New Design Concept of Multilayer Supermirrors for Hard X-Ray Optics

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ABSTRACT

It is important to enhance the reflectivity of multilayer supermirrors in 10–100 keV region used for hard X-ray optical systems. For this purpose design methods of multilayer supermirrors have been investigated at the grazing angle of 0.3 deg. by means of the X-ray etalon or phase matching configuration. It means that the 1st and higher order Bragg reflections emanated from different periodic lengths cooperatively enhance the reflectivity at energy bands concerned. The X-ray etalon method is useful for multi-band mirror with the band width of 5 keV or so, but becomes a bit difficult to make the energy band wider (> 10 keV) connecting gaps between isolated bands. Because heavy oscillation of reflectivity curve occurs due to adjacent distructive and constructive interference. The phase matching method is useful to get smooth reflectivity in the broad energy band and is possible to enhance the 2nd order Bragg reflection in higher energy region. We present the design of hard X-ray telescope sensitive in 25–40 keV region by means of multi-block supermirrors of Pt/C multilayers. The effective area was obtained to be more than 100 cm^2.

Keywords: multilayer; supermirror; X-ray telescope; hard X-ray; X-ray etalon

1. INTRODUCTION

Development of depth-graded multilayers, so called supermirror aims at applying to hard X-ray optical systems, such as X-ray telescope and X-ray microscope for the practical use. The performance of a supermirror hard X-ray telescope has been demonstrated in the energy range of 25–36 keV by making use of Pt/C multilayer supermirrors with 26 layer pairs.[1] The advantage of supermirrors is to make possible enhance the reflectivity in the wide energy region beyond the critical energy at a given grazing angle. Now it becomes promising to get 40 % smooth reflectivity in 25–40 keV at the grazing angle of 0.3 deg..[2] In this case the minimum periodic length(d) is 30 Å, which is still larger than the technological limit of 15 Å. However there is obvious limitation to extend the energy region by reducing d, since the attenuation of incident X-rays is caused by elastic scattering and photoelectric absorption in the upper multilayers.

Design methods of multilayer supermirror have been proposed to maximize the integrated reflectivity in a given energy band with the minimum number of layer pairs by means of parameter optimization of d, number of layer pairs and thickness ratio of heavy element to d. Most of calculations were carried out by making use of the first order Bragg reflection. Joensen et al[3,4] proposed the concept of continuously graded multilayers similar to neutron diffraction optics to extend the energy region up to 80 keV at 0.2 deg. grazing incidence.

We have tried to design multi-block method taking into account phase matching of all d-values in the total thickness and making use of higher order reflection. The reflectivity calculations were performed in the energy range 20–40 keV at 0.3 deg. grazing angle by adjusting d-values and number of layer pairs. The average reflectivity would be expected to be 40–50 %. The upper limit of energy range is defined by the penetration depth of incident X-rays. These results are compared with non-phase-matching multi-block method as previously reported.[2]

We present the experimental results of Pt/C multilayers and supermirros and optimum design of a supermirror hard X-ray telescope.

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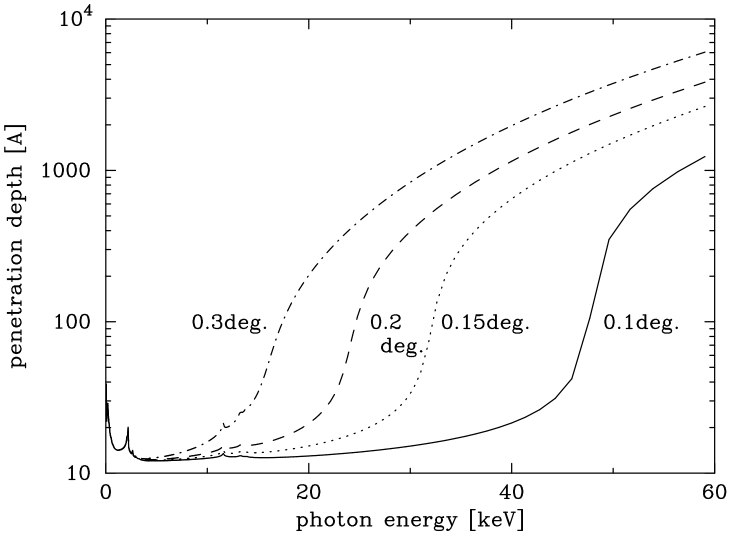

