Transmission properties of the X-ray window for the SIXA spectrometer

T. Tikkanen and J. Huovelin

Observatory and Astrophysics Laboratory, P.O. Box 14 (Tähtitorninmäki), FIN-00014 University of Helsinki, Finland

Abstract

The ultrathin X-ray entrance window for the spaceborne spectrometer SIXA was characterised using synchrotron radiation. X-ray absorption fine structure near the absorption edges of the constituting elements (aluminium, carbon, oxygen and nitrogen) was measured. Large scale positional variations were also studied. In addition, the opacity of the window was tested by observing the effect of photocurrent in the detector generated by light leaked through the window.

1 Introduction

SIXA (Silicon X-Ray Array) spectrometer [1] is a focal plane instrument of the SODART X-ray telescope onboard the Spectrum-X-Gamma satellite. SIXA is an array of 19 discrete Si(Li) detector elements which collect X-rays in the range 0.5–20 keV with an energy resolution of about 200 eV at 6 keV. The elements are circular with an active diameter of 9.2 mm and they are arranged in a hexagonal pattern with a centreline distance of 12 mm. The detector crystals are kept at a temperature of about 120 K by a passive cooling system. X-rays focussed by the telescope enter the detector through an entrance window which forms a part of the cooler shield.

The X-ray entrance window for SIXA was fabricated by Metorex International Oy. A specific advantage of this window construction [2] is that a polyimide mesh is utilised to support an ultrathin polyimide membrane. Thus the active area of the window (70 mm in diameter) is shadowed by the support structure only at the lowest X-ray energies. In addition to being transparent in X-rays, the window is required to be tight against heat leakage, opaque to light from near IR to far UV and compatible with space environment. The window comprises two separate units, both coated with aluminium.
Because the window absorbs a considerable fraction of the softer X-rays, determination of its X-ray transmittance is an important part of the detector characterisation. Transmission properties can be fairly well predicted from tabulated data for the constituent elements over the energy range of SIXA except for the regions above the K absorption edges of aluminium and oxygen. Transmission in these regions is affected by X-ray absorption fine structure (XAFS) which depends on the chemical structure of the materials.

We applied synchrotron radiation from the electron storage ring BESSY to investigate the soft X-ray transmission properties. In addition to the energy dependence of the transmittance, we studied the dependence on the position on the window surface. As SIXA consists of large elements which do not have any spatial resolution, only large scale positional variations were of interest. Furthermore, we studied the opacity to light, which is required to suppress the degradation of the X-ray detection performance by photocurrent in the Si(Li) crystals.

2 X-ray window units

In the fabrication process a layer of BPDA-PPD PI-2610 polyimide was first made by spin casting a low viscosity polyamic acid resin onto a silicon wafer and baking the resin for conversion to polyimide. Next the support grid was formed of photosensitive PI-2732 polyimide which was patterned into a hexagonal honeycomb structure with a 500 µm pitch. Finally, the silicon substrate was removed and a 30 nm layer of aluminium was sputtered on both sides. Thus one window unit consists of a thin layer of polyimide, a polyimide support grid, and a layer of aluminium on each surface. The chemical composition of the polyimide is H_{10}C_{22}N_{2}O_{4} and its bulk density is about 1.4 g/cm³. The density of the thin film polyimide is about 5% higher.

A set of window units was manufactured and the best ones were selected for the flight model (FM) and the flight spare model (FSM) of SIXA. The polyimide parameters of these as well as a few other units used for calibration are given in Table 1. Nominal aluminium thickness is 60 nm for all units in the table. Native oxide layers of thickness of about 3 nm are formed on the aluminium coatings. Thicknesses of the polyimide membranes were measured with a calibrated profilometer and they varied from 237 to 275 nm. However, it was found later that a soft coating on a hard substrate, such as polyimide on silicon, is compressed during the measurement [3]. The tabulated values have been corrected to account for the error. The shadowing figures are averaged, which is sufficient because the detector elements are large compared to the mesh (the active area covers 300 hexagons).
3 X-ray transmission

3.1 Experiment

Window units 19 and 14 were used for the X-ray transmission measurements. The main purpose of the experiment was to measure the X-ray absorption fine structures which would be used to calculate the transmission properties of the FM and FSM window units. As all window units are composed of similar layers produced by the same process, they are likely to have similar XAFS.

