One directional polarized neutron reflectometry with optimized reference layer method

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In the past decade, several neutron reflectometry methods for determining the modulus and phase of the complex reflection coefficient of an unknown multilayer thin film have been worked out among which the method of variation of surroundings and reference layers are of highest interest. These methods were later modified for measurement of the polarization of the reflected beam instead of the measurement of the intensities. In their new architecture, these methods not only suffered from the necessity of change of experimental setup but also another difficulty was added to their experimental implementations. This deficiency was related to the limitations of the technology of the neutron reflectometers that could only measure the polarization of the reflected neutrons in the same direction as the polarization of the incident beam. As the instruments are limited, the theory has to be optimized so that the experiment could be performed. In a recent work, we developed the method of variation of surroundings for one directional polarization analysis. In this new work, the method of reference layer with polarization analysis has been optimized to determine the phase and modulus of the unknown film with measurement of the polarization of the reflected neutrons in the same direction as the polarization of the incident beam.
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I. INTRODUCTION

As an atomic scale probe, neutron reflectometry with polarized neutrons has a vast application to the study of layered media and thin films. Each material has a unique scattering length density (SLD) for neutrons which can be used as a unique characteristic for determining the type and thickness of that material.[1] In other words, retrieving the nuclear scattering potential of neutrons from reflectivity data can be used as a powerful tool for identifying the unknown samples. However, measuring the intensity of the reflected neutrons from the sample would not lead to a unique result for the SLD of the sample. In the scattering process, the reflectivity $R(q) = |r(q)|^2$ is measured and the information of the phase of the complex reflection coefficient $r(q)$ is lost. As a result, two different layers with different phase information can have the same reflectivity. Hence, the full knowledge of the phase of complex reflection coefficient is necessary in order to retrieve a unique result from the reflectometry experiments.[1,2]

In the past decades, several theoretical methods which suggest solutions to this so-called *phase problem* have been worked out such as variation of surroundings medium[3,4] and the method of reference layers.[5,6] The variation of surroundings medium approach makes use of the controlled variations of the scattering length density of the incident and/or substrate medium. And the method of reference layers is based on the interference between the reflections of a known reference layer and the unknown surface profile. Either of the methods suffer from the experimental difficulties regarding the change of the substrate or reference layers for each reflectivity measurement.[4,7] This inefficiency was recovered by using polarized neutrons and magnetic layers as substrate[8,9] or reference layer.[10–12] Later on, these methods were enhanced to measure the polarization of the reflected beam to determine the phase of reflection.[13] Although the polarization based approaches had been theoretically proven to be efficient, their experimental implementation was limited by the ability of the reflectometers in the measurement of the polarization direction. As these methods required at least two measurements of polarization of the reflected beam in different directions,[11–13] their experimental implementations were not practical with reflectometers which can only measure the polarization of the reflected neutrons in the same direction as the incident beam.

In a recent work,[14] we developed the method of variation of surrounding with one directional polarization analysis and discussed the possibility of experimental implementation of the method. In this new work, we have optimized the method of reference layers based on the measurement of the polarization of the reflected beam in the same direction as the incident neutrons.

In Sec. II, the foundation of the optimized reference layer method is formulated. Section III deals with numerical examination of the method for an unknown sample. The SLD of the sample is also retrieved from the phase information which is obtained from optimized reference layer method. The paper ends with further discussions on the experimental challenges of the method.

II. OPTIMIZED REFERENCE LAYER METHOD

Scattering of neutrons from a sample is described by optical potential, $v(x) = 2\pi\hbar^2\rho(x)/m$, where $\rho(x) = \rho_n \pm \rho_m$ is the scattering length density of the sample as a function of

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