Laterally graded periodic Mo/B_4C multilayer for extreme ultraviolet wavelength of 6.8-11.0 nm*

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Abstract: Laterally graded periodic $[Mo/B_4C]_{60}$ multilayer mirrors for an EUV interval of 6.8-11.0 nm were deposited by direct current magnetron sputtering on silicon substrate. The structure properties and performance of laterally graded $[Mo/B_4C]_{60}$ multilayers were investigated by grazing X-ray reflectivity measurements and synchrotron radiation reflectance measurements. The results show that the multilayer period thickness *D*-spacing varies linearly from 4.39 nm to 7.82 nm in the long direction of the sample, indicating the average *D*-spacing gradient of 0.054 nm/mm. Reflectance of all measured point on the mirror is about 10% at the incident angle of 45°. Spectral width (FWHM) of the reflectance peaks varies from 0.13 nm to 0.31 nm with the increase of multilayer period thickness.

Key words: EUV; laterally graded periodic multilayer; Mo/B_4C; magnetron sputtering; synchrotron radiation

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EUV and soft X-ray are powerful sources used in microscopy, astronomical observation, biological science and material science. However, the weak refraction of EUV and soft X-ray in all materials, coupled with high absorption, makes conventional refraction-based optics not suitable for EUV and soft X-ray region. Multilayer mirrors, consisted of alternate layers with high electron density materials (Mo, W, Sc, etc.) and low electron density materials (Si, C, B_4C, etc.), can reflect the EUV and soft X-ray radiations. High electron density materials are selected as the absorber while the low electron density ones are used as the spacer. On the basis of Bragg's formula, high reflectance can be achieved when period thickness of multilayer satisfies the Bragg's formula either for a particular wavelength or a particular grazing angle due to the constructive interference of all the interfaces[1-3].

A problem for uniform multilayer mirrors when applied in EUV and soft X-ray region is the small working wavelength range due to their single period thickness structure. There are two ways to solve this problem: depth graded structured multilayer and laterally graded structured multilayer. For a depth graded structured multilayer, the period thicknesses vary with depth so that each bilayer is effectively tuned to a different X-ray wavelength. It can achieve broadband reflectance along the whole multilayer mirror[4-5]. For a particular wavelength at a fixed incidence angle, only one bilayer period thickness satisfies the Bragg's formula in a depth graded multilayer. Thereby, the reflectance is relatively low compared with uniform multilayer mirrors. Furthermore, due to the aperiodic structure of depth graded multilayer, spectral bandwidth will be broadened and significantly influence the spectral resolution. As an alternative, laterally graded multilayer mirror has been studied in previous articles[6-7]. For a laterally graded multilayer structure, period thicknesses vary continuously along the horizontal direction. Either the desired working wavelength or incidence an-

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gle can be simply achieved by translating the laterally graded multilayer to the corresponding position with the particular periodic thickness. Laterally graded multilayer not only simplifies the experiment alignment but also achieves high reflectance over a broad working wavelength with high spectral resolution. Chain Liu *et al* designed two different masks and fabricated two linearly graded W/C multilayers with average gradient of 0.027 nm/mm for tunable X-ray double-monochromator applications[6]. Transmittance of the double-multilayer monochromator was more than 50% in the 9.9 to 10.1 keV range. Using graded multilayers in a double-monochromator configuration, one can conveniently adjust the bandpass and peak positions of the transmitted beams. Laterally graded multilayer provides an attractive way for polarization studies on magnetic materials and useful applications in EUV metrology, astronomy and microscopy in EUV and soft X-ray range[8].

