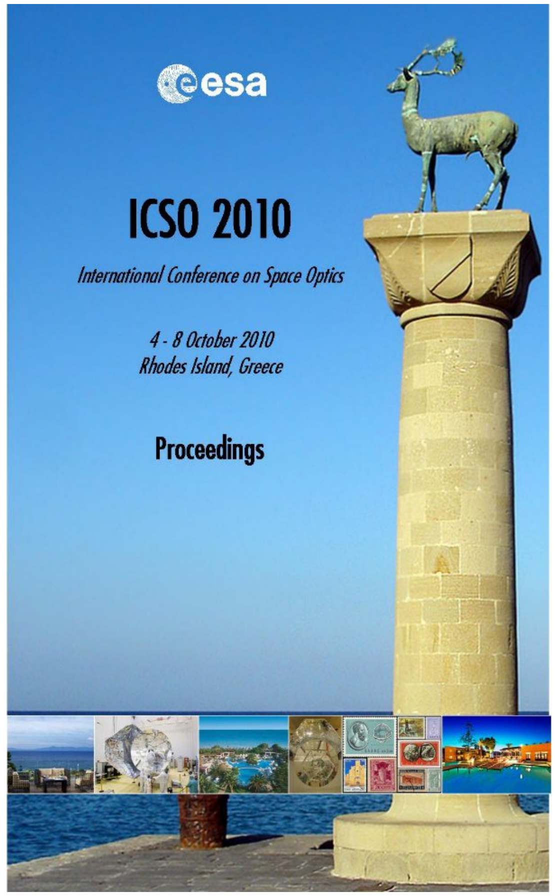
International Conference on Space Optics—ICSO 2010

Rhodes Island, Greece

4–8 October 2010

Edited by Errico Armandillo, Bruno Cugny, and Nikos Karafolas



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International Conference on Space Optics — ICSO 2010, edited by Errico Armandillo, Bruno Cugny, Nikos Karafolas, Proc. of SPIE Vol. 10565, 105652L · © 2010 ESA and CNES
CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2309240

SILICON PORE OPTICS FOR THE INTERNATIONAL X-RAY OBSERVATORY

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I. ABSTRACT

Lightweight X-ray Wolter optics with a high angular resolution will enable the next generation of X-ray telescopes in space. The International X-ray Observatory (IXO) requires a mirror assembly of 3 m² effective area (at 1.5 keV) and an angular resolution of 5 arcsec. These specifications can only be achieved with a novel technology like Silicon Pore Optics, which is developed by ESA together with a consortium of European industry.

Silicon Pore Optics are made of commercial Si wafers using process technology adapted from the semiconductor industry. We present the manufacturing process ranging from single mirror plates towards complete focusing mirror modules mounted in flight configuration. The performance of the mirror modules is tested using X-ray pencil beams or full X-ray illumination. In 2009, an angular resolution of 9 arcsec was achieved, demonstrating the improvement of the technology compared to 17 arcsec in 2007. Further development activities of Silicon Pore Optics concentrate on ruggedizing the mounting system and performing environmental tests, integrating baffles into the mirror modules and assessing the mass production.

II. INTRODUCTION

The International X-ray Observatory (IXO) is an astrophysics mission proposed by NASA, ESA and JAXA [1]. Within ESA, IXO is a candidate for a Large Mission (L-class) in the ESA Cosmic Visions 2015-2025 (CV1525) science programme.

In order to achieve the scientific goals of IXO, a Wolter I type [2] X-ray telescope with an effective area larger that 2.5 m² (at 1.25 keV) and an angular resolution of 5 arcsec (below 7 keV) half energy width (HEW) is required [1]. The mass constraints of available launchers exclude the mirror technologies used by the last generation of X-ray space telescopes, like polished glass shells of Chandra [3] or replicated Nickel shells for XMM Newton [4]. Existing lightweight X-ray optics technologies like foils or micro-pores cannot deliver the required angular resolution. Therefore, the development of a novel X-ray optics technology is required to enable IXO.

Different technology development programmes for the IXO optics are currently pursued. The ESA baseline is the Silicon Pore Optics (SPO) technology [5], which is based using commercially available Silicon wafers as mirror plates. The NASA baseline is the Slumped Glass Optics technology [6], which uses thin glass sheets formed by slumping on a super polished mandrel. A similar slumping technology is also investigated by ESA as a backup [7].

This paper describes the SPO technology, the design and manufacturing of the optics for the IXO telescope and the current status of the technology development of ESA.

