# Stacking of Silicon Pore Optics for IXO

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Abstract

Silicon pore optics is a technology developed to enable future large area X-ray telescopes, such as the International X-ray Observatory (IXO), a candidate mission in the ESA Space Science Programme 'Cosmic Visions 2015-2025'. IXO uses nested mirrors in Wolter-I configuration to focus grazing incidence X-ray photons on a detector plane. The IXO mirrors will have to meet stringent performance requirements including an effective area of ~3 $m^2$ at 1.25 keV and ~1 $m^2$ at 6 keV and angular resolution better than 5 arc seconds. To achieve the collecting area requires a total polished mirror surface area of ~1300 $m^2$ with a surface roughness better than 0.5 nm rms. By using commercial high-quality 12" silicon wafers which are diced, structured, wedged, coated, bent and stacked the stringent performance requirements of IXO can be attained without any costly polishing steps. Two of these stacks are then assembled into a co-aligned mirror module, which is a complete X-ray imaging system. Included in the mirror module are the isostatic mounting points, providing a reliable interface to the telescope. Hundreds of such mirror modules are finally integrated into petals, and mounted onto the spacecraft to form an X-ray optic of four meters in diameter.
In this paper we will present the silicon pore optics assembly process and latest X-ray results. The required metrology is described in detail and experimental methods are shown, which allow to assess the quality of the HPOs during production and to predict the performance when measured in synchrotron radiation facilities.

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

## 1. INTRODUCTION

The International X-ray Observatory (IXO), a joint ESA/NASA/JAXA mission candidate, will be the largest X-ray telescope ever flown and shall image X-rays from sources with energies from 0.1 to 10 keV. The science requirements demand for IXO an effective area of more than 3 $m^2$ (at 1.25 keV), a focal length of 20 m (and thus a diameter of ~ 4 m) and an angular resolution better than 5". In the energy range where IXO shall operate, X-rays can most efficiently be focused by using grazing incidence reflections from high-Z surfaces with a roughness better than 0.5 nm rms. Imaging requires an even number of reflections (i.e. a Wolter-1 configuration) and the angular resolution requirement imposes stringent constraints on the figure of the mirrors.

To build such types of X-ray optics several manufacturing techniques have been established. The straight-forward approach to achieve e.g. a parabolic mirror is to grind and polish the desired material, typically glass, that is later being coated, until both figure and finish are of sufficient quality to reflect X-rays. This approach is successfully used to produce mirrors for synchrotron facilities and has also been used for example for the X-ray telescope Chandra [1], which demonstrated that it is possible to achieve an angular resolution of 0.5" on an effective area of 0.04 $m^2$ using polished gold coated glass surfaces. However, this technique has the two major drawbacks of being very time consuming and of requiring a relatively thick substrate. For astrophysical missions the X-ray lens is traditionally built from a set of concentric mirror shells. Polishing the inner surfaces becomes almost impossible, especially when one wants to keep the weight low and therefore the shell as thin as possible. Therefore a replication technique has been developed that uses high-accuracy super-polished mandrels. A gold layer is deposited on the highly-polished master mandrel and an electrolytic nickel shell is electro-formed on the gold layer. This thin shell is then taken off and combined with other shells to form a lens with a large collecting area. The process is fairly conventional but is complicated by the required tight tolerances and the inherent flexibility of the thin shells. Furthermore one requires for each shell a new master mandrel. This process produces X-ray optics with similar figure and roughness properties to that of the high-accuracy mandrel. By nesting nickel shells replicated from a high-accuracy mandrel also larger X-ray optics were made, as demonstrated with XMM-Newton [2], which achieved a collecting area of 0.43 $m^2$ at an angular resolution of 13”.

IXO will have to achieve a 7 times larger effective area and a 3 times better angular resolution than XMM/Newton and the requirements for the IXO optics can therefore be summarised as follows:

1. The mirrors have to be light-weight and therefore thin
2. The mirrors require a surface roughness of less than 0.5 nm.
3. The mirrors require a high-Z coating like gold or iridium.
4. All thin mirrors have to be mounted in a 4 m diameter structure and have to be co-aligned to form a common focus of <1 mm diameter at a distance of 20 m.
5. The total required polished mirror area is ~1300 $m^2$.

