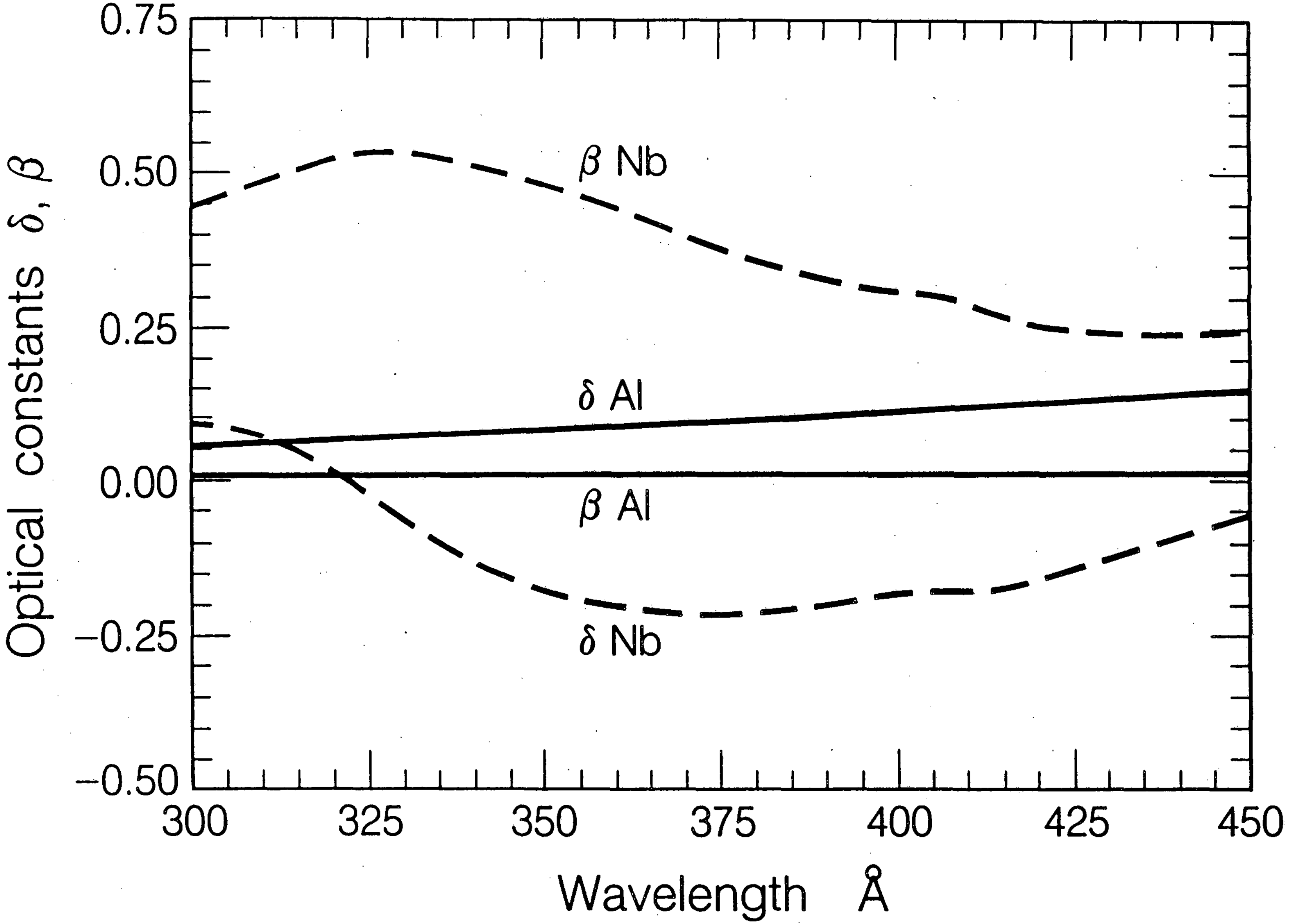

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Figure 1

