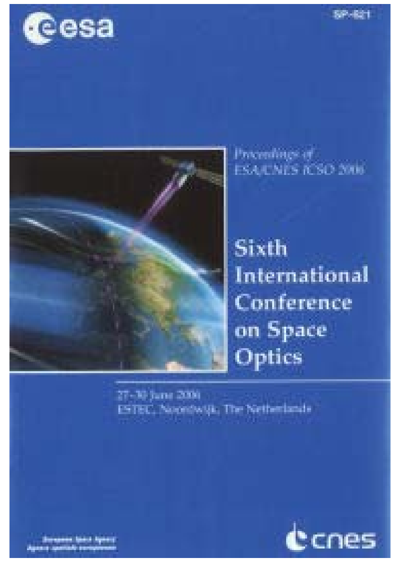
International Conference on Space Optics—ICSO 2006

Noordwijk, Netherlands

27–30 June 2006

Edited by Errico Armandillo, Josiane Costeraste, and Nikos Karafolas



On the development status of high performance silicon pore optics for future x-ray telescopes

Stefan Kraft, M. Collon, R. Günther, R. Partapsing, et al.

International Conference on Space Optics — ICSO 2006, edited by Errico Armandillo, Josiane Costeraste, Nikos Karafolas, Proc. of SPIE Vol. 10567, 105671V · © 2006 ESA and CNES
CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2308117

ON THE DEVELOPMENT STATUS OF HIGH PERFORMANCE SILICON PORE OPTICS FOR FUTURE X-RAY TELESCOPES

Stefan Kraft, M. Collon, R. Günther, R. Partapsing, M. Beijersbergen[(1)], M. Bavdaz, D. Lumb, A. Peacock [(2)], K. Wallace[(3)]

[(1)] *cosine Research BV, Niels Bohrweg 11, 2333 CA Leiden, The Netherlands, Email: stefan.kraft@cosine.nl*
[(2)] *ESA, ESTEC, Science Payload and Advanced Concepts Office, Keplerlaan 1, PO Box 299, 2200 AG Noordwijk ZH, The Netherlands, Email: marcos.bavdaz@esa.int*
[(3)] *ESA, ESTEC, Mechatronics and Optics, Keplerlaan 1, PO Box 299, 2200 AG Noordwijk ZH, The Netherlands, Email: kotska.wallace@esa.int*

ABSTRACT

Silicon pore optics have been proposed earlier [1] as modular optical X-ray units in large Wolter-I telescopes [2] that would match effective area and resolution requirements imposed by missions such as XEUS [3][4]. Since then the optics have been developed further and the feasibility of the production of high-performance pore optics has been demonstrated [5]. Optimisation of both the production and the assembly process allowed the generation of optics with larger areas with improved imaging performance. Silicon pore optics can now be manufactured with properties required for future X-ray telescopes. A suitable design that allows the implementation of pore optics into X-ray Optical Units in Wolter-I configuration was recently derived including an appropriate telescope mounting structure with interfaces for the individual components. The development status, the achieved performance and the requirements regarding future mirror production, optics assembly and related metrology for its characterisation are presented.

1. INTRODUCTION

Presently flying X-ray telescopes such as XMM-Newton [6] and Chandra [7] are based on optics consisting of closed shells, which need to be generated by replication from cylindrical mandrels or through direct polishing of machined shells. The imaging performances of those telescopes have reached point spread functions down to 1” through very good figure and finish. Production of such high quality optics is very cost intensive and at the limit of current technologies. It is not astonishing that the tuning of the production process towards the 1” level has in the past taken more than one decade. A modular production process for larger optics areas, as it is now under development, faces similar challenges since it needs to provide high performance optics at much larger areas that can be produced fast, cheap and with a reliable performance at a cost envelop similar to that of previous missions. The program now concentrates on building the first X-ray Optical Units (XOUs), each consisting of two High Performance Pore Optics (HPOs) that are then co-aligned as a tandem to form a conically approximated Wolter-I optics. Several of such XOUs that shall be integrated into a larger structure (see contribution 301772 – this conference) are in production. This shall demonstrate the feasibility and assess the technology readiness level. We present the process chain and the facilities required for building HPOs, integrating, aligning, and fixing them into XOUs. Concepts for building the necessary structures and metrology have been derived and the first XOU has been assembled. In order to understand further development we also address the needs for a large scale production