The limit imposed by the launch mass and the large diameter of 4 m prohibits the approach of XMM and Chandra of using long and therefore relatively thick and thus heavy shells; to reduce the mass, the IXO optics must be made thin and therefore segmented (requirement #1). Segmentation however means that thousands of individual mirrors (requirement #5) with a very low surface roughness (requirement #2) have to be fabricated, coated (requirement #3) mounted and co-aligned (requirement #4).

One approach to achieve this is to use thin slumped glass sheets which replicate the figure and the roughness off a high-accuracy mandrel [3-5]. There the difficulty is to solve the problem of mounting these thin shells without distorting their figure.
A novel, entirely different approach, is to directly use commercially available highly-polished wafers and to interconnect them to stiff blocks, prior to mounting and alignment. These novel optics, termed Silicon Pore Optics (SPO), are under development by the European Space Agency (ESA) [6-9].

## 2. SILICON PORE OPTICS

Silicon Pore Optics use commercial, double-sided polished high-grade 12” wafers which are mass-manufactured by the semi-conductor industry and which have the required surface roughness and flatness [10] to form X-ray optics. Using established mass production processes the individual mirrors are first diced from a wafer and then the backside is grooved, which leaves a thin membrane and a number of ribs (Figure 1). During all of these production steps the initial very low surface roughness of the silicon wafer has to be preserved using protective layers. Parameters like the membrane thickness, the rib pitch, the rib width, the plate width and its length can all be adjusted to optimize the optical performance or the mechanical behaviour of a stack. To reduce stray-light the sidewalls can be made non-reflective during production.

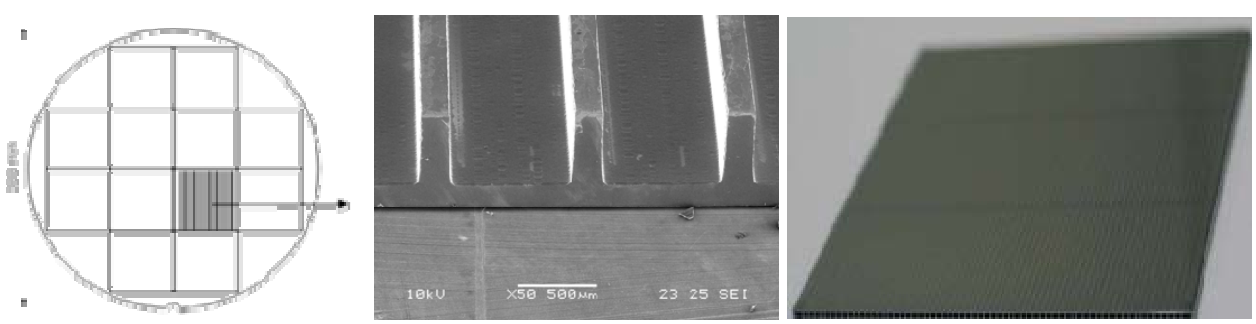


**Figure 1 (left) Silicon Pore Optics are made from commercial high-quality 12” silicon wafers which are diced into plates. (middle) The plates are ribbed (reflecting surface pointing downwards). The 0.17 mm wide ribs have a pitch of 1 mm and the membrane is 0.17 mm thick. The plates are then wedged along the rib direction (not shown) and a patterned iridium coating is applied on the reflective surface (right). The pattern keeps the areas free where the next plate will be bonded. The plate shown has dimensions of 66 x 66 $mm^2$ and a thickness of 0.775 mm.**

The mirror plates are then cleaned and elastically bent, using a fully automated stacking robot, into a conical shape. The mirrors remain flat along the pores since the Wolter-I geometry of a parabolic and a hyperbolic mirror can, for long focal lengths, be approximated by two cones (‘conical approximation’). The achievable angular resolution is then limited by the height of a single pore [11]. In the case of IXO with a focal length of 20 m and using pores with a height of 0.6 mm this results in a lower limit to the half-energy width (HEW) of about 3”. To reduce the lower limit we explore shaping the mirrors also in longitudinal direction. Using the same automated assembly robot the plates are then aligned and stacked by direct silicon bonding (Figure 2) onto a silicon mandrel. Note that only the figure of that mandrel is replicated, not its roughness. Multiple mirrors form together a stack, in which the X-rays are reflected off the reflective membrane inside a pore. Due to the inherent stiffness of the stacks, the figure of the individual mirrors remains preserved during further mounting and integration [12-15]. Two of such stacks are co-aligned and integrated into brackets to form a so-called mirror-module.