Figure 1. Penetration depth of a single layer of Pt against X-ray energies

2. DESIGN OF MULTILAYER SUPERMIRRORS

The peak reflectivity of multilayers are defined by periodic length(d), number of layer pairs(N) and the thickness ratio(Γ) of a heavy element layer(d_H) to $d = d_H + d_L$ at the fixed energy(E) and grazing angle(θ). d_L is a layer thickness of light element. d is derived from the Bragg condition as follows,

$$m\lambda = 2d\sin\theta_m\left(1-\frac{2\delta-\delta^2}{\sin^2\theta_m}\right)^{1/2}$$

$$\lambda[\text{Å}]\ E[\text{keV}] = 12.3985$$

where m is reflection order and δ is atomic scattering factor of constituent materials weighted with thickness ratio. The maximum number of layer pairs is estimated from the ratio of d to the penetration depth($z_{1/e}$) which are shown in Fig. 1 for a single layer of Pt at the grazing angle of 0.1, 0.15, 0.2 and 0.3 deg.. The peak reflectivity(R_p) of each Bragg reflection order is expressed as monotonically increasing and gradually saturated function of d and N, which also depends on Γ in the different way as shown in Fig. 2. If Γ=1/2, even order reflections will disappear due to the destructive interference. The bandwidth of the Bragg peak is given as $\Delta E(\text{FWHM}) = E/mN$. One more important parameter is the interfacial roughness(σ) which significantly contributes to the reduction of reflectivity as a function of $\exp(-(2\pi m\sigma/d)^2)$ like Debye-Waller factor. These are the basic constraints for the calculation of the Bragg reflectivity. Practically we impose conditions of $d > 20$ Å, $d_H > 10$ Å, $N < 200$ layer pairs and $\sigma > 3$ Å upon the supermirror design. These values are estimated from our experimental work for Pt/C multilayers.[5]

In the hard X-ray region(10–100 keV) it is well known that supermirrors are useful to extend the energy band and get higher reflectivity at the fixed grazing angle beyond the critical angle. However the attenuation of incident X-rays in the multilayer structure limits the attainable range of the energy band times mean peak reflectivity , so called integrated reflectivity due to the finite penetration depth. We have tried to optimize the supermirror design of Pt/C by means of multi-block multilayers with d = 60–30 Å at the grazing angle of 0.3 deg. The mean reflectivity in the 20–40 keV range is expected to be more than 40 % by adjusting d, N and Γ. If we only use the first order Bragg reflection, we can get the smooth reflectivity of 40 % in 25–40 keV region.

2.1. Broad band supermirror

In order to cover the energy band 20–40 keV at 0.3 deg. incidence, periodic lengths of multilayers are derived to be 60–30 Å. Taking into account the peak reflectivity, bandwidth and penetration depth of a multilayer, we can select suitable sets of d, N and Γ to get the highest mean reflectivity in a given energy band. We have calculated the reflectivity of Pt/C multilayer supermirror stacked with 8 blocks of multilayers with d = 60 Å at the top and 30 Å at the bottom with 84 layer pairs in total, as shown in Fig. 3. The thickness of Pt is fixed to be 15 Å except for the top

