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A linear Bragg–Fresnel optics fabricated for 1D focusing of 18 nm X-ray radiation

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Abstract

The theoretical and technique results of a 1D focusing linear Bragg–Fresnel optics working at 18 nm X-ray radiation are given in the present paper. A theoretical method describing its optical performances is introduced briefly, the parameters of the diffraction pattern are presented. The preparation of multilayer mirrors, the decision of X-ray absorber layer thickness and the fabrication process of the diffraction pattern are described. The studied results of thermal and chemical stabilities for Mo/Si multilayer structure are shown. Some measured results for the 1D focusing linear Bragg–Fresnel optics are given. © 1999 Elsevier Science Ltd. All rights reserved.

Keywords: Linear Bragg–Fresnel optics; Fabrication; Diffraction pattern; Mo/Si multilayer

1. Introduction

The efforts of combining the most advanced technologies in thin film deposition and microfabrication have led to the development of a new category of optical element, Bragg–Fresnel optics [1, 2], which couples multilayers and diffraction patterns in the X-ray wavelength region. The Bragg–Fresnel optics benefit from the high efficiency at near normal incidence due to the multilayer structure and from the high spectral or spatial resolution provided by the diffraction pattern (lateral structure). In contrast to the transmission diffraction optics, the Bragg–Fresnel optics have much higher mechanical and thermal stability, which is of great importance for applications with high brightness X-ray sources.

During the last three years, we have studied the Bragg–Fresnel optics using both theoretical and experimental methods. A scheme based on quantum scattering theory was developed [3] to evaluate the optical performances including the scattering power density distribution and the diffractive efficiency. A series of computer codes were developed to calculate the working parameters of the diffraction pattern and to predict the optical performances of Bragg–Fresnel optics. In the fabrication process of Bragg–Fresnel optics, a number of Mo/Si X-ray multilayers were deposited on supersmooth Si wafers by ion beam sputtering (IBS). Using electron beam (EB) evaporation, an Au layer was coated on each multilayer as an X-ray absorber. A comparison study was done between the technique of combining UV lithography and a lift-off process and that of combining UV lithography and chemical etching in the generation process of the diffraction pattern. Then the diffraction pattern was generated on the absorber layer through the approach of combining UV lithography and a lift-off process to reduce the chemical and/or thermal attack on the Mo/Si multilayer structure. Because the stability of the multilayer structure in the fabrication process and in the application was often the essential and important factor for Bragg–Fresnel optics, the chemical and thermal stability of Mo/Si multilayers, therefore, was studied through a sequent simulation of chemical and/or thermal attacks in the fabrication and application process [4]. The experimental study results of stability

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were not only very useful for obtaining the optimal technical parameters in the pattern generation process but also exhibited the physical characterization of the X-ray Mo/Si multilayer structure.

In the present paper, the study results for 1D focusing Bragg–Fresnel optics working at 18 nm X-ray radiations are shown, especially the detailed information about the fabrication of diffraction patterns.

2. Theoretical method and results

Until now all the theoretical methods for Bragg–Fresnel optics were based on considering X-ray as a wave front and the description of its optical performances was determined by the use of Maxwell's equations, but here we consider the X-rays as a particle-flow and evaluate the performances of Bragg–Fresnel optics by using quantum theory. In our theoretical method, the incidental X-ray radiation is regarded as a particle-flow scattered by the scattering medium with three-dimensional scattering potential, which is composed of the diffraction pattern and multilayer structure. The wave function in this case is obtained by solving the Schrodinger equation and the expression of the scattering wave amplitude is obtained by the boundary condition of the scattering wave in quantum theory. According to the equation of particles-flow density in quantum mechanics, which is described by the scattering amplitude and the observation point distance, we finally obtain the equations of scattering power density and diffractive efficiency. More detailed information about the theoretical method can be found in Ref. [3]. The theoretical results on the design parameters of the diffraction pattern are presented in this section.

For the 1D focusing linear Bragg–Fresnel optics working at 18 nm X-ray radiation that we designed, its diffraction pattern could be described as:

$$V_x(x) = \sum_{j=0}^{N}\left[\mathrm{rect}\left(\frac{x}{a\sqrt{2j+1}}\right) - \mathrm{rect}\left(\frac{x}{a\sqrt{2j}}\right)\right] \tag{1}$$

where a is the half-width of the center zone in the diffraction pattern, j is a positive integer with a range of [0, N] (N is zone-numbers) and rect is a rectangle function.

Using Eq. (1), we calculate the parameters of the diffraction pattern for a utilization with a 200 mm focal length and a 7° incident angle, the half-width of the center zone is 60.4 μm, the width of the outer zone is 3.95 μm, the total zone number N is 59 and the size of the diffraction pattern is 0.929×7 mm.