2. PRODUCTION OF HIGH PERFORMANCE PORE OPTICS

2.1 Production and preprocessing of the base material

Silicon is an excellent material for X-ray mirrors, because it is commercial available as extremely flat plates or wafers. Although any wafer can be used for this application, for this production of HPOs we use 12” wafers that are produced by Wacker Siltronics. Those provide the best available performance and a large area so that several plates of different shape can be obtained from a single wafer. Larger wafers also yield better polishing results since the larger areas involve less edge area problems. The quality of the wafer surface is good enough so that no post-processing is required for the X-ray mirrors. It is intended not to alter this industrial production process since otherwise huge cost impacts must be expected. Fortunately, the standard wafer thickness matches the requirements for the pore optics so that no special production runs need to be implemented. Presently 11 mirror plates, with dimensions of 66×66 mm^2, can be extracted from one wafer. An XOU of the telescope is expected to consist of about 2×100 plates. It is expected that about 35.000 wafers are required to

Proc. ‘6th Internat. Conf. on Space Optics’, ESTEC, Noordwijk, The Netherlands, 27-30 June 2006 (ESA SP-621, June 2006)

assemble the complete telescope. Before the plates for the assembly are structured, the wafers are coated to protect the surface. This process is performed in the wafer handling facility of Infineon in Dresden. The entire process is carried out in ultra clean environment where only wafer coming directly from Wacker are treated. We note that this process is completely commercial of the shelf and does not need further interaction or optimization.

2.2 Plate structuring

The previously mentioned wafers are shipped to Infineon in Munich, where the plates are extracted from the wafers. Presently each wafer, attached to a foil carrier, is individually diced by a diamond coated saw. After the wafers have been cut into smaller squares, the plates need to be structured to generate the ribs of the plates. This is done by cutting grooves into the plate and subsequently etching those grooves or channels so that tensions are removed. This process needs careful tuning to avoid damage or artifacts. After the structuring, the protective coating needs to be removed and the plates have to be cleaned and shipped. Metallic coating of the plates might further be advantageous to enhance the reflectivity of the mirrors. However there is a certain freedom in the choice when and how to apply the coating as this depends eventually on the coating method. One complication in the plate production is the introduction of a wedge, approximating the required conical shape of the HPOs.

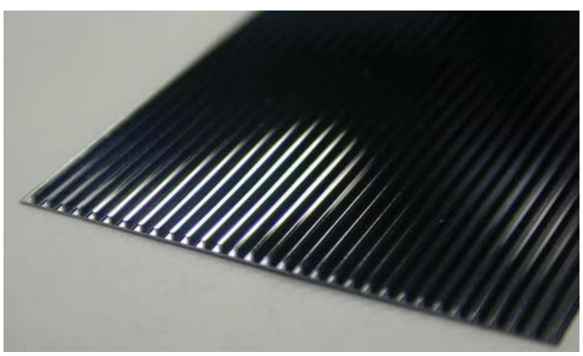


Fig. 1. A structured Si wafer that forms a ribbed mirror plate and the base material for the X-ray optics.

Obviously this process that is now implemented for 2 m radius of curvature needs to be adapted so as to obtain several different shapes suitable for different radii, since for the XEUS optics, radii of curvature between 0.63 and ~2.12 m are required. In a baseline design of the XEUS optics with 35 m focal length, plate lengths between ~30 mm and ~120 mm are required to match the conical optics design, having a resolution of ~2". This requires the production of a total mirror area of ~1.500 m^2. For this area a total number of about 250.000 plates need to be produced. An impressive number indeed that makes clear that an industrial process is required for the production of all telescope mirrors. To achieve realistic time scales, the number of plates expected to be produced per day is about 100, which means also that the future production will have to produce within one day the amount that is presently produced within half a year in the R&D production.