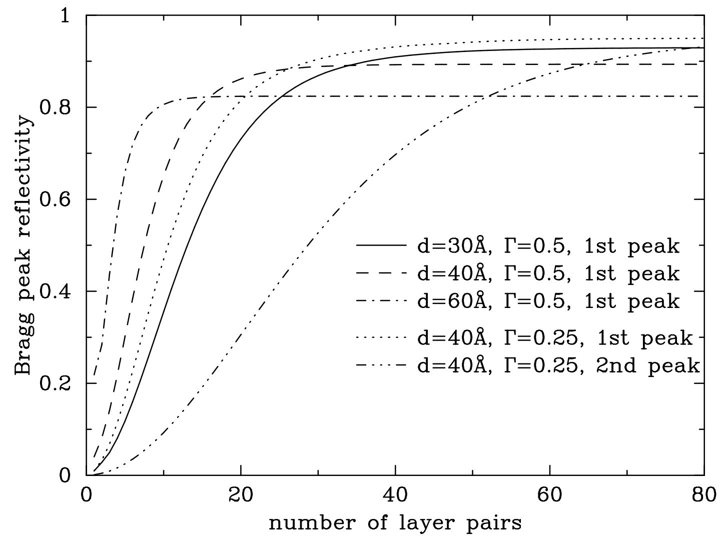

Figure 2. Peak reflectivities of Pt/C multilayers with different d-values against number of layer pairs for different Γ(incident angle(θ_i)=0.3deg.)

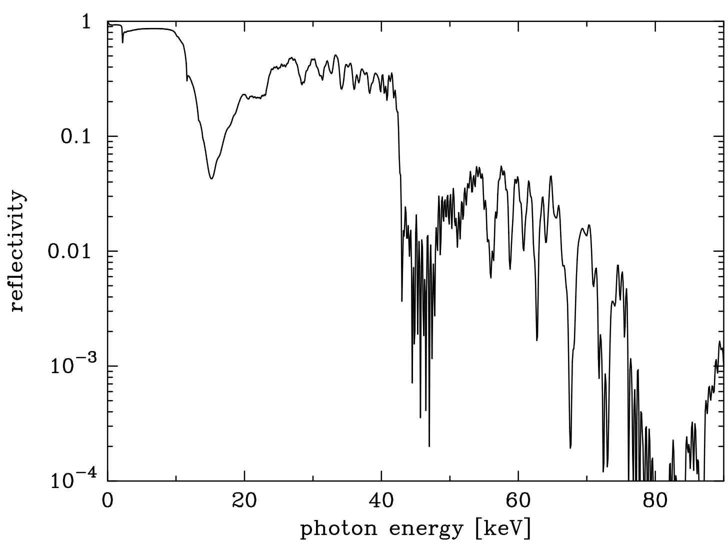

Figure 3. Reflectivity of 8 block supermirror(θ_i=0.3deg., (d, N)=(60,2),(48.3),(43.6,5),(40,7),(37,11),(34.3,14),(32,18),(30,24),Pt=15Å, Γ_{1st}=0.5, σ=0.0Å)

block. Since d of the top block is twice as the bottom block, the second order reflection overlaps on the first order of bottom multilayers. There appears heavy oscillation of reflectivity curve around 40 keV, so that $\Gamma = 1/2$ is set for the top block to eliminate the second order Bragg reflection. This oscillation structure is caused by the thickness between the top and bottom block similar to an X-ray etalon. it is important to control the phase angle of incident X-rays changing the layer thickness concerned. The reflectivity of lower blocks is saturated by the attenuation of upper blocks. It is not helpful to increase the number of layer pairs. Only way to increase the reflectivity is to make use of the second order reflection of upper blocks. We think that the difference of minimum to maximum energy is factor of two for a broad band supermirror in case of keeping the mean reflectivity of 40 %.

