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EASYREF: Energy analysis system for reflectometers

Frédéric Ott*

Laboratoire Léon Brillouin CEA/CNRS UM12, Centre d'Etudes de Saclay, 91191 Gif sur Yvette Cedex, France

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Abstract

We present a compact device, which can perform the energy analysis of a white neutron beam with an energy resolution of 5–10% for wavelengths λ ranging between 0.2 and 2.5 nm. We propose that such a device could be used on neutron reflectometers in order to get rid of the disk chopper or the monochromator. Gains in flux of 1 to 2 orders of magnitude can be foreseen for specular reflectivity measurements.

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Keywords: Neutron; Energy analysis; Reflectivity; Reflectometry; Optics; Spectrometry

1. Introduction

Neutron scattering offers a wealth of techniques to study solid state matter [1]. The flux on neutron spectrometers are, however, not comparable to what is available in synchrotron facilities. One of the limitations in thermal neutron scattering is that it is not possible to build detectors which can resolve the neutron energy. When a thermal neutron is detected, it is fully absorbed and its kinetic energy which is of the order of a few meV is negligible compared to its mass energy. Thus, when spectroscopic information is required, two different techniques can be implemented: (i) either use a diffracting crystal after the sample which analyzes a specific energy [2] or (ii) use a Time-of-Flight (ToF) technique which measures the neutron energy by measuring its travel time between the source and the detector [3]. In both cases, a lot of neutrons are wasted. In the first case, only a single energy can be analyzed at a time. In the second case, on continuous sources, the beam requires to be shaped into pulses by using choppers. This process also wastes a lot of neutrons. In order to improve the use of the neutron beams on continuous sources, we propose an optical device which performs the equivalent of an energy analysis on a white neutron beam. Its characteristics make it ideal for specular reflectivity measurements. This idea was already proposed some time ago by C.F. Majkrzak [4].

2. Principle

The possibility of illuminating the sample with a white beam and then directly measure the reflectivity at once is appealing since it means that the neutron flux on the sample can be multiplied by a factor 20–100 since no chopper or monochromator is required. Designs using refraction in prisms [5] and magnetic quadrupoles [6] have been proposed (Fig. 1). Both designs have limitations.

We propose a new design based on reflective optics. The principle is based on the combination of multi-layer (ML) monochromator mirrors and a Position Sensitive Detector (PSD) (see Fig. 2). Ideally, each monochromator (index i) reflects a wavelength band $\{\lambda_i-\delta\lambda/2;\ \lambda_i+\delta\lambda/2\}$. The diffracted beams are spatially spread on the PSD and the wavelength is directly determined by the position on the detector. The reflectivity is thus measured at once for all wavelengths.

*Tel.: +33 1 69 08 62 21; fax : +33 1 69 08 82 61.
E-mail address: Frederic.Ott@cea.fr

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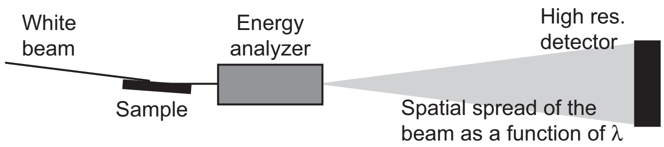

Fig. 1. Principle of specular reflectivity measurements using an energy analysis device. A full white beam is sent onto a sample. After reflection, the different wavelengths are spatially spread in an energy analyzer. The reflectivity signal is measured at once for all wavelengths on a position sensitive detector.

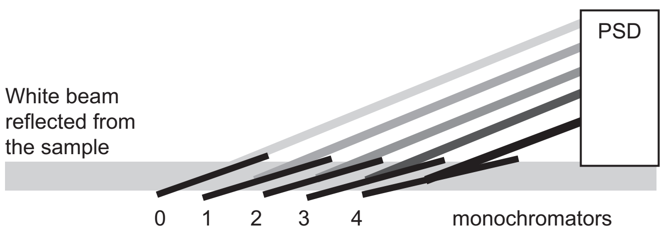

Fig. 2. The reflected beam is sent on stacked monochromators. The incidence angle on each monochromator varies so that each monochromator diffracts a different wavelength band. The wavelength is directly determined by the position on the detector.