The soft X-ray transmittance of the two window units was studied at the SX700 plane grating monochromator beamline [4] of the radiometry laboratory of the Physikalisch-Technische Bundesanstalt (PTB) which is located at the BESSY synchrotron facility. Control over the position of the beam was provided by a movable sample holder. The beam covered the area of about 5 hexagons of the honeycomb grid structure with its full width at tenth maximum (1.5 mm horizontal and 0.8 mm vertical). Consequently, the fraction $S$ of the beam shaded by the grid was affected by the precise positioning of the beam, and the values of $S$ during separate measurements varied about the average shadowing given in Table 1.

Transmittance as a function of energy was obtained by scanning photon energies from 60 eV to 1800 eV with steps varying from 0.1 eV to 10 eV, depending on the expected detailed features in the transmittance curve. The beam was positioned at the centre. The results are plotted in Fig. 1. The similarity of the two window units throughout the measured range, including the absorption edges, suggests that XAFS is indeed identical for all SIXA window units. The near-edge structures of the polyimide constituents resemble those reported for other windows manufactured by Metorex [5], while XAFS of aluminium is different which is natural because there are no AlN layers in our windows.

Dependence on position was studied by performing line scans in the $x$ direction across the window surface at a few settings of the $y$ coordinate. This was repeated at four discrete energies slightly below the K edges of the elements C, N, O and Al. The scan step was 2 mm. Transmission along the scanned lines is shown in Fig. 2. It was originally measured in arbitrary units and later scaled to the transmittances of the energy scans by fitting a second order polynomial to the data from the scan along $y = 0$ and setting the value of the polynomial in the centre (its $x$ coordinate being that obtained in the analysis in section 3.3) equal to the energy scan transmittance at the respective energy. The transmittance grows with the radial distance from the centre of the window.
3.2 Analysis of energy scans

The model of the transmittance of a window unit is

\[ T = \exp \left( -\sum_{j=1}^{3} \left( \frac{\mu}{\rho} \right) \rho_j t_j \right) \left\{ 1 - S + S \exp \left( -\left( \frac{\mu}{\rho} \right)_4 \rho_4 t_4 \right) \right\}, \]  

(1)

where the sum goes over the three thin film materials (aluminium, oxide and polyimide) and index 4 refers to the grid. This equation, with the experimental data for \( T \), was applied to calculate the mass attenuation coefficients \((\mu/\rho)\) wherein the fine structures are incorporated. The transmittance of the FM window units was then calculated using the model and the values of Table 1 for \( S \) and the layer thicknesses \( t_j \).

The experimental data is compared to the model (Eq. 1 with absorption data from ref. [6] and window parameters from Table 1) in Fig. 3a. The difference between the residuals of the two window units is plotted in Fig. 3b. The residuals exhibit considerable structure above each absorption edge with very similar shape for the two units. Most of the residuals can therefore be attributed to XAFS which can extend several hundred eV above the K edges. The residuals in the range 600–1550 eV are due to the deviation of the actual beam shadowing \( S \) during the energy scans from the average values in Table 1. Measurement errors and errors in the \( t_j \) data of Table 1 are also partly responsible for the residuals. Because the contribution to the residuals from the errors in the \( t_j \) is smaller than the features arising from XAFS, more accurate values for the \( t_j \) than those in Table 1 can not be abstracted from the data. Moreover, derivation of layer thicknesses from transmission data yields poor results in general, because the dependence of \( \mu/\rho \) on the X-ray energy is very similar for all materials outside the XAFS regions. In consequence, when fitting a function of the form of Eq. 1 to the data, the thicknesses are strongly correlated and their best-fit values have very large error ranges.

