Development of X-ray pore optics: novel high-resolution silicon millipore optics for XEUS and ultra-low mass glass micropore optics for imaging and timing

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ABSTRACT

Producing the next generation of X-ray optics, both for large astrophysics missions and smaller missions such as planetary exploration, requires much lower mass and therefore much thinner mirrors. The use of pore structures allows very thin mirrors in a stiff structure. Over the last few years we have been developing ultra-low mass pore optics based on microchannel plate technology in glass, resulting in square, open-core glass fibres in a concentric geometry. The surface roughness inside the pores can be as low as 0.5 nm due to the extreme stretching of the surface during production. We show how improvements in the production process have led to an improved quality of the fibres and the quality of stacking the fibres in the required geometry. To achieve even higher imaging quality as required for XEUS we have developed in parallel a novel pore optics technology based on silicon wafers. The production process of silicon wafers is extremely optimised by the semiconductor industry, leading to optical qualities that are sufficient for high-resolution X-ray focussing. We have developed the technology to stack these wafers into accurate X-ray optics, set up automated assembly facilities for the production of these stacks and present very promising X-ray test results of 5.3 arcsec HEW from single reflection off such a stack, showing the great potential of this technology for XEUS and other high-resolution low mass X-ray optics.

Keywords: X-ray optics, X-ray astronomy, Wolter, low mass, pore optics, micro-channel plate, silicon, wafer, stack, XEUS

1. INTRODUCTION

The development of low mass X-ray optics is key to the introduction of novel, more cost effective X-ray astrophysics missions, particularly those requiring very large apertures to explore the early universe. Also for remote sensing instruments on planetary exploration missions, which are based on X-ray fluorescence analysis, very light X-ray optics are a necessity.

Reducing the mass of a grazing incidence X-ray optic can be achieved by using a material that has a lower density and by reducing the thickness of the mirrors. Very thin mirrors will in general have more distortions which results in a lower imaging resolution. This can be prevented by producing the reflecting surfaces in a tightly interconnected structure, so that the mirrors span only small distances. This is achieved in pore optics. In this paper we present two technologies that we have developed to produce X-ray pore optics: one based on glass fibres, leading to ultra-low mass optics, and one based on silicon wafers, leading to high resolution optics.

High-resolution X-ray optics for applications in the energy range from 0.1 to 10 keV, a main region of interest for high-energy astrophysics, are typically based on the Wolter-I design (figure 1). Two reflections are required to produce a real image, the first from a parabolic and the second from a hyperbolic surface. Such an optic is traditionally built from concentric mirror shells, either full circle or sectors thereof, that are nested to cover a large fraction of an annular aperture and that are mounted by their ends. In a pore optic one wall of each pores is used as the reflecting surfaces, and the side walls provide extreme stiffness to the structure.

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Figure 1. The principle of a Wolter-I optic (left): incoming X-ray photons are reflected under grazing incidence from a parabolic and then a hyperbolic surface of revolution, traditionally made from a number of nested shells. A Wolter-I optic, or an approximation of it using conical surfaces, can be implemented using a large number of rectangular pores in concentric circles (right).

The surfaces do not necessarily have to follow exactly the parabolic and hyperbolic surfaces of the Wolter-I design. If the reflecting surfaces are short compared to the focal length, the effect on the imaging resolution of conical instead of parabolic or hyperbolic surfaces (conical approximation) can be made sufficiently small. In the azimuthal direction the reflecting surface inside a pore does not have to follow a circle, provided that the width of a pore is smaller than the required size of the focal spot. Because the walls in the pore structure can be very thin the reflecting surfaces can be stacked very densely, effectively leading to small pores and short optics. This allows to produce high-resolution optics even with flat reflecting surfaces inside the pores. The complete system, however, still focuses the rays, since the reflection surfaces are concentric and the inclination of the surfaces increases with the radius (figure 1 right).

Due to the thin walls in a stiff structure, a pore optics is much more compact and very light. Note that the surface area (geometric area of the mirrors themselves) remains in total the same, but is distributed over many more shells. In a traditional approach, where the mirror shells are individually produced, aligned and mounted, such a design would become prohibitive.

In this paper we present recent developments in the production of glass micropore optics based on stacking glass fibres using micro-channel plate technology, and present the recent development of silicon millipore optics based on silicon wafers from the semiconductor industry.

