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PERFORMANCE OF TRANSITION METAL--CARBON MULTILAYER MIRRORS FROM 50 to 350 eV

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ABSTRACT

We report measurements and theoretical calculations of the reflectivity and resolving power of multilayer mirrors made of alternate layers of a transition metal (Co, Fe, V, and Cr) and carbon (2d ≈ 140 A) from 80 to 350 eV.

INTRODUCTION

Recent developments in thin film technology have made it possible to fabricate coatings, multilayer mirrors, that enhance surface reflectivity in the vacuum ultraviolet and soft x-ray region.[1,2] Multilayer mirrors form an artificial crystal lattice consisting of alternate layers of high and low atomic number (Z) materials. The high Z material acts as a scattering plane while the low Z material acts as a spacer between the high Z planes. Like a natural crystal these coatings obey Bragg's law, $\lambda/2d=\sin\theta$, i.e., the ratio of the incident wavelength, λ, to the 2d spacing of the multilayer equals the sine of the incident angle, θ, measured from the mirror surface. We have measured the reflectivities of four transition metal (Co, Fe. Cr, and V)--carbon multilayer mirrors between 80 and 350 eV. The 2d spacing of the mirrors was ≈ 140 A. The angular range examined was 15° to 80°.

Calculations of the multilayer mirrors performance may be made using the equations of classical electrodynamics[3] and compilations of the optical constants of the relevant materials.[4] Peak reflectivity calculations were performed and compared to the measured peak reflectivities.

Extrapolation of the calculated reflectivity was required because of a lack of optical constant data in the region below 100 eV. Inclusion of the effects of interfacial roughness which reduces the multilayer mirror reflectivity yields excellent agreement between the calculated and measured values. It is important to note that other factors, such as uncertainties in the optical constants and diffuse boundaries may also contribute to the reduction in the reflectivity.

EXPERIMENT

The multilayer mirrors used in the present investigation were fabricated by electron beam evaporation.[1] An in situ soft x-ray (γ = 31.6 or 67.6 A) monitor was used to maximize the reflectivity of the multilayer during fabrication. The structure which results is not a regular lattice with constant layer thickness throughout, rather the thickness ratio of the low Z to high Z material increases towards the surface of the multilayer mirror. Table I includes the average characteristics of the multilayers studied in this experiment.

Table I Multilayer Characteristics

	V-C	Cr-C	Co-C	Fe-C
Average 2d spacing (A)	134	134	143	143
Number of layer pairs	15	14	20	20
Average thickness ratio high Z/low Z	0.7	0.7	0.4	0.4

The reflectivity measurements were performed at the Stanford Synchrotron Radiation Laboratory. The photon beam from the synchrotron was monochromatized by a "grasshopper type" (Rowland circle grazing incidence) monochromator with a 1200 l/mm grating. The samples could be rotated (θ) independent of the detector (2θ). A single channetron electron multiplier with a micromachined aluminum photocathode was used to measure the reflected, I_R, and incident, I_0, S-polarized photon beams. Data was collected by fixing the sample and detector angles and scanning the photon energy. The errors in the reflectivity $R = I_R/I_0$ were approximately 20%.

DATA AND ANALYSIS

Figure 1 shows the measured peak reflectivity vs. energy for the multilayer mirrors listed in Table I. This may be compared to calculations of the peak reflectivity based on the method of P. Lee[5] and the optical constant compilations of Henke, et. al.[4] Unfortunately, the optical constant tabulations are incomplete below 100 eV, therefore the calculated reflectivities between 80 and 100 eV are linear extrapolations of the reflectivity above 100 eV. It is reasonable to expect this extrapolation to be accurate for all the materials except iron which has a 3s electron binding energy of 92 eV. Changes in the optical constants associated with this resonance may make the extrapolation less accurate. Figure 2 shows the reflectivity ratio (calculated/measured), R_R, vs. energy for all the samples listed in Table I.

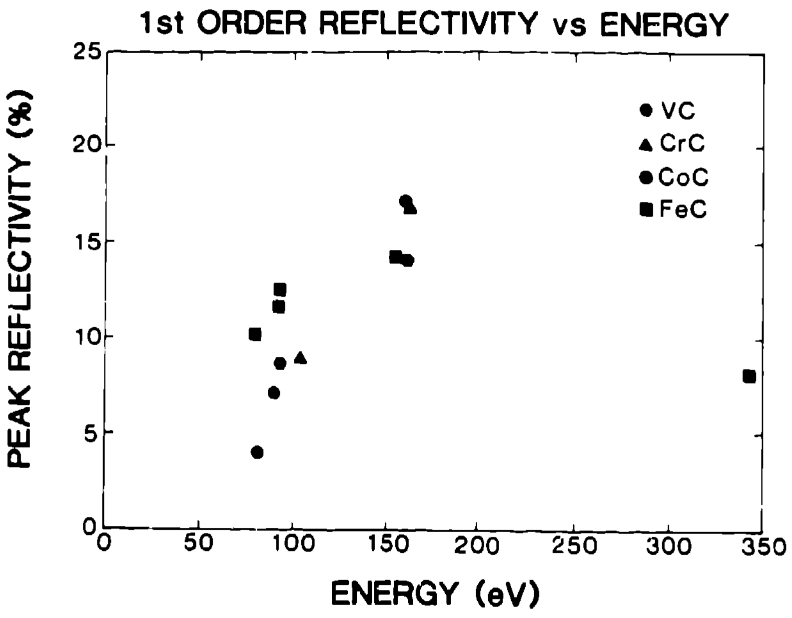

Fig. 1. Measured peak reflectivity vs. energy for several transition metal-carbon multilayer mirrors. The effective 2d spacing for the mirrors was approximately 140A. The angular range was 15° to 80°.

