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# Novel Optics for X-Ray Telescopes

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**Abstract** Thermally formed thin glass foils and optically shaped Si wafers are considered to be among the most promising technologies for future large space X-ray telescopes. We present and discuss the recent progress in these technologies, as well as the properties of test mirrors produced and tested. For both technologies, both flat and curved samples have been produced and tested. The achieved profile accuracy is of the order of 1 micrometer or better, while the bending technologies maintain the intrinsic fine surface microroughness of substrates (better than 0.5 nm for glass and around 0.1 nm for Si wafers).

**Keywords** X-ray telescopes · X-ray optics · X-ray astronomy

## 1 Introduction

The majority of future space X-ray astronomy and astrophysics projects require accurate but light and high-throughput multiple nested X-ray optics. There are quite numerous applications requiring the use of innovative and high-quality X-ray reflecting

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foils and flats in X-ray instrumentation including X-ray imaging devices. These applications include the X-ray optics of the Wolter 1 geometry, the X-ray wide field optics of the Lobster-eye geometry, grazing-incidence X-ray flat mirrors, bent X-ray mirrors, various X-ray focusing elements, X-ray waveguides, X-ray planar capillaries, etc. They are based either on the replication of flat masters or on other methods of preparation of reflecting foils. The thin X-ray reflecting flats and foils have started to play an increasingly important role in innovative and high-sensitivity future experiments in X-ray astrophysics. They have opened new room for various novel approaches and innovative solutions including those never discussed before [3] [4] [5] [6].

It is obvious that the most important use of innovative X-ray reflecting foils and flats is in the future large-aperture and high-sensitivity X-ray imaging experiments. For the IXO telescope (ESA/NASA/JAXA) and analogous space projects, a segmented Wolter 1 telescope is proposed. There are some other plans for large Lobster-eye segmented modules, as well as for segmented Kirkpatrick-Baez systems. The segmentation of the mirror surfaces is extremely important not only for the production of mirror shells, but also for keeping the weight of large telescopes within reasonable limits [1] [2].

Future large X-ray telescopes (such as IXO considered by ESA/NASA/JAXA or Constellation X by NASA) [18] require precise and light-weight X-ray optics [14]. Novel approaches and technologies are supposed to be used. In this contribution, we refer to preliminary results of test X-ray mirrors produced by glass thermal forming (GTF) and by shaping Si wafers. Both of these technologies seem to be promising and worth being further investigated. Both glass foils and Si wafers are commercially available, have excellent surface microroughness of a few 0.1 nm, and low weight (the volume density is  $2.5 \text{ g cm}^{-3}$  for glass and  $2.3 \text{ g cm}^{-3}$  for Si). Innovative technologies are expected to be exploited in shaping these substrates to achieve the required precise X-ray optics geometries without degradation of the fine surface microroughness.

There is a growing need for large segmented X-ray foil telescopes of various geometries and geometrical arrangements [7] [8]. This includes the large modules of the Wolter 1 geometry (the one to be used for the X-ray astronomy mission IXO), the large Kirkpatrick-Baez (K-B) modules (as these can play an important role in future X-ray astronomy projects as a promising alternative and one less laborious to produce) as well as the large Lobster Eye modules in the Schmidt arrangements. Although these X-ray optics modules differ in the geometry of their foils/shells arrangements, they do not differ much from the point of the view of the manufacture and assembly of the foils or shells, and also share all the problems of calculations, design, development, weight constraints, manufacture, assembling, testing, etc. It is evident that these problems are common and rather important for many of the large-aperture X-ray astronomy projects.

We have developed various laboratory samples of the above mentioned X-ray optics modules based on high-quality X-ray reflecting gold-coated glass foils. Glass represents a promising alternative to the recently widely used electroformed nickel shells, the main advantage being much lower specific weight (typically  $2.5 \text{ g cm}^{-3}$  compared with  $8.8 \text{ g cm}^{-3}$  for nickel); however, the technology needs to be further exploited and improved to achieve the required accuracy. For the large prototype modules of dimensions equal to or exceeding  $30 \times 30 \times 30 \text{ cm}$ , mostly glass foils with a thickness of 0.75 mm have been used, although in future this thickness can be further reduced down to 0.3 mm and perhaps even less (we have successfully designed, developed and tested systems based on glass foils as thin as 30 microns, albeit for much smaller sizes of the modules). More recently, the use of precisely shaped silicon wafers in advanced space X-ray optics

has also been explored, and first laboratory samples have been developed and tested. These preliminary results are also briefly presented and discussed in this paper.

