

Back-Up Technologies for IXO

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ABSTRACT

We report on recent progress with development of astronomical X-ray optics based on thermally formed glass foils and on bent Si wafers. Experiments with thermal glass forming have continued adding wider range of evaluated and optimized parameters. Recent efforts with Si wafers have been focused on their quality improvements such as flatness and thickness uniformity in order to better meet the requirements of future X-ray astronomy projects applications, as well as on study of their surface quality, defects analysis, and methods for its reproducible measurement. The role of substrates quality in performance of final mirror arrays, as required by large future space X-ray astronomy experiments was also studied.

1. INTRODUCTION

Future large X-ray telescopes (such as IXO/XEUS considered by ESA³ or IXO/Constellation X by NASA) require precise and light-weight X-ray optics. Novel approaches and technologies are hence to be exploited. As the weight issue plays an important role and at the same time the large collecting area must be achieved in order to get deep sensitivity limits, the thin X-ray reflecting flats and foils play an increasingly important role in future experiments in X-ray astrophysics. They have opened a new space for various novel approaches and innovative solutions including those never discussed before. 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. The Wolter 1 telescope is proposed to be segmented in the ESA/NASA/JAXA IXO telescope and analogous space projects, but considerations also exist for large Lobster eye segmented modules, as well as for the segmented Kirkpatrick-Baez systems. The segmentation of the mirror surfaces is extremely important not only for the production of mirror shells, but also for the keeping the weight of large telescopes in a still reasonable limits².

In this contribution, we refer on preliminary results of continued efforts to design, to develop, and to test X-ray mirrors produced by precise shaping of silicon wafers and by glass thermal forming (GTF). Both of these technologies seem to be promising and worth to be further investigated. Both glass foils and Si wafers are commercially available, have excellent surface micro-roughness 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 micro-roughness. It should be noted that although glass and more 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 carbon¹⁶. However in this paper, we will focus on recent progress on thermally formed glass foils and on shaped silicon wafers. We note that with recent selecting the IXO project for

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further study and considerations within the ESA/NSSA/JAXA space science programs, such efforts are especially valuable, as they can provide alternative mirror technology for this and analogous projects.

In the following Sections we report on status and recent results of continued development and tests of X-ray optics samples based on two perspective and light-weight substrates, namely glass foils and silicon wafers. The careful investigations have indicated that both types of substrates require further improvements in order to meet the high requirements (especially on angular resolution of 5 arcsec or better) of future space X-ray astronomy missions such as IXO by ESA/NASA/JAXA. Further improvements must be also applied to stacking and forming technologies, but no X-ray array of high accuracy can be constructed with low quality substrates. Here we have to take into account that both glass foils and Si wafers are usually mass-manufactured for other purposes than optics and imaging X-ray mirrors. Albeit both substrates exhibit low volume density as well as reasonable surface quality, for use in X-ray optics with superfine angular resolution this quality must be further improved.

Silicon wafers are produced mainly for the customers in semiconductor industry by a mass-production. This means that the Si wafers on the market are optimized for the semiconductor industry use, not for the X-ray optics applications. Our investigations have indicated that while the surface micro-roughness is (as a result of chemical polishing) mostly fully adequate for use in X-ray telescopes, there is still chance to modify the manufacturing technology in order to achieve better values of other important parameters such as flatness and thickness homogeneity. In Section 2 of this paper we present some preliminary results of these efforts which can be valuable also for experiments with active X-ray optics.

For the alternative material substrate, **glass foils**, the mostly used choice is the borosilicate float glass from the Schott production. The obvious preferences of use of glass foils in astronomical X-ray optics are the wide range of available thicknesses (from only 30 μm), the large dimensions of sheets available, as well as low cost (if compared with Si wafers). Another advantage is that precise bending and hence shaping to precise optical surfaces is in the case of glass foils much easier than for Si wafers. On the other hand, the glass foils available on the market exhibit typically micro-roughness in the range of 0.3 to 0.5 nm, i.e. worse than those of standard Si wafers. The flatness is not optimal as well as thickness homogeneity. This is a result of the fact that the glass borosilicate float foils available on the market are a result of mass-production for purposes other than use in optics and X-ray optics. Nevertheless, some of the important parameters could be improved either directly in the manufacturing process, or by a special treatment afterwards.

