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Silicon Pore Optics for Future X-ray Telescopes

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***Abstract*— Lightweight X-ray Wolter optics with a high angular resolution will enable the next generation of X-ray telescopes in space. The candidate mission ATHENA (Advanced Telescope for High Energy Astrophysics) required a mirror assembly of 1 m² effective area (at 1 keV) and an angular resolution of 10 arcsec or better. These specifications can only be achieved with a novel technology like Silicon Pore Optics, which is being 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 recent upgrades made to the manufacturing processes and equipment, ranging from the manufacture of single mirror plates towards complete focusing mirror modules mounted in flight configuration, and results from first vibration tests. The performance of the mirror modules is tested at X-ray facilities that were recently extended to measure optics at a focal distance up to 20 m.**

***Index Terms*—X-ray optics, X-ray astronomy, ATHENA, pore optics, X-ray telescopes, X-ray testing, high energy astrophysics**

I. Introduction

Reflective optics for X-rays require grazing incident mirror systems, e.g. Wolter optics, with design properties very different from conventional optical systems built for the ultraviolet, visible or infrared spectrum. Furthermore, as X-rays are strongly absorbed in the atmosphere, astronomical observations can only be performed with space telescopes. Due to the high mass of X-ray optics, this an important design driver for X-ray missions.

The current generation of operating X-ray telescopes is using either high-resolution but heavy optics with limited effective area based on precision polished, thick (2-3 cm) glass shells (Chandra) or medium resolution, lighter weight Nickel shells (XMM-Newton) or lower-resolution but light weight optics using Aluminum foils (Suzaku) or thin (<1 mm) slumped glass shells (NuStar). For the next generation x-ray missions, lightweight optics providing both a large effective area and an angular resolution, below 10 arcsec HEW (half energy width), are needed.

Silicon Pore Optics (SPO) technology was developed in the past years by ESA, together with a European consortium, to provide such lightweight and high-resolution x-ray optics. SPO was selected as the baseline technology for the former IXO and ATHENA mission candidates [1-3].

II. Design of Silicon Pore Optics

Silicon Pore Optics make use of the materials and processes available from the semiconductor wafer industry. 300 mm Silicon wafers are commercially available in several standardized versions. Their outstanding surface and figure quality (surface roughness < 0.1 nm over 50x50 µm², total thickness variation < 1 µm over 300 mm) makes them an ideal component for x-ray mirror systems. Most importantly, their price is orders of magnitude below any comparable super-polished surface of similar size and they are available in very large quantities.

The challenge of SPO technology is to bend and mount the flat wafers to form the required parabolic and hyperbolic surfaces for a Wolter X-ray optics. In particular the mounting of the mirror surfaces also has to be robust against the environmental conditions required of a space telescope without degradation of the mirror shapes. Silicon Pore Optics solve this challenge by structuring the Si wafer into mirror plates (typically 7x7 cm² large) consisting of a mirror membrane and many ribs (1 rib per mm plate width) which connect one mirror plate with the next one (see Fig. 1). As both sides of the mirror plates (rib bottoms and mirror surface) maintain the super-polished surface of the original wafer, the plates can be stacked on top of each other and a strong covalent bonding is achieved without adhesives being needed. This results in rigid, self-supporting stacks of typically 30-45 mirror plates (see Fig. 2) with a pore matrix through which X-rays can propagate and be reflected by the Si surfaces. For high energy X-rays, a structured single or multilayer coating can be applied before stacking to increase reflectivity.

A Wolter I type of optics is realized by taking two stacks, representing the mirror surfaces for the parabolic and hyperbolic part (or approximations thereof), and placing them behind each other (see Fig. 3). The angle between these two stacks has to be set with arcsecond accuracy to achieve a good angular resolution of the optics at a defined focal length. Due to the compact size of the stacks, this alignment can be done under X-ray illumination or with a small interferometer setup. The relative position of the two stacks is then fixed by gluing them into brackets, which also provide the mounting interface to the telescope structure. The resulting element is called an SPO mirror module. Being an optical system with two reflections, the mounting alignment requirements into the telescope structure are much more relaxed compared to the geometric requirements of the plates and stacks inside the mirror module.

A space telescope would finally consist of several hundreds of these mirror modules (see Fig. 4). The small size of each module has many advantages. Manufacturing and testing can be done with table-top sized equipment and the large number of smaller sized elements (mirror plates and brackets) enable the use of economic manufacturing methods in a medium or mass production environment. Especially the processing of the mirror plates benefits from the commercial machines and processes available in the semiconductor industry, already optimized for a high manufacturing throughput.

The details of manufacturing the mirror plates, the coating process and the robotic stacking can be found elsewhere [4,5,6], this paper concentrates on presenting the currently achieved optical performances, the environmental qualification status and some recent updates of the robotic stacking tools, the SPO mirror module design and X-ray beamlines.