Although glass and recently silicon wafers are considered to represent most promising materials for future advanced large aperture space X-ray telescopes, there exist also alternative materials worth further study, such as amorphous metals and glassy carbon [11]. In this paper, however, we will focus on thermally formed glass foils and on shaped silicon wafers.

## 2 THERMAL GLASS FORMING

The volume density of glass is nearly four times less than that of electroformed nickel layers. This is why we have carried out an extended study focused on applications of gold-coated glass foils with a thickness of between 0.03 mm and 1 mm. The glass foils may be used either as flats, or they may be shaped or thermally slumped to achieve the required geometry. In spite of the promising inherent properties of glass a lot of work is still waiting to be done in order to mature glass foil technologies, to prove their potential, and to show successful applications. The glass foils and flats were used e.g. in Lobster Eye X-ray telescope test modules (with a thickness of foilsof between 0.03 and 0.75 mm and sizes between 3 and 300 mm). The experience acquired this way can also be applied to the other types and arrangements of multi-foil X-ray optics (MFO).

Glass foils for the MFO can be used either flat or curved, while the curved foils can be either bent (without heat) or thermally shaped. Bent glass foil optics has already been successfully used for a test laboratory sample for a XEUS-like optics module (the 0.75 mm thick and 300 x 300 mm large glass foils were bent to achieve the required parabolic profile). The thermal forming of glass is not a new technology since it has been used in various regions of glass industry and glass art as well as in the production of Cerenkov mirrors. However, the application of this technology in X-ray optics is related to the need to significantly improve the accuracy and minimize the errors. As a first step, small (76 x 26 mm, 0.75 mm thick) glass samples of various types provided by various manufacturers have been used and thermally shaped. The geometry was either flat or curved (cylindrical or parabolic). The project continues with larger samples and further profiles. Although we focus on curved shells, since the main goal is to develop a technology meeting the requirements for the large future X-ray telescopes with the Wolter geometry, the replication of flat foils represent another important application. This approach is expected to improve the flatness of X-ray flats (foils) needed for e.g. Lobster Schmidt lenses.

The small glass samples were thermally formed at the Centre for Advanced X-ray Technologies, Reflex, Prague (now RITE, Rigaku Innovative Technologies Europe), as well as at the Institute of Chemical Technology in Prague. For large samples (300 x 300 mm), the facilities at the collaborating Optical Development Workshop in Turnov have been used. Already for these tests, our idea is to develop technology suitable for inexpensive mass production of thin X-ray optics shells. This means that we avoid expensive mandrels and techniques not suitable for mass production or too expensive. Numerous glass samples have been shaped and tested. The shapes and profiles of both mandrels as well as the resulting glass replicas have been carefully measured by metrology devices. The preliminary results show that the quality of the technology process and resulting quality of the thermal glass replica can be significantly improved by optimisation of the material and design of the mandrel, by modification of the thermal

forming process, as well as by optimisation of the temperature. After the (partly significant) modifications and improvements we obtained the resulting deviation of the thermally formed glass foil from the ideal designed profile of less than 1 micrometer (peak-to-valley value) in the best case. However, this value is strongly dependent on the exact temperature, so we believe that further improvements are still possible. The fine original microroughness (typically better than 1 nm) of the original float glass foil was found not to be degraded by the thermal forming process.

We note that our approach to thermal glass forming is different from those used by other authors [17] [19].

