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Design of an apparatus for polarization measurement in soft X-ray region[☆]

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ABSTRACT

A novel apparatus for polarization measurement in the soft X-ray region has been designed, constructed, and installed in the evaluation beamline for soft X-ray optical elements (BL-11) at the SR Center of Ritsumeikan University, Shiga, Japan. It allows us to perform conventional reflection and transmission measurements including rocking curve measurement as well as polarimetric and ellipsometric measurements based on the rotating-analyzer method by using six independently movable motorized stages. As a preliminary test of the apparatus, the reflection profile of a Mo/SiO_2 multilayer mirror prepared by an ion beam sputtering technique, which is designed as a reflection polarizer for use of 13.9 nm, has been measured by the apparatus. The result is compared with that by an existing reflectometer, and the azimuth angle dependence of the reflection intensity has been demonstrated. Consequently, it is shown that the apparatus has the capability to perform the rotating-analyzer ellipsometry.

1. Introduction

The increasing demand for comprehensive polarimetric measurements is pressing in the soft X-ray (SX) region. In the energy range between 0.7 and 1 keV in which the *L* absorption edges of transition metals are located, circularly polarized SX is useful for studies of magnetic properties of materials such as magnetic circular dichroism (MCD) measurements. In order to discuss the experimental results quantitatively, experimenters need information on the actual polarization state of the probe light. It is because the MCD signal is proportional to the degree of circular polarization of the probe beam used. It should also be kept in mind that the rotation of the plane of polarization and the degradation of the degree of polarization might result from reflection and diffraction of the beamline optics. Therefore the polarization state of the probe light should be characterized in advance of the experiment by polarization measurement.

Quantitative evaluation of the actual polarization state of light requires a combination of phase shifter (or phase shifting polarizer) and analyzer usable at the same energy as the probe light. In the energy range between 100 eV and 300 eV, polarization measurements have been performed by using a polarimeter or ellipsometer equipped with multilayer phase shifter and analyzer such as Mo/Si, Ru/Si and Cr/C [1–4]. Recently development of polarizing elements for use in the higher region has been progressed [5,6]. A W/B_4C multilayer has been reported to work as the practicable polarizer for 710 eV, although the reflectance for s-polarization at 850 eV remarkably decreases to 0.4% from 5.2% [7]. In the higher energy range than about 0.7 keV, it becomes difficult to develop practicable phase shifters, even polarizers, and consequently to perform polarization measurements. On the other hand, in the higher energy region than 6 keV, single crystals, e.g., Si, Ge, and diamond, in Bragg or Laue geometry are of advantage rather than multilayers, and they are utilized for the evaluation and generation of linearly and circularly polarized x-rays, and helicity switching [8–10].

In our previous study [11,12], mica crystalline has been clarified to work as a high-efficiency polarizer at 880 eV. The linear polarization degree of light emerged from an undulator has been evaluated by using a versatile apparatus for polarimetry and ellipsometry (ELLI) [13] equipped with micas as the polarizers. Furthermore, mica film of ~5 µm thickness has been found to be a promising candidate as a transmission quarter-wave plate at around 1 keV by simulation calculation [14]. It means that, in principle, it allows us to determine completely the polarization parameters by use of mica. To certify these features, it should be verified by the polarization measurements. Unfortunately one of the six drive shafts equipped in the ELLI, i.e., the detector arm is mechanically coupled to the incident angle of the analyzer. It is inconvenient to the alignment and the polarization measurements in the energy range of around 1 keV. It is because the reflection band width becomes narrower than that in low energy region [11,12]. From this viewpoint, it should be more profitable for the polarization measurement to have the capability to change all axes independently to perform conventional reflection and transmission measurements including rocking curve measurement. Therefore, referring to the ELLI, we decided to develop a polarimeter

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and ellipsometer equipped with fully independent drive shafts to realize the complete polarization analysis in the SX region.

2. Rotating-analyzer method with a phase shifter

Rotating-analyzer ellipsometry by means of an analyzer A and a detector D is one of the well-known polarization measurements as shown in Fig. 1(A). When the azimuth angle η is rotated along the optical axis of a probe beam fixing the incident angle ω and the detection angle θ, the intensity $I(\eta)$ of the reflected light from A follows the modified Malus' equation expressed as

$$I(\eta) = I_a(1 + C\cos 2(\eta - \delta)), \tag{1}$$

where I_a is the average of the maximum $I_{\max}$ and minimum $I_{\min}$ of the reflected light, δ is the azimuth angle of the major axis of the polarization ellipse of the incident light, and C is the contrast factor of the incident light defined as