2.3 HPO and XOU assembly

The core technology and most challenging part of the optics production is the assembly of the plates into a HPO – compare Fig. 2. Success of the assembly process is dependant very much on the cleanliness of the plates and the assembly equipment. Experience shows, that the assembly would be largely facilitated if the plates would be delivered clean and preferably hydrophilic. Clean means here that the plates should essentially be particle and dust free. In practice both requirements are difficult to achieve on small scale in the laboratory. The remainder of the assembly process involves mainly highly accurate bending and alignment procedures, which should become further optimised once the process is industrialized.

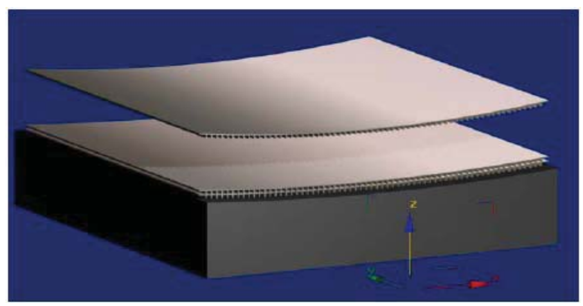


Fig. 2. Visualisation of the assembly concept. Structured Si plates are bent into a highly accurate cylindrical shape and are stacked successively on top of each other.

After the plates are cleaned, the plates are assembled into an HPO onto a highly accurate mandrel - a cylindrical silicon former with a polished top surface with an exact radius of 2 m. Improvements on the polishing has resulted into a surface deviation along the cylinder axis of the mandrel of less than 1 fringe at a wavelength of 633 nm. Reflection of X-rays along the cylinder axis on such a surface would generate a spot width of 3.4". Within the limited accuracy of the shape of the cylinder the requirements for XEUS are reached if the plates perfectly reproduce this shape. Finite element modelling analysis is ongoing to predict the stability, the response to particle inclusions and the behaviour of the HPO under variation of certain production parameters.

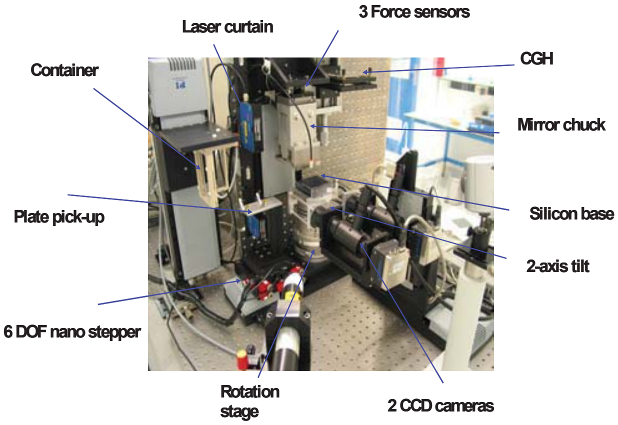


Fig. 3. The X-ray Optics Assembly Tool (XOAT) as installed in the cleanroom of the Cosine Research Centre in Leiden.

The assembly process makes use of an assembly tool that allows performing many highly accurate manipulations. The produced surface or figure is controlled by interferometric measurements with an accuracy of $\lambda/20$. Due to the demanding cleanliness requirements for the bonding process the assembly of plates into an HPO is automated and installed in a class 100 cleanroom facility. The X-ray Optics Assembly Tool (XOAT) that has been designed, installed and optimised allows remote assembly of the HPOs so that the major source of contamination from human presence is disclosed. A photo of the core elements of XOAT is shown in Fig. 3.