3. Fabrication process

A number of important parameters relevant to the fabrication process of the diffraction pattern stood out: outer zone width, which determines the resolution of 1D focusing linear Bragg–Fresnel optics, absorber layer bar/groove ratio, groove depth and groove profile. Correct spacing, width of zones, accurate placements of the zones, accurate shape and smoothness of the pattern are very important in the fabrication of the Bragg–Fresnel optics. Manufacturing inaccuracies and geometrical distortions as well as thermal and chemical attacks in the generation process have to be minimized not to reduce its optical performances.

4. Multilayer mirror fabrication

All the Mo/Si multilayer samples are deposited at the same time on the standard (100) silicon wafers in an ion-beam sputtering system using a Kaufman type ion gun. Alternating layers of elemental molybdenum and silicon are deposited by Mo and Si targets mounted on the rotatable target holder. The deposition process is in-situ monitored using a quartz crystal vibration monitor, which is calibrated before deposition. The multilayer consists of 15 bilayers of 8.53 nm period with Mo deposited at first and Si deposited lastly and the deposition rates of Mo and Si were about 0.53 and 1 nm/min, respectively. The pressure of the argon sputter gas was 4×10^{-2} Pa.

5. Diffraction pattern fabrication

5.1. Establishment of the thickness of X-ray absorber

When a beam of X-ray radiation passes through a material, the intensity is exponentially attenuated,

$$I = I_0 \exp(-\alpha t) \tag{2}$$

where t is the thickness of the material, α is the linear attenuation coefficient and I_0 and I are the radiation intensities before and after X-ray passing through the material, respectively. Generally, α could be expressed as:

$$\alpha = \frac{4\pi\beta}{\lambda} \tag{3}$$

where β is the absorption coefficient in the complex refractive index of the material and λ is the wavelength of X-ray radiation.

According to Eqs. (2) and (3), we obtain the curves of X-ray radiation intensity versus the thickness of the Au absorber layer at $\lambda = 17.7$ nm and $\lambda = 18.2$ nm

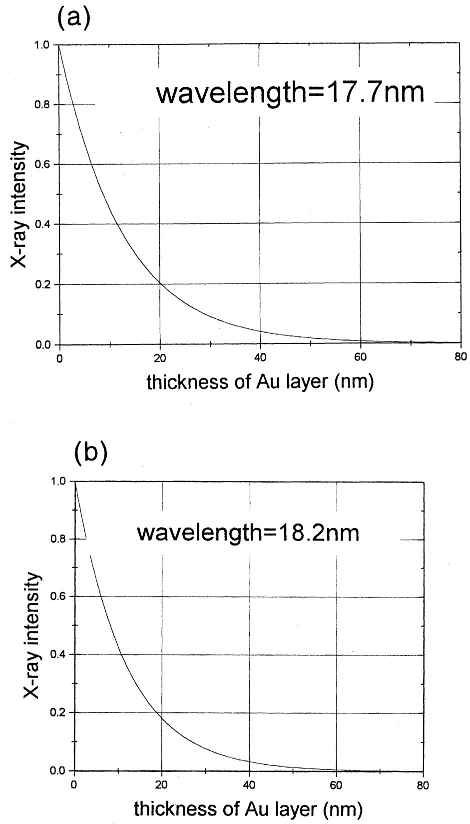

Fig. 1. The curves of X-ray radiation intensity versus the thickness of the Au absorber layer at (a) $\lambda = 17.7$ nm and (b) $\lambda = 18.2$ nm.

(see Fig. 1). From Fig. 1, we could see for X-rays with the wavelength range 17.7–18.2 nm, that the radiation is almost all absorbed when the thickness of the Au layer exceeds 50 nm. So we decide on 50 nm as the limit thickness of the Au layer. Considering the adhesion between the Mo/Si multilayer and the Au absorber layer, we deposit about 5 nm Cr layers between the Mo/Si multilayer and the Au layer.

5.2. Diffraction pattern generation

In general, the manufacture of high-resolution optical components involves several stages: the generation of a high-resolution pattern and then its transfer to the substrate. It requires a lithographic tool of writing fine linewidth features with a high precision, a recording medium or resist with very high resolution capability and a suitable transfer process that permits one to transfer the features of the pattern from the resist to the substrate without loss of resolution. For the 1D focusing linear Bragg–Fresnel optics in our case, the fabrication process has to generate the pattern without destroying the multilayer structure under the Au absorber layer. We try two approaches of combining UV lithography and a lift-off process as well as combining UV lithography and chemical etching and the approach of combining UV lithography and a lift-off process is used to fabricate the diffraction pattern of the 1D focusing linear Bragg–Fresnel optics to reduce the chemical and/or thermal attack on the Mo/Si multilayer structure.