2. SILICON WAFERS AS X-RAY OPTICS SUBSTRATES

The 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 and already during the manufacturing process it is lapped and polished (either on one or on both sides) to very fine smoothness and thickness homogeneity (of the order of 1 μm).

The recent baseline optics for the IXO X-ray telescope design suggested by ESA 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, favored to handle the thermal environment and simplify the alignment process¹⁷. 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 chip is 100 mm x 100 mm¹⁷.

In this and previous papers^{20, 21} we refer on the development of alternative design of innovative precise X-ray optics based on silicon wafers. Our approach is based on two steps, namely (i) on development of dedicated Si wafers with properties optimized 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 neighboring 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 arrays have to be developed. The recent 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 preferences of the application of Si wafers in space X-ray optics are (i) the low volume density which is nearly 3.5x 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 μm over 100 mm, and (iii) very small surface micro-roughness either on one or on both sides. On the other hand, 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 represents 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).

It is obvious that in order to achieve the very high accuracy required by future large space X-ray telescope experiments like IXO, 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 production of silicon wafers is a complex process with numerous technological steps, which can be modified and optimized to achieve the optimal performance. This can be useful also to further improve the quality of the X-HPO optics.

The standard micro-roughness of commercially available Si-wafers (we have used the products of ON Semiconductor Czech Republic) is of order of 0.1 nm as confirmed by several independent measurements by different techniques including the Atomic Force Microscope (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 well. In fact, the micro-roughness of Si wafers exceeds significantly the micro-roughness 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. The most of 100 mm and 150 mm Si wafers used for technologies with photolithographic detail $\sim 5 \mu\text{m}$ show deviations from the plane of order of few tens of microns and thickness uniformity of few microns. For more advanced technologies with sub-micron details, flatness parameters have to be improved. ON Semiconductor Czech Republic has developed technological process for higher wafer flatness and further steps are planned to improve the deviation from an ideal plane and the thickness uniformity. As already mentioned, these and planned improvements introduced at the stage of the Si wafers production can be applied also for other design of Si wafer optics including the X-HPO.

2.1 Development of raw Si wafers technology

In addition to the results achieved before^{20,21}, further investigation has been performed with emphasis of various aspects of quality improvements necessary for superior quality of X-ray optics based on shaped Si wafers.

In the Tab. 1, we list dopants used in semiconductor technology, including their related parameters. We note that, as the application in space optics is different from typical use in semiconductor industry, the choice of dopant type and amount is still to be optimized, and this will be a part of our next study.

Tab. 1: Overview of dopants used in semiconductor technology. Segregation coefficient, i.e., dopant concentration in crystal / dopant concentration in melt at the melt/crystal interface k_0 , maximal solubility c_s^m , evaporation speed g and relative difference of dopant-silicon and silicon-silicon bond lengths δ_r are main parameters of Czochralski process.

Dopant	k_0	c_s^m (cm ⁻³)	g (cms ⁻¹)	δ_r (%)
B	0.800	6.0×10^{20}	8×10^{-6}	-25
As	0.300	1.8×10^{21}	8×10^{-3}	0
P	0.350	1.3×10^{21}	1.6×10^{-4}	-7
Sb	0.023	7.0×10^{19}	1.3×10^{-1}	+15

As the silicon substrates are used in X-ray optics modules i.e. shaped to X-ray mirrors of Wolter, or alternatively, the Kirkpatrick-Baez geometry, one of important parameters to be improved is the flatness. As the definition of flatness used in the semiconductor industry differs from analogous definition used in physical science, we illustrate the definitions of three basic parameters used in semiconductor industry namely TTV, TIR, and WARP (Fig. 1).

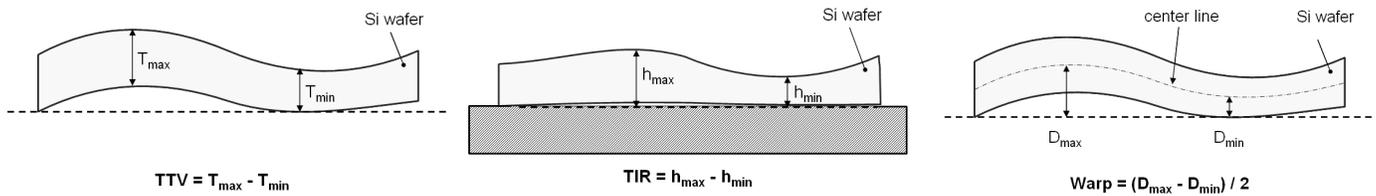


Fig. 1: Definition of silicon wafer flatness: TTV –Total Thickness Variation, TIR – Total Indicator Reading, WARP - difference between the maximum and minimum deviations of a wafer's median surface with respect to a reference plane.