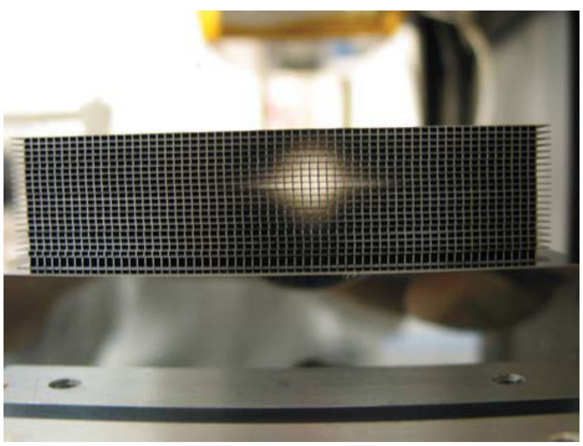


Fig. 4. Photograph of a High Performance Pore Optics on top of a polished former as recently produced by cosine Research.

More than 100 mostly small HPOs have been assembled in order to constantly improve the performance of these optics. Nowadays the production of HPOs with 20 plates is routinely performed. One of such an HPOs is shown in Fig. 4. Two HPOs are then integrated into a tandem or XOU.

The alignment of the HPOs with respect to each other is critical and we have presently chosen for a controlled assembly taking place at the synchrotron radiation facility BESSY in Berlin at the radiometry laboratory of the PTB. This allows controlling the alignment of the HPOs with two metrology tools: by optical means and by use of the X-ray beam. In that way the performance verification and the metrology can be done by the same setup in the same configuration.

Fig. 5. Layout of a larger X-ray Optical Unit that is made of two High Performance Pore Optics.

We summarise the work flow of the production process in Fig. 6. The core process of the production, the HPO assembly, is carried out in the cleanroom facilities at the Cosine Research Centre in Leiden.

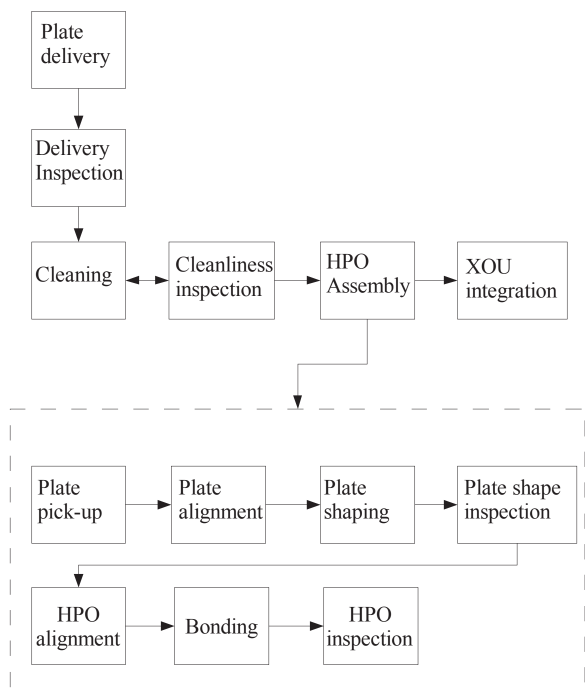


Fig. 6. The workflow of the production process starting from plate delivery up to its integration into an XOU.

3. PERFORMANCE VERIFICATION

A threefold control of the performance is implemented into the optics production. The first control is performed before and during the assembly. This concerns plate imperfections and cleanliness before integration and shape accuracy after plate assembly. The shape verification is very accurate and performed by an interferometer that allows accurately predicting the performance. After the production, the plate is sent to the synchrotron facility and tested to verify the performance by scanning the HPO across the beam. This requires a pencil beam with steady X-ray energy and several metrology tools for reflectometry. Once that it has been ascertained that the quality is sufficient, two HPOs are assembled and integrated into and XOU at the same facility and are then scanned again. Performance can be compared with the expectation from the measurements during the HPO production. Since the prediction of the optics as a whole is difficult to derive from the pencil beam measurements, another final test with broad band and wide field illumination is performed at the PANTER facility of MPE in Munich.

Preliminary tests have been made and a setup is now under consideration for a test configuration with a larger focal length. Full beam illumination can be performed as well on larger petals (telescope subunits). We mention here that for a future production process, about one XOU unit needs to be assembled and verified with respect to its performance within two days. Several tens of XOUs are then integrated into one petal structure to undergo further system testing.