2. SILICON MILLIPORE OPTICS

The requirements for XEUS are very challenging when compared to the state-of-the-art large collecting area telescope XMM-Newton\cite{1, 2}:

- 20 times larger collecting area: from 0.5 m$^2$ to 10 m$^2$, requiring of the order of 3000 m$^2$ of mirror surface. This requires the use of an industrial material and process.

- 3 times better resolution: from 15 arcsec to 5 arcsec and a goal of 2 arcsec. This resolution has been achieved using existing technologies but this would lead to an extremely large and heavy telescope. Instead a perfect starting material should be used, and the production of modules should be decoupled from their integration.
Figure 2. The surface roughness of high-grade commercial wafers is measured to be between 0.4 and 0.5 nm RMS between 5 and 500 mm\(^{-1}\) (left, 5 nm peak to peak). An interferogram of a sliced wafer (right) shows that it is dominantly cylindrically curved, however by no more than 1.5 \(\mu\)m peak to peak; the corresponding half-energy width is 1 arcsec.

- 10 times lighter: from 2000 kg m\(^{-2}\) to 200 kg m\(^{-2}\) collecting area at 1 keV. This requires very thin mirrors, and this can only be achieved for large areas when the optics are inherently stiff.

The glass micropore optics that we have been developing over the last few years (see below) will most likely not be able to meet these requirements, due to the fact that the inside of the pores is not accessible during production, so that the quality of the reflecting surfaces is determined by the intrinsic quality of the glass and the production process. We therefore have developed a technology that is based on the following ideas:

- as starting material we use silicon wafers from the semiconductor industry,
- the wafers are stacked into a pore structure with concentric cylindrical surfaces.

It has been proposed and tested to use silicon wafers before, but without the pore structure the imaging quality is not sufficient.\(^4\) For a discussion of the XEUS mission and general aspects of the optics we refer to earlier publications.\(^5, 6\)

2.1. Production method

Commercially available high-grade silicon wafers are mechanically almost perfect, and silicon has a density that is much lower than the nickel that was used for XMM-Newton (2.3 instead of 8.9). Standard wafers are today already processed to high accuracy in terms of roughness and flatness (figure 2) and planparallelism. Traces along the length of a wafer show height variations at length scales up to 70 mm of no more than 100 nm.

The process starts by taking rectangular cuts of wafers, and treating the back side with a chemo-mechanical process such that ribs remain with a very accurate height and a highly polished surface (figure 3).

To stack the plates they are bent into a cylindrical shape with the required radius, and then pressed onto the previous plate, thus forming a pore structure (figure 4). This results in a direct optical bond between the highly polished ribs and the surface of the previous plate. After the stack is built it could be heated to make the bonds (partially) covalent.
Figure 3. The optics are built up from rectangular cuts of commercial silicon wafers. The wafers are processed chemomechanically such that ribs remain, providing a thin membrane with ribs of very accurate height and highly polished surfaces.

Figure 4. Ribbed plates are stacked onto a mandrel that provides the correct starting curvature.

The accurate height of the ribs, a direct result of the good plan-parallelism of the wafers, ensures that the plates are accurate concentric cylindrical or conical surfaces. Before stacking, the ribs can be etched such that their height varies by about 1 μm over a typical length of 70 mm, which provides the required small angle between consecutive plates.

To stack the plates we have set up assembly facilities in our laboratories. An automated optical assembly system was developed and placed in a class-100 clean room environment (figure 5). The system is fully computer controlled and has 16 actuators, some of them nano-actuators, an interferometer, digital microscopes with real time image analysis (Fig. 6), and force sensors.

3. PERFORMANCE

Over the last year we have produced and tested about 10 prototype stacks. They typically consist of 5 to 6 plates of 70x70 mm² (figure 7). These stacks were measured at a synchrotron facility using pencil beams with varying energy and diameter.
Figure 5. A fully automated stacking robot was developed to stack the plates. The setup is placed in a class-100 environment in the cosine clean room laboratories.

Figure 6. Real-time image analysis of digital microscope images provides alignment to μm accuracy (left). Interferometry is used to measure the shape of the plates to high accuracy during stacking (right).
Figure 7. Front side of a prototype stack consisting of 6 plates of 70x70 mm$^2$, providing 5x31 pores with a total area of 2 cm$^2$.

