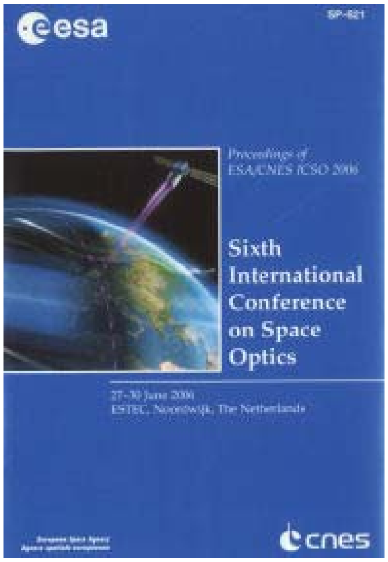
International Conference on Space Optics—ICSO 2006

Noordwijk, Netherlands

27–30 June 2006

Edited by Errico Armandillo, Josiane Costeraste, and Nikos Karafolas



SP-621

Proceedings of ESA/CNES ICSO 2006

Sixth International Conference on Space Optics

27–30 June 2006
ESTEC, Noordwijk, The Netherlands

Novel technologies for space x-ray optics

R. Hudec, L. Pína, V. Semencova, A. Inneman, et al.

International Conference on Space Optics — ICSO 2006, edited by Errico Armandillo, Josiane Costeraste,
Nikos Karafolas, Proc. of SPIE Vol. 10567, 105673L · © 2006 ESA and CNES
CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2308125

NOVEL TECHNOLOGIES FOR SPACE X-RAY OPTICS

R. Hudec(1), L. Pina(2,3), V. Semencova (2,5), A. Inneman(2), M. Skulinova(1) , L. Sveda(2) , M. Mika(5), R. Kacerovsky(5), J. Prokop(5), V. Brozek(4), J. Sik(6)

(1) Astronomical Institute, Academy of Sciences of the Czech Republic, 251 65 Ondrejov, Czech Republic,
Email:rhudec@asu.cas.cz
(2)Centre of Advanced X-ray Technologies, Reflex, Prague, Czech Republic
(3)Czech Technical University, Faculty of Nuclear Sciences, Prague, Czech Republic
(4)Institute of Plasma Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic
(5)Institute of Chemical Technology, Prague, Czech Republic
(6)ON Semiconductor Czech Republic

ABSTRACT

The future space X-ray astronomy imaging missions require very large collecting areas at still fine angular resolution and reasonable weight. The novel space X-ray optics substrates such as Silicon wafers and thin thermally formed glass enable wide applications of precise and very light weight (volume densities 2.3 to 2.5 gcm^{-3}) optics. The recent status of novel technologies as well as developed test samples with emphasis on precise optical surfaces based on novel materials and their space applications will be presented and discussed.

1. INTRODUCTION

Future large X-ray telescopes (such as XEUS considered by ESA[13] or Constellation X by NASA) require precise and light-weight X-ray optics. Novel approaches and technologies are to be exploited. In this contribution, we refer on preliminary results of test X-ray mirrors produced by glass thermal forming (GTF) and by shaping Si wafers. Both glass foils and Si wafers are commercially available, have excellent surface microroughness of few 0.1 nm, and low weight (the volume density is 2.5 g cm^{-3} for glass and 2.3 g cm^{-3} for Si). Innovative technologies are to be exploited how to shape these substrates to achieve the required precise X-ray optics geometries without degradations of the fine surface microroughness. 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 other alternative materials worth further study such as amorphous metals and glassy carbon[16].

2. THE X-RAY OPTICS BASED ON GLASS

The volume density of glass is nearly four times less if compared with electroformed nickel layers. The glass foils may be used either as flats, or alternatively may be shaped or thermally slumped to achieve the required geometry. 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 with the need to significantly improve the accuracy and minimize the errors. As the 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.

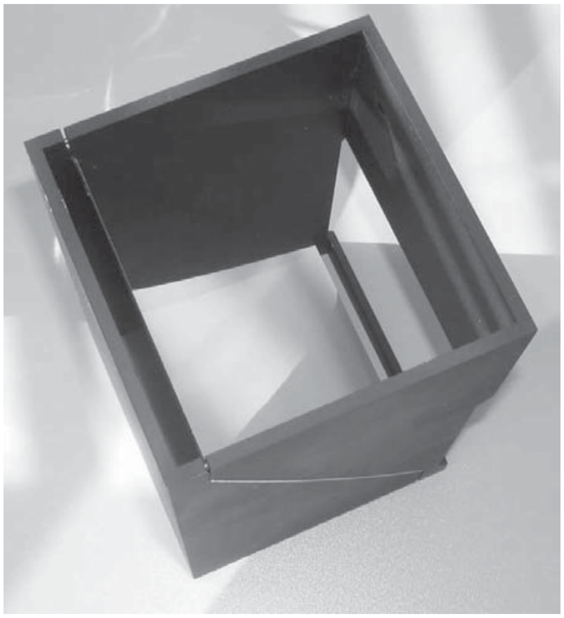


Fig. 1. Thermally formed parabola (gold-coated glass 150 x 100 x 0.75 mm).

