Design and fabrication of broad angular range depth-graded C/W multilayer mirror for hard X-ray optics

Zhong Zhang (张 众), Zhanshan Wang (王占山), Fengli Wang (王凤丽), Wenjuan Wu (吴文娟),
Hongchang Wang (王洪昌), Shuji Qin (秦树基), and Lingyan Chen (陈玲燕)

Institute of Precision Optical Engineering, Department of Physics, Tongji University, Shanghai 200092

Received December 21, 2004

In this paper, a depth-graded C/W multilayer mirror with broad grazing incident angular range, consisting of three multilayer stacks, each of which has different period thickness d and the layer pair number, was designed and fabricated by direct current (DC) magnetron sputtering. For calculating the definite performance of such a mirror, the saturation effects of the interfacial imperfection, such as interface roughness and diffusion, were emerged. The reflectivity of the mirror was measured by the X-ray diffraction (XRD) instrument at Cu K_α radiation ($\lambda = 0.154$ nm), the measured reflectivity was about 30% in a broad grazing incident angular range (0.55°—0.85°). By the fitting data, the thickness of each layer is almost same as the one designed and the roughness in the multilayer is about 0.85 nm, which is larger than the prospective value of 0.5 nm.

OCIS codes: 220.0220, 230.0230, 310.0310, 340.0340.

Recently, with the development of hard X-ray telescopes[1−3] and the third generation synchrotron sources[4], hard X-ray focus optics have been applied widely. For such applications, the reflective mirrors with relatively broad angular range for hard X-ray radiation such as Cu K_α line ($\lambda = 0.154$ nm), are required to extend the view field and flux of optics, where bent crystal and single layer metal mirrors cannot be used because of too small grazing incident angle. The periodic multilayer mirrors have higher reflective angle than the critical angle of single layer metal mirrors, but their narrow angular range limits their application in hard X-ray focus optics. More currently, depth-graded hard X-ray multilayer mirrors were developed because they have broad grazing incidence angular range or wider energy band. The depth-graded multilayer mirrors can provide a large angular range to extend the view field and flux of optical system. In this letter, one kind of depth-graded multilayer mirrors has been designed, fabricated, and measured for Cu K_α radiation ($\lambda = 0.154$ nm).

Based on the intensive research[5−8] into multilayer design and fabrication with various material combinations, C/W layer pair was chosen to compose the depth-graded multilayer mirrors for hard X-ray. The depth-graded multilayer mirror is an aperiodic multilayer consisting of some periodic multilayer stacks, each of which has different periodic thickness (d) and number of layer pairs (N). Such a mirror has almost the same reflectivity over an incident angular range, it is so-called supermirror. The peak reflectivity (R), incident angle at peak reflectivity (θ), and the incident angular range (δ_θ) of the Bragg peak of each block are functions of d, N, and λ (the wavelength of X-ray). Here, N is so optimized that the integrated reflectivity ($R \times \delta_\theta$) is maximized at the smallest number N. For given incident angle range of interest, d and N for each block are so determined that the reflectivity from each block fills the angular ranges without gaps or unnecessary overlaps. Another key parameter is the ratio Γ of absorbing layer thickness d_{a} to period d. Γ does not influence the first order Bragg peak much, but has higher order peaks largely. Our current design adopts a value $\Gamma = 0.4$ to enhance the first order Bragg peak. The detail of the simulation and the optimization of supermirror design were described by Yamashita *et al.*[1,9].

Figure 1 shows a model reflective curve of a C/W depth-graded multilayer consisting of three multilayer blocks. The structures of the blocks from the top layer (vacuum side) to the bottom layer (substrate side) are d = 9.0—9.1, 6.3, and 6.0 nm, and the layer pair numbers of the blocks are N =2, 3, and 9, respectively. Note that the periods of the first block are not constant, but graded, to obtain smooth reflectivity curve as a result of superposition. The interfaces in the multilayers are well known to be not ideal because of the roughness and diffusion between the two layer materials, and they would result in a reflectivity decrease. In this letter, we set the interface roughness factor $\sigma = 0.5$ nm, and use the equations

