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Characterization of Mo/Si soft X-ray multilayer mirrors by grazing-incidence small-angle X-ray scattering

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ABSTRACT

The morphology of buried interfaces plays a key role in high performing Mo/Si soft X-ray mirrors. We show that grazing-incidence small-angle X-ray scattering is a highly effective and non-destructive diagnostic technique for analysis of buried interfaces. The parameters of average interface autocorrelation function can be determined unambiguously. Additionally period thickness, roughness of interfaces and an effective number of vertically correlated periods can be extracted. The multilayer mirrors were prepared by e-beam evaporation on heated and unheated substrates, ion beam assisted e-beam evaporation, ion beam sputtering and RF magnetron sputtering. The latter three techniques produce multilayer mirrors with comparable interface roughness. The differences in lateral correlation length and Hurst parameter are found.

1. Introduction

The morphology of surfaces and interfaces plays an important role in the application of multilayer thin films. In the field of applied optics the rough interfaces/surfaces produce the diffusely scattered at the expense of the specularly reflected light. In this paper we will concentrate on the problem of interface roughness of molybdenum–silicon (Mo/Si) soft X-ray multilayer mirrors. The Mo/Si mirrors are used in the next generation of EUV (extreme ultraviolet) lithography working at 13.5 nm wavelength [1]. They have also proved their significance as high-reflecting mirrors for synchrotron storage rings and FLASH free-electron lasers [2]. The possibility to tailor not only the amplitude of reflected radiation but also the phase led to the fabrication of a chirped multilayer mirror for attosecond pulses [3–5]. Briefly, the Mo/Si soft X-ray mirror is the "workhorse" in today's soft X-ray science. The engineering and monitoring of multilayer interfaces with low intrinsic roughness and sharp density contrast is one of the most important tasks of applied multilayer research.

The Mo/Si mirrors have been fabricated by numerous deposition techniques such as e-beam evaporation [6], ion beam assisted e-beam evaporation [7], single and dual ion beam sputtering [1,8], DC and RF magnetron sputtering [9] and pulsed laser deposition [10]. Here we concentrate on the characterization and comparison of some of these techniques. The method used is the grazing-incidence small-angle X-ray scattering (GISAXS). This technique allows for non-destructive unambiguous interface characterization as shown by Saldit et al. [11]. The information on multilayer period, gamma value, interface roughness, lateral correlation length, Hurst parameter and vertical correlation length can be obtained. We demonstrate that compact table-top GISAXS systems can be used for multilayer characterization. We compare the results with those measured on a synchrotron storage ring.

2. Theoretical background

A convenient description of a statistically rough interface can be represented by height–height autocorrelation function of roughness in the direct space, or, by its Fourier transform, called power spectral density (PSD) in reciprocal space [12]. In the following we use the autocorrelation function $C(r)$ proposed by Sinha et al. [13].

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$$C(r) = \sigma^2 \exp\Big(-[r/\xi]^{2H}\Big) \tag{1}$$

Here σ is the interface root-mean square (RMS) roughness value, ξ is the lateral correlation length and H is the Hurst parameter. In order to describe the correlated roughness in the multilayer stack it is convenient to introduce the $C_{jk}(r)$ cross-correlation function

$$C_{jk}(r) = \sqrt{C_j(r)C_k(r)}\exp\big(-|z_j - z_k|/L_{vert}\big) \tag{2}$$

where $C_j(r)$ is the autocorrelation function of the jth interface, L_{vert} is the vertical correlation length, z_j and z_k are the coordinates of interfaces j and k, respectively [14]. This model of the vertical roughness correlation proposed by Ming et al. has only limited validity because it assumes a single vertical correlation length which is in contrast with a real growing surface described by the Edwards and Wilkinson [15] model. Here, low spatial frequencies of the interface roughness are replicated better than the higher ones. Despite this fact the above model was used in the calculations presented here because it allows fast numerical modeling of measured data. It will be shown in the experimental part that the decay of vertical correlation length for higher spatial frequencies of the interface roughness can account for only a minor contribution to the observed signal. A more rigorous model of the vertical roughness replication relying on PSD functions was presented by Stearns [16].

Let's assume a multilayer soft X-ray mirror with a period $\Lambda = d_{Mo} + d_{Si}$ where d_{Mo} and d_{Si} are thicknesses of the molybdenum and silicon layers, respectively. The total multilayer thickness is $N.\Lambda$ where N is the number of periods. The interface roughness is probed by scattered X-rays incident under a small grazing angle α_i on the inspected multilayer stack. The incident X-ray radiation gets scattered by the wave-vector transfer $\vec{q}$ of the multilayer stack. Multilayer stacks with a zero roughness possess only the q_z component of the scattering vector $\vec{q}$ perpendicular to the sample surface. In this case we observe only discrete points at $q_z = 2\pi m/\Lambda$ in the reciprocal space where m is the number of Bragg order. The presence of rough interfaces is manifested by non-zero scattering components q_x and q_y parallel to the sample surface. The q_x, q_z components define the plane of reflection. In the reciprocal space a rough multilayer is represented by a series of Bragg sheets located at $q_z = 2\pi m/\Lambda$ and having a width $\delta q_z \cong 2\pi m/(N_{eff}\Lambda)$ where N_{eff} is an effective number of the multilayer periods with correlated roughness. Measurements in the coplanar geometry, i.e. in the (q_x, q_z) plane, do not permit a reliable determination of the multilayer parameters due to a limited range of q_x values imposed by reflection geometry [8,17,18]. In contrast, the non-coplanar geometry gives access to much larger values of the other lateral scattering vector component q_y allowing for an unambiguous determination of the multilayer parameters like the lateral correlation length and Hurst parameter [11,19,20].

