Design and fabrication of one-dimensional focusing X-ray compound lens with Al material

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A method based on Fourier spectrum analysis for predicting the performances of the X-ray compound lenses is briefly introduced, the theoretical result obtained is the same as that of Fresnel-Kirchhoff approach. A kind of technique named moulding is developed for fabricating the one-dimensional (1D) compound X-ray lens with Al material and the fabrication process is presented. In addition, a two-time coating method is used to improve the numerical apertures of the compound lenses. Furthermore, the focusing performance of the Al compound X-ray lens under the high energy X-rays is measured.

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The X-ray compound lens is a novel X-ray refractive optical device for focusing high energy X-rays. Since it was proposed and first successfully demonstrated in 1996[1], many publications of the further researches on this device appeared[2−7]. The compound X-ray lens is working under X-rays with energy larger than 5 keV where other devices (such as multilayer X-ray mirrors, Fresnel zone plates, Bragg-Fresnel elements, etc.) cannot be used or cannot work efficiently. The alignment of the X-ray compound lens in the X-ray beam is easier due to its straight optical path. Furthermore, the X-ray compound lens is very robust, compact, and easy to handle. Therefore the compound X-ray lens is very attractive for the development of X-ray analytical investigations with a spatial resolution in the micrometer and sub-micrometer range.

A widely used theoretical method for designing the X-ray compound lens is based on the Fresnel-Kirchhoff approach. The complex amplitude distribution $U(\rho)$ of a point ρ in the focal plane of an X-ray compound lens can be calculated according to the Fresnel-Kirchhoff integral equation, the focusing performances and the transmission efficiencies of the compound X-ray refractive lenses can be then obtained. Because it is quite intricate to calculate $U(\rho)$ from the Fresnel-Kirchhoff integral equation[3,8], a method based on Fourier spectrum analysis[9] is briefly presented for designing a one-dimensional (1D) focusing X-ray compound lens in the present paper. For the fabrication technique of the 1D focusing X-ray compound lens, a kind of two-times coating method is used, and the result shows that the etching depth can be largely increased. Therefore the numerical aperture of the 1D X-ray compound lens is improved. Because of the difficulties of electroplating for Al material, a kind of technique named moulding is used to fabricate the 1D focusing X-ray compound lens with Al material. The measurement of the focusing performance of the Al compound X-ray lens under the high energy X-rays is done on Beijing Synchrotron Radiation Facility (BSRF). Some measurement results are shown in this paper.

Unlike the lens used in the visible-light region, the performance of X-ray compound lens is relative with both the refraction effect and the absorption. Therefore the diffraction screen $H(r)$ can be defined as $H(r) = A(r)\cdot\tau(r)$, where $\tau(r)$ is the transmission coefficient and $A(r)$ is the attenuation coefficient. Considering that a compound X-ray lens is composed of a group of N plano-concave elementary lenses positioned in line with axial symmetry, the diffraction screen function is accordingly written as[3]

$$\begin{cases} H_N(r) = C_1 \exp\left[-\frac{2\pi\beta N r^2}{\lambda R}\right]\exp\left[-i\frac{\pi\delta N r^2}{\lambda R}\right] \\ C_1 = \exp\left[-\frac{4\pi\beta dN}{\lambda}\right]\exp\left[i\frac{2\pi}{\lambda}\left(t-\delta d\right)N\right] \end{cases}, \quad (1)$$

where λ stands for the wavelength of incident X-rays, β and δ are related to absorption and refraction respectively in the expression ($\tilde{n} = 1-\delta-i\beta$) of the optical constant in X-ray region, R is the radius of the concave surface, d and t are the center thickness and the edge thickness of the elementary lens, respectively.