The design of laterally graded multilayer for synchrotron radiation reflector and polarization analysis requires determining the best materials combination. B_4C-based multilayers have shown relatively high theoretical reflectance in the previous researches owing to the low absorption coefficient of B at wavelengths longer than the B-K edge near 6.6 nm[9]. Higher theoretical reflectivities at 1.5° off normal incident angle can be achieved with La/B_4C and Ru/B_4C multilayers in 7 nm wavelength, which are 63.4% and 43.5% respectively. However, the reaction between the lively La and B_4C at the interface and the serious diffusion at the interface of Ru and B_4C caused a dramatic loss to the reflectance[10-12]. Mo/B_4C stack has stable physical and chemical properties. It can form multilayer structure with smooth interfaces and good thermal stability[12-14]. Mo/B_4C multilayer was more widely used in the practical multilayer application for soft X-ray near 7 nm. In this paper, a Mo/B_4C layered system is designed for synchrotron radiation as a broadband reflecting mirror for extreme ultraviolet wavelength interval of 6.8-11.0 nm. Laterally graded $[Mo/B_4C]_{60}$ multilayer sample was prepared by magnetron sputtering on silicon wafer. The quality and optical property of the sample are evaluated by grazing incidence X-ray reflectivity and synchrotron radiation reflectance measurements.

1 Experimental details

Mo/B_4C laterally graded multilayer films of 60 bilayers were grown on polished Si (100) wafers (30 mm wide and 70 mm long) by direct current (DC) magnetron sputtering in argon of 99.999% purity. The base pressure was well below 1.5×10^{-4} Pa. During the deposition process, a 0.15 Pa argon pressure was used in the deposition chamber. Two 4-inch(10.16 cm) ring sputtering sources were used. The target purities were 99.95% for Mo and 99.5% for B_4C. The plasma discharges were established with a DC power of 120 W for B_4C target and a DC power of 40 W for Mo target.

The individual Mo and B_4C layer thicknesses in laterally graded multilayers were adjusted by two specially formed deposition flux shaping masks fixed on the top of shield cans and directly above the sputtering targets. The film thickness distribution of magnetron sputtering and the profile-coating technique have been extensively studied in the previous studies[7,15]. The profile of the mask aperture was designed according to the required thickness profile. For masks used in the deposition process, the width of the aperture (perpendicular to the substrate moving direction) was 110 mm, and the length (along the substrate moving direction) at different transverse positions was determined by calculating the total material accumulated at these positions when the substrate passes over the aperture. As shown in Fig. 1, the substrate was moving linearly at a constant speed during the deposition. The distance from the

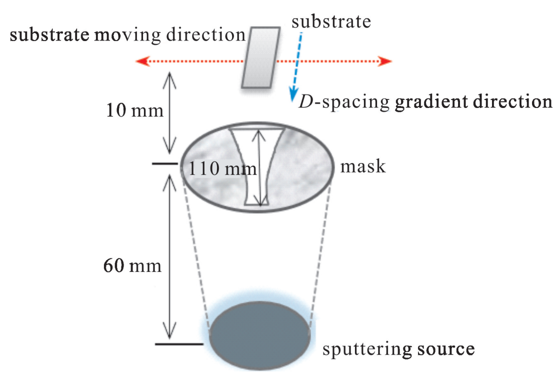

Fig. 1 Schematic diagram of the configuration used for the graded sputter deposition

target to the mask was 60 mm and from the mask to substrate was 10 mm. The substrate faced downward and it was driven by a computer-controlled stepper-motor to pass each magnetron source.

After deposition, the multilayers were investigated with grazing incidence X-ray reflectivity (GIXRR) on a five-circle diffractometer with the Cu-Kα line at 8.04 keV (0.154 nm). The size of X-ray spot was 100 μm ×2 mm. GIXRR measurements were made in θ-2θ geometry over the range of $0°<\theta<8°$. Fits to the GIXRR data were used to determine layer thicknesses and interfacial parameters. EUV reflectance measurements were performed with synchrotron radiation (SR) by reflectivity-meter at the National Synchrotron Radiation Laboratory (NSRL). The reflectivity measuring device and measuring method have been described in Ref. [16]. An 1800 L/mm monochromator grating was used in the measurement. The wavelength resolution was better than 0.05 nm and the size of focused X-ray spot was 1×5 mm^2. The sample stage was placed in a vacuum chamber with a pressure greater than 1.5×10^{-4} Pa. EUV reflectance measurements of the multilayer sample were made in the wavelength range of 6.0-11.0 nm with an incident angle of 45°. The reflectance measurements were performed every 5 mm interval along the gradient direction of the multilayer sample.