However, the difference between the residual curves of the two units can be attributed to relative errors in the \( t_j \) between the units. We reduced the relative errors with a set of relative corrections \( \Delta t_j \), where the corrected values of the layer thicknesses \( t_{j,19} \) and \( t_{j,14} \) of the two units are \( t_{j,19} + \Delta t_j \) and \( t_{j,14} - \Delta t_j \). First we minimised the \( L^1 \) norm of the difference in the range 60–530 eV with the beam shadowing and the corrections of the thin film thicknesses as free parameters. This energy region was chosen because it contains structures which bear relationships with these parameters, whereas the intermediate region 530–1560 eV was excluded because in this region measurement errors are greater than the errors attributable to the \( t_j \) (see e.g. the abrupt changes in the difference curve at 690 eV and 900 eV, and note that the absolute deviation of the data from the model is much smaller at the lower energies where the transmitt-
The result was $S_{19} = 0.162$ and $S_{14} = 0.160$, $\Delta t_{\text{Al}} = 0.27$ nm (for the original aluminium thickness before oxidation), $\Delta t_{\text{pi}} = 0.96$ nm, and $\Delta t_{\text{ox}} = -0.56$ nm. Next the correction of the grid thicknesses was sought that minimised the $L^1$ norm of the difference in the range 1560–1800 eV, yielding $-0.26$ µm. The residuals with the new window parameters are plotted in Fig. 3c and their difference in Fig. 3d.

The $\mu/\rho$ of aluminium was solved from Eq. 1 for both units, and the result is shown in Fig. 4 for the two XAFS regions above the K and L absorption edges. The fine structures are typical of a solid, consisting of a multiple scattering peak in the narrow XANES (X-ray absorption near-edge structure) region just above the absorption edge and oscillations from single scattering in the wider EXAFS (extended XAFS) region. Small differences between the two units are seen in the K-edge XAFS, and EXAFS clearly continues beyond 1800 eV. The results for carbon, nitrogen and oxygen are presented in Fig. 5. The difference in the oxide thickness between the two units may be responsible for the apparent difference in the cross section of oxygen (the oxide contributes 12% to XAFS in unit 19 and 14% in unit 14).

The remaining differences between the transmission data and the results calculated from Eq. 1 using the extracted $\mu/\rho$ data are plotted in Fig. 6. Data from the two units were averaged and interpolated in the appropriate energy ranges (carbon in 283–400 eV, nitrogen in 400–530 eV, oxygen in 530–605 eV and aluminium in 73–282 eV and above 1554 eV) to yield the XAFS data for the modelling of the flight model window. The K-edge EXAFS of aluminium was extrapolated into 1800–2000 eV with a third-order polynomial. The result is shown in Fig. 7. The resulting transmittance of the FM window is plotted in Fig. 8.

### 3.3 Analysis of line scans

The line scans were analysed by solving a group of four nonlinear equations, constructed using Eq. 1 and the data at the four energies, at each beam position. The four variables were $S$ and the layer thicknesses, excluding the oxide which is the least absorbing. The results for the total aluminium thickness and for the polyimide membrane thickness are plotted in Fig. 9. The overall radial variation is clearly explained by the total aluminium thickness which decreases with the radial distance owing to the nature of the sputtering process. Variations in the polyimide thickness do not exhibit any radial pattern.

As suggested by the curves in Fig. 9, $t_{\text{Al}}$ can be modelled to good accuracy
with the functional form

\[ t_{\text{Al}}(r) = \left[ 1 - \left( \frac{r}{r_0} \right)^2 \right] t_{\text{Al}}(0). \quad (2) \]

This equation was fitted to the data with \( r_0 \), \( t_{\text{Al}}(0) \) and the coordinates of the centre as free parameters. The best-fit \( r_0 \) was 77.74 mm for unit 19 and 77.56 mm for unit 14. The values for \( t_{\text{Al}}(0) \) were 60.43 nm (unit 19) and 59.61 nm (unit 14), in good accord with the \( \Delta t_{\text{Al}} \) of the energy scan analysis.

