New Design Concept of Supermirror for Hard X-ray Telescope

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ABSTRACT

We studied about new design of supermirror and inerfacial roughness for the X-ray telescope above 40 keV. We have developed hard X-ray telescope above 10 keV using platinum-carbon multilayer supermirror. In our balloon borne experiment, named "InFOCμS" launched in this June, the supermirror expand the upper-limit of energy band of X-ray telescope up to 40 keV. We are trying to improve supermirror design to have energy band up to 70 keV. In previous design, the absorption of upper layers and lower-limit of layer thickness prevent us to extend the energy band. In this paper, we optimize design parameters of supermirror and use second Bragg peak, and we obtained high reflectivity up to 70 keV.

We studied about interfacial roughness of platinum-carbon multilayer to design the supermirror, because the interfacial roughness is very serious problem such high energy region. In many cases, simple Debye-Waller factor can't represent measured reflectivity. We introduced two different roughness for Pt/C and C/Pt interfaces. This model well fit the data and make us possible to design the supermirrors.

1. INTRODUCTION

In previous X-ray telescopes, total reflection of gold or other metal surface are used to reflect the X-ray. The energy band of the X-ray telescope is limited by critical energy of total reflection and extreme grazing incidence angle is needed for hard X-ray region. Japanese satellite ASCA has wide energy band using multi-nested thin foil mirrors optics.[1] However, The critical energy of total reflection is still limited the energy band of X-ray telescope below 10 keV.

The multilayer reflector using Bragg reflection is essential for the imaging in the hard X-ray region. Furthermore, depth graded multilayer, which is called "supermirror", is used to obtain high reflectivity in wide energy band.

We developed hard X-ray telescope using platinum-carbon multilayer supermirror for a balloon borne experiment named "InFOCμS" launched on this June.[2] In this experiment, the supermirrors are designed to maximize the reflectivity in 20 – 40 keV energy band.

In this paper, we try to extend the energy band of supermirror up to 70 keV. We make new design concept of supermirror using second Bragg reflection to extend the energy band. Furthermore, we will report our study of interfacial roughness of Pt/C multilayers. Interfacial roughness is serious problem in high energy region. Especially, reflectivity of second Bragg reflection is very sensitive to interfacial roughness. We have to use precise theoretical model to design the supermirrors for high energy region.

2. NEW DESIGN OF SUPERMIRROR UP TO 70 KEV

2.1. Design policy

Our supermirrors are consisted from some constant d-spacing multilayers. Each multilayer block is piled up on the substrate and each of the blocks are designed to have different periodic length to widen the energy band.[3] The block which has long periodic length corresponds to lower energy, and allocates near the surface, because low energy X-ray easily absorbed by upper layers. However, absorption by upper layers still prevent us to extend the energy. In our previous design, the energy band was limited up to 40 keV. Therefore, we have to optimize the design parameters including number of block, periodic length of bilayer and number of bilayers of each block to extend the energy above 40 keV.

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We introduce the integrated reflectivity IR $= \int R(E)dE$, where E is photon energy and R(E) is reflectivity, to estimate performance of supermirror. To extend the energy band, we have to reduce the number of layers keeping IR obtained by the previous design.

Figure 1 shows an example of reflectivity of a previous designed supermirror which is consists 4 constant-d multilayer blocks superposed on the reflectivity curves of individual blocks. The number of bilayers of each blocks is determined to have highest IR.[3] The intervals of peak energy between two blocks are proportional to width of two peaks to achieve flat response. Because of absorption of upper layers, peak reflectivity of lower block (corresponding block IV in figure 1) must be higher than that of upper layers to achieve flat response. Thus, large number of layers are required for lower blocks to obtain high reflectivity and makes peak width narrow in inverse proportion to N. If we added next block to extend the energy band in figure 1, we need 25 bilayers to expand energy band only less than 2 keV. It means that we need so many layers to extend the energy band, and it causes increase of X-ray absorption.