III. SILICON PORE OPTICS TECHNOLOGY

The Silicon Pore Optics technology is based on the use of 300 mm Si wafers for the reflective surface as well as for forming the structural elements. Standard 300 mm Si wafer as produced for the semiconductor industry offer a super-polished surface (roughness < 0.1 nm) as required for X-ray mirrors. Therefore, no expensive and time consuming polishing processes are required to manufacture the mirrors for SPO. The figure of the mirror surface required for a Wolter I optics (or its approximation) is obtained by bending and stacking several mirror plates as illustrated in Fig. 1. Each mirror plate has a pore array separated by ribs on the backside of the reflective area. These plates are elastically bent into the required Wolter I shape and subsequently bonded onto the underlying plate. The high surface quality allows for direct bonding without using any glue. The resulting SPO stack is a stiff, monolithic silicon block with pores through which the X-rays can be reflected on the curved mirror surfaces. Two of such stacks are then aligned and assembled by two brackets to form a mirror module, i.e. an off-axis Wolter I type focusing optics. The brackets also provide the interfaces to fix the mirror module to the telescope structure.

The manufacturing of SPO is based on established semiconductor industry processes and equipment that allow to handle and machine Si wafers with a high precision, cleanliness and throughput. Therefore, the current manufacturing process can be scaled up to an automated mass production of a large number of SPO mirror modules as required for IXO.

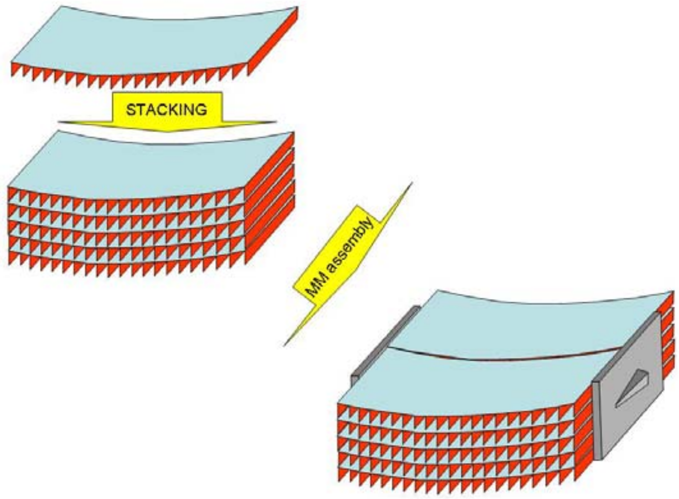

Fig. 1. Illustration of the Silicon Pore Optics technology. Several curved mirror plates are stacked by direct bonding of the silicon surfaces. Pores inside the mirror plates allow the X-rays to pass through the optics. Two SPO stacks are connected by brackets to form a mirror module for focusing X-rays by two reflections.

IV. SILICON PORE OPTICS DESIGN FOR IXO

A. Telescope Design

The SPO technology foreseen for IXO is based on a modular approach (see Fig. 2) to populate a large aperture with many (~1600 for IXO) mirror modules. The largest mirror modules (at inner radii) each have a volume below 1 litre and a mass below 1 kg. This allows easy handling and using small machines during manufacturing and testing.

The mirror assembly is organised further into eight identical petals, each holding about 200 mirror modules depending on the detailed petal design. The size of one petal is about 1.6 x 1.4 x 0.4 m³ with a mass (including mirror modules and margins) of below 180 kg. Candidate materials for the petal structure are CeSiC® or CFRP. The size still allows to test the optical performance of individual petals in available large aperture X-ray facilities. A CeSiC® petal prototype has been demonstrated within the SPO technology development programme [8]. The eight petals will be integrated into an optical bench, which forms the 3.5 m diameter telescope.

The modular approach allows to produce spare mirror modules and petals that can be exchanged in the case of a failure. Exchanging a mirror module of an already populated petal is possible without affecting the other modules.

Another advantage of the modularity is, that the most critical alignments are done during the assembly of the two SPO stacks of the mirror modules at a dedicated alignment facility. Here, tolerances of below 1 µm and 1 arcsec have to be met. The tabletop assembly of the SPOs and mirror modules involve interferometric and X-ray measurements, which monitor the required accuracy during the processes. The integration of the mirror modules into the petal and the petals into the optical bench has less critical positioning requirements.