3.4 Discussion

The significance of the radial variation is modified by the point spread function PSF of the SODART telescope. For an on-axis point source and ideal alignment of SIXA with SODART, PSF decreases rapidly with small values of \( r \) and more slowly when \( r \) increases, and the estimated fraction of photons encircled in the central element is about 0.6 depending on the energy [7]. The count rate at energy \( E \) in a certain detector element is

\[ C(E) = \int \Phi(h\nu) A_{\text{eff}}(h\nu) \left[ \int \text{PSF}(h\nu, \vec{r}) \epsilon(h\nu, r) \, da \right] P(h\nu, E) h \, d\nu, \quad (3) \]

where \( \Phi \) is the incident photon flux, \( A_{\text{eff}} \) is the effective area of SODART, the surface integration is over the active area of the element and \( \epsilon \) is the detection efficiency and \( P \) the response function of the element. Assuming perfect homogeneity of the crystal, \( \epsilon(h\nu, r) \) equals \( T(h\nu, r) \) times a function of \( h\nu \).

\( T(r) \) with the radial dependence given by Eq. 2 varies very slowly near the centre of the window. The surface integral over the central element lies between the two limits obtained by letting PSF approach a delta function and letting PSF be constant:

\[ T(h\nu, 0) \int \text{PSF} \, da \geq \int \text{PSF}(h\nu, \vec{r}) T(h\nu, r) \, da \geq \langle T \rangle \int \text{PSF} \, da, \quad (4) \]

where the average of \( T \) over the active area of the central element (radius \( R \)) is given by

\[ \langle T \rangle = \frac{\int T \, da}{\int da} = T(h\nu, 0) \frac{e^{FR^2} - 1}{FR^2}, \quad (5) \]

where \( F(h\nu) = r_0^{-2} t_{\text{Al}}(0) \mu_{\text{Al}}(h\nu) \). The relative difference of the two limits is below \( 5 \times 10^{-4} \) in the energy range of SIXA; thus the first limit is a very good
approximation for an on-axis point source.

For the other elements, the integration yields

\[
\langle T \rangle = \frac{T(h\nu, 0)}{FR^2} \left[ -1 + e^{FD^2} \sum_{k=0}^{\infty} \frac{(FD)^{2k}}{(k!)^2} C_k \right],
\]

(6)

where \( D \) is the distance between the centre of the element and the centre of the window, and

\[
C_k = \begin{cases} 
e^{FR^2} & \text{if } k = 0, \\ R^{2k} e^{FR^2} - \frac{k}{P} C_{k-1} & \text{if } k > 0. \end{cases}
\]

(7)

The results calculated for the elements in the SIXA array are shown in Fig. 10. The differences between the elements are at most 1% in the energy range of SIXA. When weighted with PSF as in the surface integral in Eq. 3, the averages become even closer to \( T(h\nu, 0) \), because \( T \) varies more slowly than PSF even for the outer elements. In any case, the smallness of the differences between the elements shows that Eq. 2 with \( r_0 = 77.7 \) mm obtained by fitting to the experimental data from units 19 and 14 is a more than sufficiently accurate model of the positional variation of \( T \) across the SIXA window.