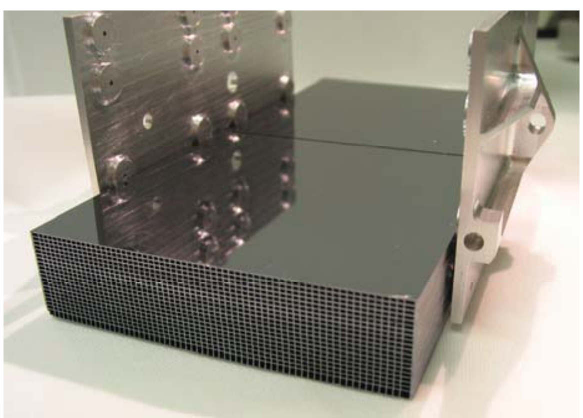


Fig. 7. Integration jig to assemble a pair of HPOs into an XOU. The two HPOs are co-aligned and integrated using brackets to form a Wolter-I X-ray lens.

We note that additional to these performance verifications, it is required to perform further tests to verify that the configuration is qualified for a space application. Those tests are vibration, thermal and structural tests, which are foreseen in the near future.

HPO performance has been tested several times and the achieved point spread functions meet the requirements for XEUS within medium sized areas of a few square centimetre. The first XOU has been built recently [8] and optical testing is not yet complete. Nevertheless it can already be reported that the above outlined integration concept is preliminarily established and that the first X-ray lens made of silicon pore optics has successfully been assembled. XOU-1 was mounted inside the vacuum chamber of BESSY and the top surface of HPO-P was aligned accurately to the required grazing incidence angle α at 2 m radius and 50 m focal length*. A pencil beam of 2.8 keV photon energy and 0.1 mm geometrical size (FWHM) was used to probe the reflection properties. The CCD detector, located at a distance of 5 m, had to be vertically displaced by 200 mm, in order to record the image shown in Fig. 8, confirming the correct setting of the 4α angle.

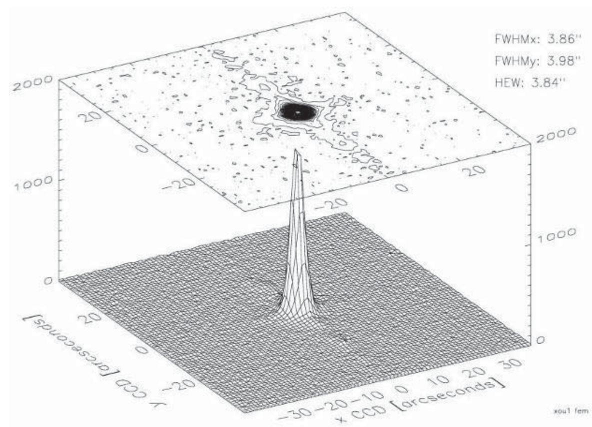


Fig. 8. First recorded reflection of an X-ray beam imaged by a silicon pore optic, integrated and fixed in Wolter-I configuration (XOU-1). A 2.8 keV pencil beam, with an initial HEW of 3.1" has been reflected under a grazing incidence angle of 0.57 deg inside pore 31 of the 1st plate and been recorded at a distance of 5 m at a height of 0.2 m corresponding to a 4 α angle of 2.29 deg. The two HPOs (HPO-H #122 and HPO-P #125) have been assembled on a cylindrical mandrel with a radius of curvature of 2 m.

The image (Fig. 8) of the double reflection has a HEW of 3.8" and one can observe a broadening of the beam by scattering along the beam direction. Detailed tests and analysis will be carried out on the XOU to verify the correct alignment, to determine the optical axis and to identify possible distortions. Full beam illumination

* Note that in the technology development program the telescope focal length was initially assumed to be 50 m.

at the PANTER facility and at BESSY are planned and part of the technology development program.

4. NEAR TERM CRITICAL DEVELOPMENT NEEDS

Bonding of the plates has proven to be under control as far as the assembly process is concerned. Annealing on the other hand is required to achieve sufficient strength of the connection between the plates. An annealing process will be established and it shall be demonstrated in the near future that annealing is successful, strengthens the bond on the whole area and does not affect the plate shape or reflection properties. Subsequent pull and vibration tests should be performed to test the ultimate stiffness and robustness of the HPOs and XOUs. Some of the tests will be performed initially within the running programme.

