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High-resolution and light-weight Silicon Pore X-ray Optics

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ABSTRACT

Silicon Pore Optics (SPO) have been invented and developed to enable X-ray optics for space applications that require a combination of high angular resolution while being light-weight to allow achieving a large mirror surface area. In 2005, the SPO technology development was initiated by the European Space Agency (ESA) for a flagship X-ray telescope mission and is currently being planned as a baseline for the NewATHENA mission scheduled for launch in the 2030s. Its more than 2 m diameter mirror will be segmented and comprises of 492 individual Silicon Pore Optics (SPO) grazing-angle imagers, called mirror modules. Arranged in concentric annuli and following a Wolter-Schwartzschild design, the mirror modules are made of several tens of primary-secondary mirror pairs, each mirror made of silicon, coated to increase the collective area of the system, and shaped to bring the incoming photons to a common focus in 12 m distance. The mission aims to deliver an angular resolution of better than nine arc-seconds (Half-energy width) and effective area of about 1.1 m^2 at an energy of 1 keV.

We present in this paper the status of the optics production, and illustrate not only recent X-ray results but also the progress made on the environmental testing, manufacturing and assembly aspects of SPO based optics.

Keywords: X-ray optics, X-ray astronomy, silicon, wafer, stack, pore optics, X-ray telescopes, ATHENA, ARCUS, SPO

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1. INTRODUCTION

Over the past 15 years, extensive research and development efforts have been dedicated to advancing Silicon Pore Optics (SPO) [1]. These efforts are driven by the need to support future x-ray telescopes, such as NewATHENA, a significant component of the European Space Agency's ambitious Cosmic Vision 2020 program [2 - 6].

NewATHENA demands exceptionally lightweight reflective optics with a polished and coated surface area totaling approximately 300 square meters. Furthermore, a target angular resolution of less than nine arcseconds is required, all while adhering to a strict mass limit of 1000 kg [7]. At the time of inception, there were no existing x-ray mirror technologies capable of meeting these exacting demands [1]. Consequently, Silicon Pore Optics (SPO) emerged as a groundbreaking x-ray optics innovation, pioneered and developed through collaboration between ESA and its partner organizations [8-18].

The size of NewATHENA's large mirror necessitates an unprecedented level of mass production for the modular optics, spanning from individual mirror plates to the assembly of the entire optics system. To achieve this, the optics have been divided into smaller units known as mirror modules, and NewATHENA will incorporate 492 of these modules, each falling into one of 13 different types corresponding to its respective annulus. The production of these mirror modules must be completed within a tight timeframe of two to three years to align with the telescope assembly schedule.

For ESA to officially adopt NewATHENA and, by extension, Silicon Pore Optics for production, it is imperative that the technology reaches a high Technology Readiness Level (TRL) of 5 to 6. To prepare for adoption, ESA, in collaboration with cosine and other partners, has increased its efforts to ensure that the technology is ready for mass production at all levels.

This paper provides a comprehensive overview of the latest advancements achieved up to the mirror module level. It is worth noting that additional ESA initiatives focus on the preparations for the assembly, integration, and testing of the mirror modules within the overall optic structure. These efforts are detailed in separate sections within this publication [1].

A holistic development approach has been embraced, wherein the optics are continually refined and enhanced through iterative processes. Early prototypes are constructed, rigorously tested, and subsequently improved upon. This approach has yielded an optics system that has reached an advanced stage of development, where any remaining challenges and risks can be effectively targeted and resolved.

2. MASS PRODUCTION OF SPO MIRROR MODULES

All equipment for the mass production of the optics is in place completing the production chain for the development of the technology. Optimization of the production processes and ramping up as well as further tightening production will be done during the engineering model (EM) and qualification model (QM) phases.