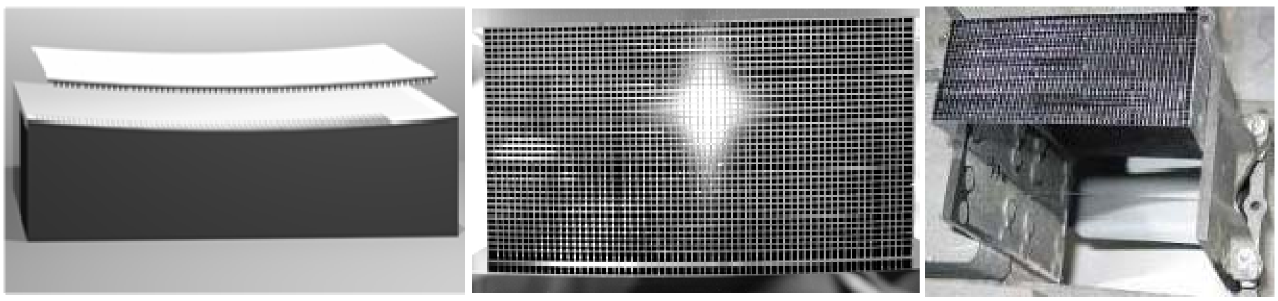

**Figure 2 The ribbed, wedged and coated silicon plates are elastically bent into cylindrical or conical shape (left). 45-70 of such plates are stacked on top of each other (middle) by an assembly robot. Two of such stacks are co-aligned and integrated into a mirror module and mounted inside a petal (right).**

Silicon Pore Optics have reached end of 2007 a technology readiness level (TRL) of 4 by performing a breadboard validation in laboratory environment: We have demonstrated the entire chain from plate production up to petal integration. This included the critical alignment step of integrating two stacks into a mirror module. The related ESA technology development project completed in 2007 with the demonstration of 17” HEW measured at 3 keV on mounted optics in flight representative configuration [16].

## 3. RECENT DEVELOPMENTS

In 2008 we have concentrated the development effort on the basic element, the stack, being the most critical element in the technology development. A number of targets were set to mature the TRL:

1. PSF improvement
2. First steps towards industrialisation of the mass production process
3. Development of high energy coatings
4. Preparation for environmental testing
5. Baffling

Significant effort was spent on further improving on the figure of the optics, which is mainly determined during stacking. The afore mentioned stacking robot is a fully automated system which is specifically developed to stack SPOs and which is a combination of standard semiconductor systems and newly developed tools. This robot has been completely redesigned and the latest, 3rd generation is operational since February 2009. The complete system has a footprint of a few $m^2$ only and is installed in a class 10 clean area. The process is summarised as follows:

A batch of plates is being cleaned and mounted inside a cleaning container, next to the stacking robot. Note that coating [17] is done before plate cleaning and therefore integrated in the presented work flow. In the centre of the stacking robot a robotic arm is located which handles the plates between the different process steps, after the initial plate cleaning step (see Figure 3).