The wedge implementation process has been demonstrated earlier, but some difficulties were recently encountered, because the roughness of the surface of the ribs was affected negatively, so that the plates hardly bond after wedge implementation. A post polishing process in principle improves again the surface roughness and is presently under investigation. Alternatives for the wedge implementation such as graded coatings should therefore be investigated already now, while the post-polishing process is still under investigation.

Coating of the plates is not particularly difficult, but complicates the process flow since the plates have to be maintained or made hydrophilic. A coating with masks that leave the areas for the bond on the ribs free and uncontaminated should be demonstrated and it should be further worked out at which level of the production process the coating could be implemented. Coating of the ribs potentially offers also a method to implement a wedge, if the bonding method is changed from direct to Eutectic Au or to anodic bonding [9][10][11][12].

A key investigation required to assess future cost analysis is the conceptual layout of the industrial HPO production robot and the beamline[13] performance validation with multiple beams followed by an advanced image analysis. Based on the previous evaluation, we give in Fig. 9 a conceptual layout of a possible future assembly robot.

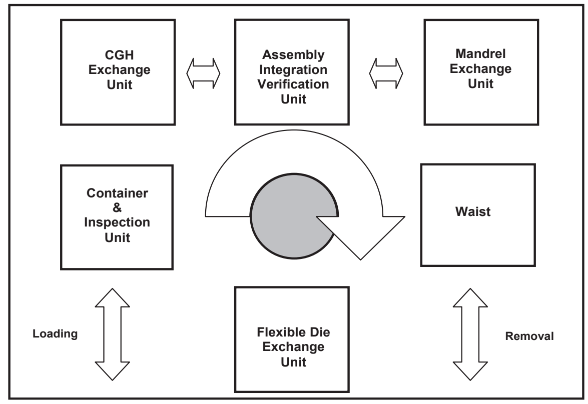


Fig. 9. Conceptual layout of the assembly robot. The core element in the centre is used to extract, move and supply all mirrors to the assembly and integration unit.

The assembly station could be based on a central arm that can be rotated so as to move the plates from one process location to another. Intermediate stations can be introduced around the central arm. This central rotational arm needs to be essentially stiff and shall not generate any particles. For that reason it is proposed that only two degrees of freedom are implemented, which are a rotational and a vertical movement. The remaining required degrees of freedom can be implemented into the other units. The Container Unit with the plates will have a rotational degree of freedom and the possibility of an on-axis (with respect to the central arm) movement. An inspection system on top of the (open) container inspects the plate. If the plate is not sufficiently clean or has particles, it is directly disposed on the waist container together with its carrier to repeat the cleaning process. If it passes the inspection, it is picked up by a plate die that can also bend the plate into the desired curvature and which moves it to the HPO base and attaches the plate onto the stack. The shape of the HPO is successively controlled by an interferometer. Speed is optimized by adapting the height of the plate container to the stack height, so that the movement of the accurate container unit is minimized and fast.

The production of the optics for the whole telescope will involve a change in the radius of curvature in discrete steps between 0.63 m and 2.12 m. Since 16 different radii configurations are expected it is necessary to allow for a change of the base mandrel and the interferogram optical unit that generates the cylindrical wave front, We note in this context that the variation of the radius has not yet been addressed. Smaller radii could cause difficulties in the bending flexibility of the plates. A reduction of the plate thickness would provide sufficient bending flexibility, enhance the effective area by 10% and reduce the mass by ~20%. It is therefore recommended here as well to demonstrate the assembly with plates that have a thickness and rib width of only 100 µm.