The geometrical quality of a standard 150 mm Si wafer used for technologies with photolithographic detail $\sim 5 \mu m$ is illustrated on Fig. 3. For comparison wafer for sub-micron photolithographic detail produced in ON Semiconductor Czech Republic is in Fig. 3. The measurements of 24 silicon wafers flatness, as well as upper specification limit (USL) for semiconductor, flatness not demanding application, are plotted in Fig. 4. All these wafers were manufactured by ON Semiconductor Czech Republic with novel method for high flatness.

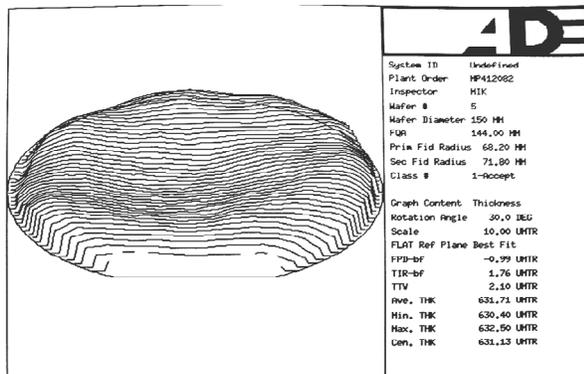


Fig. 2: Example of flatness measurement of standard 150 mm silicon wafer used for technologies with photolithographic detail $\sim 5 \mu m$. Measured in 1275 points with ADE 7000 Wafercheck. Thickness in the wafer center (Cen. THK) 631.13 μm , minimal measured thickness: (Min. THK) 630.40 μm , maximal measured thickness (Max. THK) 632.50 μm ; Total thickness variation: $TTV = (Max. THK) - (Min. THK) = 2.10 \mu m$; $TIR: 1.76 \mu m$.

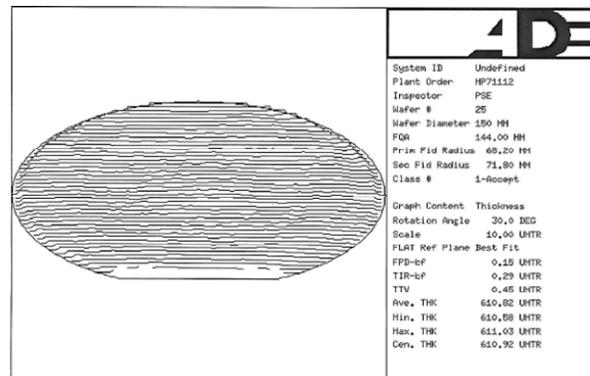


Fig. 3: Example of flatness measurement of 150 mm silicon wafer developed for sub-micron technologies in ON Semiconductor. Measured in 1275 points with ADE 7000 Wafercheck. Thickness in the wafer center (Cen. THK) 610.92 μm , minimal measured thickness (Min. THK) 610.88 μm , maximal measured thickness (Max. THK) 611.03 μm . Total thickness variation: $TTV = (Max. THK) - (Min. THK) = 0.45 \mu m$; $TIR: 0.29 \mu m$.