$$D_j = \exp\left[-\frac{1}{2}\left(\frac{4\pi\sigma}{\lambda}\right)^2 \sin\theta_{j-1}\sin\theta_j\right], \qquad (1)$$

$$N_0\cos\theta_0 = N_j\cos\theta_j, \qquad (2)$$

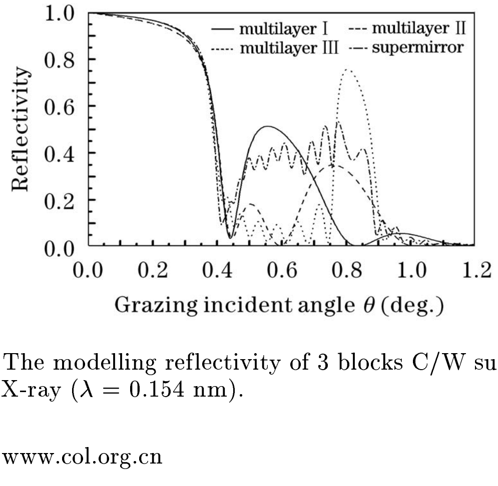

Fig. 1. The modelling reflectivity of 3 blocks C/W supermirror for X-ray ($\lambda = 0.154$ nm).

1671-7694/2005/070422-03 http://www.col.org.cn

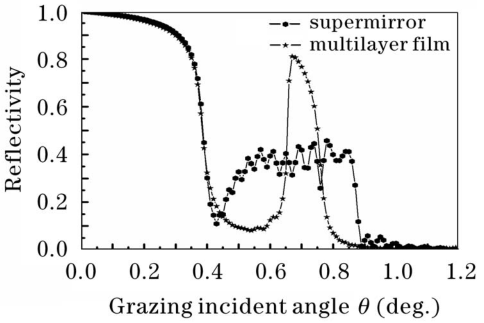

Fig. 2. The modelling reflectivity of C/W depth-graded mirror and periodic multilayer film with the same roughness (σ = 0.5 nm).

based on Nevot-Croce model, to simulate the precise reflectivity of multilayers. Here N_0 is the refractive index of incident medium, σ is the root mean square value of the effective roughness, N_j is the refractive index of the jth layer, and θ_j is the grazing incidence angle at the jth layer.

The precise calculation results are shown in Fig. 2. It is clear that the angular response of the depth-graded multilayer (14 layer pairs) is extended compared with the multilayer with constant period (44 layer pairs).

The depth-graded C/W multilayer described was deposited on a polished silicon substrate (15×20 (mm)) by a direct current (DC) magnetron sputtering coater. The base pressure of vacuum system was (5.5±0.5) × 10^{-5} Pa, and the argon (99.99% purity) pressure was fixed at about 0.66 Pa during deposition. The powers applied to W and C magnetrons (Lesker company) were held constant at 25 and 130 W, respectively, and −200 V bias voltage was applied to the substrates. The distance between the targets of W or C and the deposited substrates is about 80 mm. The deposition rates for W and C were about 0.027 and 0.02 nm/s, respectively, which are calculated from film thicknesses determined by X-ray reflectivity measurements[10]. The thickness of each layer was controlled by the time when the substrate stays over each of the tungsten and carbon targets.

The reflectivity for different grazing incident angles was measured by D1 X-ray diffraction (XRD) instrument (BEDE company, UK), whose characterized X-ray radiation is Cu K_α line. As shown in Fig. 3, the reflectivity of the depth-graded multilayer is about 30% in the angular response range of 0.55°—0.85°. According to the comparison between Fig. 3 and Fig. 2, the peak reflectivity of the depth-graded multilayer decreases because the diffusion and interface roughness are larger than those predicted in design. The fitting parameters include the interface roughness factor (σ) and the thickness of each layer in the supermirror structure. By the fitting data, the interface roughness (σ) is about 0.85 nm, which is larger than the prospective value of 0.5 nm. This is the reason why the reflectivity of deposited supermirror is lower than that of designed supermirror. Additionally, the thickness of each layer is a little different compared with that predicted, as shown in Fig. 4. It is proved that the deposited rate of each material is stable during the production process.