Proc. '6th Internat. Conf. on Space Optics', ESTEC, Noordwijk, The Netherlands, 27-30 June 2006 (ESA SP-621, June 2006)

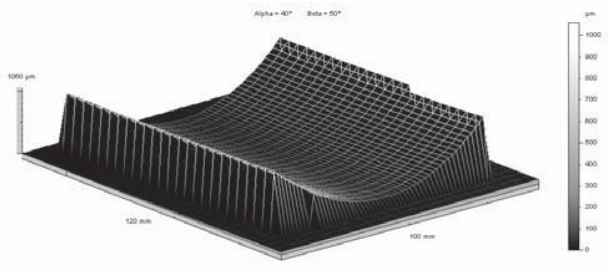


Fig. 2. Thermally formed glass sheet, 100 x 150 x 0.75 mm parabola, Still optical profilometer 3D plot.

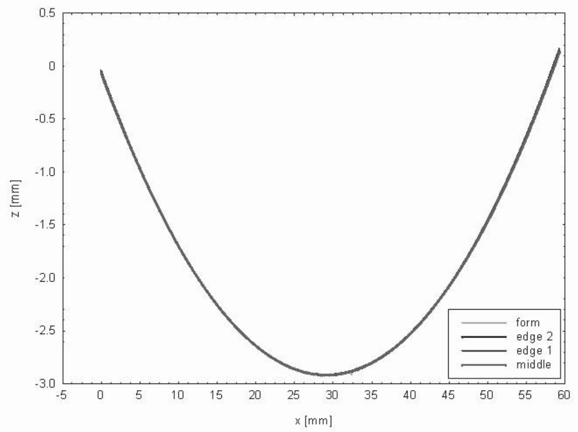


Fig. 3. The glass bent mirror, cylindrical shape, 75 x 25 x 0.75 mm, comparison mandrel with formed glass.

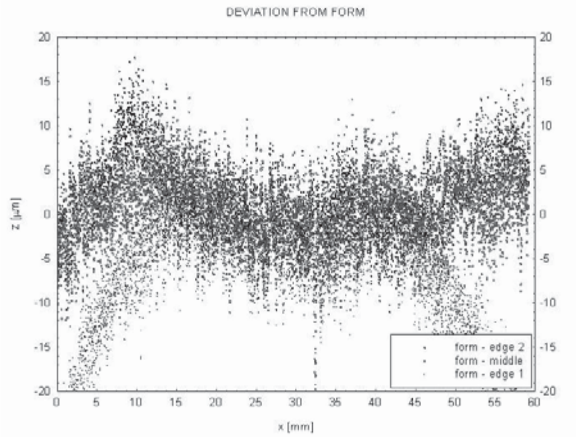


Fig. 4. Deviation formed glass from mandrel, Taylor-Hobson profilometer.

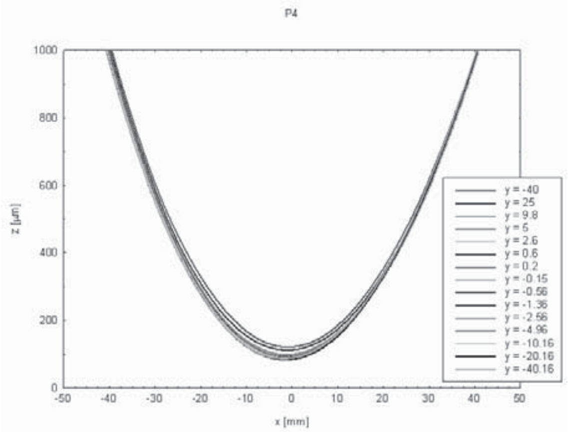


Fig. 5. The glass bent mirror, 100 x 150 x 0.75 mm, parabolic shape (comparing profiles at various positions including both edges and glass sheet centre).

