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Retrieval of the complex reflection coefficient from nano scale thin films by using polarized neutrons and magnetic substrates

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ABSTRACT A method is proposed for overcoming the famous 'phase problem' in neutron specular reflectometry. It is shown that the complex reflection coefficient of any unknown non magnetic layer, with real scattering length density, can be determined by using a magnetic transmitted media and by measuring the polarization of the reflected beam relative to the incident beam. The method follows directly from a recent one which is limited to a one-dimensional neutron polarization. Here, the theory is generalized for a neutron polarization of arbitrary direction. We show that some combinations between the polarization of the incident and reflected beam must be used to determine the reflection coefficient. Also, it is shown that instead of full polarization or reflectivity analysis, some combinations between polarization and reflectivity can be used in the analysis process. The method is supplemented with a schematic example to test the method and its stability in the presence of experimental uncertainties and roughness of the interfaces.

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1 Introduction

Neutron specular reflectometry is a powerful technique for determining the scattering length density (SLD) depth profile of thin materials [1]. In this technique, neutrons are reflected at the grazing incident by the thin film and the reflected intensity is measured as a function of momentum transfer $Q (Q = 4\pi \sin\theta/\lambda$, where θ is the incident angle and λ is the wavelength of the neutron). Subsequently, after determination of the reflectivity $R(Q)$ (modulus of the reflection coefficient, $r(Q)$) one needs to extract the SLD of the film as a function of depth. However, extraction of the SLD from the reflectivity has been hampered by the so called 'phase problem' which is widely discussed in structural analysis [2, 3]. This problem refers to the fact that for unique reconstruction of the SLD profile, the phase of the reflection coefficient is needed and in the absence of the phase, generally more than one SLD can be found corresponding to the same reflectivity [4, 5].

Several proposals have been worked out to solve this famous problem [6–12]. In this paper, we have shown that the complex reflection coefficient of any unknown non magnetic sample with real SLD can be determined by using a magnetic substrate and analyzing the polarization of the reflected beam instead of the reflectivity. The method has generalized a recently proposed method [12] in which we assumed that the incident beam is polarized in the depth direction (i.e. normal to the reflection surface) and the incident medium is a vacuum. Here, we consider an incident beam polarized in an arbitrary direction and a non vacuum incident medium. This generalization causes more complex algebra, however, it leads to more flexible ways for extracting the complex reflection coefficient of unknown samples.

The layout of the paper is as follow: first, in Sect. 2, the polarization of the reflected beam is determined as a function of the polarization of incident beam, the transfer matrix elements of an unknown sample and the refractive index of incident and transmitted media. Then, it is shown that by measuring the polarization of the reflected beam and using some combination between this parameter and the polarization of the incident beam, three unknown parameters can be extracted. These parameters completely determine the modulus and the phase of the complex reflection coefficients of the reversed unknown sample surrounded on both sides by uniform media. In Sect. 3, a realistic example is used to illustrate the method. Also, by using this computer simulation, the stability of the method is tested in the presence of experimental uncertainties and the roughness of the interfaces.

2 Method

Explanation of the method requires the relation between the polarization of the reflected beam and the incident beam. To drive this relation, we use the transfer matrix method. In specular reflection from a film (i.e. in the absence of significant nonspecular scattering) the solution of the Schrödinger equation reduces to a one-dimensional Schrödinger wave equation. The transmitted and reflected coefficients for the unknown sample with thickness L mounted on top of a magnetic substrate can be calculated exactly from the 2×2 transfer matrix which carries the exact wave function and its first derivative across the film, from front edge to back;

$$\begin{pmatrix} 1 \\ \mathrm{i}h_\pm \end{pmatrix} t_\pm \mathrm{e}^{\mathrm{i}QL/2} = \begin{pmatrix} A(Q) & B(Q) \\ C(Q) & D(Q) \end{pmatrix} \begin{pmatrix} 1 + r_\pm \\ \mathrm{i}f\,(1 - r_\pm) \end{pmatrix} , \quad (1)$$

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