The effect of XAFS on actual observations was studied by comparing data from a simulated observation to a model which neglects XAFS in the window materials. The simulated target was the Crab Nebula which was assumed to be a point source with a simple power-law spectrum (\( \Phi \propto E^{-2.2} \)) modified by interstellar absorption (\( N_H = 3 \times 10^{21} \) cm\(^{-2} \)). This kind of spectrum with no emission or absorption line features is useful for revealing spurious lines arising from instrumental effects not properly accounted for in the response matrix. Both the simulated data and the model were calculated for the central element of SIXA from Eq. 3, where the surface integral in Eq. 4 was approximated by \( 0.6 \times T(h\nu, 0) \) and \( A_{\text{eff}} \) was obtained from measurements with SODART telescope models [8]. \( T \) shown in Fig. 8 was used for the simulated data, while \( T \) for the model was calculated from Eq. 1 with the data from ref. [6]. The model by Scholze and Ulm [9] was used for \( P \) and the rest of \( \epsilon \) with experimental XAFS data for the K edge of silicon [10]. Poisson noise, which results from the stochastic nature of the X-ray emission and detection processes, was added to the data assuming an observation time of \( 5 \times 10^3 \) s. The result of the simulation is presented in Fig. 11a. Spurious line features can hardly be distinguished from Poisson noise, but if the noise was omitted from the calculation, it is observed that there is an emission line feature at 1.8 keV (equivalent width 1.5 eV, maximum residual 0.5%), an absorption line at 0.6 keV (equivalent width 0.4 eV, maximum residual 0.3%) and a continuous feature below the energy range of SIXA.
The smallness of the overall effect of XAFS and the similarity of XAFS for the two window units suggest that the derived XAFS is accurate enough for the flight model. The main advantage of characterising the actual FM window would have been the reduction of the uncertainty propagating from the uncertainties in the layer thicknesses and polyimide densities. The uncertainty of the transmittance including the propagated uncertainties of the layer thicknesses is shown in Fig. 8. Uncertainties given in Table 1 were used for the polyimide membranes and grids. The mean deviation of the nominal value from the values of $t_{Al}(0)$ derived from the line scans (section 3.3) was taken to be the standard deviation of $t_{Al}$, while $|\Delta t_{ox}|$ (section 3.2) was used for $t_{ox}$. The uncertainties of the derived XAFS, based on the difference in the data from the two window units, were negligible. Uncertainties of $S$, the densities or the cross sections from ref. [6] may have small contributions to the real uncertainty.

The significance of the uncertainty is illustrated in Fig. 11b with a simulated case that the actual transmittance of the FM window is greater than modelled by the estimated uncertainty. The residual would then be 2.2% at 0.5 keV and decrease towards higher energies, falling below 1% at 0.8 keV.

4 Light transmission

4.1 Sensitivity of SIXA to light

The photocurrent generated in a detector element is

$$I_{ph} = qA \int \Phi(h\nu)T(h\nu)\eta(h\nu)h\,d\nu,$$  

(8)

where $\Phi$ is the incident flux, $A$ is the active area of the element and $\eta(h\nu)$ is the quantum efficiency. Fluctuations in the total current $I_{ph} + I_l$ (where $I_l$ is the leakage current) are a source of parallel current noise. Expressed in terms of the number of carrier pairs, the magnitude of the noise is

$$\sigma_T^2 = \sqrt{\frac{N_S^2}{q}(I_{ph} + I_l)},$$  

(9)
where $N_s^2$ is a noise index which depends on the signal shaping [11] (about 5 $\mu$s for SIXA). The FWHM energy resolution is

$$\Delta E = \sqrt{(\Delta E_0)^2 + \left(\frac{2.35 W}{q} N_s^2\right)^2 I_{ph}},$$

(10)

where $\Delta E_0$ is the FWHM with no photocurrent and $W$ is the mean pair-creation energy.

For example, the energy flux from a star of magnitude 5 is $2.0 \times 10^5$ eV/(cm$^2$s). With an average photon energy of 2 eV, the flux on the focal plane of SODART is then $1.1 \times 10^8$ cm$^{-2}$s$^{-1}$. If all photons were absorbed in one element with 100% efficiency, the photocurrent without a window would be 12 pA and the resolution would be degraded by 60 eV (from 200 eV). If $I_{ph}$ was reduced by two magnitudes with a 1% transmitting window, the resolution would increase by 0.7 eV only.