2 Results and discussion

The results of grazing incidence X-ray reflectivity measurements are shown in Fig. 2. For the convenience of comparison, the reflection curves were, in turn, translated vertically by two orders of magnitude.

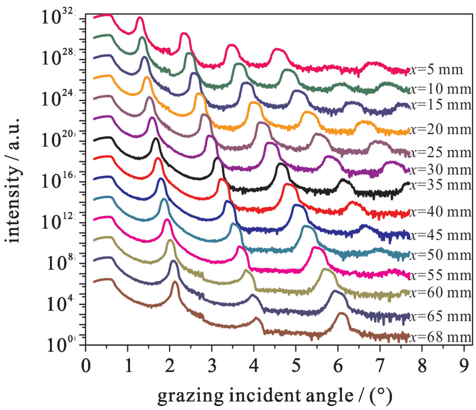

Fig. 2 GIXRR curves measured at 8.04 keV of different point location x along the mirror

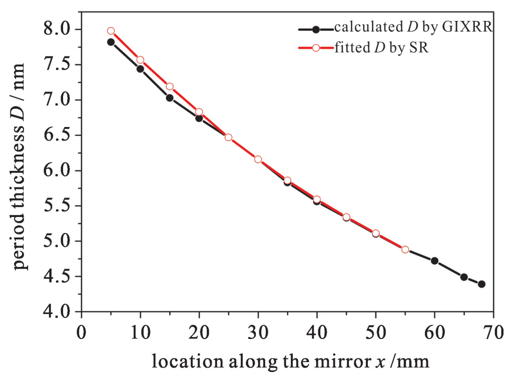

Fig. 3 Period thickness D of measured location x along the sample

Fig. 2 shows that the Bragg reflective peaks shift monotonically towards the large angle direction as the measured location x changes from 5 mm to 68 mm. It can be noticed that the higher order Bragg peaks are spread out. This is due to the fact that the X-ray beam has a lateral size of 2 mm along the direction of the D-spacing gradient. Hence, the X-ray effectively probes a 2 mm area with spread D-spacing, leading to the widening of the Bragg peaks. The angle positions of the peaks are determined by the multilayer period thickness and the incident X-ray wavelength according to the Bragg's law. Therefore, it can be inferred from the GIXRR curves that the shift of Bragg peaks represents a variation of the multilayer period thickness at different location x along the sample. Based on the Bragg's formula, the multilayer period thicknesses D were calculated according to the angle value of the Bragg peaks. The calculated results are listed in Table 1.

Fig. 3 shows the distribution of multilayer period thicknesses. The horizontal axis represents the location x along the sample in the long direction, and the vertical coordinate represents the multilayer period thicknesses. It can be concluded that multilayer period thicknesses vary continuously along the horizontal direction of the sample from 7.82 nm to 4.39 nm with an average gradient of 0.054 nm/mm as the measured location x increases from 5 mm to 68 mm.

The EUV reflectivity of multilayer was measured by synchrotron radiation (SR) at the incident angle of 45°. Fig. 4 shows the measured and fitted results. The measured reflectance data are plotted as open circles,