The differential cross-section for the scattered radiation by a multilayer stack within the Born approximation (BA) is given as [21]

$$\left(\frac{d\sigma}{d\Omega}\right)_{diff} \approx \sum_{j,k}^{N} Q_{jk}\left|T_j^i T_k^i T_j^f T_k^f\right| e^{i(q_{jz}z_j - q_{kz}z_k)}$$
$$Q_{jk} = \frac{1}{q_{jz}q_{kz}^*} e^{-\frac{1}{2}\left((\sigma_j q_{jz})^2 + (\sigma_k q_{kz}^*)^2\right)} \Delta\rho_j \Delta\rho_k \int_0^\infty r J_0\left(q_{||} r\right)\left(e^{q_{jz}q_{kz}^* C_{jk}(r)} - 1\right) dr \tag{3}$$

where q_{jz} is the normal component of the scattering vector $\vec{q}$ in the jth layer, $q_{||}^2 = q_x^2 + q_y^2$ is the in-plane component normal to q_z, σ_j is

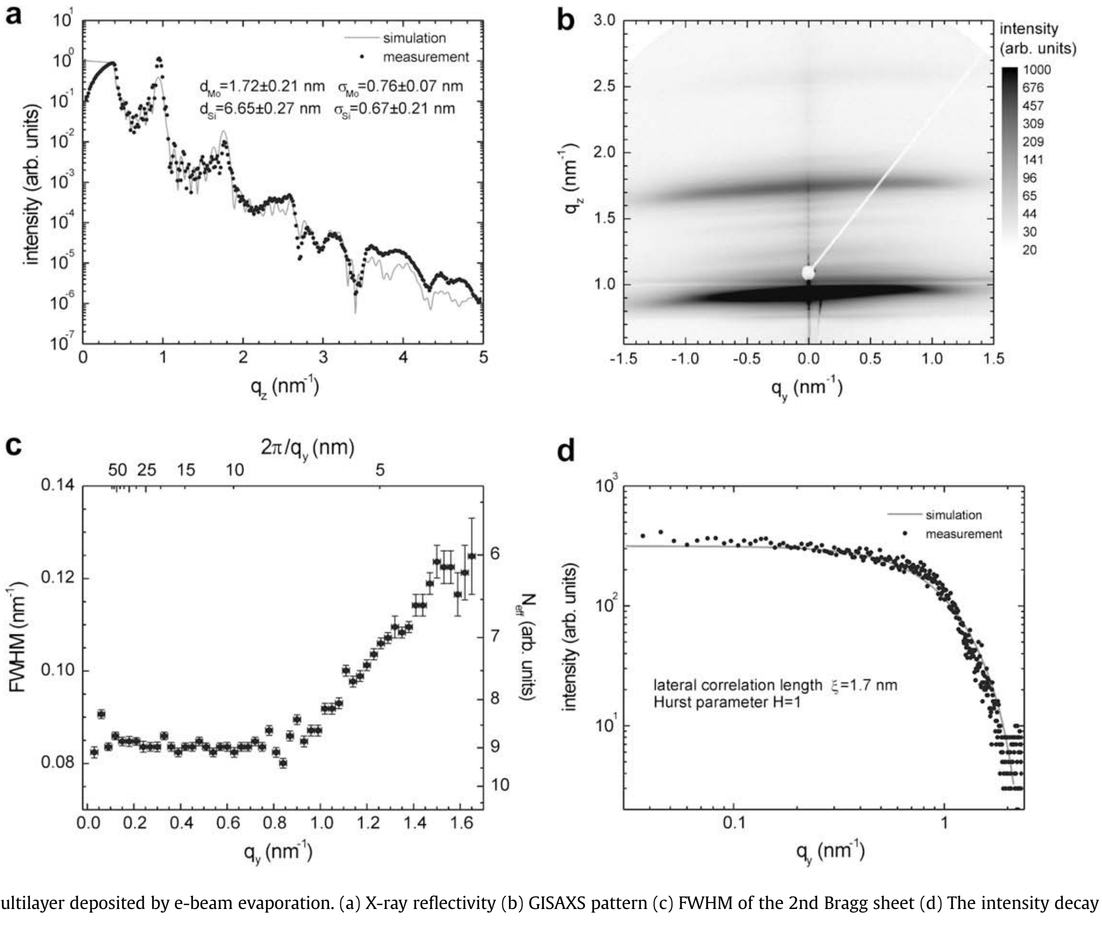

Fig. 1. The Mo/Si multilayer deposited by e-beam evaporation. (a) X-ray reflectivity (b) GISAXS pattern (c) FWHM of the 2nd Bragg sheet (d) The intensity decay of the 2nd Bragg sheet.