Supposing a planar monochromatic X-ray wave impinges on the compound lens, the Fourier transform of $H(x,y)$ can be expressed as $H(\xi,\eta) = \iint H(x,y)\exp[-i2\pi(\xi x+\eta y)]\mathrm{d}x\mathrm{d}y$, in which $2\pi(\xi,\eta) = \frac{k}{z}(x',y')$, (x,y) stands for the point r in the object region, and (x',y') the point ρ in the image region. Thus we have

$$\left|U(x',y')\right|^2 = \left|C\exp(ikL_0)H(\xi,\eta)\right|^2 = \left|H(\xi,\eta)\right|^2. \quad (2)$$

From Eq. (2), we can see that if we can get Fourier transform of the diffraction screen function, then we can get the intensity distribution in the focal plane. Because the diffractive screen function $H_N(r)$ is circular symmetrical, it is convenient to introduce Fourier-Bessel transform to obtain $H(\xi,\eta)$. By means of some mathematic process, finally the intensity distribution of point ρ in the focal plane of the X-ray compound lens can be concluded as[9]

$$I_N(\rho) = \frac{1}{4}|C|^2 \exp\left(-\frac{8\pi\beta Nd}{\lambda}\right) \cdot \left(\frac{\lambda R}{N\beta}\right)^2 \cdot \exp\left[-\frac{\pi N\delta^2}{\lambda R\beta} \cdot \rho^2\right]. \quad (3)$$

Hence, the intensity distribution of the compound X-ray lens in the focal plane is Gaussian-like distribution. From Eq. (3), we can see that the larger the ratio δ^2/β is, the more the number N of elementary lenses is, and the smaller the radius R of concave surface is, the better the focusing performance of the lens. However, it implies that the smaller the R, the smaller numerical aperture. Furthermore, the intensity of focus is getting lower when R is becoming smaller and N is becoming larger. Therefore these parameters have to be carefully designed in order to obtain better focusing performances.

A comparison between the index of refraction (δ) and the index of absorption (β) for the X-rays with high energy (> 5 keV) shows that the low-Z materials (such as Al, Be, Li, B, and Si) seem more suitable for fabricating the compound X-ray lenses[5]. In general, the 1D focusing X-ray compound lenses are fabricated by mechanically drilling holes in kinds of metals such as Al material. Although this kind of technique is quite simple and cheap, the precision of the size and shape of the lenses is lower. In our research, a three-dimensional (3D) microfabrication technology is used to fabricate the 1D focusing X-ray compound lenses.

The fabrication process is shown in Fig. 1. Firstly, a layer of polyimide (PI) is spin-coated on a cleaned substrate and is baked, and Cu film with thickness of 300—500 nm is deposited on the top of PI as the seed layer for electroplating. And then the first layer of AZP4903 photoresist is spin-coated on Cu film and is baked, the second layer of AZP4903 photoresist is spin-coated on the first layer and baked for the two-time coating method. By exposing the sample through the mask patterned with the structural parameters of the compound lens we designed, the photoresist pattern of the 1D X-ray compound lens is obtained. Next, by electroplating the metal materials Cu, the pattern of the 1D compound lens is transferred to Cu material. By removing the photoresist, a mold with Cu material for the 1D X-ray compound lens is obtained. Finally, by filling the powder of Al material in the Cu mold of the 1D X-ray compound lens, and then removing the Cu mold, the 1D focusing X-ray compound lens with Al material is obtained.

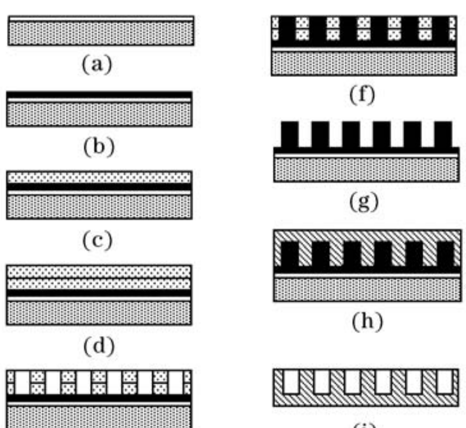

Fig. 1. Fabrication process of 1D focusing X-ray compound lens with Al material. (a) Spin-coating of PI film; (b) sputtering a Cu film; (c) one-time coating and baking of photoresist; (d) two-time coating and baking of photoresist; (e) exposing and developing of photoresist; (f) electroplating; (g) removing of photoresist; (h) moulding of Al; (i) removing the mold.

According to the theoretical results introduced above, the 1D focusing X-ray compound lens with Al material is designed, whose parameters are shown as follows. The working wavelength is 0.15 nm (around 8 keV), the geometrical aperture is 1.4 mm, the length of the compound lens is around 20 mm, and the focal length of the lens is around 1.5 m. Accordingly the number of elementary lenses is 40 and the radius of concave surface is 500 μm for the X-ray compound lens.