Figure 8. Measurements of the scattering (left) and the reflectivity confirm the excellent surface roughness of the wafers also after processing. The large-angle offset in this figure is caused by detector background, not scatter. The reflected spot (right) which has a footprint of 0.05x5 mm on the surface of the mirrors is not noticeably larger than the incident beam, which has a divergence of 1.5 arcsec.

Measurements of the scatter distribution (figure 8) as well as the reflectivity as a function of energy have verified that the surface roughness of the reflecting surfaces corresponds to a roughness of about 0.4 to 0.5 nm RMS.

The reflected spot size of a beam with a footprint onto the mirror of about 50x5000 µm (Fig. 8 (right)) was measured not to be significantly larger than the incident beam which has a divergence of 1.5 arcsec. This confirms that medium-scale errors (ripple) are of the order of 1 arcsec or less.

Figure 9(left) shows the point spread function that is constructed from pencil beam measurements covering the central 70% of the aperture, corresponding to about 2 cm$^2$. The half-energy width is about 5.3 arcsec, and the FWHM is about 7.9 arcsec, for reflection by a single stack. The area outside the central 70% of the stack is of less quality because of problems with bonding the first plate onto the mandrel. This problem is already visible in Fig.2(right), and arises from the fact that the mandrel has no flat facets underneath the ribs and is currently polished to a normal optical quality only.

Figure 9(right) shows the result that is obtained when this stack would be used to fill a full circle. The HEW is the same as for a single stack, but the FWHM goes down to 3.1 arcsec due to the effect from adding up an elongated PSF over all angles in a circle, which results in a circularly symmetric PSF.
Figure 9. The point spread function of one of the measured stacks as constructed from pencil beam measurements over the central 70% of the aperture (left). The HEW is 5.3 arcsec. The FWHM of a single stack is 7.9 arcsec, which is large compared to the HEW due to the large asymmetry of the PSF. The point spread function of one of the measured stacks (right), taking into account the effect of placing the stacks along a full circle just as it would be in the final optic. The encircled energy is again 5.3 arcsec, but the FWHM is reduced to 3.1 arcsec.

Figure 10. The production principle of micropore optics based on micro-channel plate technology. A square glass core is inserted into a cladding of a different type of glass, and using an oven it is drawn into a thin fibre. These are stacked into a pre-stack and this is drawn again into a thin fibre. The resulting multi-fibre is stacked into a radial geometry, thin plates are cut from it and the cores are etched away, leaving millions of square pores.
Figure 11. The improved method to produce the cladding glass leads to a much sharper corner and more even distribution of the cladding glass (right) than before (left).

4. GLASS MICROPORE OPTICS

Over the last few years we have been developing a technology that leads to even lower mass X-ray optics, based on micro-channel plates (MCPs). MCPs were developed and are being mainly produced for night vision applications, and already look back on a significant heritage. In the past we have reported the production of the first X-ray lens fabricated and tested, based on radially stacked glass multi-fibres.\(^3\) In figure 10 the principle of production is illustrated. The first optic demonstrated the possibility to produce very low mass X-ray optics looking very much like a bi-convex glass lens in the visible. While being a major step forward, it also made the current limitations of the technology evident: the angular resolution of the doublet was a few minutes of arc, and the effective area only a fraction of the geometric area. To improve this the entire production method of the optics has been improved. Here we present results of these improvements, which should in the near future result in micropore optics of much better quality.

4.1. Glass and fibres

The main part of the production process is to draw a thin fiber from a thick glass block, consisting of a higher melting core glass (defining the reflecting surfaces of the pore walls) and a non-soluble cladding glass (which finally forms the MCP walls). In the first step the block consists of a precision-ground square core or about \(x\) mm of solid glass, which a square cladding around it having a wall thickness of a few mm. The fiber is drawn in a drawing tower that basically consists of an oven to melt part of the glass block and a traction system to draw the fiber. At the bottom of the tower the fiber is broken into regular lengths, and then stored.

The production method of the core glass was modified so that the thickness of the cladding is much more uniform and the corners are much sharper. This results in a much improved geometry of the cladding after the first draw (figure 11). After stacking, this results in smaller gaps between the fibres, and hence less glass flow during fusion and subsequent drawing.