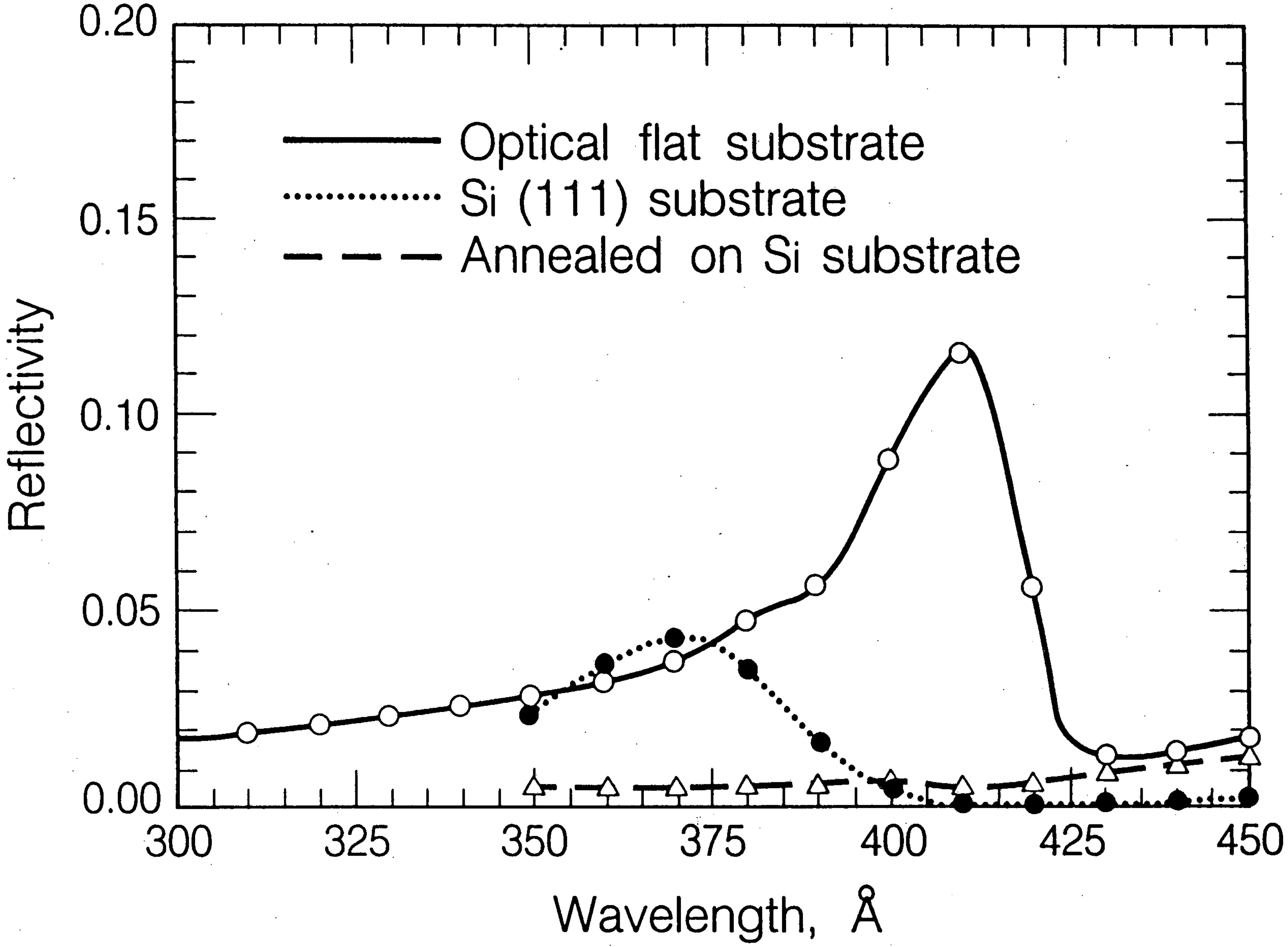

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Figure 2

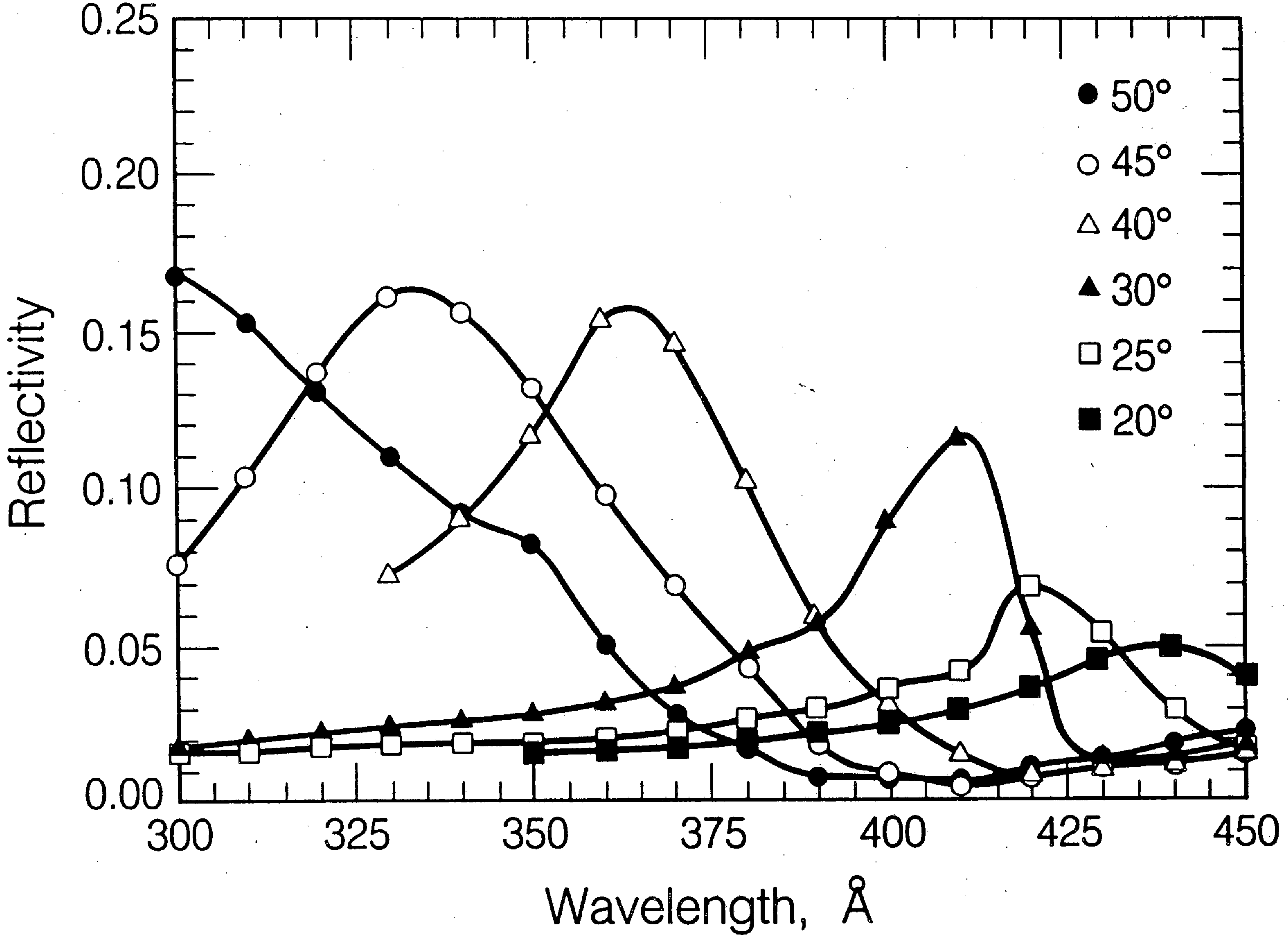