III. STATE-OF-THE-ART PERFORMANCE AND QUALIFICATION

The first generations of Silicon Pore Optics was designed for the XEUS mission candidate [7], a formation flying telescope with 50 m focal length. The technology development activities concentrated on mirror modules with a 2 m radius, i.e. to be positioned 2 m away from the optical axis of the telescope.

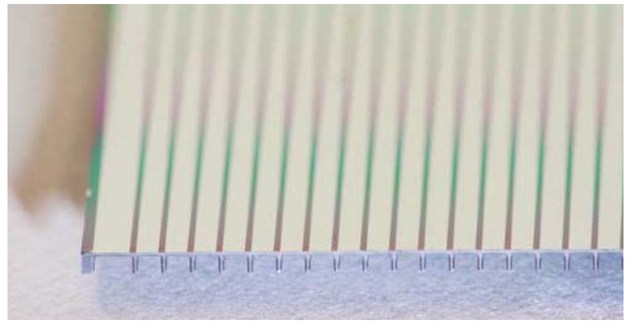

Fig. 1. Single mirror plate: the top surface has a structured coating to increase X-ray reflectivity. Below the top mirror membrane, the pores are separated by ribs acting as structural connections to a lower plate. The apparent mismatch of coating and ribs is intentional and accommodates the bending of the plates.

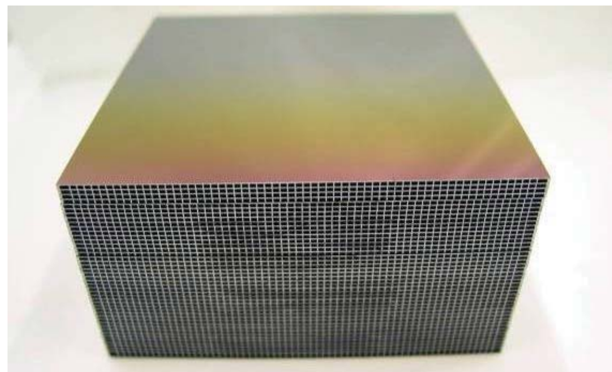

Fig. 2. SPO stack with 45 mirror plates

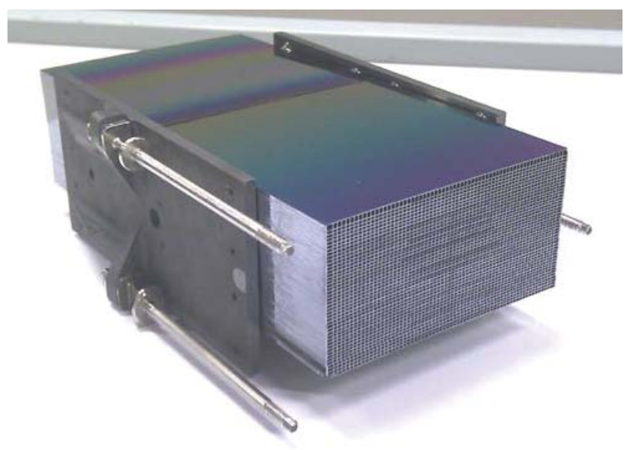

Fig. 3. SPO mirror module: two stacks with 45 plates each are glued into two CeSiC brackets. The three Invar dowel pins for isostatic interfacing with the telescope structure are also shown.

Several iterations of the manufacturing processes and hardware resulted in a well-defined and mature production environment for SPO mirror modules. The mirror plates can be processed with a high throughput, while fully automated robotic stacking is routinely done for large stacks of up to 45 plates.

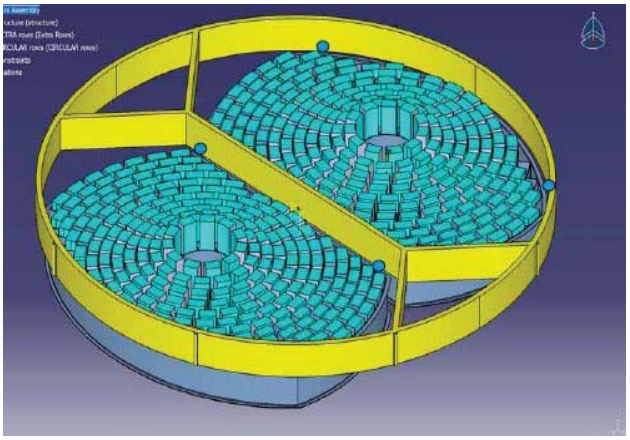

Fig. 4. ATHENA telescopes. Each of the two telescopes consists of about 250 SPO mirror modules (blue) mounted into a mirror structure (grey).