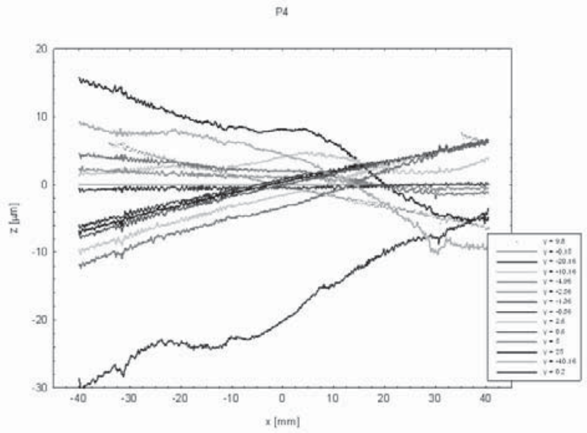


Fig. 6. Deviation of the profiles at edges from the profile in the middle of the glass sheet (y = 0=> middle of the sample, y = 40 => edge of the sample and y = -40 => second edge of the sample), Still optical profilometer.

The glass samples were thermally formed at Reflex, Prague, as well as at the Institute of Chemical Technology in Prague. For large samples (300 x 300 mm), facilities at Optical Development Workshop in Turnov have been used. Our idea is to develop technology suitable for mass and inexpensive production of thin X-ray optics shells i.e. to avoid expensive mandrels and techniques not suitable for mass production or being 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 thermal glass replica can be significantly improved by the optimisation of the material and design of the mandrel, by the modification of the thermal forming process, as well as by the optimisation of the temperature. After the (partly significant) modifications and improvements we have obtained the resulting deviation of the thermally formed glass foil from the ideal designed profile less than 1 micrometer (peak to valley value) in the best case. This value is however strongly dependent on the exact temperature, so we believe that a further improvements are still possible. The fine original microroughnes (typically better than 1 nm) of the original float glass foil has found not to be degraded by the thermal forming process. We note that our approach in thermal glass forming is different from those used by another authors[17, 19]

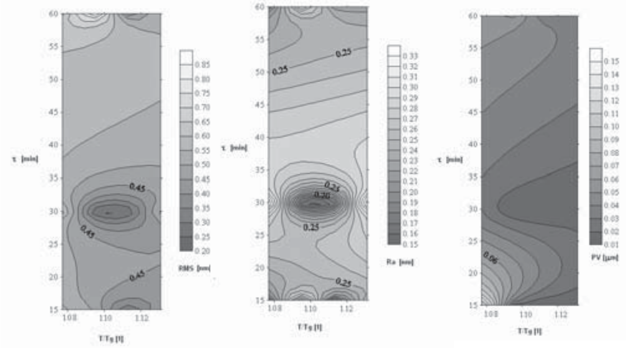


Fig. 7. The role of optimization the time and the temperature in the thermal glass forming process. Left: Optimization of RMS, Middle: Optimization of Ra, Right: Optimization of PV (peak to valley). Based on Zygo measurements.

3. X-RAY OPTICS BASED ON SILICON WAFERS

As already mentioned, another alternative recently considered as one of most promising[14, 15], is the use of X-ray optics based on commercially available silicon wafers manufactured mainly for purposes of semiconductor industry. Silicon is relatively light (volume density 2.3 g cm^{-3}) and already during the manufacture process it is lapped and polished (either on one or on both sides) to very fine smoothness (better than few 0.1 nm) and thickness homogeneity (of the order of 1 micrometer).

The main preferences of the application of Si wafers in space X-ray optics are (i) the low volume density (2.3 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 alternative approach of glass foils, (ii) very high thickness homogeneity typically less than 1 micron over 100 mm, and (iii) very small surface microroughness either on one or on both sides (typically of order of few 0.1 nm or even less).

Silicon wafers are expected to be used in the ESA XEUS project. 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), in view of achieving large effective areas with low mass, reduce telescope length, high stiffness, and a monolithic structure, favoured to handle the thermal environment and simplify the alignment process[17]. In addition, due to the higher packing density and the associated shorter mirrors required, the conical approximation to the Wolter-I geometry becomes possible. The X-HPO optics is based on ribbed Silicon wafers stacked together. The forming of the Si wafers to achieve the conical approximation is achieved by stacking large number of plates together using a mandrel. The typical size of the used Si wafers is 10 x 10 cm [17].