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Figure 3

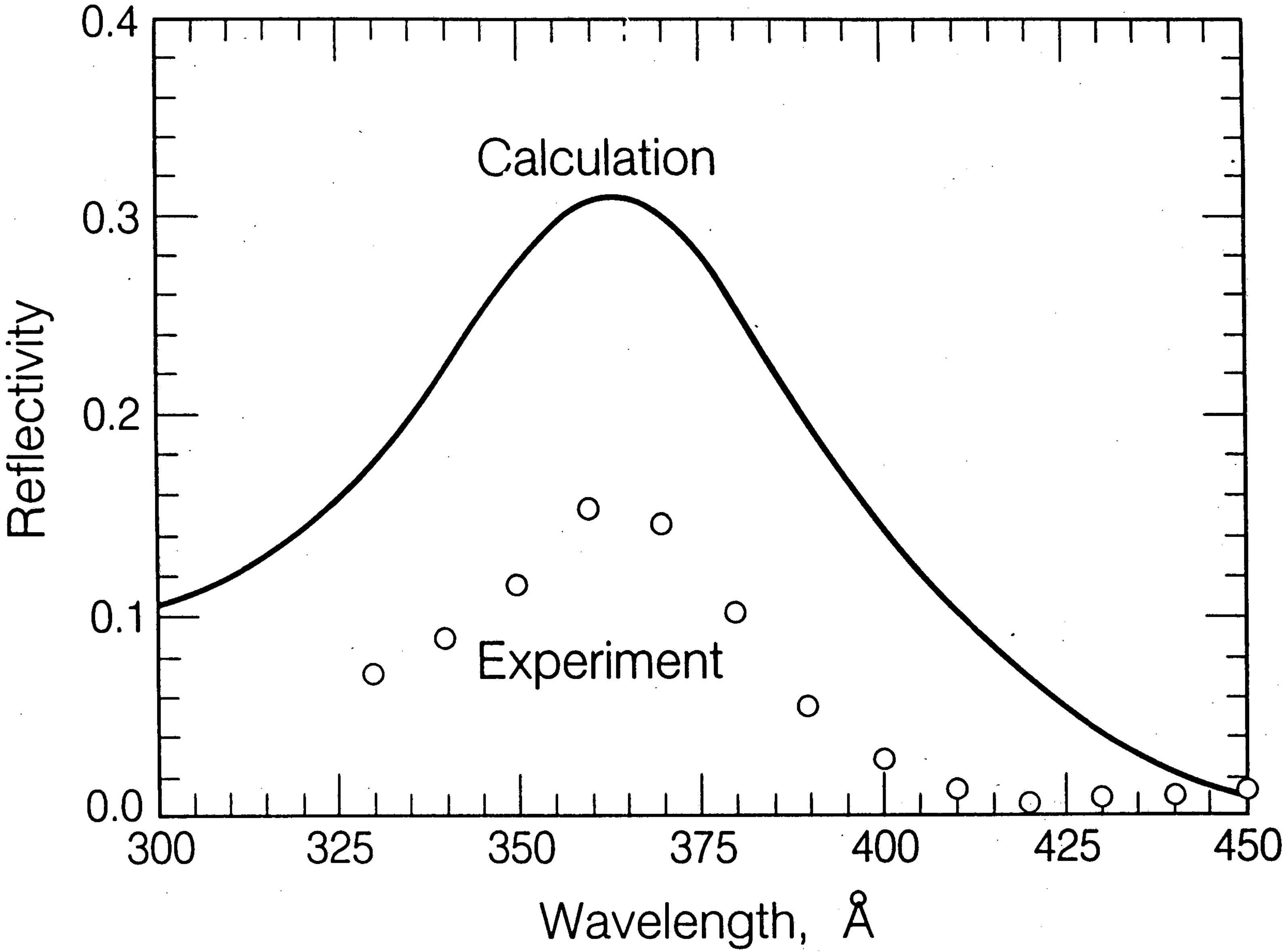