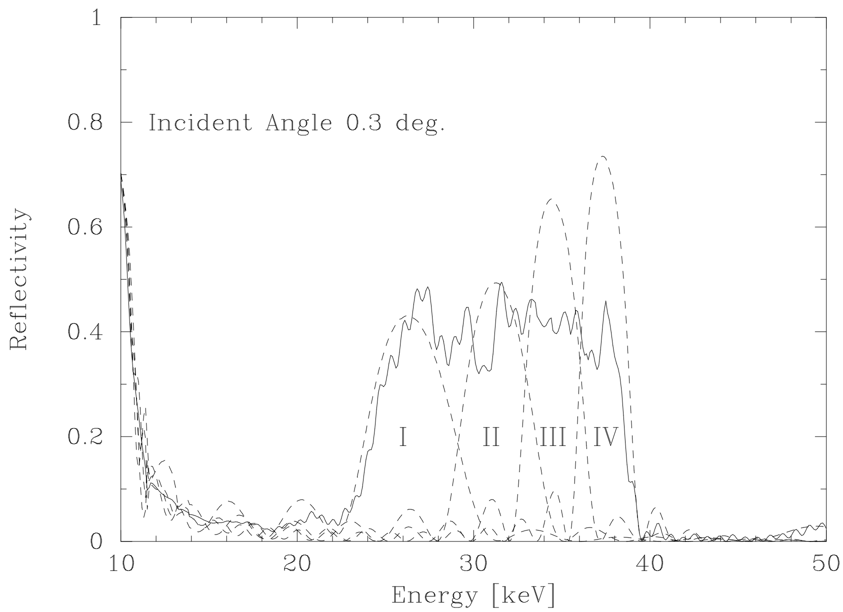

Figure 1. Calculated reflectivity curve of our supermirror consisted from 4 constant-d spacing multilayers at incident angle of 0.3 degree (solid line). The reflectivity curves of four individual multilayers are shown by break lines. The periodic length (d), number of bilayers (N) and Γ-ratio (Γ) of each blocks are (d[Å], N, Γ) = (46 – 50, 5, 0.4), (40, 8, 0.4), (36, 13, 0.4), (33, 18, 0.4).

To overcome this problem, we try to optimize design parameters of supermirror including number of blocks in new design method. First, we determined number of blocks, and choose the peak energy of each blocks to have regular interval. Next, we optimized number of layers for flat response of the supermirror. We calculated the reflectivity for various number of blocks and obtained best parameters.

As a result, number of total layers are reduced about 20%, keeping IR same as previous value. The number of blocks are increased roughly factor 1.5, and it effect on the increase of IR. Theoretically, IR increases with increasing number of blocks, but much larger number of blocks is not so effective to IR.

In figure 2, we show two reflectivity curves of supermirrors of first InFOCμS design (left panel) and our new design(right panel). These two reflectivity curves have same IR, but total number of bilayers are 60 and 48. Our new design needs only 80% bilayers compared with InFOCμS design to achieve same IR.

Furthermore, lower limit of thickness of layers are problem to expand the energy band up to 70 keV, especially in the case the grazing angle (θ) is lager than 0.2 degree. Pt/C multilayer can not keep stable structure below 25 Å periodic length of bilayer which corresponds about $\theta = 0.2$ degree at 70 keV. Second Bragg reflection is one of solution to overcome this problem.