In this paper we refer on the development of the alternative design of innovative precise X-ray optics based on Silicon wafers. Our approach is based on two steps, namely (i) on development if dedicated Si wafers with properties optimised for the use in space X-ray telescopes and (ii) on precise shaping 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 the Multi Foil Optics (MFO) is created from shaped Si wafers. For more details on MFO see Hudec et al. 2005[16]. This alternative approach does not require ribbed surface of used Si wafers, hence the problems with transferring any deviation, stress, and/or inaccuracy from one wafer to the neighbouring plates or even to whole stacked assembly will be avoided. On the other hand, suitable technologies for precise stacking of optically formed wafers to multiple array has to be developed.

However, the 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 Si wafers represent a monocrystal (single crystal) with some specifics and this 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 exception represent the thinned Si wafers with thickness below 0.1 mm). Also, while their thickness homogeneity is mostly perfect, the same is not valid for commercially available wafers for their flatness (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).

We conclude that in order the achieve the very high accuracy required by future large space X-ray telescope experiments like ESA XEUS, the parameters of the Si wafers are to be optimized (for application in X-ray optics) already at the production stage. This is why we have established a multidisciplinary working group including specialists from the development department of 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.

For precise astronomical X-ray optics, the smoothness of the reflecting surface is important. The standard microroughness of commercially available (we have used the products of ON Semiconductor Czech Republic) is of order of 0.1 nm as confirmed by several in dependent measurements by different techniques including the Atomic Force Microscope (AFM). This is related to the method of chemical polishing used during the manufacture of Si wafers. The microroughness of Si wafers exceeds the microroughness of glass foils and most of other alternative mirror materials and substrates.

On the other hand, 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. The most of Si wafers show deviations from the plane of order of few tens of microns. After modifying the technology process during the Si wafer manufacture, we were able to reduce this value to less than few microns. Also the thickness homogeneity was 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. These and planned improvements introduced at the stage of the Si wafers manufacture can be applied also for other design of Si wafer optics including the X-HPO.

The X-ray optics designs require curved surfaces. However, due to the material properties of monocrystalline Si, the Si wafers (except very thin wafers) are extremely difficult to shape. It is obvious that we have to overcome this problem in order to achieve the fine 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. Three various alternative technologies to shape Si wafers have been designed and tested to achieve precise optical surfaces. The samples shaped and tested were typically 100 to 150 mm large, typically 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 high temperature (typically more than 1000°C) 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) rely on physical and chemical processes, at this stage proprietary, and have also lead to test samples shaped to precise optical surfaces.

The tsamples of bent wafers with all three technologies have been measured including Taylor-Hobson mechanical and STILL optical profilometry as well as optical interferometry (ZYGO) and AFM analyses. It has been confirmed that all three technologies studied does not degrades the intrinsic fine microroughness of the wafer. While the two physical/chemical technologies exploited give peak to valley deviations (of real surface of the sample compared with ideal optical surface) of less than 1 to 2 microns over 150 mm sample length, as preliminary values, the deviations of first thermally bent sample are larger, of 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 PV value can be further reduced down to order of 1 micron and perhaps even below. Fine adjustments of parameters can however further improve the accuracy of the results also for the other two techniques.

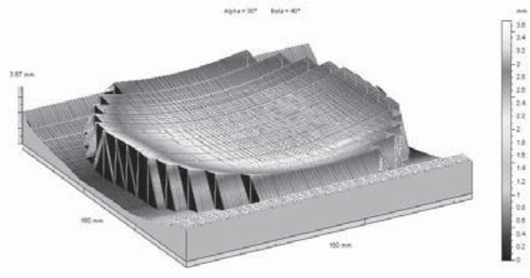


Fig. 8. 3D optical profilometry (STILL) of shaped (by technology II) Si wafer (R=1650 mm,D=150 mm, thickness 1.3 mm). Measured area 1.4 x 1.1 mm, PV 2.8 nm, Rz 2.0 nm, RMS 0.2 nm, Ra 0.2 nm.

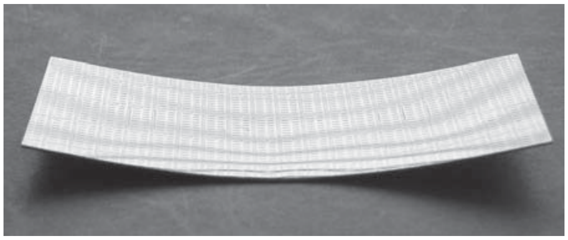


Fig. 9. Thermally formed (technology I) Si wafer to test cylinder (R = 150 mm, 72 x 23 x 0.625 mm).