We have tried another method keeping $N \times d =$ constant for all the multilayer blocks. This means that the phases of incident X-rays reflected by different d-values are matched to each other. For instance, if $N \times d = 360$ Å, $d_{max} = 60$ Å and $d_{min} = 30$ Å are given, the combinations of d and N in between are automatically determined, which

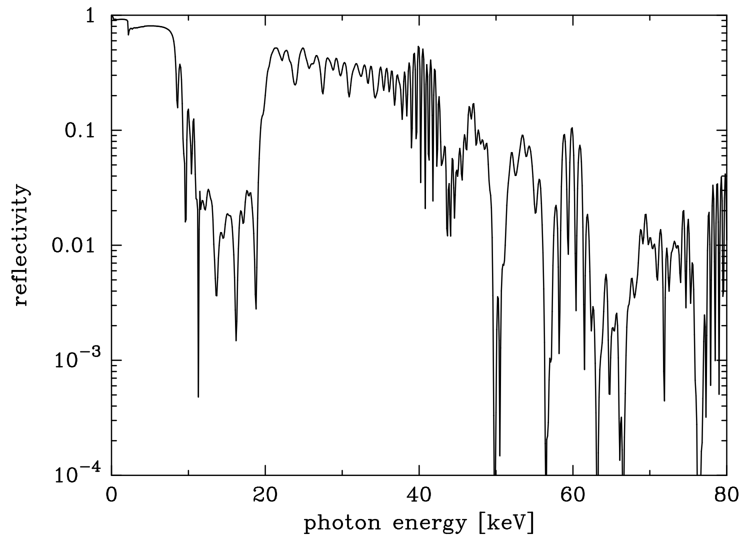

Figure 4. Reflectivity of phase-matching supermirror for $N \times d = 360$ combination of $(d, N) = (60, 6), (51.4, 7), (45, 8), (40, 9), (36, 10), (32.7, 11), (30, 12)$

correspond to number of blocks. Γ is selected to get smooth reflectivity. One of the example is shown in Fig. 4. The oscillation pattern of reflectivity is just like a harmonic one. The highest reflectivity of the 2nd order reflection is obtained for $\Gamma = 0.25$.

2.2. Multi-band multilayers

The second order Bragg reflection is quite useful to enhance the reflectivity at several isolated narrow energy bands. This is a kind of X-ray etalon. We have designed unit block of $d = 40$, 20, 30 and 30 Å layers stacked successively, as shown in Fig. 5. At every 10 keV we can get enhanced bands. Higher order reflections overlap to the first order in phase selecting d-values. The separation and bandwidth of X-ray energies are arbitrarily controlled with combinations of d, N and Γ. X-ray etalon is also useful to select energy bands changing the spacer thickness between multilayers, as shown in Fig. 6. A half wavelength difference of spacer thickness divides into two adjacent peaks with equal reflectivity. If two block multilayers are separated by a spacer layer, there appear multiple peaks corresponding to d-values. Therefore it is not easy to get a broad band mirror by means of etalon method. It behaves like multi-band reflective filter. It is useful to observe X-ray images above and below the K-absorption edge of heavy element at the same time for medical applications.

3. FABRICATION AND CHARACTERIZATION

Several types of supermirrors were fabricated by a magnetron DC sputtering method.[6,7] Their reflectivities were measured with Cu-Kα and continuous X-rays in 10–50 keV region. In Fig. 7 there shows the reflectivity of 4 blocks supermirror deposited on float glass. The same supermirror also deposited on Au surface replica mirror made of Al foil substrate and epoxy layer. Its reflectivity reduces to be 80 % of float glass substrate. We made Pt surface replica mirror on which a multilayer was deposited. Its reflectivity is comparable to float glass substrate, as shown in Fig. 8. The interfacial roughness is derived to be 3 Å. Another method was tried to directly replicate supermirror deposited on a mandrel to Al foil substrate. This is also promising to get sufficient reflectivity.

We have measured the reflectivity of 5 block supermirror at 32 keV using the SPring 8 synchrotoron facilty. The result are shown in Fig. 9, where the 2nd and 3rd order Bragg reflection are easily recognized. The higher order reflection is useful to investigated the detailed structure of supermirrors.