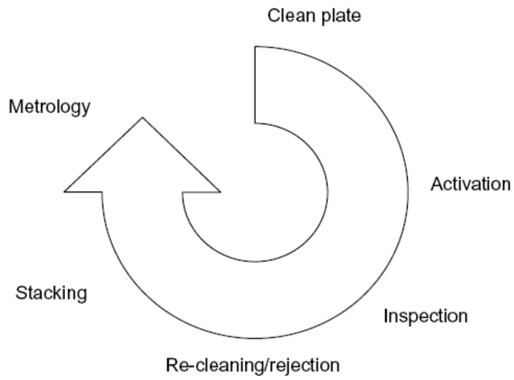


**Figure 3 Cleaning and stacking operation principle**

The robot then selects a plate and inspects it for particles. The wafer industry has many tools to inspect wafers with round edges, however for rectangular plates with ribs and sharp edges no such tools exist. We have now developed a particle detection system (PDS) based on scattered light that can detect within a few minutes on both the ribbed and the reflective size of a plate particles down to a size of 0.8 μm. Further systems to detect down to 0.1 μm particles are under development. Using the PDS it was also shown that our processes do not contaminate the plates during the stacking operation and that the limit to the cleanliness is rather determined by the initial cleaning step.

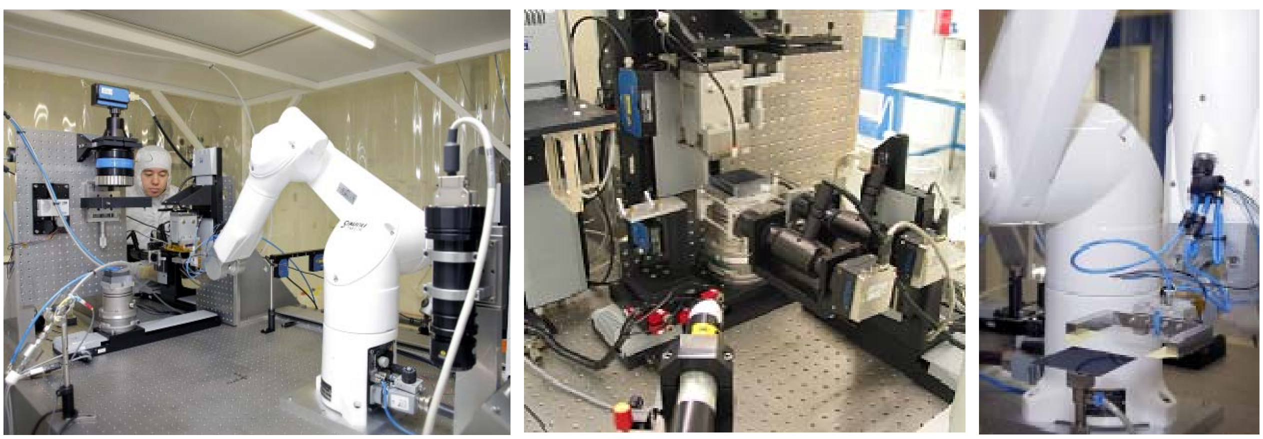

**Figure 4 Stacking robot inside the class 100 clean area at cosine. The system is installed on a vibration isolated table, consists of more than 16 axes, is fully automated and is designed to build stacks up to 100 plates high. The plates can be positioned with μm accuracy and automatically be bent into the required shape.**

After inspection the robot takes, based on the residual particle count, a decision whether to proceed with the plate or whether to reject it. The plate is then handed over to the actual stacking tool, which will elastically bend it into a cylindrical or conical shape. This tool, called a die, is then lowered onto the mandrel where it will deposit the plate or stack it onto already existing ones. The die and the mandrel are supervised by metrology systems based on auto-collimators, cameras and force sensors. We have also now integrated force measurement into the die in order to measure the dynamics of the stacking process in-situ while stacking. After the plate has been stacked its figure is measured using an interferometer equipped with a computer generated hologram acting as nulling lens. Figure errors can be measured to $\lambda/20$ and the surface deviation measurements indicate whether residual particles have been caught and what size they had.

**Figure 5 First pull tests performed on bonded plates (left). Wedged and ribbed silicon plates meeting the requirements of IXO (right).**

We have performed a first pull test to measure the breaking strength of two bonded silicon plates and it was found that the bond strength of two ribbed plates bonded flat on flat together is sufficient for the requirements of IXO. These experiments will be carried on using wedged plates in curved configuration in combination with annealing processes that can further increase, if required, the bond strength by a factor of 10.