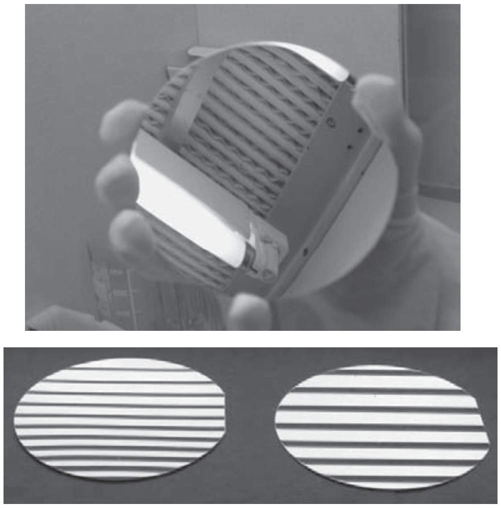


Fig. 10. Up: optically formed (technology II) Si wafer, diameter 100 mm, thickness 0.8 mm. Down: Si wafer (D = 150 mm, 1.3 mm thick) - flat (right) and optically bent (left).

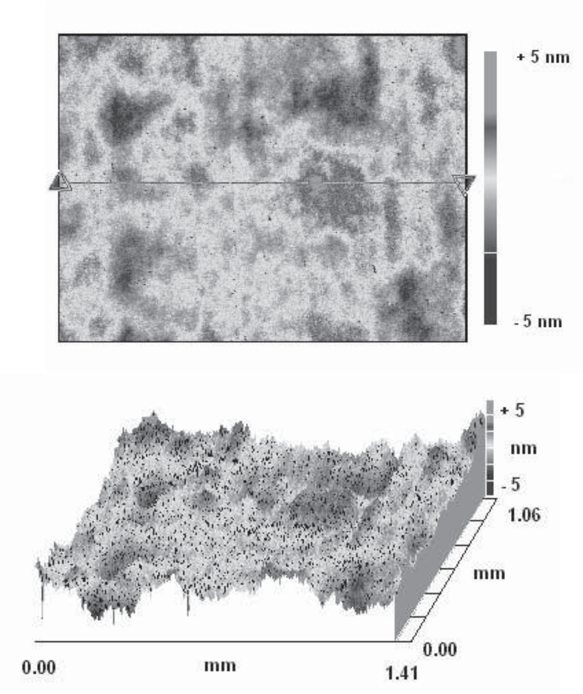


Fig. 11: Optically formed (technology II) Si wafer measurement by Zygo interferometer (2D and 3D images, measured area 1.4 x 1.1 mm, PV = 0.04 microns, RMS= 1.1 nm, Ra=0.9 nm).

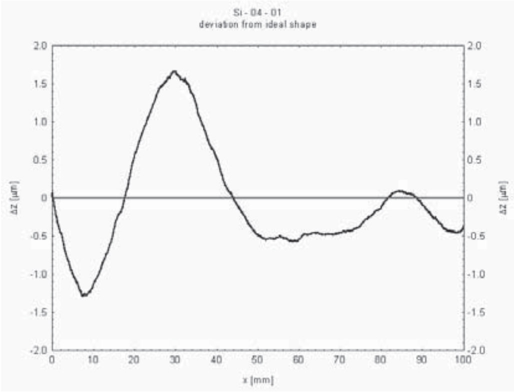


Fig.12. Peak to valley deviations of shaped Si wafer from ideal cylindrical surface (± 1.6 μm) (diameter 150 mm, thickness 1.3 mm, technology II).

Fig. 13. Test module for tests performance of glass foils vs. shaped Si wafers. Test elliptical Kirkpatrick-Baez optical system, focus 0.5 m, 58 x 50 x 100 mm, glass foils 40 x 40 x 0.3 mm, Si wafers 40 x 40 x 0.4 mm.

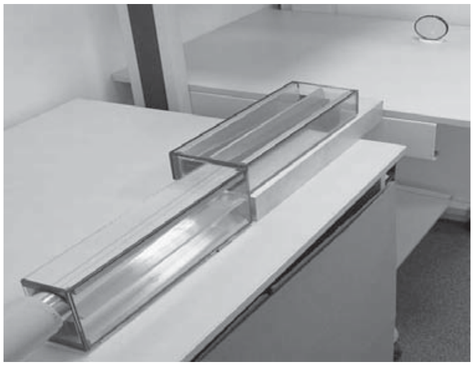


Fig. 14: Test parabolic KB X-ray imaging system based on parabolically shaped glass foils with dimensions of 300 x 100 x 0.3 mm. The complete KB

module has dimensions 108 x 320 x 50 mm and the focal length is 0.6 m.