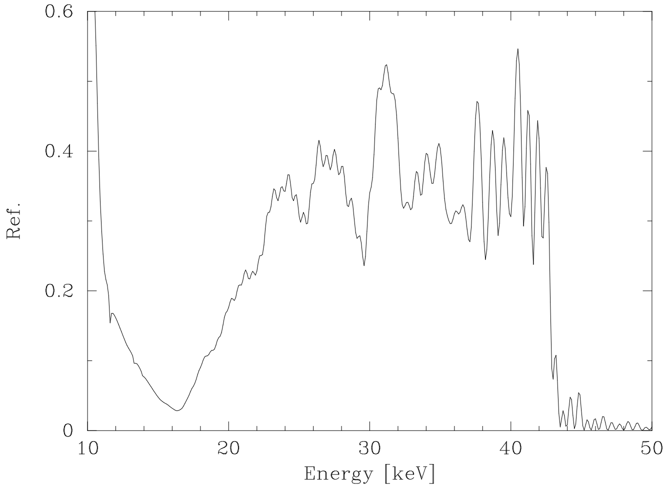

Figure 2. Calculated Reflectivity curve of first InFOCμS mirror (left panel) and new design mirror (right panel) at grazing angle of 0.295 degree. Design parameters (d[Å], N, Γ) are (59.0, 2, 0.4) (47.0, 2, 0.4) (44.0, 4, 0.4) (39.0, 8, 0.4) (35.0, 10, 0.4) (32.0, 14, 0.4) (30.0, 20, 0.4) for first InFOCμS design and (60.0, 1, 0.5) (54.5, 1, 0.4) (50.0, 1, 0.4) (46.2, 1, 0.4) (42.9, 3, 0.4) (40.0, 4, 0.4) (37.5, 5, 0.4) (35.3, 6, 0.4) (33.3, 7, 0.4) (31.6, 9, 0.5) (30.0, 10, 0.5) for new design.

The second Bragg peak reflectivity become maximum around $\Gamma \sim 0.25$. The Γ ratio is 0.3 in our design considering lower limit of Pt layer thickness.

Figure 3 shows an example of new designed supermirror at grazing angle of 0.221 degree. High reflectivity ($\sim$ 40%) is kept up to 75 keV in this figure. The design parameters are (d[Å], N, Γ) = (66.0, 2, 0.5) (56.0, 4, 0.5) (48.0, 6, 0.5) (43.6, 4, 0.4) (40.0, 6, 0.4) (36.9, 8, 0.4) (34.3, 9, 0.4) (32.0, 10, 0.4) (30.0, 11, 0.4) (28.6, 12, 0.5) (27.3, 13, 0.5) (26.1, 14, 0.5) (25.0, 15, 0.5) (24.0, 16, 0.5) (46.5, 17, 0.3) (45.3, 19, 0.3).

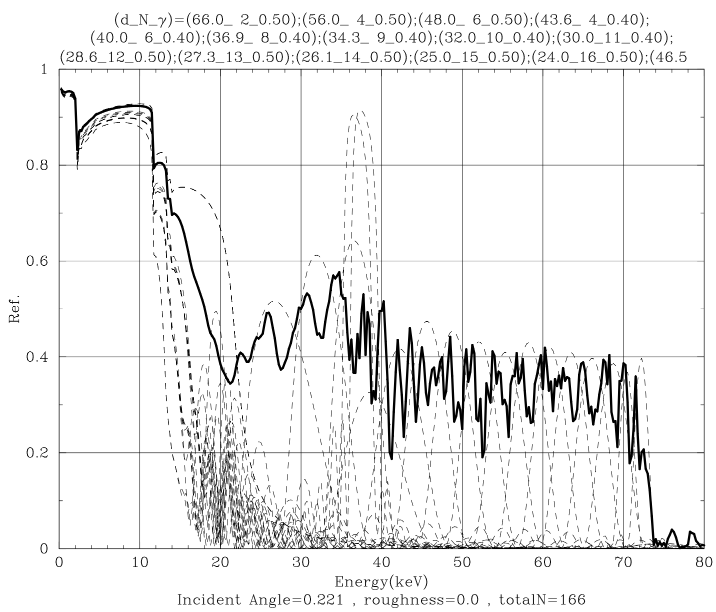

Figure 3. An example of reflectivity of new designed supermirror at grazing angle of 0.221 degree(slid line). The break line shows reflectivity curves of each blocks.

2.2. Effective area of InFOCμS telescope

We divided supermirror design for InFOCμS telescope into 13 groups,[2] and designed supermirror with new design concept. All design parameters of supermirror summarized in table 1. Figure 4 shows comparison of effective area of InFOCμS telescope between old and new designed supermirror. The telescope has 8 m focal length, 400 mm diameter and 256 pair (primary and secondary) of reflectors.

