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Ti/Al multilayer zone plate and Bragg–Fresnel lens

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By using a helicon plasma sputtering technique, a one-dimensional Ti/Al multilayer zone plate with an outermost layer width of 76 nm has been successfully fabricated. A Bragg–Fresnel lens has been made by combining this zone plate with a Ge(422) crystal. Comparison of the Ti/Al multilayer zone plate with the Ag/Al zone plate is discussed in terms of focusing efficiency.

Keywords: multilayer zone plates; phase modulation; Bragg–Fresnel lenses; microbeams.

1. Introduction

In the course of recent developments of multilayer optical devices (Vinogradov, 1995), we have fabricated and tested Bragg–Fresnel lenses (BFLs) using Ag/Al multilayer zone plates (MLZPs) (Koike *et al.*, 1996). To fabricate the MLZP, alternating layers of the two materials were deposited upon a substrate using a helicon plasma (HP) sputtering technique. BFLs were made by combining the MLZP with a Ge(422) crystal. A combination of Ag and Al was chosen since both have high deposition rates in the sputtering process. However, the focusing efficiency of the Ag/Al MLZP depends significantly on the thickness and the flatness (the homogeneity of the thickness) of the zone plate, as the phase shift of X-rays transmitted by both the Ag layer and the Al layer is quite sensitive to the plate thickness. Using two materials which have similar electron densities to fabricate an MLZP would be effective in reducing this sensitivity. Therefore, we have studied the combination of Ti and Al and formed an MLZP and a BFL using the HP sputtering technique.

2. Fabrication of MLZPs and BFLs

The fabrication process of a one-dimensional MLZP and BFL is shown in Fig. 1. Alternate deposition of the two materials was performed by the HP sputtering technique. A detailed description of the system is given by Koike & Suzuki (1995). The distance from the centre to the interface of the nth layer, r_n, is expressed as

$$r_n = (nf\lambda)^{1/2}/\sin\theta_B, \qquad (1)$$

where f is the focal length, λ is the X-ray wavelength and θ_B is the Bragg angle of the crystal. The multilayered plane was then sliced vertically and glued to the monochromator crystal. Finally, the sliced MLZP was thinned to the desired thickness. The MLZP works only as a transmission-type focusing device, but a combination of this plate with a crystal yields a BFL, which works as a reflection-type monochromatizing and focusing device. The BFL should also follow the Bragg condition

$$\lambda = 2d\sin\theta_B. \qquad (2)$$

Using (2), r_n can be expressed as

$$r_n = 2d(nf/\lambda)^{1/2}. \qquad (3)$$

This means that the device can be used in the wide wavelength range $\lambda < 2d$ under the condition that the value f/λ is kept constant. The efficiency of the MLZP is expressed as

$$I_{\rm eff} = \{\exp(-4\pi\beta_1 t/\lambda) + \exp(-4\pi\beta_2 t/\lambda) - 2\exp[-2\pi(\beta_1+\beta_2)t/\lambda]\cos\Phi\}/\pi^2, \qquad (4)$$

$$\Phi = 2\pi(\delta_1 - \delta_2)t/\lambda, \qquad (5)$$

where t is the thickness of the MLZP and δ_i and β_i are the real and imaginary parts of the refractive index, respectively. The thickness of the MLZP used for the BFL should be multiplied by $\sin\theta_B/2$, since there is a difference in path length between transmission-type and reflection-type focusing devices. From (5), t^*, the thickness required for a phase shift of π, can be expressed as

$$t^* = \lambda\sin\theta_B/4(\delta_1 - \delta_2). \qquad (6)$$

The value of δ is roughly expressed as

$$\delta \simeq 2.72\times10^{10}(Z/A)\rho\lambda^2 \qquad (7)$$

except for the wavelength region close to inner-shell absorption edges. Using (1) and (7), the term λ disappears in (6), *i.e.* t^* is independent of λ. This confirms that the device can be used in the wide wavelength range $\lambda < 2d$ as long as the value f/λ is constant. This is similar to the case of Si-BFLs made by the etching technique (Aristov *et al.*, 1989).