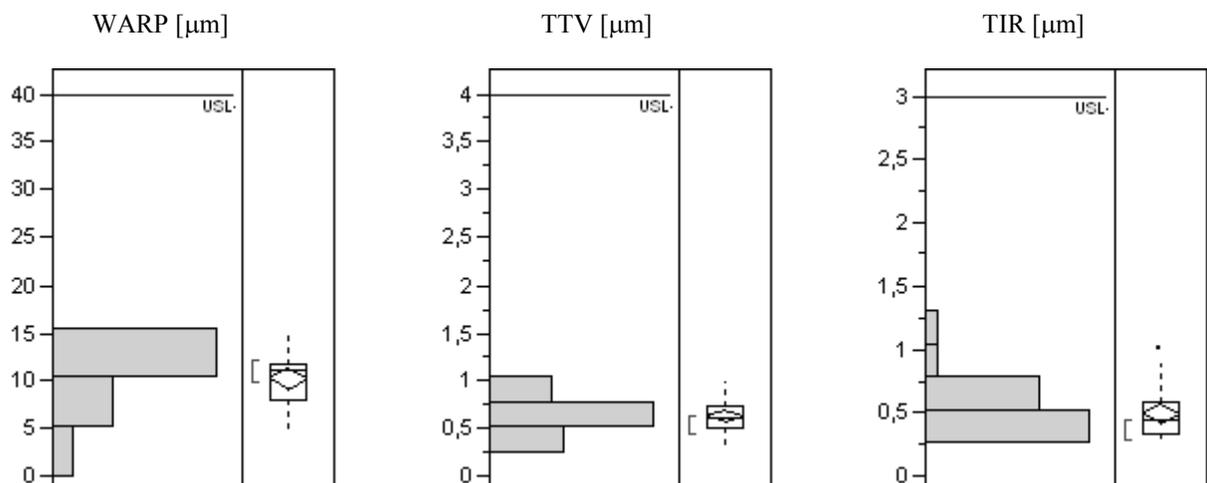


Fig. 4: Measured distributions of flatness parameters for 24 silicon wafers. Upper specification limit (USL) for semiconductor application. Wafers were manufactured with the method for high flatness.

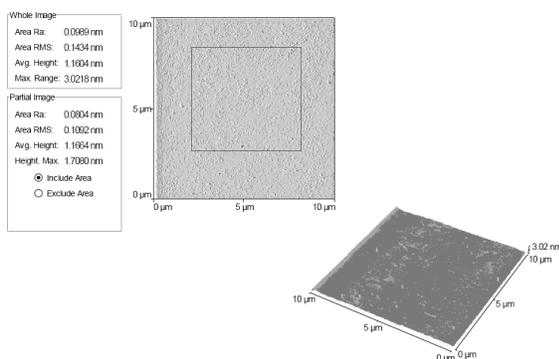


Fig. 5: Surface roughness of polished silicon wafer measured with AFM. Crystallographic orientation (100), FZ wafer slightly doped with boron. Measured area 10 μm x 10 μm, Ra = 0.10 nm, RMS = 0.14 nm.

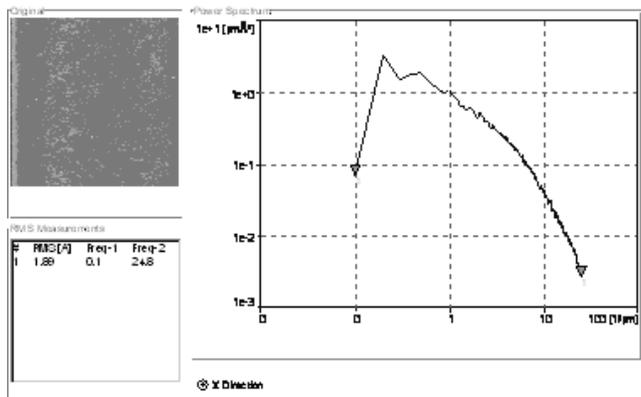


Fig. 6: Power Spectral Density (PSD) function calculated for data from AFM microscopy (Fig. 5).

Another important parameter for applications in fine X-ray imaging is the surface micro-roughness. In Fig. 5, Fig. 6 we show examples of results obtained by AFM microscopy, as well as relevant PSD (Power Spectral Density) plot. These results confirm the superior surface micro-roughness of polished Si wafers meeting the requirements of X-ray optics applications.

Based on our analysis and early investigations, the crystallographic orientation (100) is the optimal solution due to superior surface quality. Values of RMS for polished surface (100) can be as low as ~ 0.1 nm or even slightly lower (measured with AFM). There are basically two limitations – (i) defects and particles on the surface and (ii) atomic steps on the surface. Surface with crystallographic orientation (111) is characteristic by high density of atoms on the wafer surface and atomic steps of the high 0.314 nm. The distance between neighboring steps is determined by surface deviation from (111) plane (off orientation). For 1 deg deviation is this distance ~ μm, with decreasing angle of orientation this distance is increasing. On the single terrace the AFM roughness 0.06 nm was measured³². For (100) plane distance between atomic planes is in relation to silicon lattice parameter: $0.543 \text{ nm}/4 = 0.135 \text{ nm}$. It is also necessary to

remind that silicon surface has thin layer of native oxide on the surface. This oxide can be up to few nanometers thick. Deeper study of silicon surface roughness and AFM capability for its measurement is in progress.