The effective area are almost same below 40 keV (I attention that old parameters are optimized for 20 – 40 keV energy range.), but new design apparently has great advantage of old one above 40 keV. Effective area of new designed supermirror at 60 keV is about 20 cm^2 (assuming 3 Å interfacial roughness), it is more than twice of that of old design.

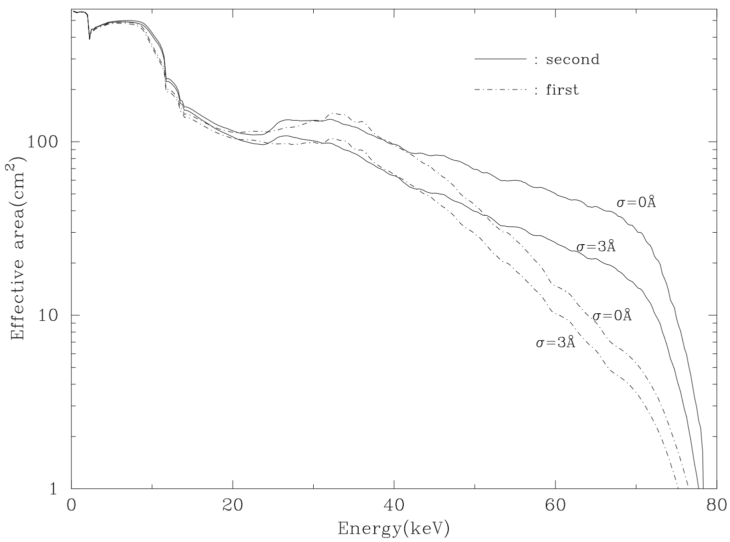

Figure 4. Calculated effective area of first InFOCμS design(dotted line) and new design (solid line) with the interfacial roughness of 0 and 3.0 Å. The parameters of telescope geometry are InFOCμS parameters.

2.3. X-ray Measurements of supermirror

An example of measurements are shown in figure 5. Because of upper limit of accelerate voltage of the X-ray tube, the X-ray energy is limited below 50 keV. Thus, we measured reflectivity of supermirror, which is designed for grazing angle of 0.211 degree, at incident angle of 0.33 degree. The model with interfacial roughness of 5 Å is well fitted the data.

In hard X-ray region, interfacial roughness is more serious problem than soft X-ray region. As shown in figure 5, reflectivity decreased with increasing X-ray energy. We have to consider effect of roughness to design the supermirror especially in hard X-ray region. We studied about interfacial roughness of Pt/C multilayers in next section.

3. INTERFACIAL ROUGHNESS OF PT/C MULTILAYER

The reflectivity of multilayer decrease with factor $\exp\left\{-\left(\frac{2\pi m\sigma}{d}\right)^2\right\}$, where σ_{DW} is interfacial roughness in Debye-Waller factor and d is periodic length (Figure 6). Interfacial roughness is very serious for short periodic length which corresponds to high energy. Especially, second Bragg peak reflectivity strongly effected by interfacial roughness. We need accurate measurements of interfacial roughness of Pt/C multilayers to design the supermirror for hard X-ray region.

In this purpose, precise theoretical model must be needed. Simple Debye-Waller model seems to be not suitable for our work. Figure 7 shows reflectivity curves of a Pt/C multilayer at Al-Kα(1.48 keV) and Cu-Kα(8.04 keV) with best fit Debye-Waller model.