B. Mirror Module Design

The basic optical element of the telescope concept for IXO is a mirror module, which is an off-axis focusing Wolter I optic. A mirror module and its parts are shown in Fig. 3. It consists of the following elements. One SPO stack provides the mirror surfaces for the parabolic part of the Wolter optic, a second stack provides the hyperbolic part. Each SPO stacks consists of a baseplate and 45 mirror plates. The pore size is 605x830 µm² and the thickness of ribs and plates is 170 µm.

Two CeSiC® brackets are glued to the two SPO stacks forming a rigid connection between them. The brackets also provide polished reference surfaces for the integration of the mirror modules and three interfaces for the mounting system.

Three flexible dowel pins made of Invar are used as isostatic mounting interface of the mirror module to the petal. The dowel pins are glued to the brackets and tightened to the petal using nuts and washers.

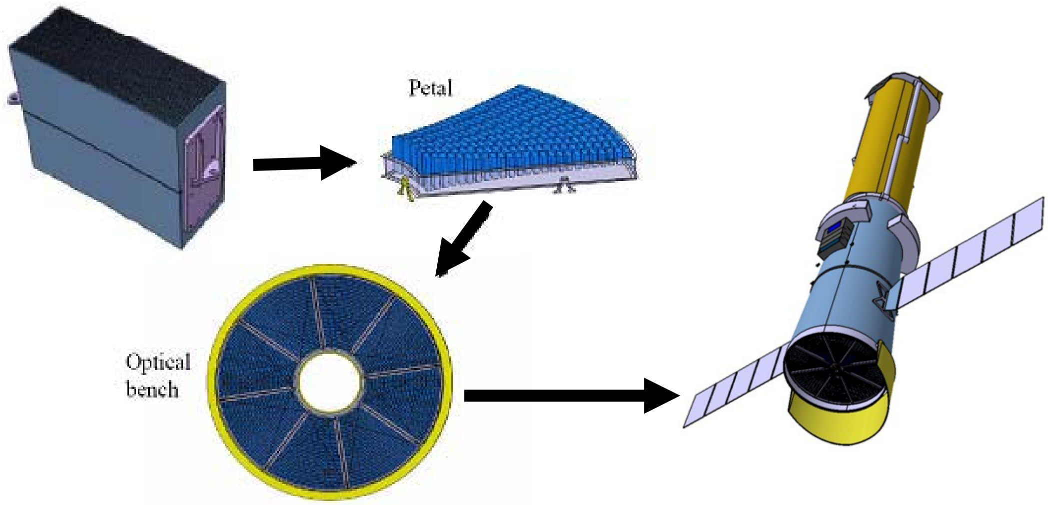

Fig. 2. Illustration of the modular approach for the IXO telescope. About 200 SPO mirror modules are integrated into a petal and eight petals are integrated on an optical bench of the spacecraft.

Fig. 3. Photos of the components of a SPO mirror module. From top left to bottom right: A SPO stack with 45 plates; a CeSiC® bracket pair; one of the three dowel pins; an assembled mirror module (without pins).

V. MIRROR MODULE MANUFACTURING

An overview of the different manufacturing steps of the SPO mirror modules is illustrated in Fig. 4 and described in the following.

Commercially available 300 mm Si wafer with a standard thickness of 775 µm are the base material for SPO. They are cut into rectangular plates by industrial wafer dicing saws. A small wedge (approx. 2 arcsec) has to be applied to the plates in order to keep the Wolter I geometry of the stacked plates. A customized, fully automated wedging process based on Si wafer processing technology was developed as described in [9]. Cutting the pores into the wafer is performed by a customized process using a standard wafer dicing saw. The mirror plates are coated to enhance X-ray reflectivity, especially for high energies [10]. This coating is structured by a lithographic process not to cover the areas required for bonding the ribs.

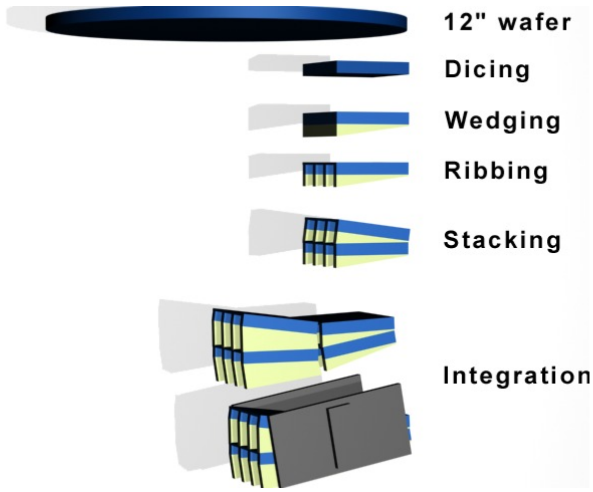

Fig. 4. Illustration of the process steps for manufacturing a SPO mirror module.

