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Multilayer Polarizing Elements for Synchrotron Radiation Soft X-Ray Region*

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Abstract Periodic multilayers of W/C and Mo/Si have been developed with magnetron sputtering technology. The parameters of period and thickness are adjusted so that the first Bragg peak appears at the Brewster angle when the photon energy is in the vicinity of K edge of carbon and L edge of silicon respectively. The experiment was implemented at Beijing Synchrotron Radiation Facility (BSRF). The reflectivities of multilayer Mo/Si and W/C can reach 32.3% at 89eV and 4.18% at 214eV respectively near the Brewster angle. The feasibility of setting up polarizer with multilayers is discussed in this paper.

Key words synchrotron radiation, soft X-ray, multilayer, polarizer

1 Introduction

With the development of scientific disciplines about synchrotron radiation, interest increases in making use of specific polarization states of photon beams for a variety of experiments, such as X-ray magnetic circular dichroism (XMCD), X-ray magnetic linear dichroism (XMLD) and so on. Kortright et al (1995) first reported Faraday rotation measurements around $L_{\mathrm{II},\mathrm{III}}$-edges of Fe with a reflection multilayer analyzer using highly linearly polarized Undulator radiation ($P \geqslant 98\%$)[1]. All those studies need purely circularly or linearly polarized light. As we know, radiation emitted from bending magnets (or insertion devices like Wiggler and Undulator) has different polarization states, which depend on the observation angle seen from the plane of electron orbit. In the first generation light source like BSRF, the light emitted from the monochromator is a mixture of linearly and elliptically polarized radiation.

Optical elements are required to analyze polarization character of beams produced by such devices. These optical elements include linear polarizers (to measure the azimuthally linear polarization dependence and quarter-wave plates (to ascertain phase relationships of different components within the beam)[2] Generally, Nicol prism and Wollaston prism are used to analyze polarized light in visible light region. In hard X-ray region ($h\nu \geqslant 2$keV), perfect crystals in Laue geometry have been used. In soft X-ray region, however, ordinary polarizer cannot be used to make soft X-ray polarizer or analyzer due to intensive absorption, so, multilayer becomes the most suitable candidate. Multilayer mirrors for SXR (soft-X-ray) have been extensively used because of their excellent characters of high throughput and high polarization in the vicinity of Brewster angle[3]. For example, the throughput and polarization of Ru/Si multilayer are 60% and 0.97 for light of wavelength 12.8 nm[4]. Gluskin (et al.[5]) constructed a SXR polarimeter with multilayer mirrors and tested it with SR from the VEPP-2M ring. Using an Hf/Si multilayer polarizer, Khandar and Dhez estimated P_L (polarization of linearly polarized light) of SR of wavelength 15.4nm from the ACO ring to be 0.73.

The polarizing optics made up of multilayer is generally called polarizer, phase shifter or analyzer. As an analyzer, the multilayer completes polarization measurement by showing different reflection results for different polarized light. Being a phase shifter, it can produce beams with polarization approaching circular from predominantly linearly polarized bending magnet radiation without changing any parameter of synchrotron radiation beam line[6,7]. Multilayers are required to

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improve the polarization degree of synchrotron light generated by bending-magnet or wiggler in BSRF. Mo/Si film and W/C multilayers show good characters in soft X-ray spectra.

In this paper, we introduce two different multilayers applied in different energy ranges. Experimental results show that they have high reflectivity, enough phase retarding and large polarization degree, which are required for mutilayer to be used. The measurement values and calculated results are given out, followed by results and discussion.

2 Experiments

Two different multilayers are designed for this experiment. One is Mo/Si used at 60eV—120eV. The period is 10nm with a thickness ratio of absorbent layer and spacer of $\gamma=0.4$. The other one is W/C multilayer to be around 200eV—280eV, whose period is 3.86nm. Both of them were fabricated by the method of magnetron sputtering and deposited onto Si wafer with vacuum 0.35—0.41Pa. The reflectivity was measured by a reflectometer witch was installed on the 3W1B Beam-line at Beijing Synchrotron Radiation Facility (BSRF) in parasitic mode[8]. The varied line space grating monochromator system provides monochromatic photon energy from 50eV to 1500eV. The energy resolution($\Delta E/E$) is about 0.01 from 100eV to 280eV, and the slit was set to 4mm(Horizontal) × 1mm(Vertical). The samples were fixed on a reflectometer, which includes a sample stage and a detector[9]. Signals are collected by silicon photodiode (AXUV-100G, IRD, USA) and indicated by electrometer (Model 6517, Kethley, USA). The detector can be rotated into 2θ while the incidence angle of sample increases from 0 to θ. To get useful reflectivity, all samples were mounted in the fixed incidence angle of 45° and the monochromator system was moved to operating energy scanning. In θ—2θ scanning mode, the incidence angle was changed step by step and we get a curve of reflection vs. angle. Every peak value corresponds to the exact angle from which we can deduce periodic depth of multilayer if the Beam-line has accurate energy point and enough energy resolution capacity. The schematic setup is shown in Fig.1. The distance between the light source and the sample is about 28m, and the size of object is approximately 10mm × 10mm.