1group 0.114 deg.	2group 0.125 deg.	3group 0.138 deg.	4group 0.151 deg.	5group 0.166 deg.	6group 0.183 deg.
(130,1,0.6)	(90,1,0.5)	(84,1,0.5)	(80,1,0.5)	(75,3,0.5)	(74.7,2,0.5)
(80,1,0.4)	(80,1,0.5)	(72,3,0.5)	(68.6,2,0.5)	(60,3,0.4)	(64,3,0.5)
(71,3,0.4)	(69,3,0.4)	(60,5,0.4)	(60,3,0.4)	(53.3,4,0.4)	(56,4,0.5)
(63,4,0.4)	(60,4,0.4)	(52.5,7,0.4)	(53.3,4,0.4)	(48,5,0.4)	(49.8,5,0.4)
(58,6,0.4)	(53.3,5,0.4)	(46.7,9,0.4)	(48,5,0.4)	(43.6,7,0.4)	(44.8,7,0.4)
(50,10,0.4)	(48.6,0.4)	(42,11,0.4)	(43.6,7,0.4)	(40,9,0.4)	(40.7,8,0.4)
	(40,8,0.4)	(38.2,13,0.4)	(40,9,0.4)	(36.9,11,0.4)	(37.3,10,0.4)
			(36.9,11,0.4)	(34.3,13,0.4)	(34.5,12,0.49
			(34.3,13,0.4)	(32,15,0.4)	(32,14.0.4)
					(29.9,16,0.5)
					(28,18,0.5)

7group 0.201 deg.	8group 0.221 deg.	9group 0.244 deg.	10group 0.268 deg.	11group 0.295 deg.	12group 0.324 deg.	13group 0.356 deg.
(69,2,0.5)	(66,2,0.5)	(60,2,0.5)	(56,2,0.5)	(56,2,0.5)	(57,2,0.5)	(50,2,0.5)
(61.3,2,0.5)	(56,4,0,5)	(54.5,3,0.5)	(48,3,0.5)	(48,3,0.5)	(42.9,6,0.4)	(40,3,0.4)
(55.2,3,0.5)	(48,6,0.5)	(46.2,4,0.5)	(43.6,4,0.5)	(43.6,4,0.5)	(37.5,6,0.4)	(37.5,3,0.4)
(50.2,4,0.5)	(43.6,4,0.4)	(42.9,4,0.4)	(40,6,0.4)	(40,5,0.4))	(35.3,6,0.4)	(35.3,4,0.4)
(46,5,0.4)	(40,6,0.4)	(40,5,0.4)	(36.9,8,0.4)	(36.9,6,0.4)	(33.3,7,0.4)	(33.3,7,0.4)
(42.5,6,0.4)	(36.9,8,0.4)	(37.5,5,0.4)	(34.3,9,0.4)	(34.3,7,0.4)	(31.6,8,0.4)	(31.6,8,0.4)
(39.4,7,0.4)	(34.3,9,0.4)	(35.3,6,0.4)	(32,10,0.4)	(32,8,0.4)	(30,10,0.4)	(30,9,0.4)
(36.8,8,0.4)	(32,10,0.4)	(33.3,7,0.4)	(30,11,0.4)	(30,9,0.4)	(28.6,10,0.5)	(28.6,10,0.5)
(34.5,9,0.4)	(30,11,0.4)	(31.6,9,0.4)	(28.6,12,0.5)	(28.6,10,0.5)	(27.3,11,0.5)	(27.3,11,0.5)
(32.5,10,0.4)	(28.6,12,0.5)	(30,11,0.4)	(27.3,13,0.5)	(27.3,11,0.5)	(26.1,12,0.5)	(26.1,12,0.5)
(30.7,11,0.4)	(27.3,13,0.5)	(28.6,12,0.5)	(26.1,14,0.5)	(26.1,12,0.5)	(25,13,0.5)	(25,13,0.5)
(29.1,12,0.5)	(26.1,14,0.5)	(27.3,13,0.5)	(25,15,0.5)	(25,13,0.5)	(24,14,0.5)	(24,14,0.5)
(27.6,13,0.5)	(25,15,0.5)	(26.1,14,0.5)	(24,16,0.5)	(24,14,0.5)	(46.5,15,0.3)	(46.5,15,0.3)
(26.3,14,0.5)	(24,16,0.5)	(25,15,0.5)	(46.5,17,0.3)	(46.5,15,0.3)	(45.6,16,0.3)	(45.7,16,0.3)
(25.1,15,0.5)	(46.5,17,0.3)	(24,16,0.5)	(45.6,19,0.3)	(45.6,16,0.3)	(44.7,17,0.3)	(44.9,17,0.3)
(24,16,0.5)	(45.3,19,0.3)	(46.6,17,0.3)	(44.9,20,0.3)	(44.7,17,0.3)		(44.1,18,0.3)
		(45.8,18,0.3)	(43.9,21,0.3)	(43.9,17,0.3)		(43.3,19,0.3)
		(45.2,19,0.3)		(43.2,15,0.3)		(42.5,20,0.3)
		(44.6,20,0.3)		(42.8,15,0.3)		

Table 1. Parameters of new design for InFOCμS telescope.

