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Design and performance of a multilayered mirror monochromator in the low-energy region of the VUV

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For the energy region from tens to hundreds of electron volts, the multilayered mirror (MLM) monochromator has never been realized due to the difficulty of reducing the background noise of the total reflection component, in spite of its usefulness in synchrotron radiation experiments. In this work, a double-crystal-type MLM monochromator equipped with a thin-film filter has been designed on the basis of trial fabrication of the mirror-driving system and of Mo/Si and Mo/C MLMs; its performance has been evaluated by calculating its output photon flux. It is shown that by using the MLMs at low incident angles, combined with an appropriate thin-film filter, it is possible to make a practical monochromator with high output photon flux and low background noise.

Keywords: multilayered mirrors; multilayered mirror monochromators.

1. Introduction

Studies of synchrotron-radiation-stimulated processes such as etching and chemical vapour deposition (CVD) began about 12 years ago (Urisu & Kyuragi, 1987) and are still attracting much interest from many researchers. The vacuum ultraviolet (VUV) photons in synchrotron radiation can excite almost all the electronic states of molecules, so a large variety of chemical reaction channels different from that in the usual thermal-CVD are expected to be opened by synchrotron radiation irradiation. In particular, core electrons, which cannot be excited using lasers, are efficiently excited by the VUV photons in synchrotron radiation. The excitation-energy dependence of a photochemical reaction is important basic data. However, it has not been sufficiently investigated in the VUV region, because of the difficulty in obtaining energy-tunable monochromated light with sufficient photon flux ($>10^{13}$ photons s^{-1}) in the VUV region.

A multilayered mirror (MLM) monochromator is already in use in the high-energy region of the VUV (Barbee *et al.*, 1987). Concerning the low-energy regions, one of the present authors previously tried to use an MLM as a dispersion element in synchrotron-radiation-stimulated experiments. However, this was unsuccessful due to the difficulty in removing the background noise, consisting of total reflection components appearing at less than a few tens of eV. Therefore, in this work, we have designed a double-crystal-type MLM (Golovchenko *et al.*, 1981; Murata *et al.*, 1992) monochromator combined with an appropriate thin-film filter. The design is based on the trial fabrication of MLMs and the driving system for them. We have found that the low-energy background noise is sufficiently removed by using the MLMs at low incident angles combined with a carbon or molybdenum filter.

2. Design of the monochromator and mirrors

2.1. *Monochromator*

We adopted the monochromator driving system proposed by Golovchenko *et al.* (1981). The centres (A and B, respectively) of the first and the second MLMs are set on the XY and YZ lines which form a rigid right angle XYZ, with the first MLM parallel and the second perpendicular to the XY and YZ lines, respectively. A pulsed motor drive slides the apex (Y) of the XYZ linearly, keeping the rotational centre (B) of the second mirror fixed. The first mirror is mechanically linked to the second mirror so that it translates in parallel with the linear motion of the apex Y, sliding on the XY bar of the right angle. It is designed so that two kinds of mirror pairs can be exchanged with each other in an ultrahigh vacuum (UHV) by rotating the mirror holders using the ultrasonic motors. This double MLM arrangement is also effective in reducing the intensity of the higher-order photons. The total reflection component decreases as the incident angle to the MLM decreases; the mechanical linkage and driving system have been designed so that the beam incident angle can be adjusted over incident angles as small as possible. The present prototype driving system has successfully covered an incident beam angular range (θ) of 10–80°.

2.2. *MLMs*

The important photon energy region for the experimental investigation of synchrotron radiation processes, especially of the core-electron excitation processes, is from a few tens to hundreds

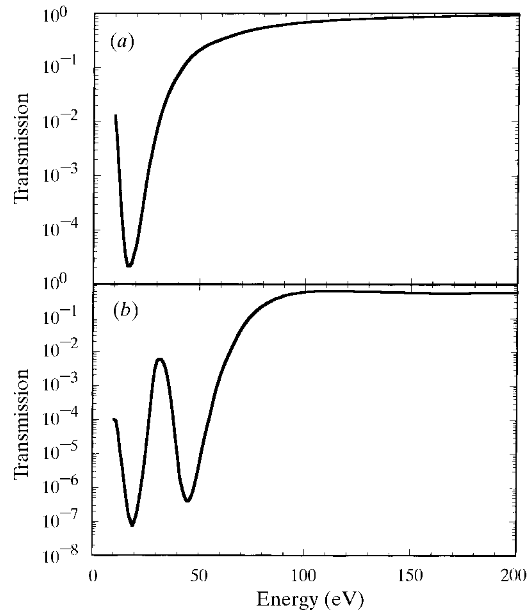

Figure 1
The calculated transmission for (*a*) a 100 nm-thick carbon filter and (*b*) a 100 nm-thick molybdenum filter.

Table 1
Specifications of optical components.