4. SUPERMIRROR HARD X-RAY TELESCOPE

We have designed a hard X-ray telescope with Pt/C supermirrors sensitive in the energy region of 25–40 keV. Inner and outer diameter and focal length are defined to be 12 cm, 40 cm and 8 m, respectively, which correspond to the

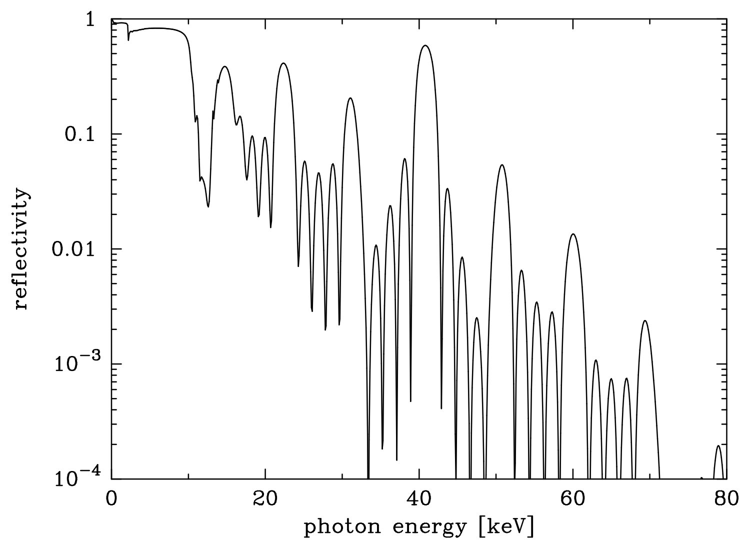

Figure 5. Reflectivity of multi-band multilayers(θ_i=0.3deg., $d = (60 + 30 + 30) \times 5$, Pt=15Å, σ =0.0Å)

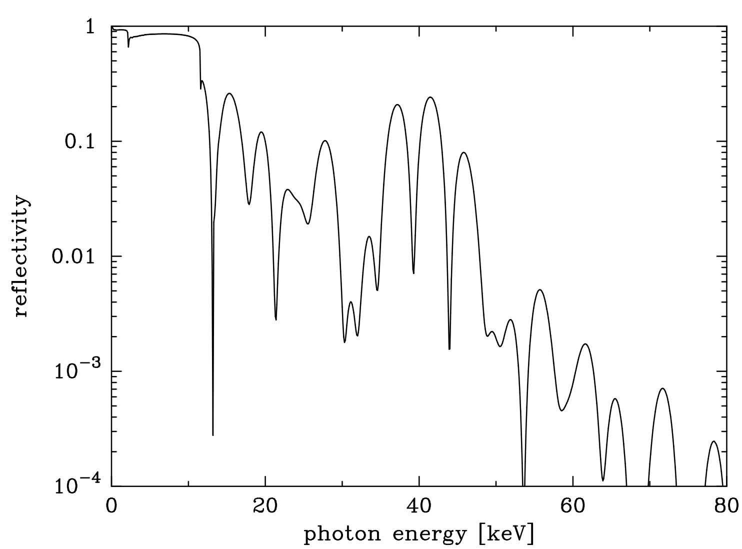

Figure 6. X-ray etalon of Pt/C multilayers(θ_i=0.3deg., (30,4)+(Pt90,C30)+(30,4), Pt=15Å, σ =0.0Å)

