Fabrication of Aberration-corrected Diffraction Grating for Soft X-ray Grating Monochromator

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Abstract: In this work, we present the design and fabrication of an aberration corrected diffraction grating for soft X-ray monochromator. Spherical mirrors, which induce spherical, coma and astigmatic aberration, degrade the performance of a grating monochromator. These aberrations are often corrected by aspherical mirrors. however, aspherical mirrors with high surface accuracy are very difficult to fabricate. We proposed a new diffraction grating, by carefully adjust the positions of grating lines, the wavefront of the diffracted light can be modified and the aberrations can be corrected under certain conditions and the performance of the monochromator can be improved. The aberrations of a typical Czerny-Turner monochromator are discussed in detail and the grating design method is proposed in this work. A lamina type aberration corrected reflective grating for soft X-ray is fabricated using e-beam lithography, and the detailed process is elaborated.

1 INTRODUCTION

These days, experiments using soft X-ray are often carried out with synchrotron radiation. To obtain light with certain energy, grating monochromator is often employed. (Saitoh, 2000; Chao, 2012) For a grating monochromator, one key factor which can affect the performance is the aberrations which can deteriorate the image quality. (Noda, 1974; Shafer, 1964; Reader, 1969)

In a monochromator which use spherical mirrors, the major aberrations are spherical coma and astigmatic aberration. At near-normal incidence a concave spherical mirror can be used to form a good image of a point object on the optical axis. However, this is no longer the case as the object is moved away from the optical axis, and the aberrations become severe for grazing incidence angles. (Mahajan, 1991)

In X-ray region, high reflectivity can only be obtained at grazing angles of incidence. For the refractive index of the reflecting medium is very close to, and slightly less than, that of the vacuum the total external reflection can occur only at grazing incident angles. At grazing incidence angles, the images are severely astigmatic, for a grazing angle of about 2°, the sagittal focal length is about 1000 times the meridian focal length.

The traditional way to correct these aberrations is using aspherical mirrors, spherical aberration can be corrected by a paraboloid mirror, and astigmatic aberration can be corrected by a toroidal mirror. Aspherical mirrors with high surface accuracy are very difficult to fabricate, and the cost is very high. Another widely employed way to correct aberrations is using toroidal grating, yet it is still difficult to fabricate and the resolution is relatively poor for they quickly go out of focus.

Diffraction gratings are often fabricated with a ruling machine or interference methods. These methods have their limitations, only strait or slightly curved grating lines can be obtained. Nowadays, with the development of nanofabrication methods, the lamina type plane gratings are easier to fabricate with lithographic methods, i.e. e-beam lithography and UV lithography (Zhao, 2008). With these methods, grating lines with arbitrarily shape and positions can be fabricated easily. Thus the wavefront errors introduced by spherical mirrors can be compensated.

In this work, we proposed diffraction grating with curved grating lines to correct the aberrations. The relation between the wavefront and the position

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of the grating line is analysed and the detailed design method is discussed in section II. The fabrication process of a soft X-ray laminar type diffraction grating is discussed in section III.

2 GRATING DESIGN

In this work, we will discuss the grating used in a Czerny-Turner monochromator, the structure is sketched in Fig. 1. This monochromator consists of two spherical mirrors and a diffraction grating. Light from the entrance slit is collimated by the first mirror, then the collimated light is then diffracted by the grating into different directions, and the light is focused by the second mirror, light with different wavelength is focused on the different positions on the exit slit plane, only light with selected wavelength can come out the exit slit.

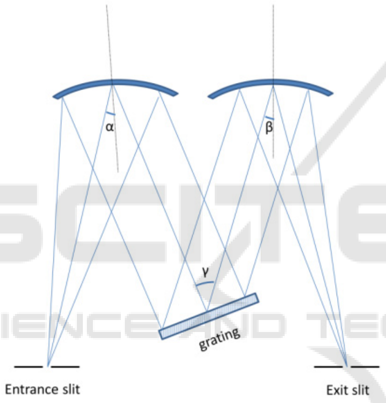

Figure 1: The Czerny-Turner monochromator composed of two spherical mirrors and a diffraction grating.

To correct the aberration, we first calculate the aberration function of the monochromator. The pupil is set on the grating plane. For simplicity, we calculate primary aberrations only. The focal length of the mirrors are F_1 and F_2, the incident angle of the chief ray on the two mirrors are α and β, the coordinates on the grating surface are r and θ. The primary aberration function can be written as:

$$\begin{aligned} w(r,\theta;\alpha,\beta,\gamma) = &-\frac{r^4}{32F_1}+\frac{\alpha r^3 cos\theta}{4F_1^2}-\frac{\alpha^2 r^2 cos^2\theta}{2F_1} \\ &-\frac{r^4(cos^2\theta cos^2\gamma+sin^2\theta)^2}{32F_2} \\ &+\frac{\beta r^3 cos\theta cos\gamma(cos^2\theta cos^2\gamma+sin^2\theta)}{4F_2^2} \\ &-\frac{\beta^2 r^2 cos^2\theta cos^2\gamma}{2F_2} \end{aligned} \tag{1}$$

The first and the fourth term represent spherical aberration of the first and the second spherical mirror, the second and the fifth term represent coma and the third and the sixth term represent astigmatic aberration.