From the results, we can find the best hit interfacial roughness are different between two measurements. This results indicates that the Debye-Waller factor depends on the X-ray energy and simple Debye-Waller model is not suitable to simulate the reflectivity of supermirror which has wide energy band up to 70 keV.

In addition, simple Debye-Waller model don't fit the measured reflectivity curves especially around second Bragg peak. This is also problem to design supermirror using second Bragg peak.

We measured the first Bragg peak reflectivity of Pt/C multilayer at various X-ray energy from 1.5 to 8 keV using continuum emission from X-ray tube. We determined interfacial roughness by fitting the reflectivity curve with two different theoretical model, One is simple Debye-Waller model and another is Névot-Croce model.[4] In figure 8, interfacial roughness obtained by this fitting are plotted against the peak energy. Interfacial roughness obtained by Névot-Croce model are almost constant, in contrast with Debye-Waller factor which decrease with increasing energy. From the results, Névot-Croce model is more suitable for our purpose compared with Debye-Waller model.

However, Névot-Croce model also cannot represent second Bragg reflection. Thus, we introduce two different interfacial roughness for Pt/C interface (σ_{Pt}) and C/Pt interface (σ_C) suggested by Ghose and Dev.[5] They analyzed Pt/C multilayer structure by combined x-ray reflectometry and X-ray standing wave techniques. We show an example of measured reflectivity of Pt/C multilayer with 4 different theoretical models in figure 9.

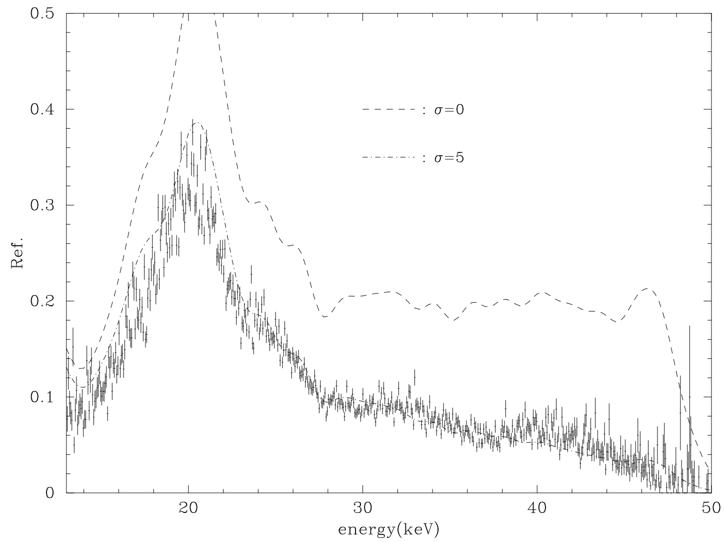

Figure 5. The measured reflectivity of new designed supermirror and theoretical curves(σ_{DW} = 0 and 5.0 Å). This supermirror is designed for incident angle of 0.221 degree, but incident angle is 0.33 degree in this measurement.