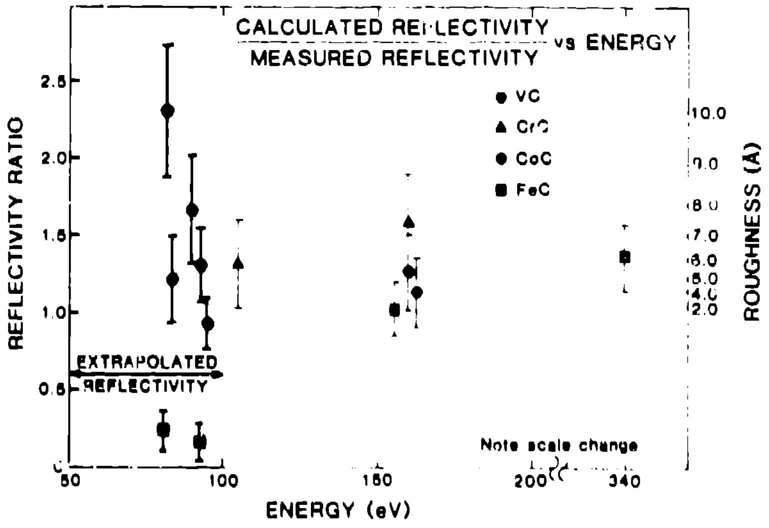

Fig. 2. The reflectivity ratio (calculated/measured) vs. energy for several transition metal-carbon multilayers. The calculated reflectivies are extrapolations below 100 eV. The roughness for a given reflectivity ratio is shown on the right hand scale.

The error bars are representative of the experiment and do not contain the uncertainties in the optical constants or extrapolations.

We note that within experimental error nearly all of the multilayers perform below calculational levels, i.e., $R_R > 1.0$. The exceptions, the FeC data below 100 eV, are probably a result of the uncertainty introduced by the extrapolation of the reflectivity below 100 eV into a resonance region in iron. Many effects may cause this reduction: surface roughness, diffuse boundaries, and uncertainty in the multilayer parameters (optical constants, material density, and material distribution). We choose to assume that all of the discrepancy is due to surface and interfacial roughness. The reduction in reflectivity for a rough boundary between two media[6] coupled with the Bragg condition is

$$R_R = \exp\left[+ (2\pi\ \sigma/d)^2\right] \tag{1}$$

where σ is the root mean square roughness.

Using the average reflectivity ratio for each sample (we have left out the Fe-C samples below 100 eV) we have calculated a σ for each sample using equation 1. The calculated roughness and sample standard deviations are summarized in Table II.

TABLE II

Multilayer Mirror	Calculated Roughness (A)	Sample Deviation (%)
FeC*	4	20
CoC	8	30
V-C	4	15
CrC	6	12

*Excluding data below 100 eV.

The right hand scale of Fig. 2 provides an indication of the roughness associated for a given reflectivity ratio.

A complete diffraction profile of a V-C sample is shown in Fig. 3. The structure observed is typical of all of the samples. The central peak has a resolving power, the peak energy divided by the full width at half maximum, of 20 which is consistent with the theoretical expectation that the resolving power is nearly equal to the number of layer pairs contributing to the reflectivity which is 15 in this case.[1] The structure in the wings of the main peak is attributed to the aperiodicity of the multilayer structure, i.e., the ratio of high Z to low Z material in the multilayer is a function of depth.

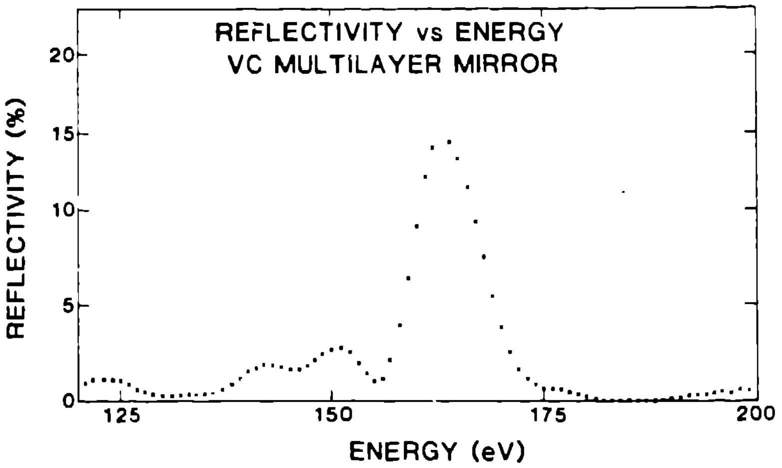

Fig. 3. The reflectivity in percent of a V-C multilayer mirror vs. photon energy.

CONCLUSION

We have demonstrated that multilayer mirrors can be used a efficient reflectors of soft x-rays for non-grazing incidence. The performance of these structures can be calculated with allowance for imperfections in the fabrication process and uncertainties in the optical constants.

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