Silicon detectors can have very high quantum efficiencies for visible light up to a cutoff wavelength which corresponds to the energy gap and is about 1.06 $\mu$m at the operating temperature of SIXA. For SIXA crystals, $\eta(h\nu)$ depends mainly on the reflection and absorption properties of the cathode coating (gold–palladium alloy) on the detector surface. In addition, the incident flux is amplified by multiple reflections between the cathode and the window. We estimated $\eta(h\nu)$ with the help of a program which was written to compute transmission properties of thin windows [3] as a part of the project Development of thin optical filters and windows at XUV wavelengths which belongs to the General Support Technology Program of the European Space Agency. The detector structure was approximated with a multilayer formed by 30 nm of gold, 3 mm of silicon and 250 nm of aluminium. The estimate of $\eta$ obtained by subtracting the absorptivity computed for a single gold layer from the absorptivity of the multilayer is presented in Fig. 12, together with $\eta$ multiplied by the amplification due to multiple reflections. The reflectances of the multilayer and of the window are also shown.

4.2 Experimental

The light transmission of SIXA window unit 16 was measured in the context of the mentioned ESA project. The measured data are plotted in Fig. 13a together with transmittance curves computed with the associated program. Interference peaks in the transmittance computed using data of Table 1 for unit 16 (dotted curve) are shifted by 100–200 nm towards shorter wavelengths compared to the measured data. Interference wavelengths depend on the thickness of the polyimide membrane, but the shift does not necessarily imply a
large error in the thickness measurement. Instead, the optical constants of
the thin film polyimide are probably different from those incorporated in the
program because the material is denser than the bulk material and the poly-
imide is also of another type. With a 20% greater thickness for the polyimide,
the computed curves come closer to the data (dashed curves). The computed
transmittance of the FM window is shown in Fig. 13b.

The transmission measurement and calculations suggest that the window is
more than sufficiently opaque. As the worst case, Sirius could degrade the
energy resolution of an outer detector element by 0.01 eV, provided that its
emission was concentrated in the region of maximum transmittance at 400–
410 nm (where it actually has a strong Hδ absorption line) and that all photons
were absorbed in one element with 100% efficiency. In the near-IR region
the maximum transmittance between the interference wavelengths of the two
units is slightly higher. However, there are no astronomical sources outside
the solar system with so high apparent magnitude in the near IR that they
could degrade the energy resolution of SIXA.

The effect of photocurrent generated by light leakage through the window was
also tested by comparing the resolution in the dark to the resolution when
the detector was illuminated with visible light. The detector used was a Si(Li)
crystal produced for SIXA, connected to a preamplifier of a type similar to
the flight electronics. The crystal was operated in a cryostat with a mylar
window, and a piece cut from the SIXA window unit 16 was placed in front of
the cryostat. The crystal was cooled with liquid nitrogen and heated to 122 K
in order to generate some dark current. Filtered light from a tungsten lamp
was applied to generate photocurrent. The emission in the wavelength range
250–800 nm was measured with a photodetector and it was of the order of
$10^{-9}$ W cm$^{-2}$ nm$^{-1}$ for the longer wavelengths at a distance of 1.2 m.

When X-rays from a $^{55}$Fe source were detected, the FWHM of the Mn K$_\alpha$
peak was 187 eV in the dark. The interval between resets of the preamplifier
was 12 s when the detector was not exposed to either light or X-rays. With
the lamp switched on, it varied from 1.1 s to 30 ms with different filters used
in front of the lamp. The reset interval is directly proportional to $I_{ph} + I_i$,
and fitting Eqs. 8 and 9 to the data yielded $I_i = 0.1$ pA. The FWHM varied
from 194 to 380 eV with the same filters. When another piece of the window
unit 16 was added, no photocurrent was observed. The incident spectra in the
range 800–1060 nm were known poorly, but the measured photocurrents were
of expected magnitude. The overall effective quantum efficiency for red and
near-IR light was roughly 30%.
5 Conclusions

The X-ray entrance window for SIXA was characterised using synchrotron radiation and two window units of a type similar to the flight model. The contribution of the X-ray window to the system response of the SIXA spectrometer was adequately well determined. It can be accounted for in the analysis of astronomical data by using the energy and spatial dependence of the window transmittance presented in this paper.