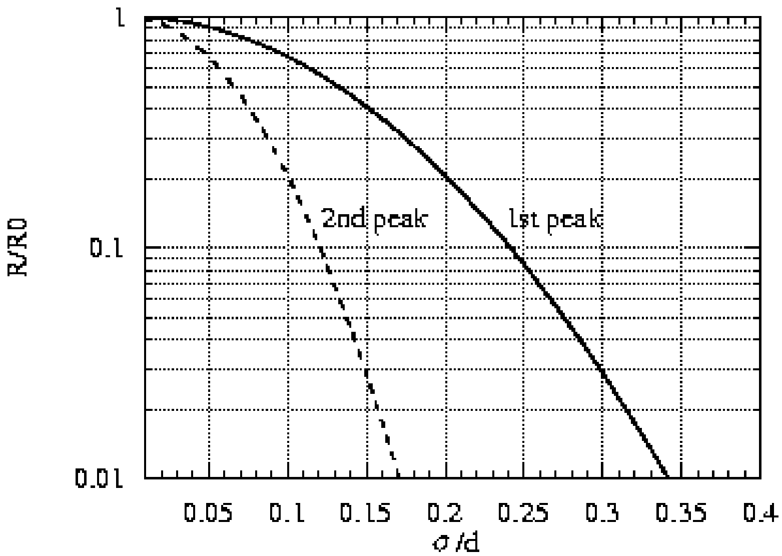

Figure 6. First and second Bragg Peak reflectivity normalized by the value in ideal case ($\sigma = 0$) against σ/d.

In this figure, simple Debye-Waller model and Névot-Croce model can't fit the measured reflectivity around the second Bragg peak. We introduce the different interfacial roughness for Pt/C (σ_{Pt}) and C/Pt (σ_C) interfaces, and obtain the best fit parameters. We found there are two sets of best-fit parameters, one is (σ_{Pt}, σ_C)= (3.0Å, 7.1Å) and another is (7.1Å, 2.8Å). These models well fit the data in figure 9. Since these two models are almost same, it is unclear which model is correct from this result. We have to continue studying.

4. CONCLUSION

In previous our supermirror design, energy band is limited up to 40 keV in InFOCμS telescope configuration (8 m focal length, 40 cm diameter). We newly designed supermirror to have energy band up to 70 keV. We optimized

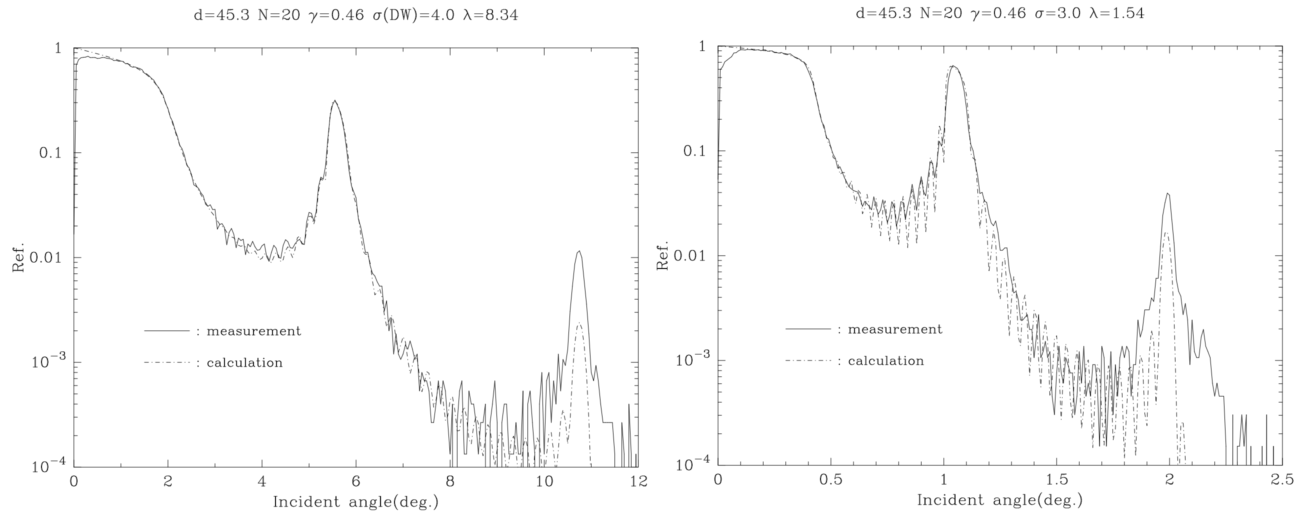

Figure 7. Measured reflectivity (solid line) at Al-Kα (left panel) and Cu-Kα (right panel) and best fit Debye-Waller model(dash-dotted line).