3. Focusing efficiency of Ag/Al and Ti/Al MLZPs

Focusing efficiencies of Ag/Al and Ti/Al MLZPs were calculated over the X-ray energy range from 1 to 30 keV using (4), as shown in Figs. 2 and 3, respectively. In these figures, broken lines indicate the thickness required for the phase shift $\Phi = \pi$, and solid lines denote the corresponding maximum efficiency. The values of the refractive index used in this calculation are those cited by Henke *et al.* (1993). Although the maximum efficiency of the Ti/Al MLZP is slightly lower than that of the Ag/Al, the required thickness of the Ti/Al MLZP is several times larger than that of Ag/Al. Fig. 4 shows calculated efficiencies as a function of thickness of MLZPs for an X-ray of 12 keV. In the case of the Ag/Al MLZP, three maxima appear at

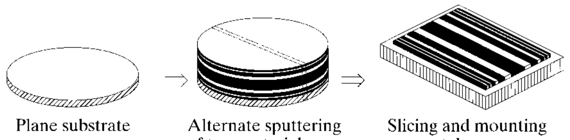

Figure 1
Fabrication process of one-dimensional MLZP and BFL.

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thicknesses of about 5.5, 16.5 and 27.5 μm, which correspond to $\Phi = \pi$, 3π and 5π. Two minima appear at thicknesses of about 11 and 22 μm corresponding to $\Phi = 2\pi$ and 4π. These findings mean that the focusing efficiency of the Ag/Al MLZP is very sensitive to the flatness, and that the tolerance in the flatness is less than 2 μm. On the other hand, the focusing efficiency of the Ti/Al MLZP is insensitive to the flatness and the tolerance in the flatness is larger than 5 μm. For this reason, the phase shift of the Ti/Al MLZP is more easily controlled than that of the Ag/Al MLZP, and the former is expected to provide a better efficiency. We have made a prototype Ti/Al MLZP using the HP sputtering technique, and combined it with a monochromator crystal to produce a BFL.

4. Fabrication of Ti/Al MLZP and BFL

A Ti/Al MLZP has been fabricated using the HP sputtering technique. The alternate deposition of the films was carried out automatically by a computer. The computer ignited the discharge, monitored the thickness of material deposited and ceased the discharge after the desired thickness of film was achieved. Fig. 5 shows a picture of the MLZP observed by SEM (scanning electron microscopy), in which Ti layers (white lines) and Al layers (black lines) are not resolved clearly except for layers around the centre. This lack of contrast is due to the similar electron densities. The MLZP was fabricated under the following conditions for both Al and Ti: Ar gas pressure, 0.7 mtorr; distance between the target and the substrate, 15 cm; RF power, 200 W; d.c. power, 100 W. The deposition rates under these conditions were 2.5 Å s^{-1} for Al and 1.4 Å s^{-1} for Ti. First, a 2.8 μm Ti layer was deposited on an SiO_2 substrate (Fig. 5, top) for protection against damage which might be caused through the slicing and thinning processes. Then a total of 303 layers of Ti and Al were alternately deposited on the substrate. The largest layer width at the centre is 3.7 μm and the outermost layer width is 76 nm. After deposition of all the layers, a 2.8 μm Ti layer was overcoated (Fig. 5, bottom). Then the multilayered plane was sliced vertically, to give a plane 1 mm in thickness. One side of this plane was polished, the polished side was glued to the Ge(211) crystal using epoxy resin and the glued plane was thinned to 10 μm. The parameters were: f = 2.7 cm, λ = 1.03 Å (12 keV) and $\theta_B = 63°$ for Ge(844) diffraction ($2d$ = 1.16 Å). The results of the experimental test will form a subsequent report.