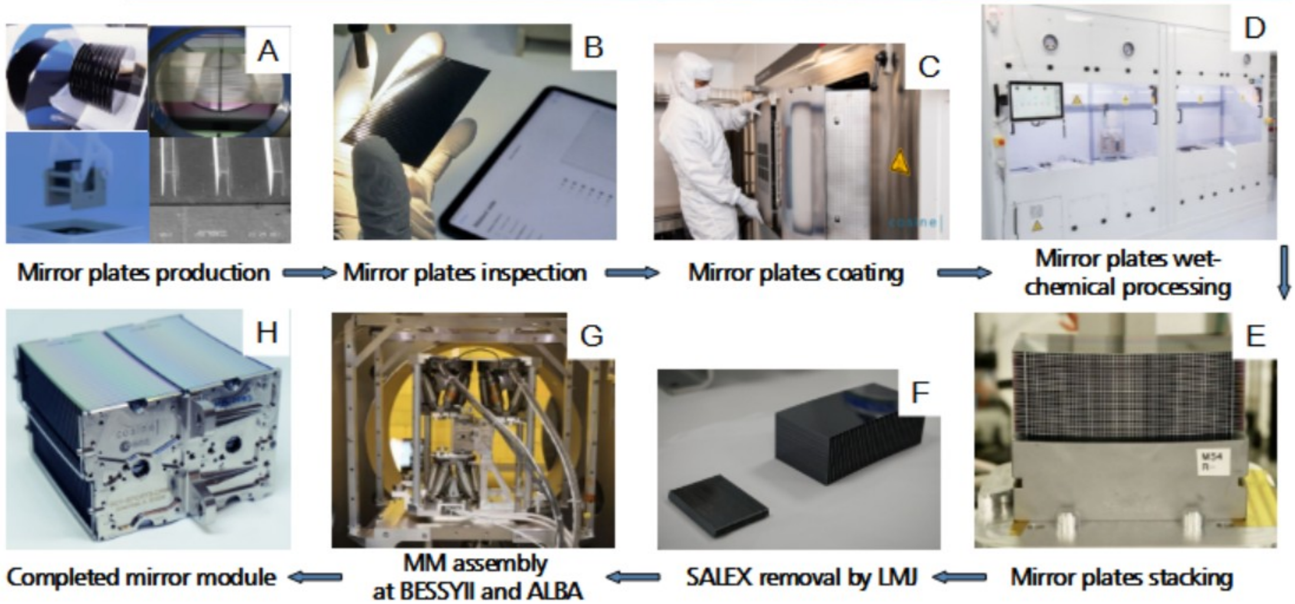

Figure 1: High-level overview of the production process for SPOs, starting turning 300 mm silicon wafers into mirror plates (A). The plates are inspected (B), coated (C) and prepared wet-chemically for stack production (D). After having produced stacks (H), the stacks are cut to their final dimensions using Laser MicroJet (LMJ) cutting (F). The stacks are being then integrated into mirror modules at the BESSYII or ALBA synchrotron radiation facilities (G, H).