We have developed two methods to apply structured coatings and have demonstrated stacks with Ir and C overcoating [18], W and Pt coatings. We have performed reflectometry to demonstrate that the silicon plates, after all processing steps and including coating have a rms surface roughness of 0.48 nm [17]. The development of wedged plates has led to plates [18] which are now also able to meet the requirements of IXO, which needs a 2.5 times larger wedge angle than XEUS as the wedge angle is proportional to the plate thickness over focal length. Simultaneously, it has been possible to reduce the cost per plate [18] and to test including additional features like integrated baffles.

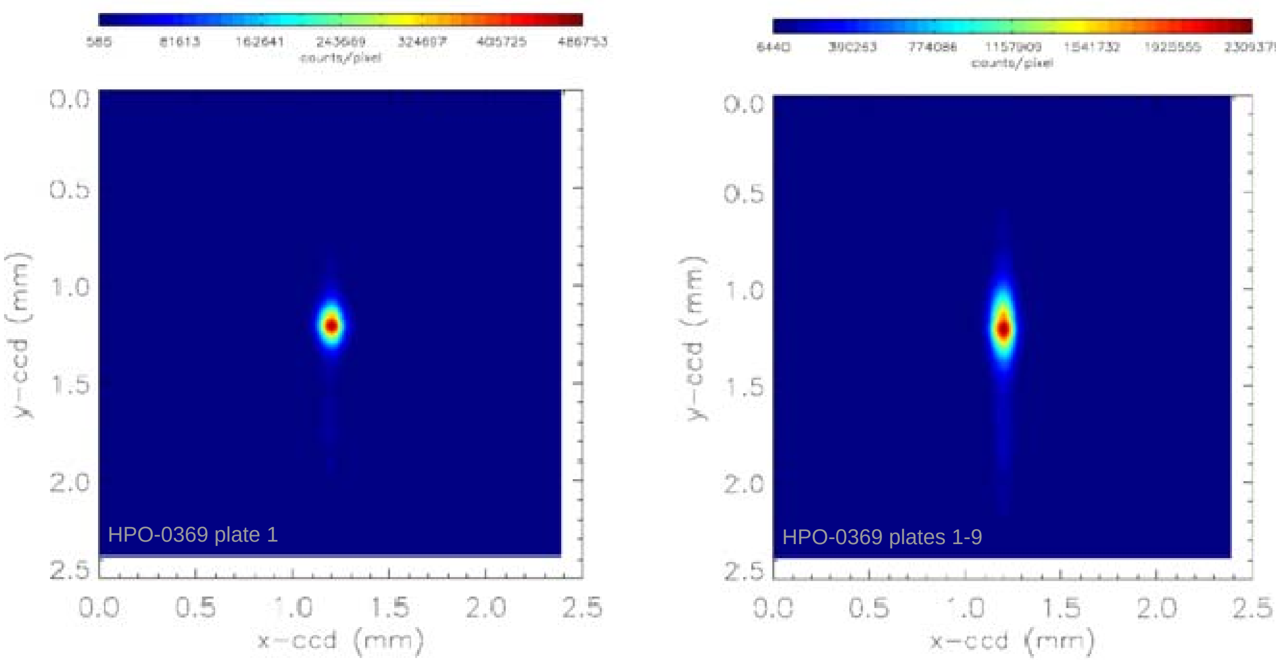


**Figure 6 LEFT: PSF of the first plate of a stack of 9 plates measured using established procedures in single reflection at 2.8 keV at the FEM beamline in the PTB lab at the BESSY synchrotron radiation facility. The full length of the plate was scanned using a 100 μm pencil beam with an intrinsic HEW of 4”. The scans where repeated every 2 mm over the full width of the plate. The resulting PSF excluding the direct beam has a HEW of 4.2”. RIGHT: The same measurement repeated on the entire stack of 9 plates. The HEW of the PSF excluding the direct beam is 7”. In double reflection this would result in a HEW of a mirror module of 10”.**

All of these measures have resulted in a significant improvement in the quality of the stacks, confirmed by X-ray measurements. Mirror modules in flight representative configuration produced in 2007 were measured, at the FEM beamline of PTB at the BESSY synchrotron radiation facility, in double reflection to have a HEW of 17” on the first 4 plates [16]. This was later confirmed by PANTER measurements.