### 3 SILICON WAFERS

#### 3.1 X-ray optics based on Silicon wafers

Another alternative recently considered as most promising [14] [15] is the use of X-ray optics based on commercially available silicon wafers manufactured mainly for the semiconductor industry. Silicon is relatively light (volume density  $2.3 \text{ g cm}^{-3}$ ) and already during the manufacture process it is lapped and polished (either on one side or on both) to a very fine smoothness (better than a few times 0.1 nm) and thickness homogeneity (better than 1 micrometer). The recent baseline optics for the XEUS X-ray telescope design is based on X-Ray High precision Pore Optics (X-HPO), a technology currently under development with ESA funding (RD-Opt, RD-HPO), with a view to achieving large effective areas with low mass, reduced telescope length, high stiffness, and a monolithic structure, suitable for the thermal environment and simple to align [15]. In addition, due to the higher packing density and the associated shorter mirrors required, a conical approximation to the Wolter-I geometry becomes possible. X-HPO optics are based on ribbed Silicon wafers stacked together. The forming of the Si wafers to achieve a conical approximation is achieved by stacking a large number of plates together using a mandrel. The typical size of the used Si wafers is 10 x 10 cm [15].

We should like to mention the development of an alternative design of innovative precise X-ray optics based on Silicon wafers. Our approach is based on two steps, namely (i) development of dedicated Si wafers with properties optimised for the use in space X-ray telescopes and (ii) precise shaping of the wafers to optical surfaces. The stacking to achieve nested arrays is performed after the wafers have been shaped. This means, that in this approach Multi-Foil Optics (MFO) is created from shaped Si wafers. For more details on MFO see [16].

This alternative approach does not require a ribbed surface of the Si wafers used, hence the problem that any deviation, stress, and/or inaccuracy will be transferred from one wafer to the neighbouring plates or even to the whole stacked assembly will be avoided. On the other hand, suitable technologies have to be developed for precise stacking of optically formed wafers to a multiple array.

The current Si wafers available on the market are designed for the use mainly in the semiconductor industry. It is obvious that the requirements of this industry are not the same as the requirements of precise space X-ray optics.

The main requirements for the application of Si wafers in space X-ray optics are (i) low volume density ( $2.3 \text{ g cm}^{-3}$ ), which is more than 4x less than the electroformed nickel used in the past for galvanoplastic replication of multiply nested X-ray mirrors

and slightly less than the alternative approach of glass foils, (ii) very high thickness homogeneity, with deviations of less than 1 micron over 100 mm, and (iii) very small surface microroughness on one or both sides (typically of the order of a few times 0.1 nm or even less).

On the other hand, Si wafers form a monocrystal (single crystal) with some specific properties and these must be taken into account. Moreover, the wafers are fragile and their precise bending and/or shaping is very difficult (for thicknesses required for X-ray telescopes i.e. around 0.3 - 1.0 mm; the thinned Si wafers with thickness below 0.1 mm form an exception). Also, while their thickness homogeneity is mostly perfect, this is not the case for the flatness of commercially available wafers (note that we mean here the deviation of the upper surface of a free standing Si wafer from an ideal plane, while in the semiconductor community usually flatness is represented by a set of parameters).

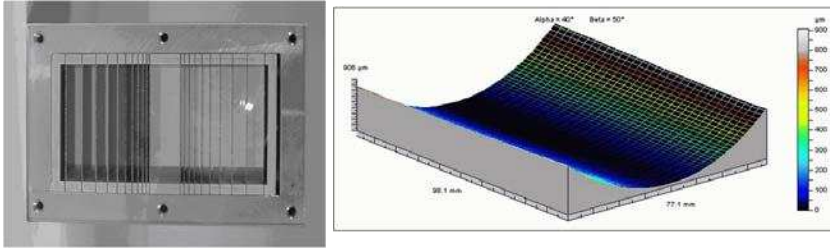
It is obvious that in order to achieve the very high accuracy required by future large space X-ray telescope experiments like IXO, for application in X-ray optics the parameters of the Si wafers already need to be optimized at the production stage. This is why we have established a multidisciplinary working group including specialists from the development department of the Si wafer industry with the goal to design and manufacture Si wafers optimized for application in X-ray telescopes. The manufacture of silicon wafers is a complicated process with numerous technological steps, which can be modified and optimised to achieve the optimal performance. This can be useful also to further improve the quality of the X-HPO optics.