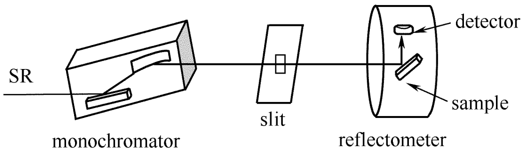

Fig.1. A typical scheme of reflectometer working with synchrotron radiation of BSRF.

3 Results & discussions

The experimental results are given in Fig.2 and Fig.3. The reflectivitys of multilayers have been measured at Brewster angle. They are only S component of the light source. According to classical formula[10], Brewster angle can be written as $\theta_B \approx \frac{\pi}{4} - \frac{\sigma}{2}$. In which, σ represents absorption coefficient, and $\sigma \ll 1$ in soft X-ray region for most materials. So Brewster angle θ_B can be regarded as 45° approximately. For reflection polarizer, reflectivity is one of the most important characters. In this experiment, the multilayer of Mo/Si has a reflection of 32.3% at 89eV with the thickness of the Mo and Si layers 2d/5 and 3d/5 respectively. It shows a good performance when $h\nu$ falls between the Mo N and Si L_{III} edges. However the calculated data (Seen from Fig. 2) where achieved by 70%, which is much greater than the experimental value. This difference is due to three possible reasons. The first one is system error of periodic thickness produced in the course of sputtering deposition. The second one comes from interface and surface roughness, which has been verified by many works[11—13]. The last one may be lower energy resolution. Table 1 gives out the simulation results.

Table 1. The simulation results of Mo/Si multilayer peak reflectivity

Peak Reflectivity	Δd%	Roughness	ΔE
70%	0	0	0
56%	1.8%	0	0
48%	1.8%	0.2nm	0
32%	1.8%	0.2nm	2.75eV

Another multilayer W/C is used for higher energy range down to K edge of C. As shown in Fig.3, the reflectivity of this periodic multilayer reaches the height of 4.18% at 214eV. This energy point departs the design value of 230eV just because of the same reason as that of Mo/Si film.

On the assumption, polarimeter is composed of two reflection polarizers made up of W/C multilayer. The intensity of

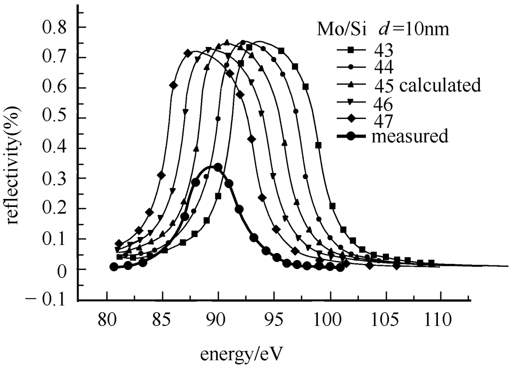

Fig.2.The measured value of Mo/Si vs.cal. reflectivity of different incident angle(@89eV).

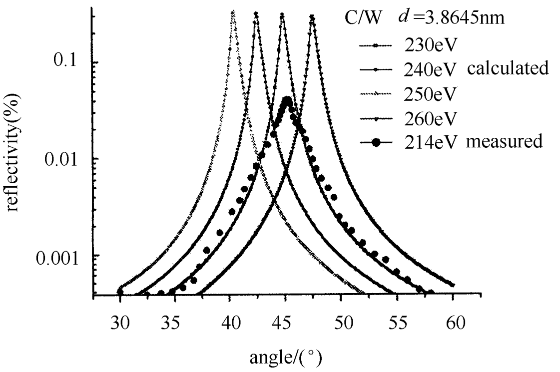

Fig.3.The measured reflectance of W/C vs.cal. reflectivity of different energy(@45°).

