Performance test of Mo/Si and MoSi$_2$/Si multilayer Laue lenses

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Abstract. A multilayer Laue lens (MLL) as a hard X-ray focusing device has been designed and fabricated. Mo/Si and MoSi$_2$/Si were chosen to form the multilayers owing to their superior properties of high diffraction efficiency and relatively sharp interface between layers. DC magnetron sputtering system was used for deposition of the multilayers. The optical properties of the MLL were measured at BL24XU of SPring-8 with 20-keV X-rays. To confirm the dynamical diffraction effect, far-field diffraction images were taken at various incidence angles and depths. The resultant intensity distributions showed similar structure to those expected by calculations. Further, an almost diffraction-limited beam size of around 30 nm was obtained.

1. Introduction

Development of X-ray optical devices for X-ray microscopy and X-ray microanalysis at a nanometer scale is advancing rapidly in recent years. Focused spot sizes of a few tens of nanometers have been obtained using Kirkpatrick-Baez mirrors [1], compound refractive lenses [2], Fresnel zone plates [3-5], and multilayer Laue lens (MLL) [6-8]. MLL was pioneered by the APS group [6-8], and this technique appears promising with regard to the achievement of a 1-nm focus with a very high diffraction efficiency, even in the hard X-ray region [9]. Their MLL is composed of WSi$_2$ and Si layers [7]. We recently designed and fabricated an MLL by DC magnetron sputtering, choosing Mo/Si and MoSi$_2$/Si as the multilayer materials owing to their superior properties of high diffraction efficiency at an X-ray energy of 20 keV. In particular, MoSi$_2$/Si multilayer has smaller interdiffusion between the layers and higher heat resistance than Mo/Si multilayer [10]. The optical properties of the MLL due to the dynamical diffraction effect have been investigated theoretically using the coupled wave theory [11,12] and experimentally using undulator radiation from SPring-8. Further, the performance of an MLL as a hard X-ray focusing device was also studied. In this paper, we report the results of these experiments.

A DC magnetron sputtering deposition system was used to fabricate the Mo/Si and MoSi$_2$/Si multilayer with each boundary $r_n$ according to the Fresnel zone configuration which is given by $r_n^2 = nf\lambda + n^2\lambda^2/4$, where $\lambda$ is the wavelength and $f$ is the focal length. The outermost zones were deposited first onto the flat Si substrate to decrease the layer disturbance, and the deposition was
stopped before it reached the thickest central zone. The minimum layer thickness was designed to be 10 nm, while the maximum thickness was designed to be 100 nm. The total multilayer thickness was 4.6 μm, and the number of layers was 248. The focal length was designed to be 1.6 mm for an X-ray energy of 20 keV. The multilayer structure was sectioned and polished to an appropriate depth.

2. Performance test
The optical properties were measured at BL24XU [13] of SPring-8. A Si (111) monochromator was used to select an X-ray energy of 20 keV. The incident beam illuminated an area much larger than the zone structure region using a crossed slit to avoid the edge effect of the slit. A far-field diffraction image was used to measure the relative local diffraction efficiency as a function of the zone position $r_n$ [7,14]. By appropriately mounting obstructions such as slits and blades, only the desired first-order diffraction beam was extracted. The tilt angle and the depth of the MLL were varied in order to study the dynamical diffraction effect, and the corresponding far-field images were captured by the CCD detector. The distance between the MLL and the CCD detector was approximately 30 cm. The depth was determined by measuring the X-ray transmission of the Si substrate of the MLL. Figures 1(a) and 2(a) show the experimentally measured intensity distributions, while figures 1(b) and 2(b) show the corresponding calculated distributions for Mo/Si MLL and MoSi$_2$/Si MLL, respectively. The horizontal axes indicate the tilt angle, which was varied from approximately $-1$ mrad to 3 mrad. One vertical line was obtained from one diffraction image with a horizontal beam width of 20 μm, and one distribution was composed of approximately 30 diffraction images. As the measured distributions agreed well with the calculated ones, the effects of volume diffraction were confirmed. In figure 1(a), intensity dips, which do not appear in calculation, appear at $r_n = 3.6$ μm. It can be considered that there is a local imperfection of the MLL structure. This result provides us with evidence whether or not the multilayer structure was properly fabricated and behaved as an MLL.

![Figure 1](image1.png)

**Figure 1.** (a), (b) The first order diffraction patterns of the Mo/Si MLL with a depth of 34 μm. (a) Measured intensity distribution. (b) Calculated diffraction efficiency distribution. (c) The measured intensity profile of the best focus point with a depth of 20 μm.

![Figure 2](image2.png)

**Figure 2.** (a), (b) The first order diffraction patterns of the MoSi$_2$/Si MLL with a depth of 38 μm. (a) Measured intensity distribution. (b) Calculated diffraction efficiency distribution. (c) The measured intensity profile of the best focus point with a depth of 15 μm [14].

Next, the focused beam size was measured by the knife-edge method. A platinum wire with a diameter of 200 μm was used as the knife-edge. The intensity of the X-rays scattered by the knife-
edge was measured using a PIN diode detector. The direct beam was blocked by a blade placed in front of the detector. The intensity of the scattered X-rays measured along the knife-edge position is proportional to the line spread function of the beam profile [4]. A piezoelectric stage that has a 2-nm resolution in the closed-loop mode was used to measure the beam size precisely. Although the knife-edge was fixed on the piezoelectric stage, the distance between the MLL and the knife-edge changed due to environmental disturbances. In order to avoid such effects, an electrostatic capacitance sensor was used to determine the relative distance between the MLL and the knife-edge. The relative position was measured at the same time that the intensity of the scattered X-rays was measured. The measured intensity distributions at the best focal point are shown in figures 1(c) and 2(c) for Mo/Si MLL and MoSi$_2$/Si MLL, respectively. The obtained beam sizes were 32.8 ± 2.2 nm and 28.2 ± 2.7 nm in the full width at half maximum. Ten measurements were performed in order to confirm the reproducibility. These values were close to the diffraction-limited beam size of 22 nm, which was estimated from the effective numerical aperture of the MLL using Rayleigh’s criterion. Measured photon flux was approximately $5 \times 10^7$ photons. The results obtained show that the beam size of the Mo/Si MLL is slightly larger than that of the MoSi$_2$/Si MLL, and that the intensity profile of the Mo/Si MLL has strong side peaks. It may be considered that the local imperfection revealed by figure 1(a) effects the intensity profile.

3. Conclusion
We investigated the optical properties of the Mo/Si and MoSi$_2$/Si MLL fabricated by DC magnetron sputtering. The effects of volume diffraction were confirmed by experimentally and theoretically. These results suggest that the MoSi$_2$/Si MLL developed in this study has considerable potential for use as a nanofocusing optical device.

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