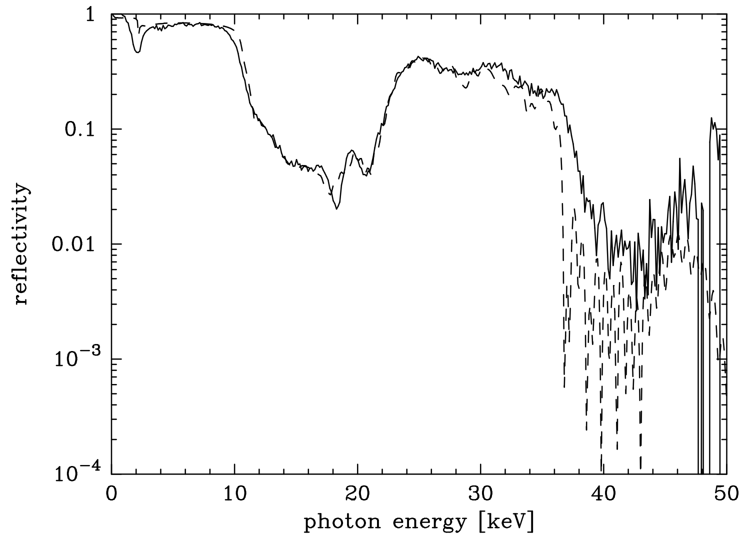

Figure 7. Reflectivity of 4 block supermirrors (θ_i=0.3deg., (d, N)=(54.2,1),(53.2,1),(52.2,1),(51.2,1),(50.2,1),(43.4,8),(39.4,13),(35.7,18), Γ=0.41, σ =4.2Å)

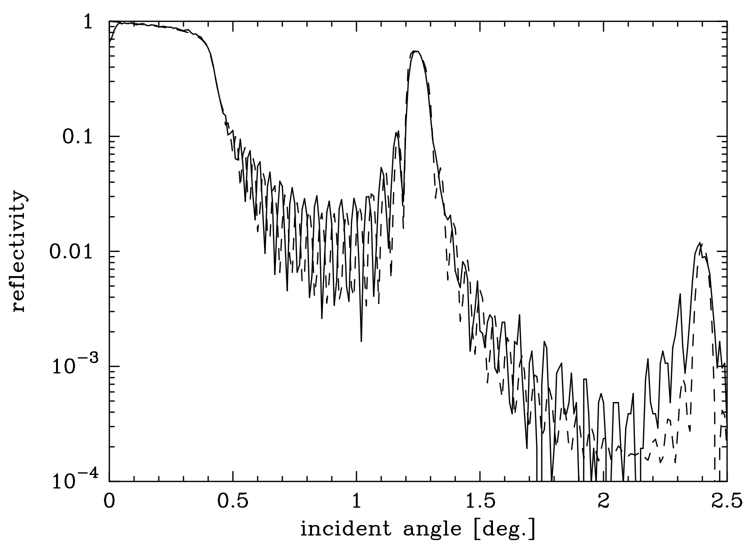

Figure 8. Reflectivity of a multilayer deposited on Pt replica mirror(X-ray:Cu-Kα, (d, N)=(37.3,20), Γ = 0.44, σ=3.0Å)

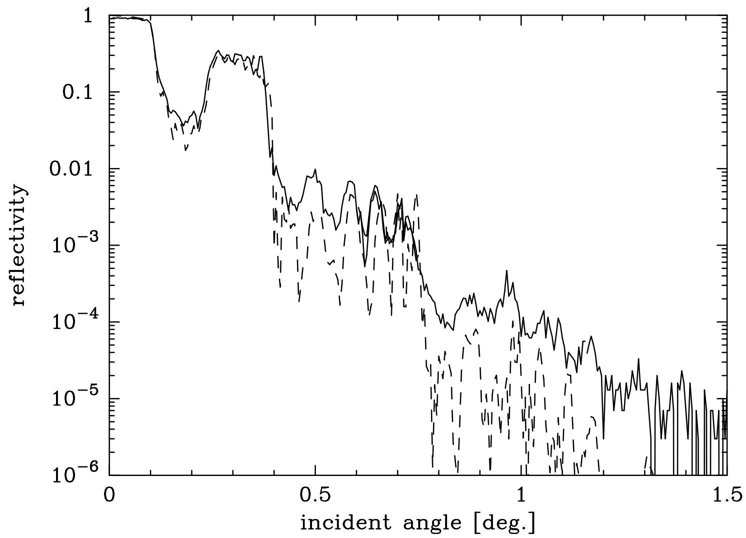

Figure 9. Supermirror reflectivity at 32 keV(θ_i =0.3deg., (d,N)=(47,1),(46,1),(45,1),(44,1),(43,1),(38,8),(34,13),(32,18),(30,25), Γ=0.4, σ=3.8)