Figure 1 depicts a high-level overview of the SPO production processes in photographs. The production process steps of SPOs are described in detail in [9]. The SPO production starts with turning standard super-polished 300 mm wafers, having a surface roughness of about 0.1 nm RMS and total thickness variation (TTV) of less than 100 nm, into structured mirror plates (A) at the mirror plates suppliers. Standard fully automated semiconductor dicing saws are used to cut wafers into smaller individual rectangular shaped plates. During the subsequent ribbing process, a number of long grooves get cut into the silicon plate leaving walls (called ribs) and a thin bottom (called membrane). Parameters such as rib width, pitch, number of ribs, membrane thickness, plate width and its length can be adjusted to meet the optical performance and mechanical property requirements of the NewATHENA optics. After laser engraving and wet-chemical wedge processing, a standard optical lithography process is being applied to pattern the reflective side of the mirror plates with a photoresist. This is the basis for making coated SPO plates. Once received by cosine, the plates undergo a visual inspection (B) to check for any non-conformities. Subsequently, mirror plates are loaded in coating carriers which are then mounted in the industrial sputtering coating machine where they are cleaned and either a single, bilayer or multilayer low-Z and high-Z coating with a thickness uniformity of better than 2% is deposited (C) to enhance the x-ray reflectivity. The lift-off and wet-chemical processing is performed in cosine’s fully automated wetbench (D) in order to prepare the mirror plates for stack production. Four automated stacking robots are being used to bend, stack and bond the patterned coated mirror plates autonomously to the desired height (E) at a speed of five minutes per mirror plate including in-situ shape monitoring metrology. Such a robotic system has a footprint of a few square meters only, is installed in an ISO-5 clean environment and can be operated remotely from outside of the cleanroom for maintaining the highest grade of cleanliness required for producing high-quality optics. After the stacking and bonding process step of individual mirror plates, a surface metrology based on phase measuring deflectometry is used to quantify small scale defects due to trapped particles in between bondable areas and large scale figure errors and thus assure the quality of the optics. With two overlapping shifts it is possible to produce two stacks within a 12-hour time window so that four stacking robots can produce eight stacks per working day meeting the flight production requirements of two coated mirror modules per day.

The produced stacks are then cut to their final NewATHENA geometry using Laser MicroJet (LMJ) cutting (F). The photos in Figure 2 show the recently commissioned and in the SPO production implemented LMJ machine in cosine’s cleanrooms and a successfully cut row-08 SPO stack with one of its SAcrificial Lateral EXtension (SALEX) parts removed.

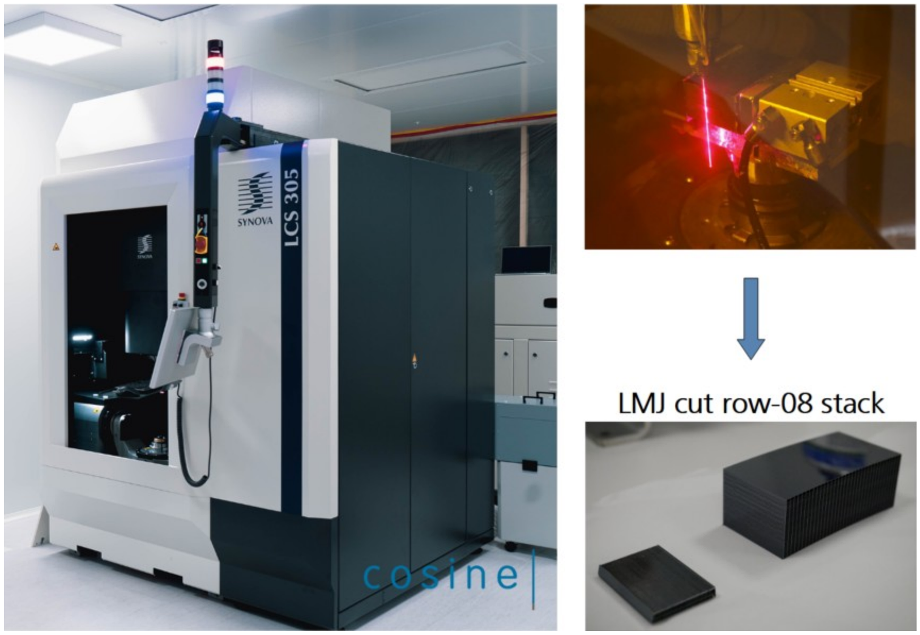

Figure 2: Left photo shows the recently commissioned and in SPO production implemented LMJ machine in cosine's clean rooms. Top right picture is a stack in the LMJ machine during the cutting process. The bright red light of the water jet is caused by inelastic scattering of the green laser light in the water. Bottom right photo shows a cut row-08 stack with one of its SALEX parts removed.

The completed stacks are then shipped to either the XPBF 2 beamline in the PTB laboratory at the BESSYII synchrotron radiation facility in Berlin, Germany or the recently commissioned MINERVA beamline at the ALBA synchrotron radiation facility in Barcelona, Spain (see Figure 3) for integrating them into mirror modules (G).