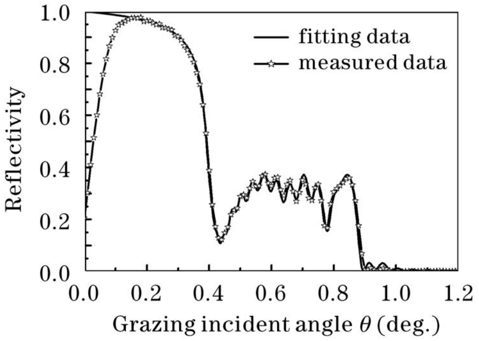

Fig. 3. The measured reflectivity of the deposited depth-graded multilayer and its fitting curve at λ = 0.154 nm.

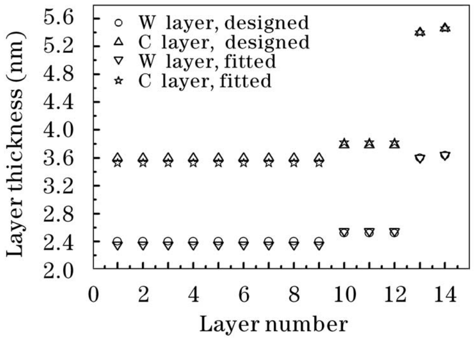

Fig. 4. Comparison between the designed and fitted thicknesses of each layer in the supermirror structure.

In conclusion, we found that at grazing incidence, the depth-graded C/W multilayer mirror, deposited by DC magnetic sputtering technology, has a much wider acceptance angular range and a higher integrated reflectivity than the C/W periodic multilayer mirror, and they may be the important considerations for X-ray imaging system.

This work was supported by the National Natural Science Foundation of China under Grant No. 60178021. Z. Wang is the author to whom the correspondence should be addressed, his e-mail address is wangzs@mail.tongji.edu.cn.

References

1. K. Yamashita, P. J. Serlemitsos, J. Tueller, S. D. Barthelmy, L. M. Bartlett, K. W. Chan, A. Furuzawa, N. Gehrels, K. Haga, H. Kunieda, P. Kurczynski, H. Takata, K. Tamura, Y. Tawara, and B. J. Teegarden, Appl. Opt. **37,** 8067 (1998).
2. Y. Ogasaka, K. Tamura, K. Haga, T. Okajima, S. Ichimaru, S. Takayashi, A. Gotou, H. Kitou, S. Fukuda, H. Kunieda, Y. Tawara, K. Yamashita, Y. Tsusaka, P. J. Serlemitsos, Y. Soong, K. W. Chan, F. Owens, S. Berendse, and J. Tueller, Proc. SPIE **4012,** 294 (2000).
3. K. Yamashita, K. Akiyama, K. Haga, H. Kunieda, G. S. Lodha, N. Nakamura, T. Okajima, K. Tamura, and Y. Tawara, J. Synchrotron Radiation **3,** 711 (1998).
4. A. M. Hussain, F. E. Christensen, G. Pareschi, and H. F. Poulsen, Proc. SPIE **3444,** 443 (1998).
5. J. F. Seely, M. P. Kowalski, W. R. Hunter, and G. Gutman, Appl. Opt. **35,** 22 (1996).
6. K. Yamashita, J. Peter, J. Tueller, S. D. Barthelmy, L. M. Bartlett, K. W. Chan, A. Furuzawa, N. Gehrels, K.

Haga, H. Kunieda, P. Kurczynski, N. Nakajo, N. Nakamura, Y. Namba, Y. Ogasaka, T. Okajima, D. Palmer, A. Parsons, Y. Soong, C. M. Stahl, H. Takata, K. Tamura, Y. Tawara, and B. J. Teegarden, Appl. Opt. **37,** 34 (1998).

7. Z. S. Wan, J. L. Cao, and A. G. Michette, Opt. Commun. **177,** 25 (2000).
8. I. V. Kozhevnikov, I. N. Bukreeva, and E. Ziegler, Nuclear Institutes and Methods in Physics Research **A460**, 424 (2001).
9. Z. Zhang, Z. S. Wang, F. L. Wang, S. J. Qin, and L. Y. Chen, Chin. Phys. Lett. **21,** 12 (2004).
10. D. L. Windt, Computer in Physics **12,** 360 (1998).