The standard microroughness of commercially available silicon wafers (we have used the products of ON Semiconductor Czech Republic) is of the order of 0.1 nm as confirmed by several independent measurements by different techniques including Atomic Force Microscopy (AFM). This is related to the method of chemical-mechanical polishing used during the manufacture of Si wafers and meets the requirements of future X-ray telescopes. In fact, the microroughness of Si wafers exceeds significantly the microroughness of glass foils and most of other alternative mirror materials and substrates.

However, the flatness (in the sense of the deviation of the upper surface of a free standing Si wafer from a plane) of commercially available Si wafers was found not to be optimal for use in X-ray optics. Most Si wafers show deviations from the plane of less than 10 microns. After modifying the technology process during the Si wafer manufacture, we were able to reduce this value to less than a few microns. Also the thickness homogeneity was further improved. In collaboration with the manufacturer, further steps are planned to improve the flatness (deviation from an ideal plane) and the thickness homogeneity of Si wafers. As already mentioned, these and other planned improvements introduced at the stage of the Si wafer manufacture can be applied also to other designs of Si wafer optics including the X-HPO.

### 3.2 Shaping of Si wafers

Due to the material properties of monocrystalline Si, the Si wafers are extremely difficult to shape. However we feel that we have to overcome this problem in order to achieve the high accuracy and stability required by future large X-ray telescopes. The final goal is to provide optically shaped Si wafers with no or little internal stress. Mechanical bending of Si wafers at room temperature on a mandrel as considered by the X-HPO technique means non-negligible internal stress, which means that we may not



**Fig. 1** Test module for test performance of glass foils vs. shaped Si wafers. Test for the elliptical Kirkpatrick-Baez optical system, focus 0.5 m, 58 x 50 x 100 mm, glass foils 40 x 40 x 0.3mm, Si wafers 40 x 40 x 0.4 mm. (left). Thermally formed glass, parabolic profile  $R = 150$  mm, 100 x 150 x 0.75 mm, STILL profilometer, Peak-to-valley deviations from ideal shape  $\sim 0.7$  microns in the best case (right).

achieve the required very long-term stability and very fine angular accuracy of order of a few arcsec.

We have considered and tested three various alternative technologies to shape Si wafers to precise optical surfaces. The samples shaped and tested were typically from 100 to 150 mm large, typically from 0.6 to 1.3 mm thick, and were bent to either cylindrical or parabolic test surfaces.

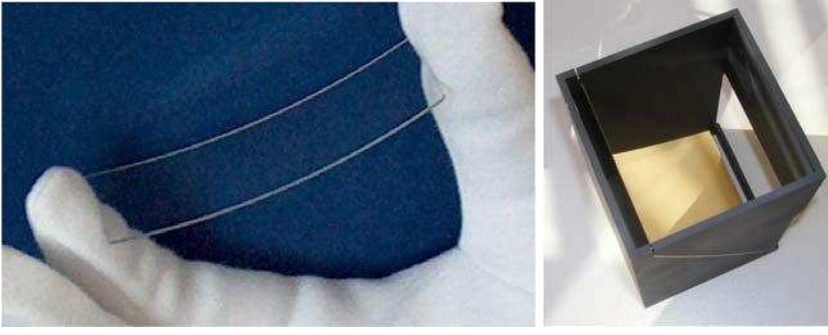
One method (technology I) is the method of plastic deformation of monocrystalline Si at high temperature i.e. thermal shaping in analogy to the thermal shaping (slumping) procedure applied for glass X-ray optics[16]. This requires very high temperature (typically more than 1000C) as well as special atmosphere during the forming to avoid the surface degradation of the wafer and of the mandrel.

The two alternative technologies (technology II and III) that have been proposed, developed, and tested rely on physical and chemical processes, at this stage proprietary, and have also led to test samples shaped to precise optical surfaces.