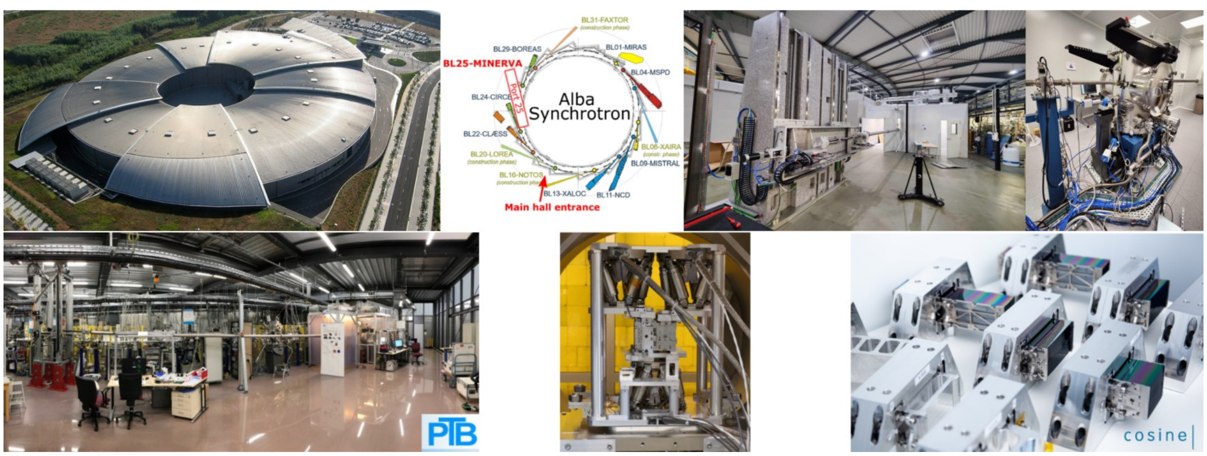

Figure 3: Top row images show the recently commissioned MINERVA beamline at the ALBA synchrotron radiation facility in Barcelona, Spain. The bottom row images represent the XPBF 2 beamline at the BESSYII synchrotron radiation facility in Berlin, Germany.

During the integration process pairs of primary and secondary stacks are co-aligned using x-rays and glued into two invar brackets, resulting in a completed mirror module (see Figure 4) which is ready for environmental testing and integration into the optical bench.