	grazing angle	configuration of multilayers	number of mirrors
1.	0.106	Pt single layer	29
2.	0.125	Pt(40) (90,1),(80,1),(70,1),(65,5)	9
3.	0.138	Pt(40) (81,1),(72,1),(65,2),(63,3)	19
4.	0.151	Pt(50) (73,2),(68,3),(64,3),(53,6)	17
5.	0.166	Pt(45) (72,2),(67,3),(63,2),(59,2),(55,8)	18
6.	0.183	(81, 2), (61, 4), (55, 4), (51, 7), (45, 10)	21
7.	0.201	(74, 2), (56, 4), (50, 5), (45, 10), (41, 15)	20
8.	0.221	(68,3),(52,5),(50,3),(45,9),(40,15)	21
9.	0.244	(64,3),(48,6),(45,3),(41,10),(37,15)	22
10.	0.268	(56,3),(44, 4), (41, 3), (37, 10), (34, 15)	22
11.	0.295	(50-46, 5), (40, 8), (36, 13), (33, 18), (31, 25)	23
12.	0.324	(48-43, 6), (38, 9), (34, 12), (31, 16), (29, 25)	22
13.	0.357	(44,4),(38,2),(36,8),(32.5,13),(30,20),(28.5,30)	13

Table 1. Pt(40) : thickness of Pt=40 Å, (d,N) : periodic length(d) and number of layer pairs(N)

grazing angle of 0.106–0.357 deg. Total number of mirror shell is 256 pieces. The design parameters are shown in Table 1. The effective area is shown in Fig. 10. It is possible to get 100 cm^2 for the interfacial roughness of 3 Å. This design was done with standard block method to optimize the supermirror structure.[2] This telescope will be used for balloon-borne observations.

5. DISCUSSIONS

The application of supermirrors to a hard X-ray telescope needs to obtain broad energy band and high reflectivity in 20–40 keV region at the grazing angle of 0.3 deg.. It is favorable to extend further the energy band and grazing angle without sacrificing reflectivity. In the point of view of multilayer deposition less number of layer pairs is recommended. We have tried several design methods to attain the best quality of supermirrors within the constraints of the practical fabrication. It is well established from our experimental work that Pt/C multilayer is the most suitable combination to get the highest reflectivity with the minimum number of layer pairs and minimize the periodic length and interfacial roughness. It also turns out that Pt replicated Al foil substrate is the best surface for depositing multilayers. The

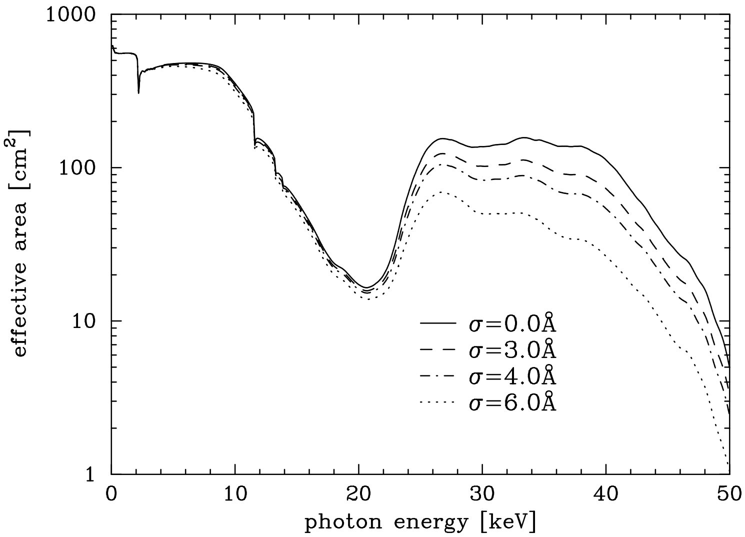

Figure 10. Effective area of supermirror hard X-ray telescope

intrinsic interfacial roughness of Pt/C multilayers was confirmed to be 3 Å by depositing on a supersmooth surface substrate.