In order to improve the drawing process an extensive metrology system has been developed to monitor and control in real time the drawing process, and measure in detail a representative fraction of the produced fibers after production (figure 12). The drawing tower will automatically cut the fibre into sections of equal length. As soon as a fibre is cut it is stored in one of several hundred separate tubes in the container, which is moved by computer control. The data is used to connect and control the production process in a closed loop, and to select the best fibres after the production.
The size control was improved by installing a two-dimensional commercially available fibre size measurement system, which measures the size of the fibre in two orthogonal directions based on obscuration of a scanning laser beam. The drawing process is directly driven by the size measurement and the recording of the size is used to determine the periods of stable draw conditions and fibre size within the required tolerance. This in combination with a more accurate stacking mould, leads to a better alignment of the fibres in the multifibre stack (figure 13).

After the first draw several hundred fibres are stacked and fused together at an elevated temperature. The resulting stack is put into the drawing tower a second time, this time to produce multi-fibres of about 1 mm consisting of several hundred fibres. Again this drawing process is monitored using the newly developed metrology system.

The multi-fibres are then stacked together into the required geometry. For an imaging optic they are stacked into a radial configuration in concentric circles. Instead of circular plates, we are now producing sectors, which
Figure 14. A new method to stack the multi-fibres into a radial geometry has reduced the distortions of the multi-fibres and improved the alignment of the multi-fibres (left: old, right: new).

allow to assemble larger optics from limited size elements. A special mould was developed to stack the multi-fibres into a sector shape, with well-defined side walls and starting cylindrical surface. In order to inspect and improve the quality of the stacking, a high-resolution camera with a metrology lens is used to inspect the quality of the stacking as it is underway. These changes have resulted in much better alignment of the multi-fibres, and elimination of the large distortions between the multi-fibres that were previously present (figure 14).

The resulting blocks are currently being cut, etched and slumped, after which we can measure the resulting improvement in X-ray focussing properties.

4.2. Applications

The extremely low mass of glass micropore optics would allow to construct very large apertures with affordable weight. Figure 15 shows the countrate that could be obtained with such an optic from a source of 1 mCrab with an inverse square powerlaw spectrum in the band 1 to 10 keV. The plot shows the countrate as a function of the radius of the optic for a few different focal lengths. At a focal length of 10 m and a radius of 4 m a countrate of $10^3$ s$^{-1}$ could be obtained, allowing to achieve millisecond resolution. Such an optic would require only a few hundred kg of glass micropore optics. These calculations assume that we are able to coat the inside of the pores with gold; with other coating materials a similar result is obtained.

The low mass also allows to construct an X-ray imaging optic with appreciable collecting area for missions that would otherwise prohibit the use of an X-ray optic. This is the case for planetary missions, where the typical mass of 0.3 kg per cm$^2$ for Ni electroformed shells is prohibitive for most applications. An imager with a focal length of 1 m and an effective collecting area of 100 cm$^2$ could be implemented using a few hundred grams of glass, allowing to fly a high-resolution X-ray fluorescence spectrometer for example to Mercury.

5. CONCLUSION

We have developed a novel type of high-resolution pore optics specifically targeted for XEUS. The resulting optics are low mass, about 200 kg m$^{-2}$ collecting area at 1 keV. The technology is based on commercially available silicon wafers, which have sufficient optical quality for this application. The wafers are cut into rectangles and ribbed. The ribbed plates are bent into a cylindrical shape and then stacked onto a mandrel, which can later be removed. The resulting stacks are rigid and can be assembled into almost arbitrarily large apertures. We have set up robotic assembly facilities and produced the first stacks with this equipment. X-ray testing of the first prototypes has shown, in single reflection, a half-energy width of 5.3 arcsec, and a FWHM (taking into account the effect of producing a full circle of these optics) of 3.1 arcsec. This performance is currently obtained over
Figure 15. The countrate that would be obtained from a 1 mCrab source between 1 and 10 keV using a glass micropore optics, as a function of radius and for a few different focal lengths.

70% of the aperture of a stack of 6 plates. A tandem of two of these stacks is expected to result in a performance of about 8 arcsec HEW and 4 arcsec FWHM. The performance is currently limited by the quality of the bond of the first plate onto the mandrel and dust accumulating on the plates. We plan to resolve these problems in the coming period, after which we will start regular production. That way we can optimise the process and improve the performance and yield, hopefully approaching the ultimate performance of this technology, which for the XEUS geometry is limited by diffraction and the conical approximation to about 2 arcsec.

The production of glass micropore optics is considerably improved through improvements in the entire production process and more tight quality control using specially developed metrology equipment. The geometry of the resulting plates is much improved; after final processing measurements will show how much the imaging properties have improved by these changes.

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