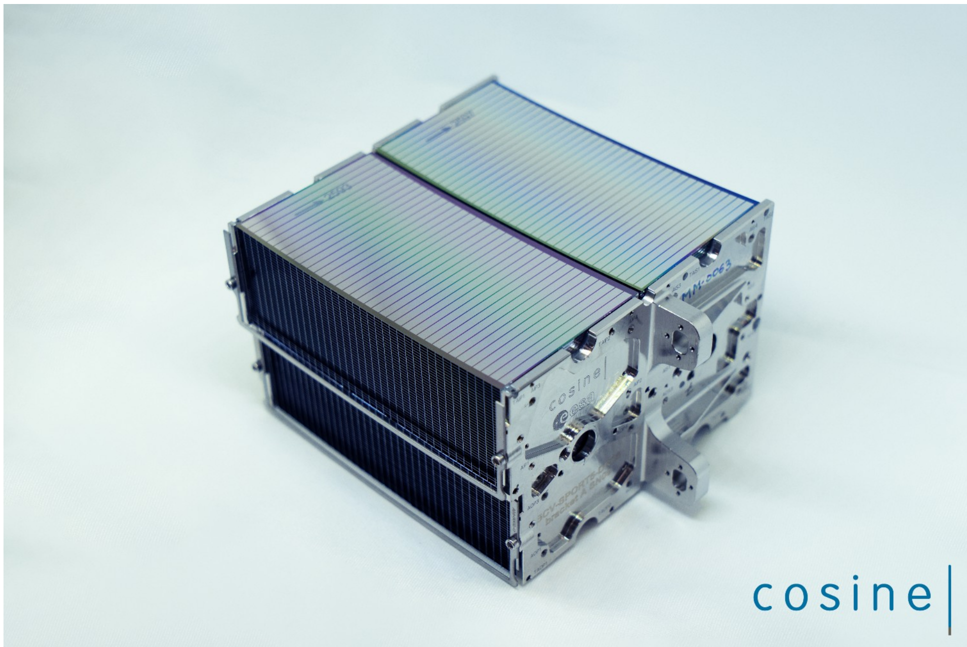

Figure 4: Patterned Ir/C coated row-08 mirror module featuring an aperture mask.

3. PERFORMANCE IMPROVEMENT

Simultaneously with our efforts to demonstrate the complete production process, we have also focused on enhancing the optical quality itself. In Figure 5, we present the evolution of the Half-Energy Width (HEW) over time, measured in double reflection using 1 keV x-rays at the XPBF 2 (x-ray parallel pencil beam facility). This facility is operated by PTB at the BESSY II synchrotron radiation facility in Berlin, Germany.

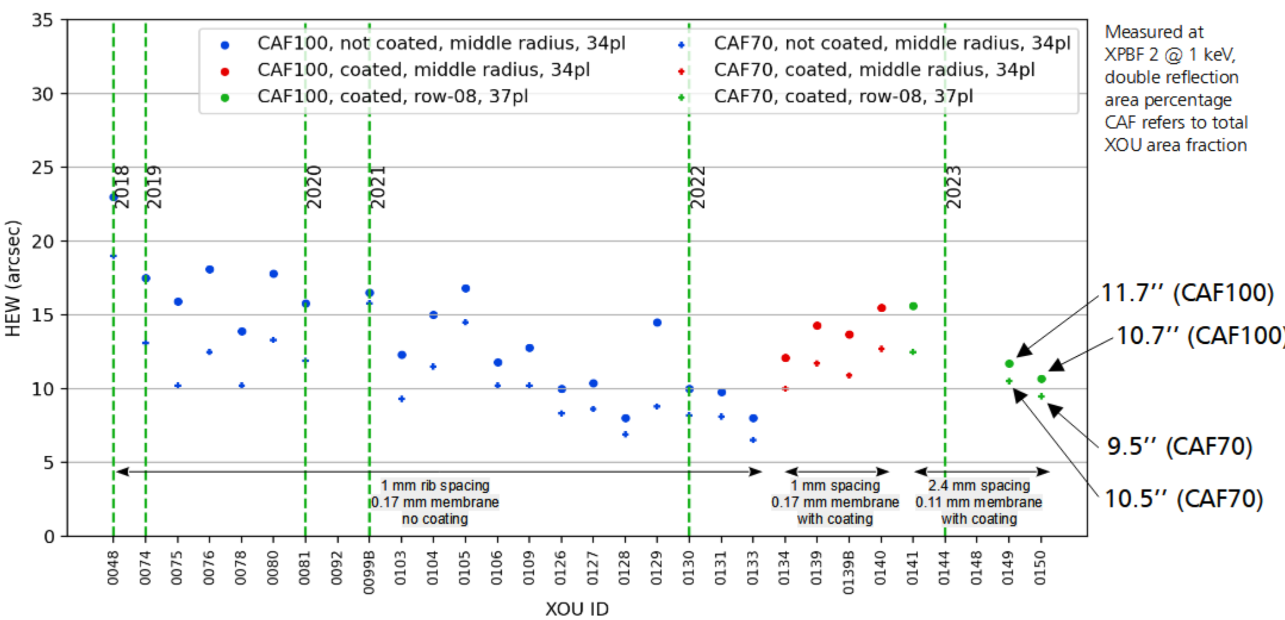

Figure 5: The time evolution of the quality (expressed as half-energy width) of uncoated and coated middle radius (r ~ 740 mm, rib pitch 1.0 mm, membrane thickness 0.17 mm) as well as row-08 (row eight of ATHENA, rib pitch 2.4 mm, membrane thickness 0.11 mm) stacks, as measured in double reflection at an energy of 1 keV at the XPBF 2 facility, operated by PTB at the BESSY II synchrotron radiation facility in Berlin, Germany.