We note that this assessment is preliminary and based on the present development status. Such an assembly system has several difficult details that must be solved to implement the above proposed process flow. It is therefore proposed to verify the feasibility of such machinery, which we term now an industrial X-ray Optics Assembly Unit (iXOAT). Some subunits can already be designed and possibly be built and verified for its functionality. Successive process verification or validation could be performed within a limited time scale. iXOAT is based on a modular concept that shall allow easily the integration and exchange of subunits. The size of one iXOAT is small allowing its implementation within an area of about $1m^2$. It should be mentioned that the key innovations are the provision of a clean and fast assembly operating with high accuracies. A demonstration of such a fast assembly core process would give confidence in the time estimates as proposed and presented earlier in this paper.

5. CONCLUSION AND OUTLOOK

In this paper we have summarised the status and have presented the different production steps that must be carried out to produce innovative X-ray optics. Production of the high performance pore optics is routinely performed in our assembly facility at the Cosine Research Centre. An outline of the high performance pore optics concept and the related production process using our novel assembly technique has been presented here and we have proposed an integral concept for the future production of the flight optics, based on the presently implemented logistic scheme. We have identified and discussed critical areas requiring additional research, with an emphasis on wedge implementation and the coating process integration. If those areas are addressed in the near future it is expected that the production of pore optics can be implemented in a sufficiently short time scale at moderate cost. After a research and development phase of about 3 years, it should be possible to produce the optics within 6 years, so that it seems to be possible to provide the large mirror area that is required for the XEUS telescope within 8 to 10 years from now.

6. ACKNOWLEDGMENTS

The authors wish to thank the team of the PTB (Physikalisch-Technische Bundesanstalt) laboratory at the BESSY II synchrotron radiation facility in Berlin, for their assistance in x-ray measurement campaigns.

7. REFERENCES

[1] M. Beijersbergen et al, ‘Silicon Pore Optics: novel lightweight high-resolution X-ray optics developed for XEUS’, Proc. of SPIE5488-137, San Diego, 2004
[2] Wolter, H. Ann der Phys 6 Fol Band 10, 1952
[3] Turner, M. J. L.; Bleeker, J. A. M.; Trümper, J.; Hasinger, G.; Inoue, H.; Kunieda, H.; Palumbo, G. G. C.; Peacock, A.; Parmar, A. N.; Bavdaz, M ‘New Century of X-ray Astronomy’, ASP Conference Proceedings Vol. 251. Edited by H. Inoue and H. Kunieda. ISBN: 1-58381-091-9. San Francisco: Astronomical Society of the Pacific, 2001., p.230
[4] M. Bavdaz et al, ‘The XEUS X-ray telescope’, SPIE Proc. 5900-35, San Diego, 2004
[5] S. Kraft et al, ‘Development of modular High-performance Pore Optics for the XEUS x-ray telescope’, Proc. of SPIE-5900-53, San Siego, 2005
[6] Jansen, F. et al. XMM-Newton observatory. Astron. Astrophys. 365, L1-L6, 2001
[7] Weisskopf, M. C., Tananbaum, H. D., Van Speybroeck, L. P. & O’Dell, S. L. Chandra X-ray Observatory (CXO): Overview. Proc. SPIE 4012, 2-16, 2000
[8] M. Collon et al, ‘Metrology, integration and performance verification of silicon pore optics in Wolter-I configuration’, Proc. of SPIE 6266-131, Orlando 2006
[9] Steen Weichel, Silicon to silicon wafer bonding for microsystem packaging and formation, PhD, Technical University of Denmark, 2000
[10] Goesele et al, Progress in silicon-to-silicon direct bonding and its application to synchrotron x-ray optics, Proc. of SPIE 3151, 1997
[11] IA. Proessl, G. Kraeuter, Wafer direct bonding: tailoring adhesion between brittle materials, Materials Science and Engineering, R25, Nos. 1-2, 1999
[12] U. Goesele T. Abe, J. Haisma and M.A. Schmidt, 1st Intl. Symp. on Semiconductor wafer bonding: Science, technology, and Applications, Proc. Vol 92-7, the Electrochemical Society Pennington, NJ, 1992
[13] M. Krumrey and G. Ulm, High accuracy detector calibration at the PTB four-crystal monochromator beamline, Nucl. Instr. and Meth. A 467-468, 1175 – 1178, 2001