$$C = (I_{\max} - I_{\min}) / (I_{\max} + I_{\min}). \tag{2}$$

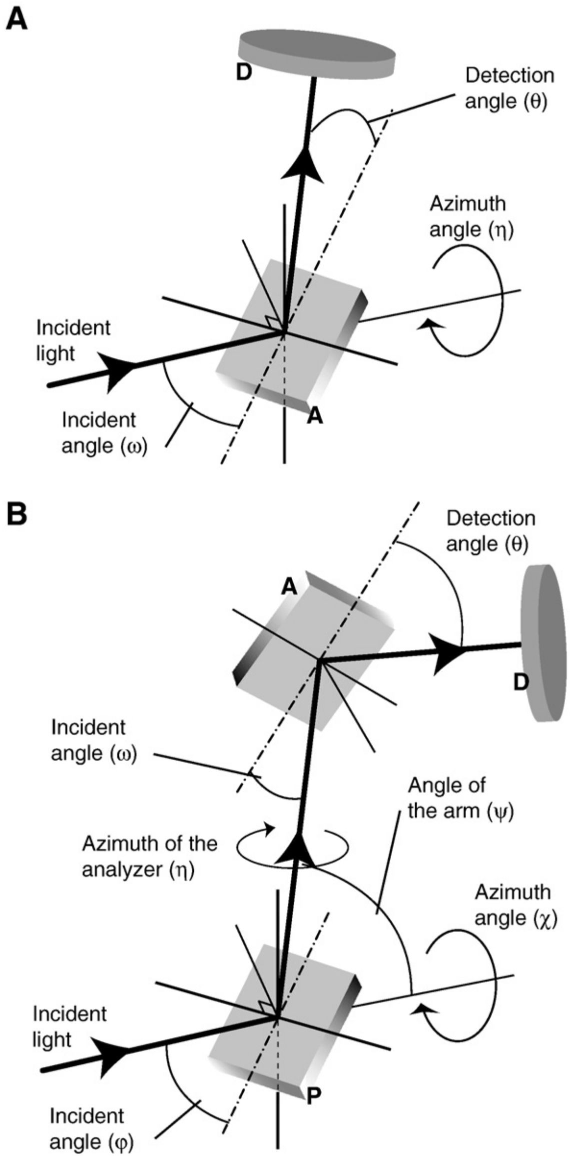

Fig. 1. Schematic diagrams of single-reflection geometry with an analyzer A and detector D (A), and double-reflection geometry based on the rotating-analyzer method with a phase shifter (or polarizer) P (B). The azimuth and incident angles of P (or A) are χ (or η) and φ (or ω), respectively. θ means a detection angle. ψ moves the position of A and D with those relative positions fixed.

We can obtain C and δ by applying the fitting function Eq. (1) to the measured data. The polarizance Z, which represents the polarizing ability of the analyzer, is defined using the reflectivities for s- and p-polarization components (R_s and R_p) of A as

$$Z = (R_s - R_p) / (R_s + R_p). \tag{3}$$

If the value of Z is given, the degree of linear polarization P_L can be derived from

$$P_L = C / Z. \tag{4}$$

If the incident light is completely unpolarized or circularly polarized light as well as Z equals zero, then $I(\eta)$ is independent of η, so that P_L cannot be determined. Thus, when both Z and P_L are unknown, another polarizer (or a phase shifter) is needed.

Fig. 1(B) shows a double-reflection geometry using both a polarizer (or a phase shifter), P, and an analyzer, A. The contrast factor of the reflected beam from P fixed at the azimuth angle $\chi = \delta \pm \pi/4$ is obtained by azimuth rotation of η, then P_L can be derived from

$$P_L = (C_1 C_2 / C_3 \cos 2\eta_3)^{1/2}, \tag{5}$$

where C_1 (or C_2) is the contrast factor of the incident beam evaluated by A (or P) in the configuration in Fig. 1(A). Also C_3 and η_3 are the contrast factor and the azimuth angle of the major axis of the polarization ellipse of the reflected beam from P in the configuration in Fig. 1(B), respectively. The above scheme makes it possible to determine simultaneously Z_i ($i = 1, 2$) of A and P, and P_L and δ of the incident light by using Eqs. (4) and (5).

If some pairs of (η_3, χ) are obtained by the measurements in the configuration shown in Fig. 1(B), then the polarization degree P and the ellipticity angle ε of light, and the extinction ratio ρ defined as the ratio of the complex amplitude for s-polarization to that for p-polarization and the phase difference Δ between s- and p-polarization components of P can be determined as fitting parameters by the following equation:

$$\tan 2\eta_3 = \frac{2\rho P(\cos 2\varepsilon \cos\Delta \sin 2(\delta - \chi) - \sin 2\varepsilon \sin\Delta)}{\rho^2 - 1 + P(\rho^2 + 1)\cos 2\varepsilon \cos 2(\delta - \chi)}. \tag{6}$$

The degree of circular polarization P_C can be derived from

$$P_C = P \sin 2\varepsilon \tag{7}$$

It is of importance that the polarization state of the incident light and the characteristics of the two polarizing elements used can be completely, simultaneously determined [15].

From the above argument, it is found that a sophisticated apparatus needs six fully independent drive shafts (η, ω, θ, χ, φ, and ψ). If so, it allows us to perform not only conventional reflection measurements (two-dimensional scans ω–θ and φ–ψ, where θ and ψ are fixed at 2ω and 2φ, respectively) but also one-dimensional scans such as rocking curve and transmission measurements. Furthermore, it is convenient to adjust the angular alignment between the optical axis and the sample position.