X-ray absorption fine structures of the constituting elements were extracted from the data obtained with two non-flight window units. The transmittance of the flight model window was calculated using the derived cross sections in the regions where XAFS appears.

Spatial variation of the transmittance was observed to have a radial pattern which is attributed to a radial variation of the thickness of aluminium. The thickness could be closely modelled as a parabolic function of radial distance from the window centre. The variation is less than 1% in the energy range of SIXA.

Transmittance of visible and infrared light was studied and it was found that transmitted light from the observed targets will have no observable effect on the X-ray energy resolution.

Acknowledgements

We thank T. Lederer of the PTB for performing the SX700 measurements. V.-P. Viitanen of Metorex International Oy is acknowledged for providing the windows and answers to several questions about them. We thank also C. Budtz-Jørgensen of the Danish Space Research Institute (DSRI) for the beam-time and help at the SX700, H. Harvela of Metorex for the light transmission data and M.-A. Jantunen of Metorex and E. Tetri of the Helsinki University of Technology for collaboration with the photocurrent test.

References

[1] O. Vilhu, J. Huovelin, T. Tikkanen, P. Hakala, P. Muhli, V.J. Kämäräinen, H. Sipilä, I. Taylor, J. Pohjonen, H. Päiväke, J. Toivanen, R. Sunyaev, A. Kuznetsov and A. Abrosimov, Proc. SPIE 2279 (1994) 532.
[2] V.-P. Viitanen, S.A. Nenonen, P. Partanen, H. Sipilä and R. Mutikainen, Proc. SPIE 1743 (1992) 245.

[3] H. Harvela, Modeling of optical properties of filters for spaceborne X-ray and VUV instruments, Master’s thesis, Helsinki University of Technology, Department of Electrical Engineering, Espoo 1995, 81 p.

[4] F. Scholze, M. Krumrey, P. Müller and D. Fuchs, Rev. Sci. Instrum. 65 (1994) 3229.

[5] M. Bavdaz, A. Peacock, A.N. Parmar, D. Fuchs, P. Müller, F. Scholze, G. Ulm and A.C. Wright, Nucl. Instr. and Meth. A 345 (1994) 549.

[6] B.L. Henke, E.M. Gullikson and J.C. Davis, Atomic Data and Nuclear Data Tables 54 (1993) 181.

[7] F.E. Christensen, A. Hornstrup, P. Frederiksen, S. Abdali, P. Grundsøe, J. Polny, N.J. Westergaard, H.U. Nørgaard-Nielsen, H.W. Schnopper, C. Hall and R. Lewis, Proc. SPIE 2515 (1995) 458.

[8] N.J. Westergaard, private communication.

[9] F. Scholze and G. Ulm, Nucl. Instr. and Meth. A 339 (1994) 49.

[10] A. Owens, S. Bayliss, G. Fraser and S.J. Gurman, report JET-X(94) UL-241 WP:2220, University of Leicester, 1994.

[11] F.S. Goulding and D.A. Landis, IEEE Trans. Nucl. Sci. NS-29 (1982) 1125.
Fig. 1. Measured transmission at the centres of window units 19 (solid curve) and 14 (dotted curve). The insets show the absorption edges enlarged.

Fig. 2. Measured transmission at different positions on the surfaces of window units 19 and 14 at four different X-ray energies. The $y$ coordinate is 0 (solid curves), 10 (plus signs) or -10 mm (squares).

Fig. 3. Adjustment of window unit parameters by the comparison of transmission data with the model: residuals (data/model - 1) with (a) parameters from Table 1 and (c) adjusted parameters for the window units 19 (solid curves) and 14 (dashed curves), (b) the difference between the two residual curves in (a), and (d) the difference between the two residual curves in (c).

Fig. 4. Cross section of aluminium above the K and L absorption edges, extracted from the transmission data of window units 19 (solid curves) and 14 (dashed curves). The dotted curves show the data from ref. [6].

Fig. 5. Cross sections of carbon, nitrogen and oxygen extracted from the transmission data of window units 19 (solid curves) and 14 (dashed curves). The dotted curves show the data from ref. [6].