Table 1　Measured results of the GIXRR shown in Fig. 2 and the synchrotron radiation (SR) shown in Fig. 4

measured location x/mm	SR reflective peak λ/nm	FWHM, $\Delta\lambda$/nm	fitted period thickness D by SR/nm	calculated period thickness D by GIXRR/nm
5	10.60	0.31	7.98	7.82
10	10.12	0.29	7.57	7.44
15	9.67	0.27	7.19	7.03
20	9.25	0.27	6.83	6.74
25	8.80	0.26	6.47	6.47
30	8.41	0.23	6.10	6.16
35	8.05	0.20	5.86	5.83
40	7.69	0.19	5.59	5.56
45	7.39	0.18	5.34	5.33
50	7.09	0.17	5.11	5.10
55	6.79	0.16	4.88	4.88

and solid lines represent the fitted curves. The measured results indicate that different location along the gradient direction on the multilayer mirror is effectively tuned to a different X-ray wavelength in reflecting geometry. The reflection peak is located at 10.6 nm near the edge of the mirror where location $x=5$ mm, and it has the trend of shifting to short wave-length direction when the location x along the mirror increases. Ultimately, the reflection peak shifts to 6.79 nm as x increases to 55 mm. Reflectivities of all measured points on the mirror are about 10%. FWHM (full width at half maximum) of the reflectance peaks varies from 0.13 nm to 0.31 nm with the increase of multilayer period.

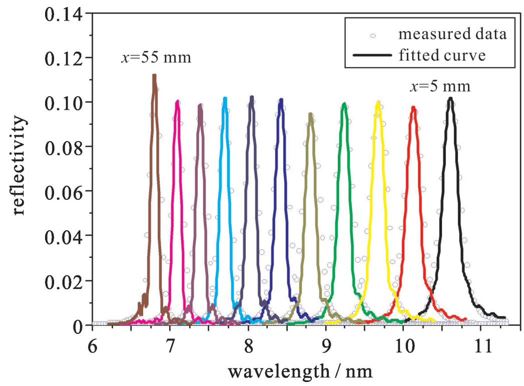

Fig. 4　Synchrotron radiation measured reflectivity data (open circles) at NSRF for different location x along the mirror with interval 5 mm and their fitted curves (lines) by IMD software

The measured synchrotron radiation reflectance curves were fitted using the IMD software to determine the layer thickness[17]. The fitting results are also listed in Table 1. By comparison, it can be noticed that the multilayer period thicknesses calculated from SR and GIXRR measurements are different (offset between 0 and 0.16 nm). This can be explained as that the measured locations were not strictly the same for two different measurements.

3　Conclusion

In summary, linearly lateral graded $[Mo/B_4C]_{60}$ multilayer sample was deposited by DC magnetron sputtering method on silicon substrate. GIXRR analysis demonstrates that the sample has a period thickness (D) varying linearly from 4.39 nm to 7.82 nm with an average gradient of 0.054 nm/mm in the horizontal direction. EUV reflectance measurement indicates that the multilayer achieves high reflectivity over a wavelength range of 6.8-11.0 nm. Moreover, FWHM of the reflectance peaks varies from 0.13 nm to 0.31 nm with the increase of multilayer period thicknesses, indicating a high spectral resolution for the multilayer sample.

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磁控溅射法制备极紫外 6.8～11.0 nm 波段 Mo/B_4C 横向梯度多层膜

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摘 要： 用直流磁控溅射法结合掩模板控制膜厚的方法在 Si 衬底上制备了工作于 6.8～11.0 nm 波段的[Mo/B_4C]$_{60}$横向梯度多层膜。利用 X 射线掠入射反射测试以及同步辐射反射率测试对梯度多层膜的结构及性能进行了测试。X 射线掠入射反射测试结果表明，多层膜周期厚度沿着长轴方向从 4.39 nm 逐渐增加到 7.82 nm，周期厚度平均梯度为 0.054 nm/mm。对横向梯度多层膜沿长轴方向每隔 5 mm 进行了一次同步辐射反射率测试，结果显示，横向梯度多层膜在 45°入射角下的反射率约为 10%，反射峰的半高全宽介于 0.13 nm 到 0.31 nm 之间。

关键词： 极紫外； 横向梯度多层膜； Mo/B_4C； 磁控溅射； 同步辐射