Best roughness values were achieved with optimized chemical-mechanical polishing of material with lower surface hardness, e.g., (100) float zone silicon or (100) heavily arsenic doped silicon. For float zone wafer are different mechanical properties given by low oxygen content. High oxygen and boron content in silicon suppress dislocation movement²⁹ contrary to heavily doped n-type silicon^{30, 31}.

Polished Si wafer represents potential substrate for the mirrors of space X-ray telescopes. Through Si wafers manufacturing technology optimization and for specified Si wafers specification (dopant, orientation, oxygen content) we can achieve thickness variation about 0.5 μm and surface roughness close to 0.1 nm.

2.2 Shaping of Si wafers

Due to the material properties of monocrystalline Si, the Si wafers are extremely difficult to shape. However 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 superior quality and stability. Mechanical bending of Si wafers at room temperature on mandrel as considered by the X-HPO technique means no negligible internal stress, which can avoid achieving the required very long-term stability and very fine angular accuracy of order of few arcsecs.

Shaping of substrates for mirror geometry is possible, e.g., via methods of optical lithography or direct wafer bonding techniques used in semiconductor industry. We have designed and exploited three various alternative technologies to shape Si wafers to 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 optics¹⁶. This requires very high temperature (typically more than 1 000°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) proposed, developed, and tested rely on physical and chemical processes, at this stage proprietary, and have also lead to test samples shaped to precise optical surfaces^{20, 21}.

The test samples of optically bent wafers with all three technologies have been carefully measured and tested. Preliminary results were presented and discussed in preceding papers^{20, 21} and recent results in this paper. The measurements include Taylor-Hobson mechanical and STILL optical profilometer as well as optical interferometer (ZYGO) and AFM analyses. It has been confirmed that all three studied technologies does not degrade the intrinsic fine micro-roughness of the wafer. While 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 μm over 150 mm sample length, as preliminary values, the deviations of the first thermally bent sample are larger, of order of 10 μm). Taking into account that the applied temperatures as well as other parameters were not optimized for this first sample, we expect that the PV value can be further reduced down to order of 1 μm and perhaps even below. Fine adjustments of parameters can however further improve the accuracy of the results also for the other two techniques. For further details on shaping of Si wafers see our previous papers^{20, 21}.