The mask of the 1D focusing X-ray compound lens is made by e-beam writing according to our design results. And then the 1D focusing X-ray compound lens with Al material is fabricated by means of the fabrication process described in Fig. 1. Figures 2 and 3 are the photoresist patterns for one-time coating and two-time coating, respectively. It is found that the depths of the patterns for one-time and two-time coatings are about 40 and 147 μm, respectively. That means that the depth of the pattern for two-time coating is obviously improved. However the smooth of the photoresist pattern is worse, and the precision of the shape of the lenses gets lower. Figure 4 is the scanning electron microscope (SEM) micrograph for the 1D focusing X-ray compound lens with Al material.

The measurement of the focusing performance of the Al compound X-ray lens under the high energy X-rays is done on BSRF. The experimental system, which is composed of the synchrotron radiation source, two Si crystals, the Al compound X-ray lens, and X-ray charge coupled device (CCD), is shown in Fig. 5. The first Si

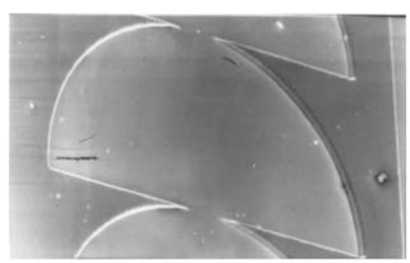

Fig. 2. SEM image of photoresist pattern for one-time coating.

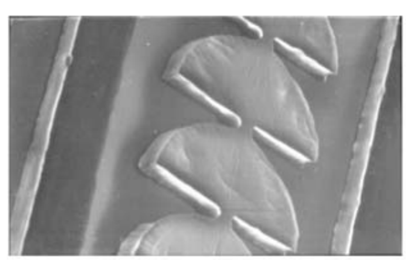

Fig. 3. SEM image of photoresist pattern for two-time coating.

Fig. 4. SEM image of 1D focusing X-ray compound lens with Al material.

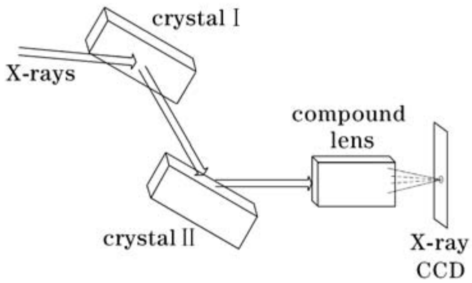

Fig. 5. Experimental setup for the measurement of focusing performance of Al compound X-ray lens.

crystal is used as a monochromator, the output X-ray from it is 8-keV monochromatic wave. The second Si crystal is used as a reflective mirror for deflecting X-rays to the Al compound X-ray lens. The focus by the Al compound X-ray lens is recorded by means of the X-ray CCD.

The measured sample of the Al compound X-ray lens is an array of three same compound lenses with 400-μm space between two compound lenses. The parameters of each Al compound X-ray lens are shown above. The measurement is done on the 4W1A beamline of BSRF. In the experiment, the electronic energy of storage ring is around 2.2 GeV, the intensity of the beamline flux is 50—70 mA, the working X-ray is 8-keV monochromatic wave, the exposure time for recording is 4.5 s, and the recording distance (measured focal length) is around 1.5 m. The measured result is shown in Fig. 6, there are three bright fine lines apart by two wide bright spots, the three lines correspond to the focusing spots by the three same Al compound X-ray lenses. The wider bright

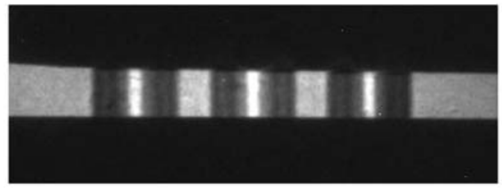

Fig. 6. Focal spots at the distance of 1.5 m from Al compound X-ray lens.

spots are caused by the X-rays through (without focusing) the space between two Al compound X-ray lenses.

In conclusion, a 1D focusing X-ray compound lens with Al material is designed and fabricated, whose focusing performances are quite good. The theoretical method is useful for the design of the compound X-ray lens and is quite straight and simple. The fabrication technique is a quite useful planar technology and is suitable for fabricating the 1D compound X-ray compound lens.

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