PROGRESS IN THE THEORY OF X-RAY SCATTERING FROM MULTILAYER STRUCTURES

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The development of multilayer (ML) reflective coatings have enabled high-resolution x-ray imaging in advanced applications such as extreme ultraviolet lithography (EUVL) and x-ray telescopes for astronomy. The performance of these coatings is limited by the nonideal structure of the layer boundaries. Specifically, intermixing at the boundaries decreases the Fresnel reflectance, which results in increased x-ray absorption in the coating and lower throughput for the optical system. Roughness at the boundaries scatters radiation out of the specular mode, resulting in lower throughput and decreased image contrast. To understand and control the performance of x-ray ML coatings, it is important to develop a theory that describes the interaction of x-rays with realistic ML structures under conditions of practical interest. We have previously developed a theory of x-ray scattering[1] that, while useful in elucidating much of the important physical behavior, has limited applicability to quantitative modeling owing to the restrictions imposed by several simplifying approximations. In this paper we extend the previous theory by removing most of these approximations, and thereby present a practical theoretical tool for modeling the performance of realistic coatings.

The key new developments are summarized as follows. The theory is reformulated within the "distorted-wave Born approximation"[2], where the zeroth order solution is Fresnel reflection, thereby removing all limitations on the incident and scattering angles. The description of the layer boundaries includes interfacial roughness represented by the power spectral density (PSD) and a diffuse region of intermixing of arbitrary spatial profile. The PSD of the interface is allowed to vary within the ML stack according to a growth model that includes replication of the roughness of the underlying layer and random roughness introduced by the film growth process. This approach naturally accounts for the partial correlation of the interfacial roughness. The incident specular field is treated dynamically, where the Fresnel coefficients are appropriately modified to account for the roughness and mixing at the interfaces. Similarly, the propagation of the scattered field is treated dynamically, that is, we include all multiple reflections of the outgoing radiation. This is particularly important for cases in which the scattered mode satisfies a Bragg condition, as occurs for small angle scattering in an imaging application.

The only significant approximation that remains in the theory is the assumption of "small roughness", expressed as $4k_o^2\sigma^2\cos^2\theta_o << 1$, where k_o and θ_o are the wavenumber and angle of the incident field, and σ is the root-mean-square value of the interfacial roughness. This criteria is equivalent to a requirement that the total nonspecular scattering be small compared to the incident field, a condition satisfied by definition for high-performance optical coatings. For example, for ML coatings designed to operate near normal incidence at a wavelength of 13 nm, the theory will be valid for interfacial roughness $\sigma \leq 0.5$ nm.

As application of the theory, we will present calculations of nonspecular scattering within the Bragg condition for typical normal incidence configurations found in imaging applications. These results will show interesting new interference effects associated with the multiple reflection of the scattered field.

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[1] D. G. Stearns, J. Appl. Phys. **65**, 491 (1989); D. G. Stearns, J. Appl. Phys. **71**, 4286 (1992).
[2] S. K. Sinha et al., Phys. Rev. B **38**, 2297 (1988).

I. Motivation

a) Real x-ray reflective coatings have nonideal interfaces which can adversely affect their performance.

1) Intermixing reduces the Fresnel reflectance of each interface.

2) Roughness due to film growth and replication of the substrate scatters radiation out of the specular mode.

b) Understanding and controlling these effects is important for applications such as EUVL, where high throughput and high contrast imaging are essential.

II) Theoretical Developments

a) Previous theoretical treatments of x-ray scattering have been limited in their applicability to realistic scattering problems. To address these limitations we have developed an improved theory that:

1) Incorporates a realistic model of the interfaces which includes both diffuseness and roughness. The roughness can change continuously through the ML stack, and the specular fields are determined to be consistent with the interfacial structure.

2) Treats the scattered field dynamically. This allows one to calculate scattering into a Bragg peak, as would be the case for imaging experiments.

3) The scattering is treated in the modified Born approximation, where the zeroth order solution is Fresnel reflection. This approach, presented previously by Sinha et al., allows the theory to be applicable to all angles of incidence.

4) The only severe restriction remaining is the "small roughness criteria" that $q_z^2\sigma^2 << 1$.

b) New expressions for specular reflection and transmission, nonspecular reflected and transmitted fields.

III) Results

a) Specular fields: comparison to previous results.

b) Nonspecular scattering.

1) Scattering within the Bragg condition.

2) Interference effects from dynamical scattering of the outgoing wave.