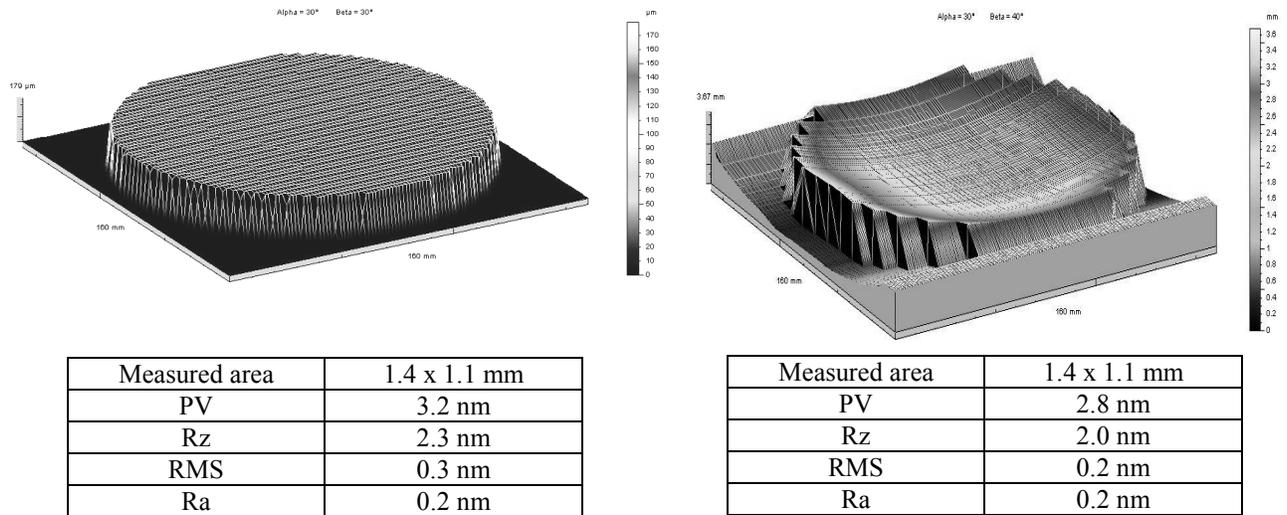


Fig. 8: Left: Flat Si wafer (dopant B) measurement by STILL optical profilometer - 3D chart (D = 150 mm, t = 0.625 mm), right: 3D optical profilometer of shaped (by technology II) Si wafer (R = 1650 mm, D = 150 mm, thickness = 1.3 mm).

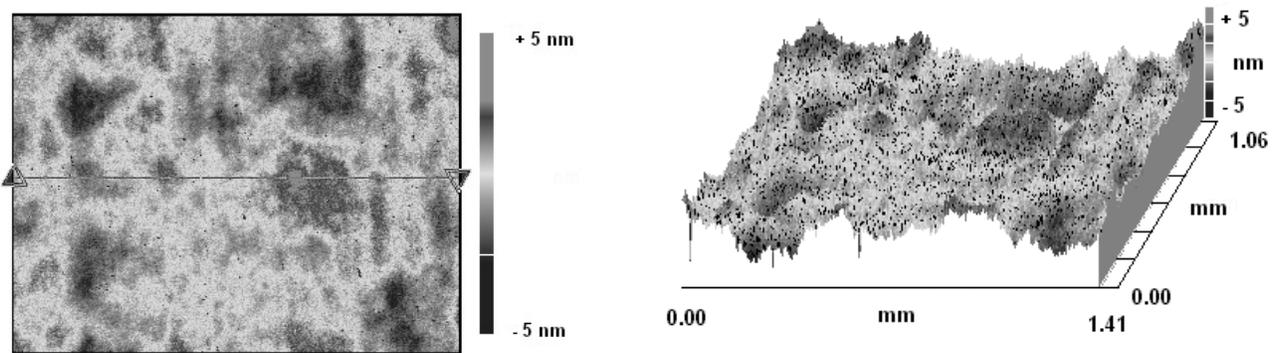


Fig. 9: Optically formed (technology II) Si wafer measurement by Zygo interferometer (2D and 3D images, measured area 1.4 x 1.1 mm, PV = 0.04 microns, RMS= 1.1 nm, Ra=0.9 nm).

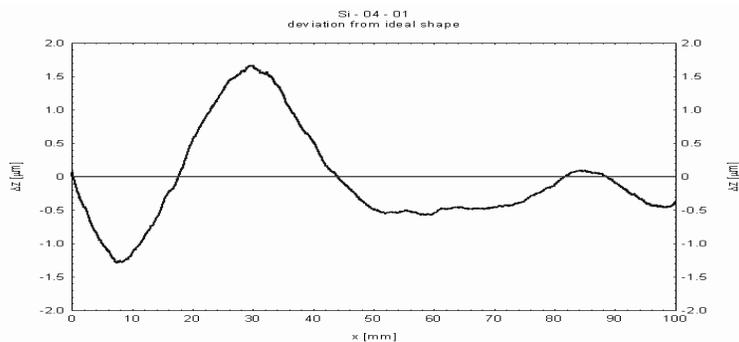


Fig.10: Peak to valley deviations of shaped Si wafer from ideal cylindrical surface ($\pm 1.6 \mu\text{m}$) (diameter 150 mm, thickness 1.3 mm, technology II).