The diffraction pattern in the 1D focusing linear Bragg–Fresnel optics is fabricated on the top of the multilayer structure by means of a multistep process outlined in Fig. 2. First, 103-B negative resist for UV light is spin-coated on Mo/Si multilayer. Then the diffraction pattern is generated on 103-B negative resist by UV light from the diffraction pattern mask fabricated by an electron beam-writing machine. During the resist pattern generation, there are several steps, they are: pre-bake, exposition, development and post-bake. After that a 5 nm-thick Cr layer and a 50 nm-thick Au layer are evaporated on patterned resist using an electron gun. Finally resist is removed by acetone and the diffraction pattern is transferred to the Au and Cr layers.

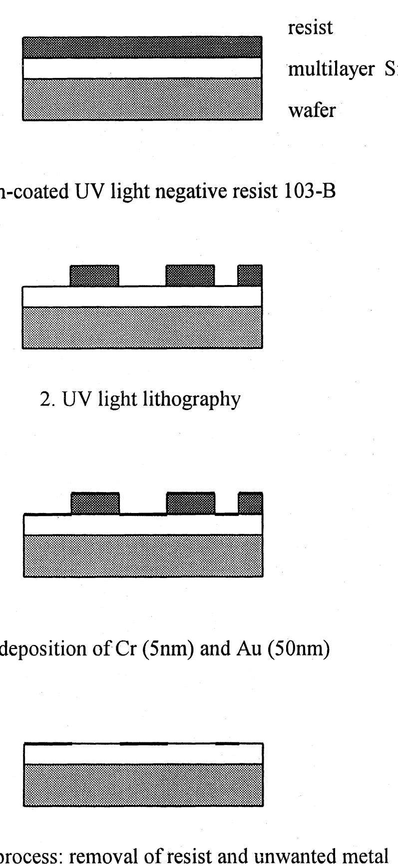

Fig. 2. Fabrication process of the 1D focusing linear Bragg–Fresnel optics.

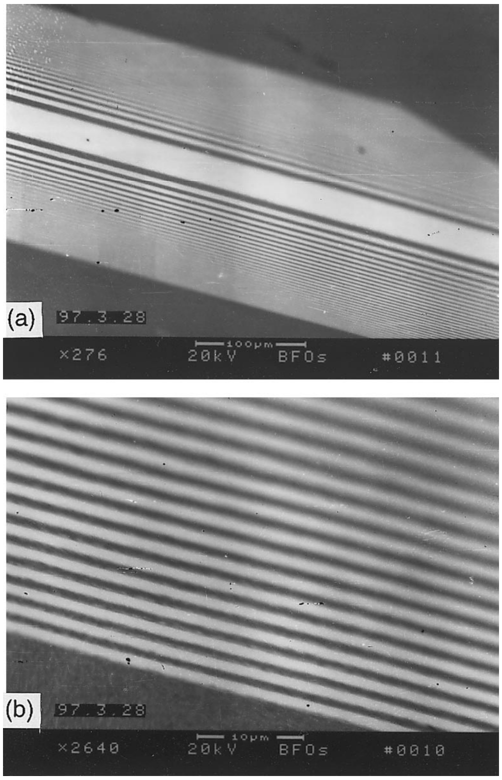

Fig. 3. Scanning electron micrographs of the 1D focusing linear Bragg–Fresnel optics. (a) Full view and (b) close-up view of the outer zones.

5.3. *Thermal and chemical stabilities of Mo/Si multilayer structure*

The multilayer structure would bear heat load and chemical load in the diffraction pattern generation and the Bragg–Fresnel optics would also bear the heat load during application to the X-ray optical systems. So the thermal and chemical stabilities of the multilayer structure in the Bragg–Fresnel optics are very important. According to the heat and chemical loads associated with the pattern generation and the using situation of the Bragg–Fresnel optics, we study [4] the stability of the multilayer structure by three kinds of experiments: (1) following real pattern generation process, (2) by the heat load only (from 360 to 770 K) and (3) by chemical reagent only. The interfacial and surface changes in the Mo/Si multilayer structure occurred during the thermal annealing and the chemical attack is investigated with small-angle X-ray diffraction technique as well as X-ray photoelectron spectroscopy (XPS) and an Olympus microscope. The results show that the Mo/Si multilayer structure is stable in the diffraction pattern generation process and the fractional variation in the multilayer period is 2.3% at 570 K. The layered structure of the Mo/Si multilayer is destroyed when the annealing temperature is increased to 770 K.

6. Results

The scanning electron micrographs of the 1D focusing linear Bragg–Fresnel optics are shown in Fig. 3. Fig. 3(a) shows almost the full view of the 1D focusing linear Bragg–Fresnel optics and Fig. 3(b) shows the close-up view of the outer zones. The micrographs are taken at 15° angle because the X-ray absorber layer is very thin. According to the scale shown on Fig. 3(b) and the angle of inclination while taking the micrographs, we obtain the width of the outer zone as about 3.94 μm. We also measured the thickness of the X-ray absorber layer by a stylus profilometer to be about 54.2 nm.

Acknowledgement

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