The mirror plates are stacked by using an automated stacking robot consisting of robotic plate handling, cleaning, bending, stacking and optical metrology [11]. A baseplate is pressed onto a mandrel which has the required conical, parabolic or hyperbolic form. The 45 mirror plates are then stacked on top of it.

Two SPO stacks are aligned to form a mirror module by using X-ray pencil beam metrology. Once the required sub arcsec alignment has been verified, the stacks are glued to the connecting brackets. This alignment is currently performed at the X-ray pencil beam facility of the Physikalisch-Technische Bundesanstalt (PTB) at the BESSY II synchrotron in Berlin, Germany [12]. The same setup is used afterwards to measure the optical performance of the assembled mirror module. Additional X-ray tests are performed at the PANTER facility of the Max Planck Institute of Extraterrestrial Physics in Munich, Germany.

VI. SILICON PORE OPTICS DEVELOPMENT STATUS

The complete production process and a detailed design for a SPO mirror module has been developed and demonstrated by now. This includes manufacturing mirror plates out of Si wafer, robotic stacking of SPO, a mounting design with detailed finite element modeling and X-ray characterization of the optical performance. Details are provided in the following paragraphs.

Mirror plates are routinely produced in an industrial clean room environment. Their final surface roughness was measured to be 0.5 nm rms. X-ray measurements on a length scale of 10 mm show a point spread function contribution of 1.8 arcsec for two reflections. Patterned coatings on mirror plates and stacking of these plates has been demonstrated (see Fig. 5a). Currently, 45 plates (one stack) can be produced within one week, being limited by the single plate handling. By using commercially available semiconductor equipment for parallel processing, robotic plate handling and quality control, a plate production rate of hundreds of plates per day is possible.

The stacking process and the current stacking robot (see Fig. 5b) have achieved a mature status. The production of stacks has been demonstrated with up to the required 45 plates (see Fig. 3). Stacking of different kind of plates (different wedge angles, coatings, radii, conical or cylindrical shapes) is possible. The present mirror modules have been produced for a radial position of 2 m. A second stacking robot for mirror modules with 0.74 m radius is under construction. Manual tests have demonstrated the stacking of mirror plates down to the inner most radii of IXO as shown in Fig. 5d. All process steps during stacking are fully automatic and executed by robotic plate handling. The stacking robot fits on a standard optical table (< 5 m^2). The current maximal stacking speed is 16 min per plate. This includes additional metrology steps, that will not be required in a mass production environment, but are useful to learn improving the stacking quality during the development phase.

A detailed design has been developed for a mounting system (brackets and dowel pins, see Fig. 3) for a 0.74 m radial position being compliant with the operational and non-operational environmental requirements of IXO [13]. A mirror module with this mounting system has been assembled for an upcoming environmental test campaign. Similar mounting systems (for old XEUS mission requirements) were demonstrated in earlier activities [8]. This includes modeling (mechanical and thermal), manufacturing, assembly, alignment, integration into petals and exchangeability of mirror modules in the petal.

All tools and processes for assembling mirror modules within the required accuracy are fully functional. The required accuracy of the SPO alignment within one mirror module has been demonstrated.