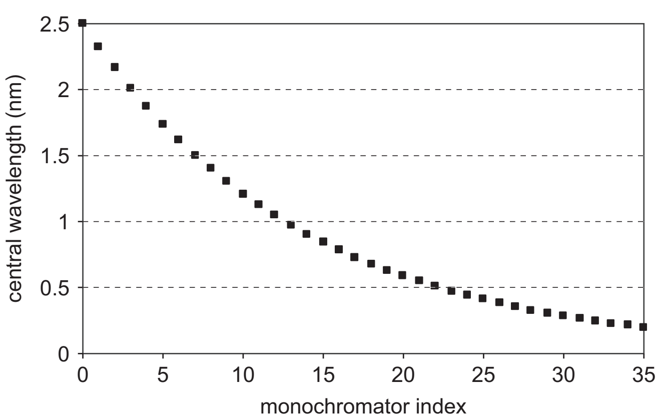

Fig. 3. Central wavelengths for a set of 35 monochromators. The wavelengths span from 0.2 to 2.5 nm. The band-pass of each mirror is set at 7%.

3. Requirements for a realistic device

The central diffraction wavelengths of the different monochromators should follow the law: $\lambda_n = (1-\mathrm{BW})^n\ \lambda_{\max}$ where BW is the monochromator bandwidth. On typical ToF reflectometers, the available wavelength band ranges from 0.2 to 2.5 nm. The values of the central wavelength for the different monochromators are plotted on Fig. 3 in the case of a wavelength resolution of 7%. This is the typical wavelength resolution used on the ToF reflectometer EROS at the LLB [7]. In this case, it would be possible to measure 35 points at once in the reflectivity curve, which is sufficient for most applications where a high resolution is not required. This is typically the case of ultra-thin soft matter films.

In a typical neutron reflectivity experiment, the sample has a length of 40 mm; the incidence angle on the sample is of the order of 2.5° and the incident divergence is 0.06° (we consider the case of low resolution experiments). In this case, 200 mm after the sample, the beam width is

$$w = 40\,\mathrm{mm} \times \sin(2.5^{\mathrm{o}}) + 200\,\mathrm{mm} \times \tan(0.06^{\mathrm{o}}) = 2\,\mathrm{mm}.$$

This means that in practical situations we have to analyze beams which have a size of several millimeters in width.

4. Geometrical arrangement of the mirrors

At the moment, it is possible to produce routinely $m = 4$ high quality monochromators [8]. The incidence angle on an $m = 4$ monochromator is given by

$$\theta_n = \lambda_n \times 4\,(\mathrm{degree/nm}).$$

The angle of incidence is then 10° for $\lambda = 2.5$ nm and 1° for $\lambda = 0.25$ nm neutrons. If we want to diffract a wavelength λ_n with a single mirror, its length is given by

$$L_n = w/\tan(\theta_n).$$

For the shortest wavelengths ($\lambda = 0.2$ nm), the monochromator length is 150 mm (see Fig. 4).

The individual lengths of each monochromator are rather large and the mirrors cannot simply be put in line one after the other; otherwise the total length of the device would be close to 2 m. It is possible to consider a more compact arrangement of the mirrors (see Fig. 5). If we assume that the silicon wafers are $e = 0.25$ mm thick, because of this finite thickness, some space is lost between each consecutive mirror and the mirrors must be slightly shifted one after the other. For each mirror, the lost space is equal to $\Delta X_i = e/\sin\theta_i$. The total loss of space is equal to 240 mm when considering the set of 35 mirrors. An extra 150 mm must be added to account for the last

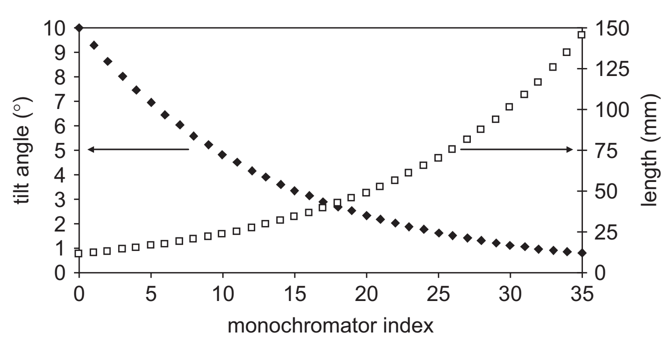

Fig. 4. Tilt angle and corresponding length of the different monochromators to analyze a 2 mm wide beam.

Fig. 5. Compact arrangement of the monochromator mirrors taking into account the finite thickness of the silicon substrates.