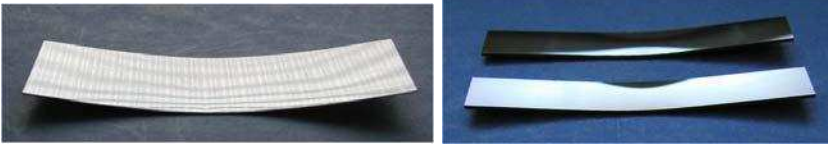
The test samples of optically bent wafers with all three technologies have been carefully measured and tested. Preliminary results are presented and discussed below. The measurements include Taylor-Hobson mechanical and STILL optical profilometry as well as optical interferometry (ZYGO) and AFM analyses.

It has been confirmed that none of the three technologies studied degrades the intrinsic fine microroughness of the wafer. While the two physical/chemical technologies exploited give peak-to-valley deviations (of the real surface of the sample compared with an ideal optical surface) of less than 1 to 2 microns over 150 mm sample length, as preliminary values, the deviations of the first thermally bent sample are larger, of the order of 10 microns). Taking into account that the applied temperatures as well as other parameters were not optimised for this first sample, we expect that the value can be further reduced down to c. 1 micron and perhaps even lower. Fine adjustments of parameters can however further improve the accuracy of the results also for the other two techniques.

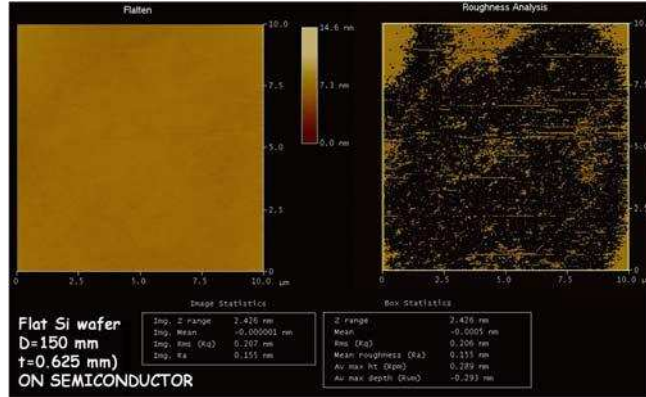
We plan to further exploit, develop, and optimize the forming technologies described above, in order to further improve the accuracy of the optical forming. Moreover we plan the detailed measurements of internal stress to guaranty the long term stability of the mirror array as required by most of the space applications (life times exceeding 10 years).



**Fig. 2** Glass foil thermally formed to a cylinder profile 75 x 25 x 0.75 mm (left). Glass foils thermally formed to a parabolic profile 100 x 150 x 0.75 mm (right).



**Fig. 3** Thermally formed Si foil to test cylinder ( $R = 150$  mm, 72 x 23 x 0.325 mm) (left). Thermally formed Si foils to test cylinder ( $R = 150$  mm, 50 x 7 x 0.625 mm)(right).



**Fig. 4** AFM measurement of a standard flat Si wafer diameter  $D=150$  mm, thickness  $t=0.625$  mm, manufactured by ON SEMICONDUCTOR Czech Republic.

## 4 CONCLUSIONS

Glass Thermal Forming and Si wafer bending are among the most promising technologies for future large space X-ray telescopes studied and discussed in this paper. In both cases, promising results have been achieved, with peak-to-valley deviations of final profiles from the ideal ones being of order of 1 micron in the best cases, with space for further essential improvements and optimization.

For the innovative Si-wafer-based X-ray optics, an interdisciplinary co-operation (team with 10 members) was created within the Czech Republic with experienced

teams including researchers from the large company producing Si wafers. Si wafers were successfully bent to the desired geometry by three different techniques. In the best cases, the accuracy achieved for the 150 mm Si wafer is 1 to 2 microns peak-to-valley for the deviation from an ideal optical surface. The experiments continue to further improve the forming accuracy.

The bending before stacking is advantageous e.g. to avoid the increase of the internal stress and to allow a very long-term stability of the mirror array. The production of Si wafers is very complex, and there is a need to modify and optimize the parameters already at the production stage.

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