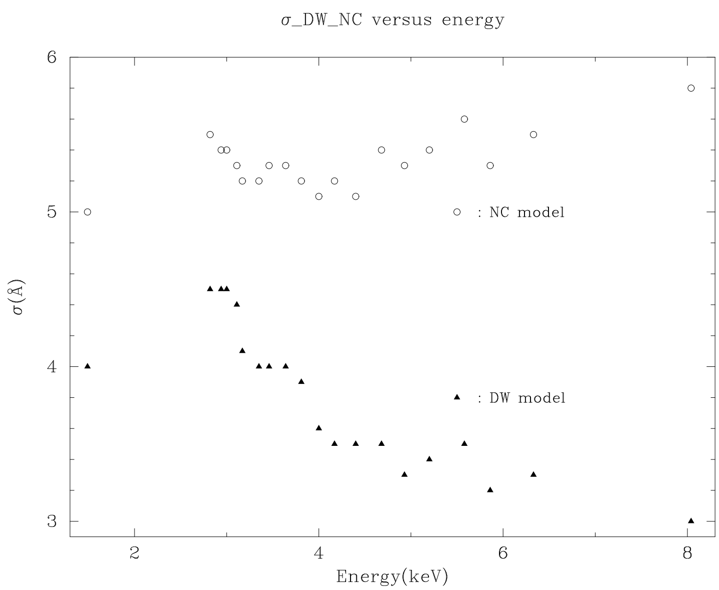

Figure 8. Interfacial roughness obtained by fitting measured reflectivity at various energy with simple Debye-Waller model (filled triangle) and Névot-Croce model (open circle).

design parameters include number of blocks and used second Bragg reflection. Our new designed supermirror make possible to obtain 20 cm^2 at 60 keV with InFOCμS telescope.

Since reflectivity of multilayer falls down by interfacial roughness especially in hard X-ray region, we have to know the interface structure of Pt/C multilayer to design the supermirror for high energy region. We introduced two different interfacial roughness for Pt/C and C/Pt interfaces to fit the measured reflectivity curves. We obtained two best fit parameters, (σ_{Pt}, σ_C) = 3.0Å, 7.1Å) and (7.1Å, 2.8Å). It is unclear which is right, thus we continue studying.

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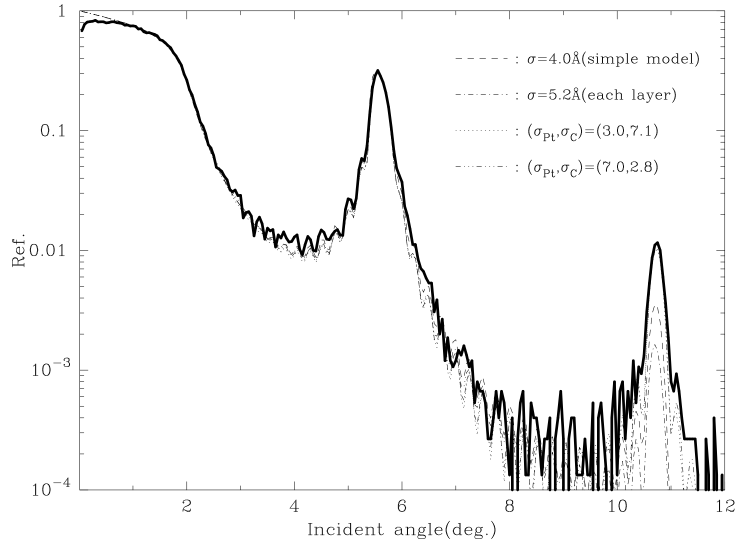

Figure 9. The measured reflectivity of multilayer (Solid line) and calculated curves of four model, simple Debye-Waller(break line), simple Névot-Croce(dashed-dot line), Névot-Croce with two different interfacial roughness (σ_{Pt}, σ_C) = (3.0Å, 7.1Å) (dotted line) and (7.0Å, 2.8Å) (dashed-dot-dot-dot line)

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