The graph in Figure 5 presents the performance evolution of the optics since 2018. For middle radius uncoated optics (rib spacing of 1.0 mm, membrane thickness of 0.17 mm) a steady improvement of production processes led to half-energy width (HEW) of better than 10 arc-seconds over 100% of the mirror surface and 6.5 arc-seconds for a 70% contiguous area fraction (CAF). In 2022, patterned Ir/C coatings have been added to the middle radius as well as row-08 (rib spacing of 2.4 mm, membrane thickness of 0.11 mm) optics. A first round of process tuning has resulted in a performance of about 11 arc-seconds for 100% CAF and about 10 arc-seconds for 70% CAF HEW, with further process improvements being implemented in the coming year.

Since the quality of the stack is affected by the thickness of the wedge layer, which is created by wedging a relatively thick silicon oxide layer in the top surface of the mirror plate, it is advisable to explore an alternative method for producing the wedge in SPO plates. Ion Beam Figuring (IBF) is a method which can be used to process a wedge directly into the silicon on wafer level and at the same time reduce the initial TTV of the wafer. An IBF machine model scia Trim 300 was procured, installed (see photo of IBF in cosine's cleanroom in Figure 6) and commissioned in quarter four in 2022. This is a fully automated 300 mm wafer IBF machine located at cosine's premises in Sassenheim, The Netherlands. The machine can automatically process a cassette of 25 wafers at once (can be upgraded with a second cassette loader to process 50 wafers without operator interruption). In addition to its capability to create a wedge and reduce TTV, the IBF process offers the advantage of creating intricate wedge geometries, such as the 0/+2 wedge configuration. These geometries can lead to an increased effective area of the optics, particularly at higher energies exceeding 6 keV. Moreover, IBF allows for the attainment of more precise wedge tolerances, directly enhancing angular resolution. Since the commissioning of the IBF system a lot of effort is being put towards further developing the process for wedge processing on wafer level. This effort is ongoing and we expect a major part of the process development to be finished by 2024.

Figure 6: Ion Beam Figuring machine including a fully automated wafer cassette loader, as installed at cosine.

4. CONCLUSION

Progress in advancing the Silicon Pore Optics (SPO) technology for NewATHENA is robust across all fronts, moving steadily towards flight production. Our collaborative efforts demonstrate a swift development pace in both the mass production capabilities and the optical performance aspects of this technology. Every partner is actively engaged in refining every step of the production process, from the initial wafer stages to the final mirror module assembly, ensuring the possibility to realise the NewATHENA optics.

The SPO technology's readiness has achieved a level of about 6, and is being readied further for NewATHENA's implementation phase. The mass production infrastructure is being fully established, with all key process steps successfully validated using actual hardware intended also for flight production. Our technology development program concurrently addresses crucial aspects, encompassing performance enhancement, mass production readiness, and adherence to cost and schedule requirements.

Notably, SPO performance is steadily advancing, with recent optics modules showcasing patterned Ir/C coatings, extensively evaluated to maintain an impressive performance of approximately 11 arc-seconds across their entire area, and a significant portion achieving even better results, under 10 arc-seconds half-energy width (HEW).

Our dedication to process optimization remains unwavering, employing the established process chain. Additionally, we are introducing enhancements such as larger rib spacing and thinner membranes in row-01 and row-15 optics as well as multilayer coatings on row-15 optics for increasing the reflectivity at around 6 keV. Simultaneously, we are making promising strides in developing ion beam figuring of wafers as the next step in elevating performance.

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