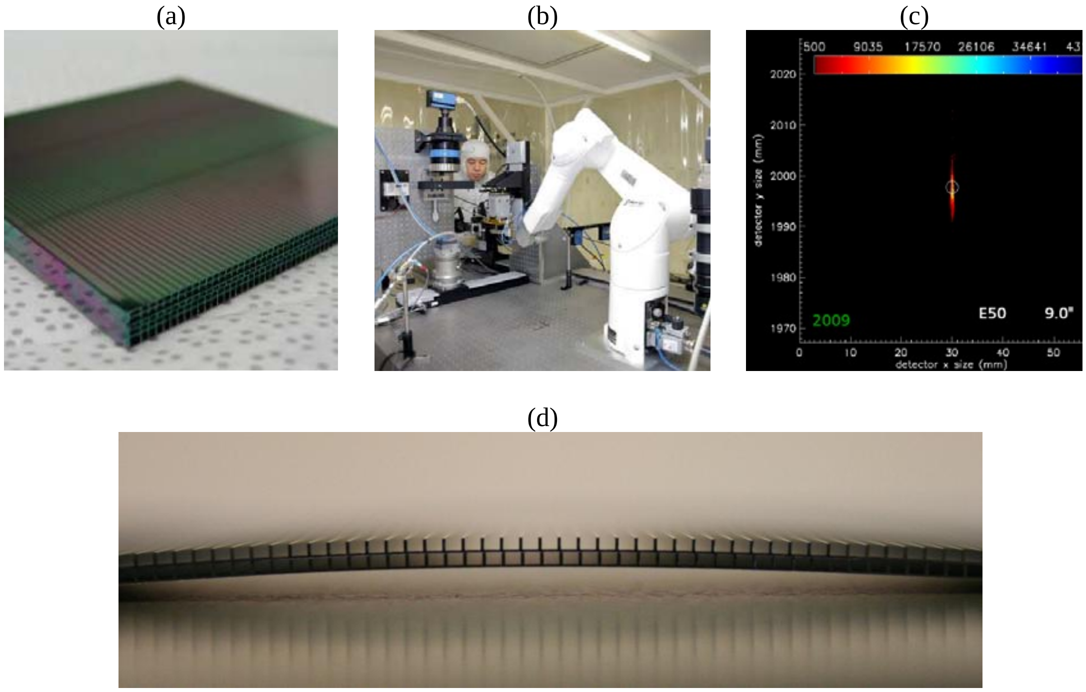

Fig. 5. (a) SPO stack of coated mirror plates
(b) Stacking robot built on a vibration isolated table in a class 100 clean environment
(c) Point spread function with 9 arcsec HEW of the first 4 plates measured with an X-ray pencil beam
(d) Bonded mirror plates curved to the inner most radii of IXO. The plates were manually bonded to each other and maintain their curvature on their own.

The latest mirror module reached an angular resolution between 9 arcsec (first 4 plates, shown in Fig. 5c) and 16 arcsec (first 20 plates). An individual mirror plate within the SPO stack achieves 4.1 arcsec HEW over 90 % of the area. The origin of the degradation of the HEW was identified by two independent methods (X-ray tests and interferograms). Stacking errors at the edges of the mirror plates are caused by residual particles and drying stains. This residual contamination is well understood [14] and standard semiconductor plate cleaning and drying systems, that are specialized for plates with sharp edges, are currently implemented in the manufacturing process.

The required effective area of 2.5 m² can be met by mirror modules with a total mass below 700 kg, including the brackets, dowel pins and margins. This corresponds to an effective areal density below 240 kg/m². The effective area of an uncoated mirror module was measured over 20 plates at the PANTER facility for different energies and 93-95 % of the theoretically predicted effective area are obtained [14]. The measured losses are attributed to plate roughness, small alignment errors, particle contamination and modeling accuracy. This is compliant with the IXO requirements, which allow for 10 % effective area degradation.

VII. CONCLUSIONS

The manufacturing process and the design of SPO mirror modules has reached a high maturity. SPO mirror modules, including their mounting, already fulfil the effective area requirements of IXO. Compliance with environmental conditions has been demonstrated by finite element models and a test campaign is currently prepared. X-ray measurements of a mirror module with 20 plates show an angular resolution of 16 arcsec. Compared to the telescope of the current X-ray mission XMM-Newton, the presently available SPO mirror modules have a comparable optical performance but are 10 times lighter.

90 % of the area of an individual mirror plate within the SPO stack already achieves 4.1 arcsec HEW. The current limitations for achieving the 4.3 arcsec HEW over 100 % of the entire 45 plate pairs as required for IXO have been found to be dominated by residual contamination at the borders of the mirror plates. Solutions have been identified and are currently implemented.

The past developments have shown a continuous progress of the SPO technology fully in line with the expectations. Therefore, SPO are a very promising technology for fully achieving the IXO requirement within the ongoing and planned development activities. This will provide an enabling technology for the next generation of high energy astrophysics space missions.

VIII. ACKNOWLEDGEMENTS

We would like to thank our industrial and institutional partners and the people involved in the technology development activities. Major contributors were: R. Partapsing, G. Vacanti, M. Erhard, C. Körner, D. Kampf, C. van Baren, C. Jensen, F. Christensen, M. Freyberg, W. Burkhard, M. Krumrey, P. Müller, L. Cibik.

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