Total reflection zone plate for 15 nm line focus of 10 keV X-rays

X-ray focusing is a promising technique since it provides a secure high-spatial resolution to various X-ray analytical procedures. The focusing performances are rapidly improving, particularly in the hard X-ray region. Fresnel zone plates (FZPs), utilizing diffraction by a coaxial circular grating with decreasing spacing, and Kirkpatrick-Baez (KB) mirrors, consisting of tandem-arranged two parabolic or ellipsoidal mirrors for individual focusing in the orthogonal directions, have been widely used as typical focusing devices in the hard X-ray region. These devices that can achieve a focusing size of sub-100 nm are commercially available. Moreover, new focusing devices, such as multilayer Laue lenses and graded multilayer KB mirrors, have recently been developed and achieved the focusing size of around 10 nm, and the best focal size of 7 nm using 20 keV X-rays has been reported [1]. However, these focusing devices require ultrahigh precision for their configuration and, hence, special technology is needed for their fabrication.

Generally, when an object drawn on a flat plate is observed under a glancing condition, the observing size becomes small in the glancing direction according to the glancing angle. A schematic of this effect is shown in Fig. 1. The total reflection zone plate (TRZP) is a focusing device utilizing this effect to reduce the difficulty of fabrication. This device consists of reflective zones on a flat substrate as shown in Fig. 2, so that it can focus X-rays with a grazing incident angle satisfying the total reflection condition when the zone boundary is arranged under the same condition for conventional FZP; a path difference of diffracted X-rays cause by every adjacent zone is equal to a half the wavelength at the focal point. The effective zone size becomes much smaller than a drawn size on the substrate because the grazing incidence angle for total reflection is very small in the hard X-ray region. Since the ratio of sizes becomes greater than 100, no special process is required for the fabrication, even though the theoretical size of focus is near 10 nm. Such reflection-type zone plate has been proposed early and developed with some unsatisfactory experiments, although a theoretical consideration suggests that the TRZP has sufficient nanofocusing potential [2]. We have developed a linear-type TRZP for nanofocusing of synchrotron radiation X-rays. The focusing size of 14.4 nm, near the diffraction-limited size, has been experimentally achieved using 10 keV X-rays of undulator emission [3].

Table 1 shows parameters of the fabricated TRZP with the designed grazing incident angle of 6 mrad and X-ray energy of 10 keV. A conventional silicon wafer of 0.5 mm thickness was used as the substrate. A pattern consisting of a thousand zones made of platinum is drawn over 2.44 mm on the substrate. The pattern can be processed by conventional electron beam lithography since the zone thickness is small (20 nm) and the finest zone width is large (0.7 μm). This TRZP works as well as a binary-type FZP, since only the reflected/diffracted X-rays from the reflection zone contribute to form the focus. Half of the full zone structure was drawn to separate the focal beam from direct reflection from the substrate. The focal length (distance between the focal position and center of the full zone r_0) is 4.16 mm, and hence, the working distance (distance between the focusing point and the finest zone r_N) is 1.72 mm. The theoretical focusing size estimated using Reyleigh's criterion with the geometrically defined numerical aperture is 14.7 nm. This is much smaller than the finest drawn zone size of the TRZP.

Focusing test of the TRZP was performed using monochromatic X-rays of 10 keV at Hyogo-ID beamline **BL24XU**. Then, the coherence condition of

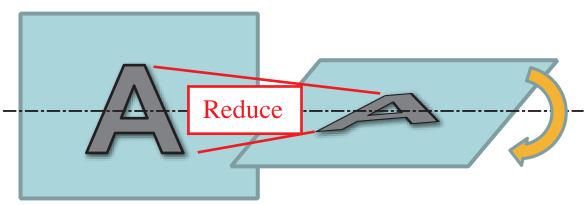

Fig. 1. Illustration of size reduction effect in glancing view.

Table 1. Parameters of fabricated TRZP

Substrate	Silicon wafer
Zone material	Pt/Ti
Zone thickness (nm)	10/5
Number of zones: N	1000
Finest zone width (mm)	0.7
Pattern length (mm): r_N	2.4
Grazing incident angle (mrad)	6
Effective aperture size (μm)	14.4
Effective finest zone width (nm)	4.2
Focal length f (mm)	4.16
Diffraction-limited focal size (nm)	14.7

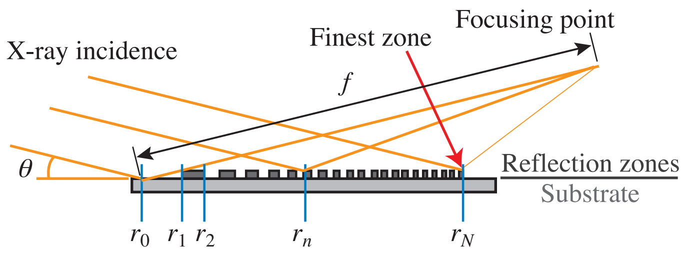

Fig. 2. Schematic of the total reflection zone plate.

the incident beam is sufficient to form a diffraction-limited focus for the TRZP with an effective aperture size of 14.6 μm and with the total zone number of 1000. The focusing beam was evaluated by a knife-edge scanning procedure in dark-field geometry. This procedure can be used to directly measure a line spread function of a focal beam with any differentiated process following the conventional knife-edge scan procedure. The spatial response is very high because of the edge-diffraction effect caused by the knife edge [4]. Figure 3 shows the measured intensity distribution of the line focus of the TRZP. A platinum wire of 300 μm diameter was used as the knife edge and scanned in the best focal plane at 2 nm steps with a piezoelectric translation stage. The focusing size of 14.4 nm in FWHM was obtained as an average of 41 repeated measurements.

Although the focusing beam includes undesirable peaks around a main peak, the main peak surely has a nearly diffraction-limited size. This shows that X-rays diffracted by not a small region of zones including near both sides of the TRZP can interfere with the phase at the focal position. According to an inspection of the drawn pattern of the TRZP, the side peaks configured by X-rays with out of phase may due to a figure error of the substrate such as warping by deposition process. Therefore, a better result may be possible only with a small upgrade for further TRZP. Moreover, the TRZP can be applied for point focus generation by introducing KB configuration, or by advanced patterning for point focusing or by introducing a conical substrate. It can be said that the TRZP is one of the most promising approaches for nanofocusing in the hard X-ray region.

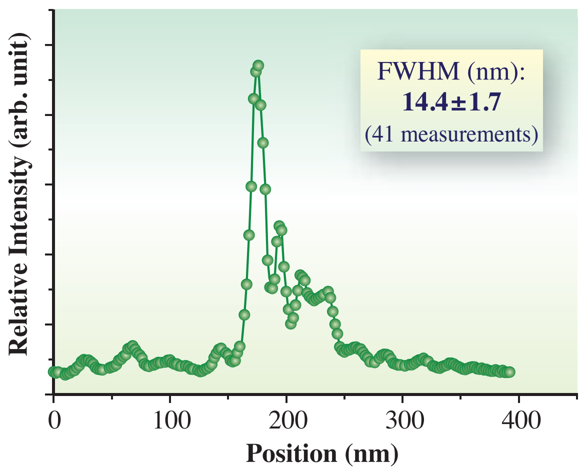

Fig. 3. Measured intensity distribution of line focus obtained with the TRZP.

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