With the aberration function, we can corrected it by modify the grating. The principle is shown in fig.2. We started with a traditional grating with equally spaced grating lines. As shown in fig.2. By displacing a grating line by Δx, the diffracted wavefront is changed by Δw. According to diffraction rules, the change of wavefront can be written as.

$$\Delta w = \lambda n\frac{\Delta x}{d} \tag{2}$$

Where λ is the wavelength of the light, n is diffraction order and d is the period of the grating lines, respectively. While the aberration is different from place to place on the grating, the displacement of one grating varies and the grating line is curved.

With equation (1) and (2), we can get down to draw the grating layout. As the grating lines are curved and unequally spaced, it cannot be fabricated by a traditional grating ruling machine. We use an e-beam to fabricate this grating.

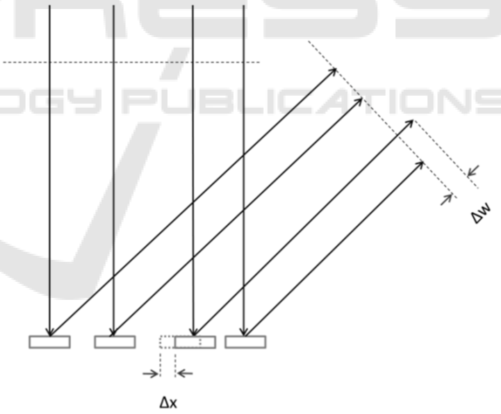

Figure 2: Modifying the wavefront of the diffracted wave by displacing the grating line.

There are three types of X-ray diffraction grating: (a) amplitude; (b) blazed; (c) laminar. In X-ray region, light incident on the grating at a grazing angle, the laminar type grating is the best type. In principle, blazed gratings can be used to diffract all of the incident intensity into a given order. However, the blaze angle must be less than the incidence angle, i.e., than the critical angle, and should be as small as feasible in order to illuminate as much of the land as possible. As the grating pitch becomes finer, less of the land is illuminated for a given incidence angle, and the grating will become ineffective. Under this circumstance, the laminar type is suitable.

3 FABRICATION

The grating is fabricated on a 152mm×152mm×6.35mm silicon plate. It is the largest sample which our e-beam writer (JBX-6300FS, JEOL, japan) can handle; and it can share the same cassette with an industry standard 6025 mask. To get a flat surface, the thickness of the plate is very important. The silicon plate was polished to be very flat and very smooth, the surface flatness is less than 60nm with in 100mm in diameter, and the surface roughness is less than 0.5nm.

To reduce the writing time, we used SAL-601, a negative tone, chemically amplified resist from the Shipley Corporation, to pattern the grating. The exposure dose of SAL-601 is about 20-50 uC/cm2, much lower than that of PMMA or ZEP520A. Consequently, the e-beam writing time is reduced to about 70 hours.

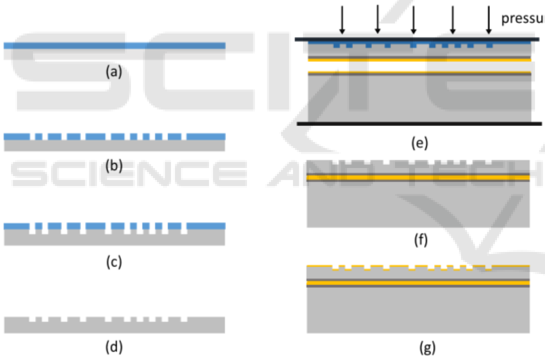

Figure 3: Process flow: (a) A 4 inch silicon wafer was spin coated with a layer of negative tone photoresist SAL-601 (Shipley Corporation); (b) Lithography was performed with a 100 kV e-beam writer (JEOL JBX-6300FS). Photoresist was developed in CD26 after a 105 °C 3 min PEB; (c) Silicon was etched by a high-density plasma etching system (ULVAC NE550); (d) Photoresist was removed by plasma etching with oxygen and the wafer was diced into a 100mm×40mm slice by a laser dicing machine. (e) The thin slice of grating was bonded to a 30mm thick bulk silicon. (f) The protective layer on both side of the grating was removed and the surfaces were cleaned thoroughly; (g) The surface of the grating was coated with a thin layer of gold (50nm) by using a magnetron sputtering system.

The process that we have implemented is sketched in Fig. 3. The silicon plate is cleaned by acetone, ethanol and DIW and is baked in an oven at 105℃ to remove moisture. It is spin coated with a layer of SAL601, which is 500nm in thickness. The photoresist was baked in an oven for 30 minutes at 105℃ to remove solvent in the photoresist. A JBX-6300FS (JEOL japan) e-beam writer is used to pattering the gratings, at 2 nA e-beam current, it takes about 70 hours to pattering the gratings.