4. CONCLUSIONS

The Glass Thermal Forming and Si wafer bending belongs to the most promising technologies for future large space X-ray telescopes. 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.

An interdisciplinary co-operation (team with 10 members) was created within the Czech Republic with experienced teams including researches from the large company producing Si wafers. Si wafers were successfully bent to desired geometry by three different techniques. In the best cases, the accuracy achieved for the 150 mm Si wafer is 1 to 2 microns PV for deviation from the ideal optical surface. The experiments continue to further improve the forming accuracy.

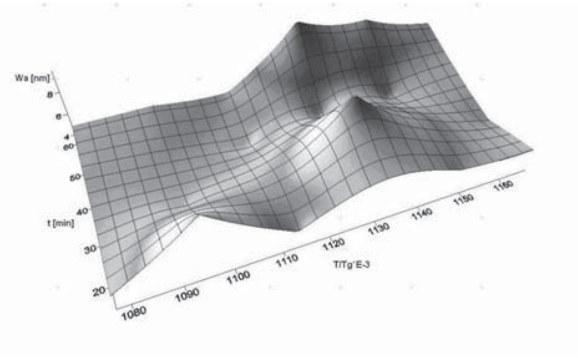


Fig. 15. The thermal glass forming optimization 3D plot based on Taylor Hobson profilometer measurements. Tg is the glass transformation temperature. The parameter Wa on the z axis corresponds to the surface waviness.

ACKNOWLEDGEMENTS

We acknowledge the support provided by the Ministry of Industry and Trade of the Czech Republic, FD-K3/052, from the Physical institute of the Academy of Sciences in Prague, as well as the Institute of the Experimental Physics of the Slovak Academy of Sciences in Kosice, in the studies of innovative technologies for future lightweight X-ray telescopes. We also acknowledge collaboration with Centre for Advanced Instrumentation, Netpark Research Institute, Sedgefield, UK, in metrology and measurements.

REFERENCES

1. Gorenstein, P. et al., SPIE Vol. **2805**, 74, 1996.
2. Gorenstein, P. , SPIE Vol. **3444**, 382, 1998.
3. Hudec R. et al., SPIE Vol. **1343**, 162, 1991.
4. Hudec R., Pina L and Inneman A., SPIE Vol. **3766**, 62, 1999.
5. Hudec R., Pina L. and Inneman A., SPIE Vol. **4012**, 422, 2000.
6. Hudec R., Inneman A. and Pina L., "Lobster-Eye: Novel X-ray Telescopes for the 21st Century", New Century of X-ray Astronomy, ASP Conference Proceedings Vol. 251. Edited by H. Inoue and H. Kunieda. ISBN: 1-58381-091-9. San Francisco: Astronomical Society of the Pacific, p.542, 2001.
7. Inneman A., Hudec R., Pina L. and Gorenstein P., SPIE Vol. **3766**, 72, 1999.
8. Inneman A., Hudec R. and Pina L., SPIE Vol. **4138**, 94, 2000.
9. Joensen K. et al., SPIE Vol. **2279**, 180, 1994.
10. Citterio O. et al., SPIE Vol. **4496**, 23, 2002.
11. Marsch H. et al., Introduction to Carbon Technologies, University of Alicante, ISBN :84-7098-317-4, 1997.
12. Ivan, A. et al., SPIE Vol. **4496**, 134, 2002.
13. Aschenbach B. et al., ESA-SP 1253, 2001.
14. Bavdaz, M.. et al., SPIE Proc. **5539**, 85B, 2004.
15. Beijersbergen, M.. et al., SPIE Proc. **5539**, 104B, 2004.
16. Hudec R. et al. Optics for EUV, X-Ray, and Gamma-Ray Astronomy II. Edited by Citterio, Oberto; O'Dell, Stephen L. Proceedings of the SPIE, Volume **5900**, pp. 276-287, 2005.
17. Ghigo, M. et al. Optics for EUV, X-Ray, and Gamma-Ray Astronomy. Edited by Citterio, Oberto; O'Dell, Stephen L. Proceedings of the SPIE, Volume **5168**, pp. 180-195, 2004.
18. Parmar A. et al., SCI-A/2006/054/NR.
19. Friedrich, P. et al. Optics for EUV, X-Ray, and Gamma-Ray Astronomy II. Edited by Citterio, Oberto; O'Dell, Stephen L. Proceedings of the SPIE, Volume **5900**, pp. 258-265, 2005.