State-of-the-art SPO mirror modules manufactured in 2010 and 2011 reached an optical performance of 16.6 arcsec HEW over the full aperture of 45 plate pairs. Testing only the sup-aperture of the first 4 plate pairs yields a better angular resolution of 7 arcsec, but also reveals a degradation of the HEW for increasing stacking height. Nevertheless, these SPO mirror modules offer a similar resolution compared to the current Nickel shell technology, whilst being 10 times lighter in effective area mass density.

The mounting system has also been iterated to become compliant with the environmental requirements of first the XEUS and later the IXO candidate missions [8]. The brackets are made from CeSiC, a ceramic material with a coefficient of thermal expansion very close to that of Silicon, minimizing thermal distortions of the mirror surfaces. Three dowel pins, made from Invar, are glued to the CeSiC brackets and provide an isostatic interface to the telescope structure. Detailed thermal and mechanical FEM analysis allowed to optimize the design to reach full compliance with all requirements.

One of the mirror modules went through a series of thermal and vibration tests. This test campaign was tailored to verify and improve the software modeling of the mirror modules. For the tests, the mirror module was mounted in a CeSiC jig (see Fig. 5), simulating the interface to the structure of a spacecraft.

First, low level vibration tests were performed to identify the lowest eigenfrequencies and the q-factor of the mirror module. The sample was vibrated with a sine sweep from 5 – 2000 Hz and an amplitude of 0.25g in the X direction. The measured eigenfrequencies are listed in Tab. I.

TABLE I. EIGENFREQUENCIES OF THE MIRROR MODULE

Mode	Measured frequency	FEM frequency	Mode shape
1	811 Hz	933 Hz	Translation X
2	1088 Hz	1055 Hz	Rotation X
3	1399 Hz	1529 Hz	Translation Y and Rotation Z

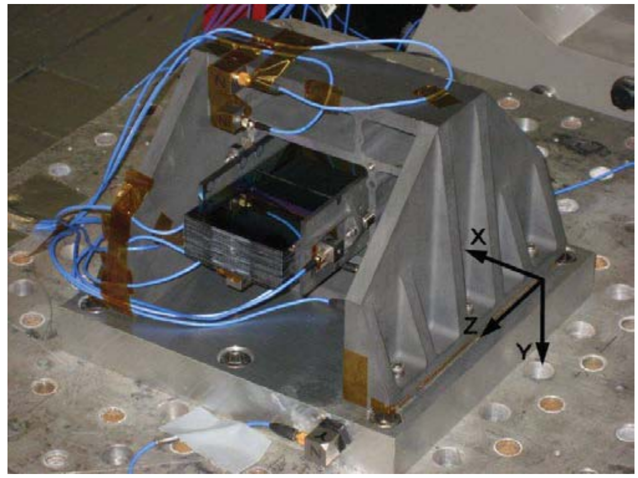

Fig. 5. Mirror module mounted on the shaker. Several acceleration sensors are connected with blue cables. The black arrows indicate the coordinate system.

While mode 2 matches very well with the FEM predictions, the other two modes are lower than expected but still within the accuracy that FEM offers for this type of simulation. The q-factor for the first mode, being the most critical one, was measured to be 21. This is in good agreement and even lower than the expected value of 25. The integrity of the mirror module was verified by comparing pre- and post-vibration x-ray tests, which showed no measurable degradation of the optical performance.

The thermal performance was tested in vacuum at the X-ray pencil beam facility (XPBF), a dedicated synchrotron radiation beamline in the laboratory of the Physikalisch-Technische Bundesanstalt (PTB) at the Bessy II facility in Berlin (D) [9]. Using infrared heat sources, the mirror module was heated from one side to 20K above room temperature. The local temperatures at different locations of the mirror module were recorded with thermocouples. No thermal gradients above 1K developed, being in line with the thermal modeling results.

After successfully verifying the thermal and mechanical modeling results, a first step towards full qualification level tests was performed. The mirror module was vibrated in a frequency range of 5 – 100 Hz (quasistatic loads) at design and qualification loads. The softest (Z) and stiffest (X) axis were used for the tests. FEM models predicted a positive margin of safety and the mirror module passed all tests without mechanical damage.

Finally, in order to verify the limits of the models and possible failure modes, the mirror module was vibrated with the maximal loads the shaker could apply to the optics (41 g for the X-axis direction), being 60% above qualification levels. Despite the FEM models predicting a negative margin of safety, the mirror module did not display any damage, indicating that the model is more conservative than reflected by the safety factors.