light from slit is I_0(The experimental value is 2.45nA).The reflection output signal of the first multilayer is 101.43pA (@45°).After reflected by the second polarizer, the intensity of SR was reduced to 4.24pA, and the final signal attenuated to $1.6 \times 10^{-3} I_0$. This value is so close to the background current that we can't distinguish it from noises(The background noise of 6517 electrometer is about 2pA).The above experiments were done in the parasitic mode of BEPC(Beijing Electron Positron Collider); under this condition, the beam light is generated parasitically during high-energy physics experiments.The electron energy and current are 1.89GeV and about 40mA respectively.But in dedicated mode, the electron energy and current are 2.2GeV and about 100mA, respectively.The signal of light intensity(I_0) received by the detector through slit under the same condition rises up to 68.34nA. Correspondingly, the measured value passing two W/C polarizers can reach 109.34pA, the Signal-to-Noise ratio is far greater than 54. This result indicates that the multilayer of W/C can be used to make polarization measurement instrument in 200eV—280eV range under the condition of dedicated mode at BSRF.

For the polarization analysis, a reflection multilayer mirror should be set up to rotated circle around the beam axis of incidence at nearly 45°. But only one is not very well, because it can't distinguish whether completely circularly polarized light or completely unpolarized radiation in this way. In order to resolve the problem, another polarizer (phase-shifter) is needed to posting into the beam. Of course, the phase shifting properties should be interesting in our research. The calculated results of phase shifting properties can be used to analysis for polarizer and analyzer. The reflection and phase retarding of a multilayer can be calculated with the exact Fresnel theory. The incident and reflected electric fields can be resolved into orthogonal σ and π components(viz. s and p components), and compare the phase changing of this input and output fields components. In order to calculate these quantities for the reflected fields, an approach based on complex Fresnel reflection coefficients has been used, the phase ϕ is calculated by $\phi_{s,p} = \tan^{-1}(\mathrm{Im}[E_{s,p}]/\mathrm{Re}[E_{s,p}])$[14]. The quantities of interest for polarization conversion are the relative phase difference between s and p components, given by $\Delta\phi = \phi_s - \phi_p$. Being a polarizer with good properties, a phase-shift $\Delta\phi$ of at least 90° or more should be observed between the two polarizations s and p. The phase shifts of s and p components with reflection of Mo/Si and W/C are show in Fig 4 and Fig 5 respectively. For the Mo/Si multilayers(Fig.4), the phase retarding of s component reaches 169 degree at 45° contrasting to -64.06 degree of p component at the same angle. Operating at this angle, the Mo/Si mirror can obtain $\Delta\phi \geqslant 90°$, the same as W/C multilayer in Fig.5. These multilayers present enough phase retarding and can be used for a phase shifter. The best performance of a reflection phase shifter in soft X-ray range will occur at 45° angle(Brewster angle). The reflectivity of the p-polarized component almost vanishes at this angle. Under this condition, the reflection multilayer will transfer incidence beam into linearly polarized light.

The third important character of this kind of multilayer is the polarization capacity of polarizer. Accurate measurement of polarization depends greatly on the polarization of the analyzer. There are two parameters that indicate the polarizer ability of changing incidence radiation into linearly polarized light directly or indirectly. The first one is polarization efficiency $R_s/$

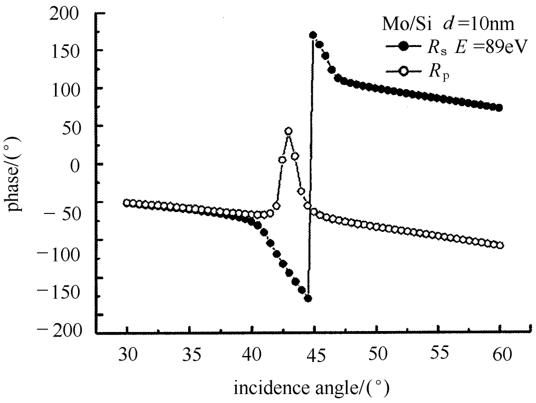

Fig.4. The calculation results of Mo/Si.

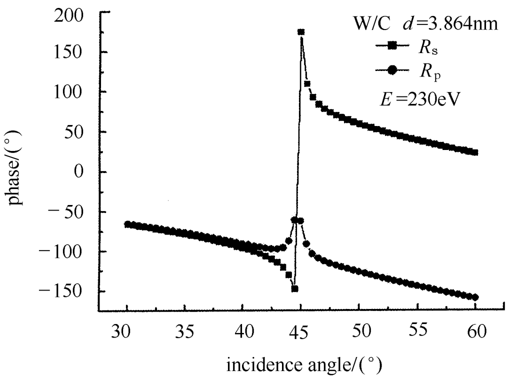

Fig.5. The calculation results of W/C.