Component	Specifications	
Mo/Si MLM	Substrate	Si wafer (40 × 40 mm)
	Number of layers	20
	Period, d	12.5 nm (12.4 nm)†
	Thickness ratio, Mo/Si	3/7 (3.25/6.75)†
	Interface roughness, σ	(0.4 nm)†
Mo/C MLM	Substrate	Si wafer (40 × 40 mm)
	Number of layers	50
	Period, d	7.5 nm (7.9 nm)†
	Thickness ratio, Mo/C	1/1 (5.5/4.5)†
	Interface roughness, σ	(0.4 nm)†

† Values determined by fitting to the observed Cu $K\alpha$ line diffraction curves.

of electron volts. In the present work our attention was focused on the region between 60 and 120 eV, a region for which fairly high reflectivity is obtained by using Mo/Si (for 60−90 eV) and Mo/C (for 85–120 eV) MLMs. This energy region includes the core-electron binding energies of Al (2*s*: 119 eV; 2*p*: 74 eV) and Si (2*p*: 103 eV), which are important materials in semiconductor processes. To reduce the background noise in the low-energy region due to the total reflection, it is necessary to use the MLM at low incident angles. The Mo/Si and Mo/C MLMs were therefore designed so that they could cover the Al 2*s* and 2*p* and Si 2*p* binding energies in the incident angle range of 10–50°. Furthermore, the detailed structural parameters have been selected so that the reflectivity is high and the reflectivity curve is symmetrical. Both Mo/Si and Mo/C MLMs with the structural parameters listed in Table 1 have been fabricated and evaluated by using the Cu $K\alpha$ line to measure the X-ray diffraction (Rigaku Corporation ART). The values of the period, the thickness ratio between Mo and Si layers or Mo and C layers, and the interface roughness characterized by a Debye–Waller factor (Bennett & Porteus, 1960), σ, determined by the fitting to the diffraction data, are listed in Table 1.

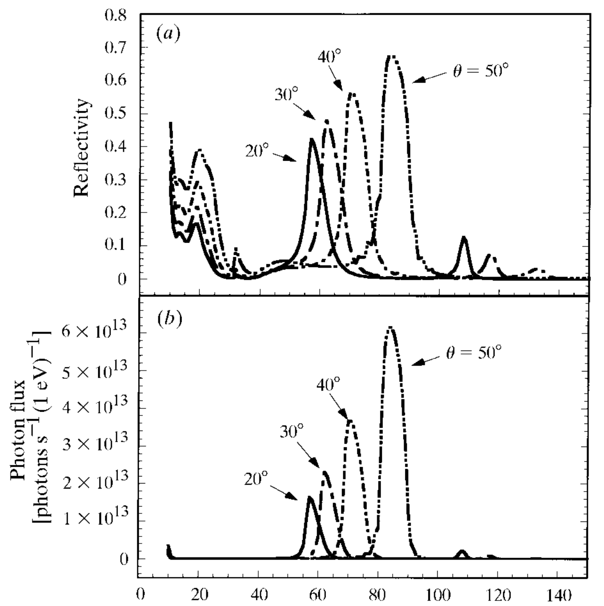

Figure 2
(*a*) Calculated reflectivity for the Mo/Si MLM and (*b*) output photon flux of the monochromator using Mo/Si MLMs plus C filter for a 100 mA ring current and a 16.56 × 12.79 mrad^2 acceptance angle of the pre-mirror, assuming that the monochromator is set up in the beamline BL-4A1 of the UVSOR.

2.3. *Thin-film filters*

The transmission characteristics of the thin-film filter have been calculated for several materials and it has been found that carbon and molybdenum are useful for reducing the background noise at energies below 70 eV. The transmission spectra calculated for 100 nm-thick carbon and molybdenum film filters are shown in Figs. 1(*a*) and 1(*b*), respectively.

3. Performance of the monochromator

The performance of the MLM monochromator, designed as described above, was evaluated by calculating what the basic characteristics, such as output photon flux, resolution, monochromaticity and tuning range, would be if the monochromator were set up as part of the beamline (BL4A1) of the synchrotron radiation storage ring at the UVSOR. In this beamline, the beam emitted from the bending-magnet light-source point is reflected by an elliptical pre-mirror with a grazing-incidence angle of 4°. The horizontal and vertical sizes of the pre-mirror are 50 cm and 3 cm, respectively, and the mirror is 2.345 m downstream from the light-source point. The beam is focused at about 6.1 m downstream from the pre-mirror with a spot size of about 0.5 × 0.2 cm. The photon flux of this beamline was calculated for a 100 mA ring current.

The reflectivities, based on the recurrent equation (Spiller, 1981), of the Mo/Si and Mo/C MLMs were first calculated by using the mirror parameters listed in Table 1, as shown in Fig. 2(*a*) for the Mo/Si case. It is known that extremely large total-reflection components appear at less than 40 eV in the case of Mo/Si.

The output beam photon fluxes calculated for various incident angles are shown in Fig. 2(*b*) for the case of Mo/Si MLM plus C filter. It is clearly shown that the filter drastically reduces the low-energy background noise. It is less than 1% (3%) of the main flux, where the value in parentheses is for the case of Mo/C MLM plus Mo filter. The higher-order photons background noise is less than 4% (0.1%). The calculated photon flux is 1×10^{14} to 5×10^{14} photons s^{-1} (3×10^{13} to 4×10^{13} photons s^{-1}) and the resolution is 5–9 eV (2–4 eV) FWHM. The calculated results are similar to those obtained with a typical undulator. Given that the MLM monochromator can select the photon energy continuously and that the mixing of higher-order photons is small, it is suggested that the present monochromator will be better than an undulator for use in synchrotron radiation experiments. We conclude from this work that the background noise due to the total reflection, which prevented the MLM monochromator from being used in the VUV low-energy region, can be sufficiently reduced by using double-crystal-type MLMs at low incident angles combined with a carbon or molybdenum thin-film filter.

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