Fig. 6. Residuals between the measured and modelled transmittance for window units 19 (solid curve) and 14 (dashed curve).

Fig. 7. Modelled linear attenuation coefficient of aluminium derived from the transmission data between 1554–1800 eV and extrapolated into 1800–2000 eV. The dotted curve shows the data from ref. [6].

Fig. 8. Calculated transmittance of the flight model window at its centre. The upper curves are for units 6 and 17 and the lowest curve is the total transmittance. The insets show the uncertainty (standard deviation) of the transmittance calculated in section 3.4.

Fig. 9. Variation of the total aluminium thickness $t_{Al}$ and the thickness $t_{pi}$ of the polyimide membrane across the window surfaces. The residuals of $t_{Al}$ after fitting Eq. 2 are plotted in the central panels. The $y$ coordinate is 0 (solid curves), 10 (plus signs) or -10 mm (squares).

Fig. 10. Transmittance of the flight model window for the elements in the SIXA array at different distances from the window centre. The curves depict the difference of the transmittance averaged over the active area of an element from the transmittance at the centre, and they apply (from top to bottom) to the outer 6 elements of the outer ring, inner 6 elements of the outer ring, and 6 inner ring elements, respectively.
Fig. 11. Illustrating the accuracy of the window characterisation with simulated observations of the Crab Nebula by SIXA: (a) simulated data compared to an absorbed power-law model spectrum folded through an instrumental response matrix where X-ray absorption fine structures in the window transmittance are neglected, and (b) assuming that the modelled transmittance of the window has an error equal to the estimated standard deviation (Fig. 8). In the upper panels the data are indicated by plus signs and the model by solid curves. In the lower panels the plus signs indicate the residuals between the data and the model, while the solid curves represent the residuals with the data without Poisson noise.

Fig. 12. Estimates of the quantum efficiency $\eta$ of SIXA detector elements, the reflectances of the detector ($R_{\text{det}}$) and the window ($R_{\text{win}}$, computed for the centre of unit 6), and an "effective" quantum efficiency $\eta^*$ which incorporates the amplification of the incident flux by multiple reflections between the detector and the window.

Fig. 13. Light transmittance of (a) window unit 16, measured (solid curves) and calculated (dashed and dotted curves), and (b) flight model window (solid curves) and its constituting units 6 (dashed curves) and 17 (dotted curves), calculated. The lower curves apply to the window centre and the upper curves to the radial distance of 2.86 cm where the active detector area ends. In order to compensate for the apparent errors in the optical constants of polyimide, 20% greater thicknesses were used for the polyimide membranes in the computation of the dashed curves in (a) and all the curves in (b).

Table 1
Polyimide membrane and grid parameters of X-ray window units fabricated for SIXA. Units 6 and 17 have been chosen for the flight model, units 1 and 9 for the flight spare model and the others were used for calibration. The given $2\sigma$ uncertainties of the polyimide membrane thickness are uncertainties of the profilometer measurement multiplied by the correction which was applied to account for a systematic measurement error.

| Unit | Membrane | Grid |
|------|-----------|------|
|      | thickness | thickness | width | shadowing |
| 6    | 283 ± 17 nm | 17–18 $\mu$m | 42 $\mu$m | 16.1% |
| 17   | 308 ± 23 nm | 20–22 $\mu$m | 46 $\mu$m | 17.6% |
| 1    | 283 ± 17 nm | 19–20 $\mu$m | 44 $\mu$m | 16.8% |
| 9    | 268 ± 13 nm | 19–20 $\mu$m | 44 $\mu$m | 16.8% |
| 19   | 308 ± 23 nm | 19–21 $\mu$m | 46 $\mu$m | 17.6% |
| 14   | 308 ± 23 nm | 24–26 $\mu$m | 44 $\mu$m | 16.8% |
| 16   | 308 ± 23 nm | 20–21 $\mu$m | 44 $\mu$m | 16.8% |