R_p(also called extinction rate), where R_s and R_p are reflectivity of s-and p-components respectively. The second one is the degree of polarization P_p. As Shown in Fig. 6, for W/C multilayer, the minimal value of extinction rate R_p/R_s is less than 3.36×10^{-4}, that means the maximal value of $R_s/R_p\geqslant 2500$. The higher this ratio, the stronger its ability to transferring. However, the maximum value of the polarization efficiency does not agree with the position of the R_s peak valve, but the R_p is minimum at the same position. Comparing with R_p/R_s, the intensity of R_s is more sensitive to the incidence angle, and polarization efficiency changes very little around the Brewster angle. To insure sufficient reflectivity, the variety of R_p/R_s with the incidence angle can be ignored generally. Thus the R_s peak value should be designed near the Brewster angle at the design energy. As shown in Fig.6, the polarization of the polarizer, which is defined by $P_p=(R_s-R_p)/(R_s+R_p)$, comes to maximum value with R_s/R_p simultaneously. The polarization of Mo/Si multilayer(shown in Fig.7) could be up to 0.99 between 40° and 47°(@89eV), Actually any photon energy between 70eV and 95eV could reaches this level. The W/C is the same as Mo/Si at nearly 230eV. Those values are enough to meet the experimental requirements. Therefore, multilayer with high polarization(P_p) should provide us with much more accurate results in soft X-ray region.

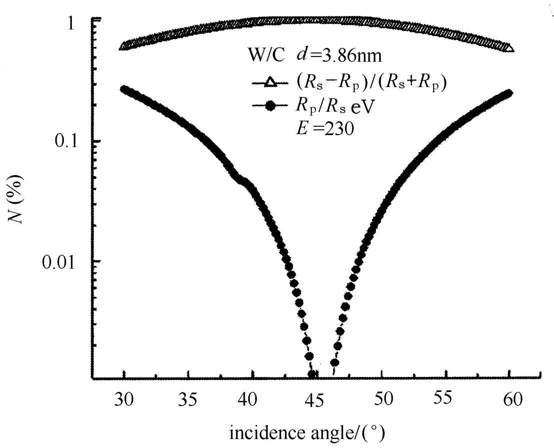

Fig.6. The calculated extinction rate and polarization of W/C multiplayer.

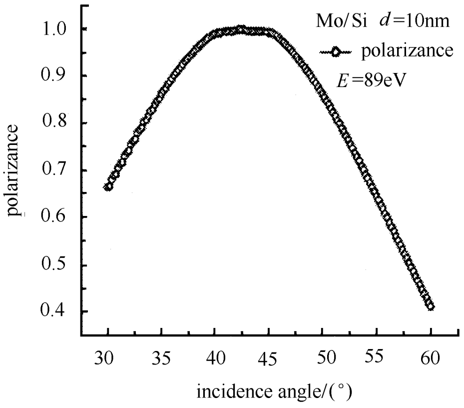

Fig.7. The calculated polarization of Mo/Si can reach 99% between 40°—47°.

4 Conclusion

The measured reflectivities of multilayer Mo/Si and W/C can reach 32.3% and 4.18% at 89eV and 214eV near the Brewster angle respectively. These reflectivities are high enough to make two-reflection polarizmeter for certain applications. The calculated phase shift of Mo/Si multilayer in symmetric Bragg geometry at $h\nu$ = 89eV indicates to provide a

great phase difference ($\Delta\phi \geqslant 90°$) between s and p electric filed components on reflection. The W/C multilayer has a similar result at 230eV. Proper designing and fabrication can make multilayer operate as an efficient linear polarizer with very high suppression for the p-polarized component at Brewster angle. They also have a higher calculated value of polarization($P_p \geqslant 0.99$) and a better signal-to-noise rate. With respect to reflectance and polarizing properties of these two multilayers, the best performance of the optical elements is achieved below the 2p absorption edge of silicon and the 1s edge of carbon. They can suit polarization research.

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同步辐射软X射线多层膜反射偏振元件研究*

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摘要　利用多靶磁控溅射方法分别镀制了W/C和Mo/Si两种周期性结构多层膜。通过对其相关参数周期数、厚度比以及周期厚度的调整,使薄膜的布拉格衍射峰出现在布儒斯特角附近,两种多层膜的应用能量范围分别落于C的近K边处和Si的L边前。在北京同步辐射装置3W1B光束线的软X射线光学实验站上进行了反射率的测量,得到W/C膜的反射率在214eV时达到4.18%;Mo/Si周期性多层膜的反射率在89eV处达到32.3%。根据测量结果,分析了在同步辐射装置作为偏振元件的可行性。

关键词　同步辐射　软X射线　多层膜　偏振元件

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