Using the same facility and measurement procedure we have recently measured the first wedged stacks produced by the new stacking robot (see Figure 6): The first plate, measured at an energy of 2.8 keV, has a point spread function (PSF) with a HEW of 4.2”. The first 9 plates have a PSF with a HEW of 7”, which correspond in double reflection to a HEW of 10”. The full length of the plates was scanned and the scans where repeated every 2 mm over the full width of the plate.

Additional measurements [20] demonstrate that scanning the plate in full length but sampling only a thin stripe within a pore is a valid approach to determine the PSF of the entire pore. Because of the stiffening effect of the ribs in longitudinal direction the mirror surface spanned between two ribs does not have local deformations on sub mm length scales. It has been experimentally verified [20] that scanning a thin stripe of 0.05 mm width and the full length of a pore (corresponding to ~6 $mm^2$ per pore) is equivalent to measure the entire width (0.83 mm) and length of that pore (corresponding to ~55 $mm^2$), which has also been demonstrated by comparison of pencil beam an full beam illumination at PANTER [16]. This does also indicate that the broadening of the PSF with increasing stack height is caused by residual particulate contamination acting on tens of millimetre length scales and not by intrinsic mid spatial frequency errors in the plates.
We are now proceeding to integrate this new generation of stacks into mirror modules and will test them in the second half of 2009.

## 4. FURTHER DEVELOPMENT

The stacking robot was initially designed to demonstrate the technology for XEUS, which had a focal length of 50 m, at a radius of 2 m. With the transition to IXO the focal length has been reduced to 20 m with a maximum outer radius of 1.9 m. This means that the required plate length for IXO, at a pore height of 0.605 mm, ranges from about 170 mm for an inner radius of 0.4 m to 26 mm at an outer radius of 1.9 m.

In the next year a second stacking robot will be built to stack plates with the same length but at a radius of 0.74 m. Additional automated plate inspection systems are being developed and installed to further improve on the cleanliness of the silicon plates, which will allow the stacks to perform significantly better than 4”. Simultaneously PTB will upgrade the X-ray test beamline at BESSY II for ESA to allow measurements at a distance of 20 m, in the focal plane of the IXO optics. Environmental testing will be prepared by performing additional pull tests on plate and stack level. These preparations also include bracket light weighting and optimisation for integration and operation of stacks at room temperature. Note that so far the production chain was demonstrated for the more demanding XEUS requirement of integration at room temperature and operation at 150 K.

In the mid term future industrialisation of the entire production process will be pushed forward. The stacking systems are already now fully automated, but require improvement in the stacking time and redundancy of the system. The yield has to be further increased and we will perform first tests with stacks with a curvature in longitudinal direction, which will allow overcoming the limits imposed by the conical approximation.

## 5. CONCLUSIONS

The status of the technology development of silicon pore optics has been presented and discussed. The entire production chain of these light-weight and modular X-ray optics has been developed, demonstrated and tested, from plate manufacture, over ribbing, dicing, wedging, coating, stacking, assembly and integration up to petal level.

State of the art is the routine automated assembly of silicon stacks consisting of several tens of plates. We have developed the next generation of the automated stacking robots. Using this robot we have built stacks with wedged plates and measured them at the BESSY synchrotron radiation facility. The stacks achieve in single reflection a HEW of 7” on the first 9 plates, which corresponds for a mirror module in double reflection to 10”. This compares to 17” on the first 4 unwedged plates measured in 2007 and demonstrates the significant improvement in stacking quality. The complete first plate exhibits in single reflection a HEW of 4.2”.

In parallel we have developed and demonstrated stacks with patterned iridium coatings with carbon over coating inside the pores. We have successfully performed the first pull tests and are now preparing environmental tests. We have developed new wedging techniques that allow meeting the requirements of IXO and we are exploring methods to overcome the performance limits imposed by the conical approximation.

The technological issues of cleanliness and bonding are being addressed by improved assembly hardware developed in the course of the ongoing technology research program and by the steep learning curve in assembling pore optics. It shall be noted that so far no show stopper has been identified that would impede improving the performance of silicon pore optics beyond 5”.

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