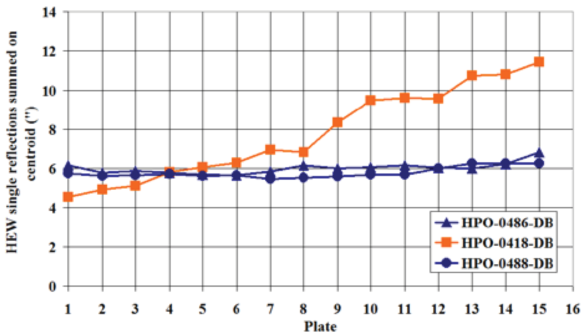

Fig. 6. Comparison of the stacking quality, as function of plate number, between the best SPO of the old robot (orange) and the first two SPOs of the new robot (blue). The HEW of a single reflection was measured at the XPBF.

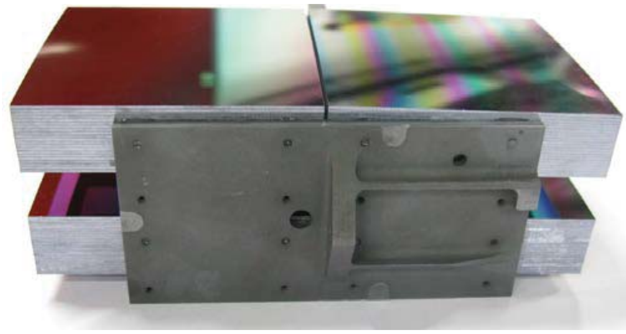

Fig. 7. The first mirror module with 20 m focal length and 0.74 m radius incorporates several updates of plate manufacturing and stacking. The design changed from using two stack per module to four stacks per module.

IV. Recent Evolutions of SPO

After demonstrating the suitability of the SPO technology for high-resolution space telescopes, the technology development moved to adapting the manufacturing equipment to the IXO telescope design with a focal length of 20 m. A representative radial position in the aperture of 0.74 m was selected for the next mirror module design iteration.

This design change required several adaptions of the manufacturing equipment. In particular, the robotic stacking facility needed to be modified substantially [10]. Bending the mirror plates to smaller radii required different mandrels and stacking dies, as well as a more flexible optical metrology. An equally important goal for the upgrade was to improve the stacking quality to reach a better HEW of the SPO mirror modules.

One of the previous limitations of the HEW was the degradation of the mirror quality with stack height. The root cause was identified to be due to lower cleanliness of the plate edges, which did not bond completely to the underlying plate. The new stacking robot was updated with a high performance semiconductor plate cleaning and drying system, that is specialized for plates with sharp edges. In addition, the particle detection system was improved to identify particles with sizes down to <500 nm. The figure metrology interferometer was replaced by a fringe reflection metrology system, which is better suited for non-cylindrical curved surfaces.

Figure 6 compares the evolution of the stacking quality between the old and the new robot. The best stacks produced by the old stacking robot more than doubled its HEW (single reflection) over the first 15 plates. Stacking with the new robot results in a constant HEW.

A second method for counteracting the increasing HEW of larger stacks was also implemented. Instead of mounting two large SPO stacks into a pair of brackets (see Fig. 3), the mirror module can also be built with several SPO stack pairs. This was demonstrated using 4 stacks (see Fig. 7) offering an additional option for increasing the angular resolution.

Manufacturing of the mirror plates has also been upgraded. The new plates have a 2.5 times larger wedge height, as needed for their more inner radial position. Laser marking of the outer edges of the plates allows to trace back each individual plate to its original position on a specific wafer and is a powerful tool to keep control over the manufacturing and stacking process involving several hundreds of plates. A new masking method was introduced, using lithographic masking, which is better suited for future mass production.

The upgraded processes and equipment were commissioned in 2011 and could successfully produce several SPO stacks with the smaller radius of 0.74 m for 20 m SPO mirror modules (see Fig. 7).

The shorter focal length of 20 m also allows to perform X-ray measurements in the focal position, instead of intra-focal measurements. Both, the XPBF in Berlin (D) and the large diameter beam Panter facility in Munich (D), now allow to position detectors at 20 m distance from the X-ray optics.

V. Conclusion and Outlook

SPO technology has successfully demonstrated its suitability for being used in future high-resolution space telescopes. For large focal lengths of 50 m, mirror modules with an HEW of 16.6 arcsec were built and detailed modeling, as well as first environmental tests, demonstrated their robustness against the space and launch environments. Building optics with shorter focal length and smaller radii has also been demonstrated by upgrading the manufacturing processes and equipment. The feasibility of being able to manufacture different radii is especially important, considering that the telescope aperture has be populated with mirror modules of different radii.

The next steps are defined in ESA's technology development plan for Silicon Pore Optics [2]. A full environmental qualification activity is currently running in order to reach a Technology Readiness Level of 5. Further optimizing the parameters of the new plate manufacturing and stacking processes is expected to improve the angular resolution to well below 10 arcsec HEW.

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