Now we have to investigate the design method of supermirrors using Pt/C multilayers. At this moment simple stacking of multilayers with decreasing of d-values to substrate is the best way to get the uniform reflectivity in 20–40 keV region. This method is applied to design a hard X-ray telescope. It is advantageous to make use of 2nd order reflection overlapping on 1st order. The phase matching in a supermirror structure is interesting method. We have to find the golden rule to optimize the supermirror structure.

6. SUMMARY

We have investigated the design method of multilayer supermirrors in the 20–40 keV region at 0.3 deg. grazing angle by making use of 2nd order Bragg reflection and etalon configuration. It is not beneficial for broad band supermirror, but useful for multi-band mirrors. Therefore we designed a hard X-ray telescope by means of standard multi-block supermirrors. The effective area was obtained to be 100 cm^2 in 25–40 keV region.

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REFERENCES

1. K. Yamashita, P. Serlemitsos, J. Tueller, S. Barthelmy, L. Bartlett, K.-W. Chan, A. Furuzawa, N. Gehrels, K. Haga, H. Kunieda, P. Kurczynski, G. Lodha, N. Nakajo, N. Nakamura, Y. Namba, Y. Ogasaka, T. Okajima, D. Palmer, A. Parsons, Y. Soong, C. Stahl, H. Takata, K. Tamura, Y. Tawara, and B. Teegarden, "Supermirror hard x-ray telescope," *Applied Optics* **37**, pp. 8067–8073, 1998.
2. Y. Tawara, K. Yamashita, H. Kunieda, K. Tamura, A. Furuzawa, K. Haga, N. Nakajo, T. Okajima, H. Takata, P. Serlemitsos, J. Tueller, R. Petre, Y. Soong, K. chan, G. Lodha, Y. Namba, and J. Yu, "Development of a multilayer supermirror for hard x-ray telescopes," *Proc. SPIE* **3444**, pp. 569–575, 1998.
3. K. D. Joensen, F. E. Christensen, H. W. Schnopper, P. Gorenstein, J. Suisini, P. Hoghoj, R. Hustache, J. L. Wood, and K. Parker, "Medium-sized grazing incidence high-energy x-ray telescopes employing continuously graded multilayers," *Proc. SPIE* **1736**, pp. 239–248, 1993.

4. K. D. Joensen, P. Hoghoj, F. E. Christensen, P. Gorenstein, J. Suisini, E. Ziegler, A. K. Freund, and J. L. Wood, "Multilayered supermirror structures for hard x-ray synchrotron and astrophysics instrumentation," *Proc. SPIE* **2011**, pp. 360–372, 1994.
5. K. Yamashita, K. Akiyama, K. Haga, H. Kunieda, G. Lodha, N. Nakajo, N. Nakamura, T. O. K. Tamura, and Y. Tawara, "Fabrication and characterization of multilayer supermirrors for hard x-ray optics," *Journal of Synchrotron Radiation* **5**, pp. 711–713, 1998.
6. Y. Tawara, K. Yamashita, H. Kunieda, K. Haga, K. Akiyama, A. Furuzawa, Y. Terashima, and P. Serlemitsos, "Multilayer supermirror coating for hard x-ray telescope," *Proc. SPIE* **2805**, pp. 236–243, 1996.
7. K. Tamura, K. Yamashita, H. Kunieda, Y. Tawara, A. Furuzawa, K. Haga, G. Lodha, N. Nakajo, N. Nakamura, T. Okajima, O. Tsuda, P. Serlemitsos, J. Tueller, R. Petre, Y. Ogasaka, Y. Soong, and K. Chan, "Development of balloonborne hard x-ray telescopes using a multilayer supermirror," *Proc. SPIE* **3113**, pp. 285–292, 1997.