For a chemically amplified resist, the post exposure bake (PEB) is a very critical process. The PEB temperature affects the line width of the photoresist and the PEB time affects the thickness of the residue resist. After many times of experiment, the PEB temperature is set to 105℃ and the PEB time is 30 minutes. After PEB, the photoresist was developed in CD26 for 3-5 minutes. The pattern on the photoresist needs to be transferred to the silicon to form a deep trench structure to eliminate stray lights reflected by the bottom of the grating. Before silicon etching, the residue photoresist should be removed using oxygen plasma. (ULVAC NE550, Oxygen 20 sccm 50w/300w for 5 seconds, 50nm of resist is removed evenly). Then the silicon is etched by a high-density plasma etching system (ULVAC NE550) with SF6 and C_3F_8. (oxygen 2 sccm, C_3F_8 60 sccm, SF_6 10 sccm, 50w/600w for 75 seconds). The etch depth is 300nm. After silicon etching, the excess photoresist is removed completely by oxygen plasma.

After been etched, the photoresist is removed by using oxygen plasma etching. Before dicing, the two sides of the wafer are protected by photoresist. The four inch wafer was diced into a 110mm×30mm slice by a laser dicing machine. After thoroughly cleaning, the back side of the wafer and the front side of the bulk silicon was coated with 50 nm of titanium and 500 nm of gold using magnetron sputtering. Ti is mainly used as Au-Si bonding layer and diffusion barrier layer, which is used to enhance the viscosity of Au-Si and avoid excessive diffusion of gold into the silicon. The external gold surfaces need to be treated very carefully to ensure successful bonding.

The gold surfaces were cleaned by ultrasonic in acetone, ethanol and deionized water, and dried by nitrogen. Then surface activation, which is a very critical process for successful bonding, was performed by an ICP-RIE system. The oxygen plasma was employed to eliminate of organic matter on the gold surfaces, then the $Ar+H_2$ plasma was used to remove the oxide layer. The treated gold surfaces should be bonded as soon as possible, otherwise the surfaces might be contaminated again and bonding could fail.

In the bonding process, the gold surfaces of both grating slice and the bulk silicon are sticked together, Fig.3.(e), and pressed firmly using a pneumatic piston with air pressure 4.0MPa. The temperature was raised to 260 °C gradually. The bonding process lasts 90 minutes. Under such pressure and temperature, the gold on the two sides diffused into each other, and the grating was bonded to the bulk silicon firmly.

To get a reflecting surface for soft X-ray, a thin layer of gold (50nm) and chromium (5nm as adhesion layer) is coated on the grating. To keep the shape of the grating, the stress of the metal needs to be controlled in a low level. The grating we fabricated is shown in fig.4.

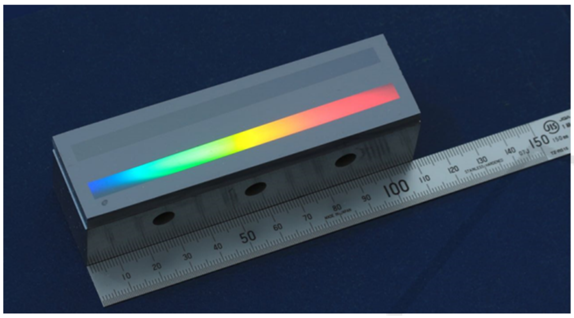

Figure 4: Aberration corrected diffraction grating grating a The grating consists of gratings of three different line density. 400 lp/mm (up); 800 lp/mm (down).

After the been fabricated, the structure of our grating is carefully check using SEM, The SEM images show that the sizes and positions of the grating lines are the same as designed.

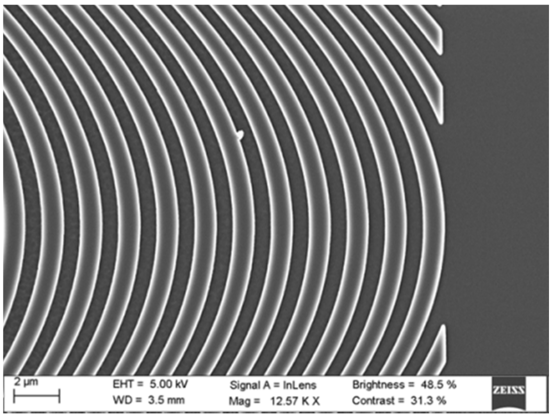

Figure 5: SEM image of the aberration corrected diffraction grating grating. The curved grating lines are designed to compensate the aberrations of a grating monochromator.

4 CONCLUSIONS

We proposed a new diffraction grating, The aberrations of a typical Czerny-Turner monochromator are discussed in detail and the grating design method is proposed in this work. The relation between the wavefront and the position of the grating line is analysed and the detailed design method is discussed. A lamina type aberration corrected reflective grating for soft X-ray is fabricated using e-beam lithography, and the detailed process is presented.

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