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Figure 4

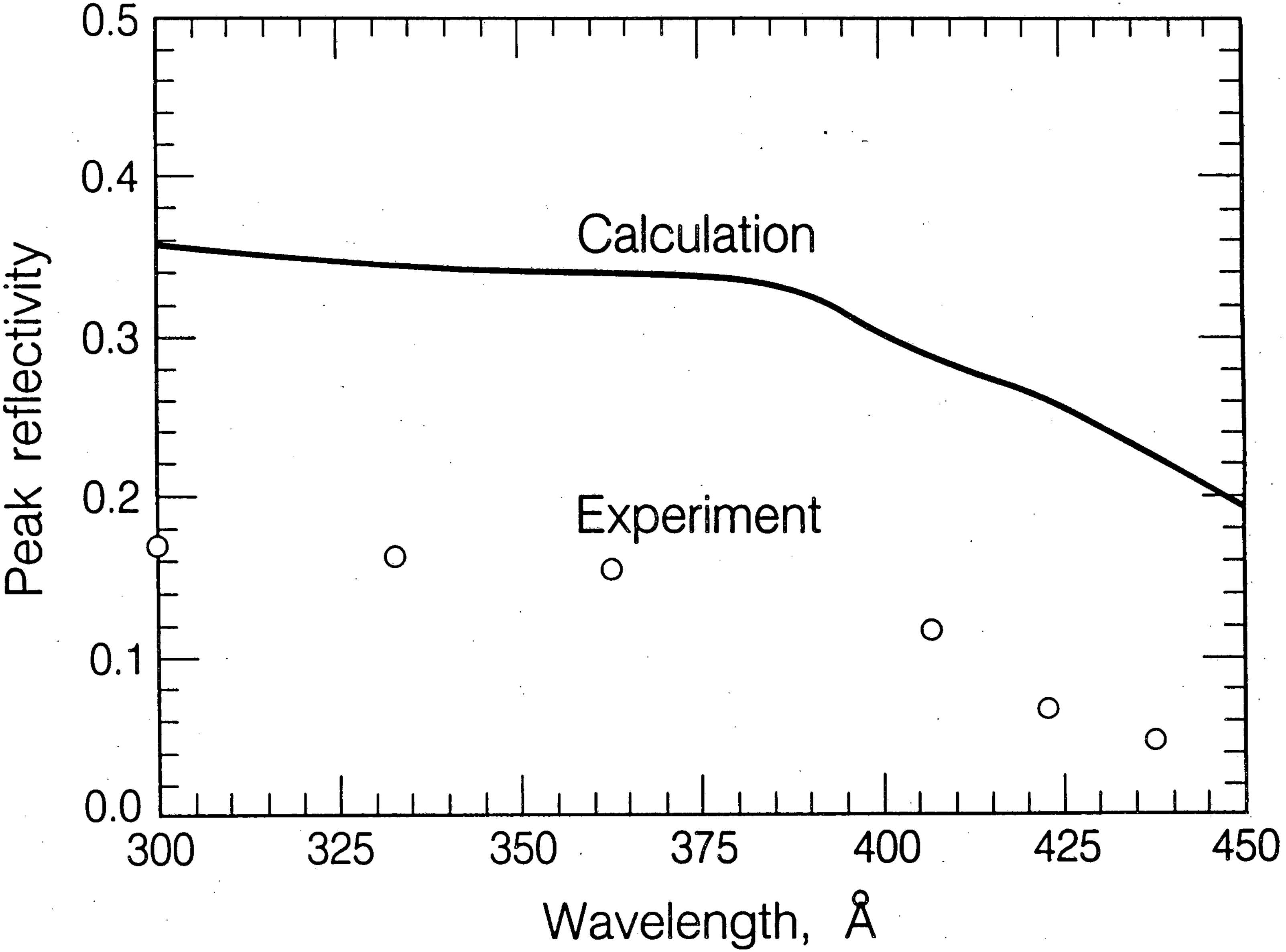

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Figure 5

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