5. Conclusions

A one-dimensional Ti/Al multilayer zone plate has been successfully fabricated using a helicon plasma sputtering technique. Comparison of the Ti/Al MLZP with the Ag/Al MLZP is discussed in terms of the focusing efficiency, and the superiority of the Ti/Al over the Ag/Al MLZP is demonstrated

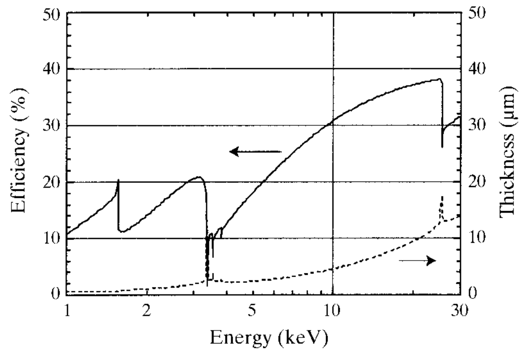

Figure 2
Calculated thickness and corresponding efficiency required for a phase shift of π as a function of X-ray energy in the case of an Ag/Al zone plate.

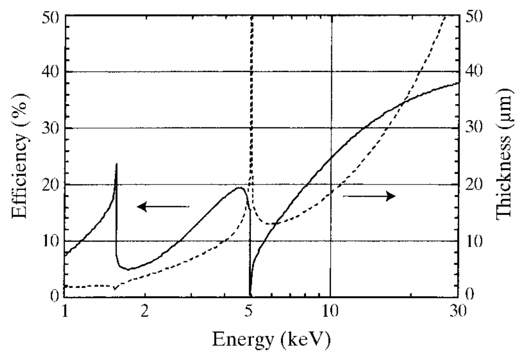

Figure 3
Calculated thickness and corresponding efficiency required for a phase shift of π as a function of X-ray energy in the case of a Ti/Al zone plate.

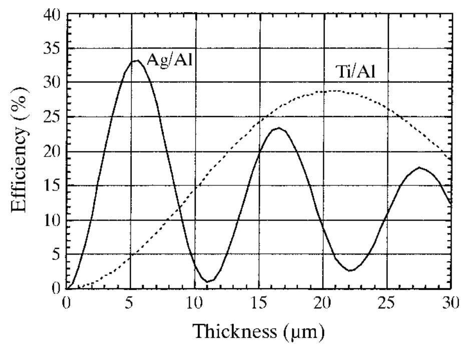

Figure 4
Calculated efficiency as a function of thickness of MLZPs for 12 keV X-rays. The solid curve denotes the efficiency of Ag/Al MLZP, and the broken curve is that of Ti/Al MLZP.

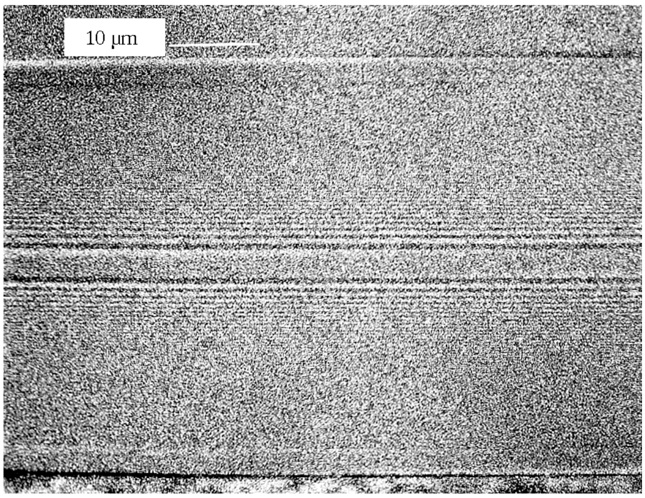

Figure 5
SEM image of the Ti/Al MLZP.

by the feasibility of phase control. A Bragg–Fresnel lens has been made by combining this zone plate with a Ge(422) crystal.

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