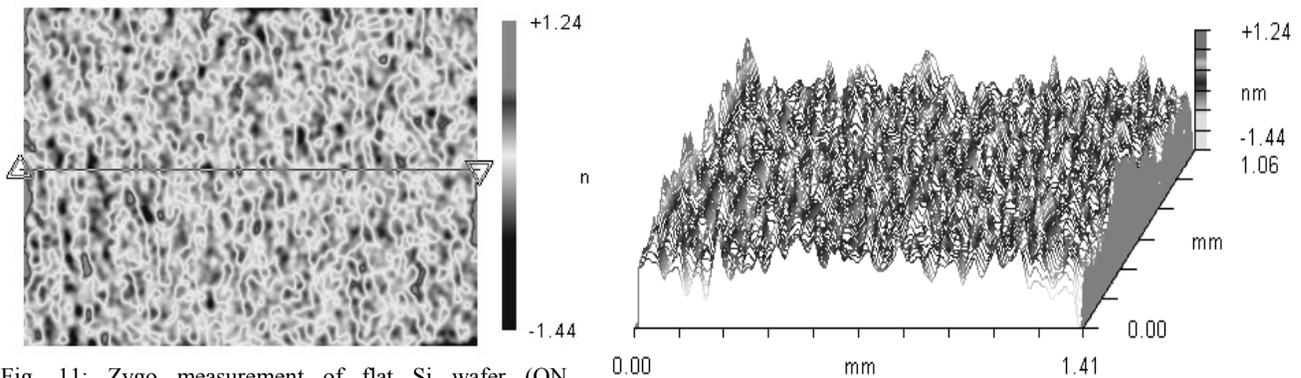


Fig. 11: Zygo measurement of flat Si wafer (ON Semiconductor, diameter 150 mm, dopant B).

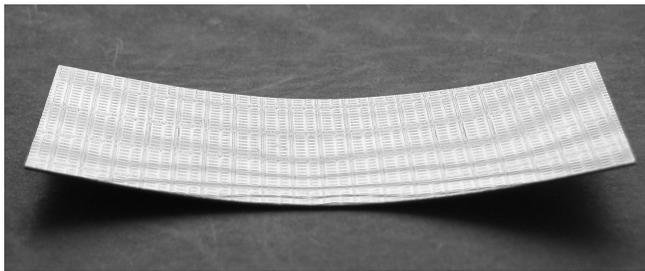


Fig. 12: Thermally formed (technology I) Si wafer to test cylinder ($R = 150$ mm, $72 \times 23 \times 0.625$ mm).

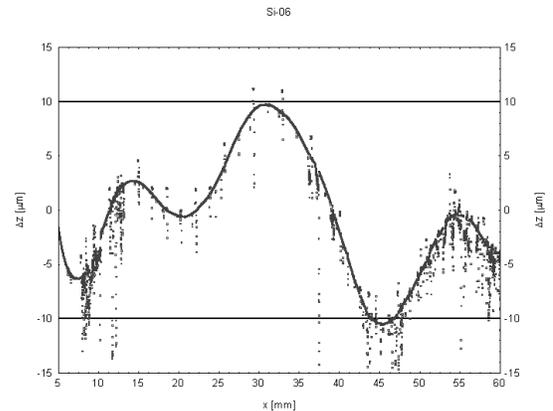


Fig. 13: Shape deviation of thermally formed Si wafer from ideal cylinder ($\pm 10 \mu\text{m}$).

3. THE THERMAL GLASS FORMING OF X-RAY OPTICS

Glass foils for X-ray mirrors arrays can be used either flat or curved, while the curved foils can be either bent (without heat) or thermally shaped. 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 (76×26 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 represents another important application. This approach is expected to improve the flatness of X-ray flats (foils) needed e.g. for Lobster Schmidt lenses, but also for advanced active (adaptive) X-ray optics.

The details of experiments with glass thermal forming were already published before^{20, 21}, in this paper we focus of more recent developments in which new alternative arrangements were studied. The small glass samples were thermally formed at Rigaku Innovative Technologies Europe, RITE, Prague, as well as at the Institute of Chemical Technology in Prague. For large samples (300×300 mm), facilities at collaborating Optical Development Workshop in Turnov have been used. Already for these tests, our idea is to develop technology suitable for mass and inexpensive production of thin

X-ray optics shells. This means that we 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 technology process and resulting quality of the thermal glass replica can be significantly improved by the optimization of the material and design of the mandrel, by the modification of the thermal forming process, as well as by the optimization 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 μm (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 micro-roughness (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}. Further details are given in preceding papers^{20, 21}.

In this section we present examples of preliminary results of recent study of thermal glass forming using alternative special composite mandrel arrangement, different from procedures used before^{20, 21}. In our recent experiments we did not apply any additional pressure on the top of a glass samples. We did 9 different heat treatments at 620°C, 640°C and 660°C for three different soaking times 60, 75 and 90 min. The shape of the formed glass foils was measured using a Taylor-Hobson profilometer. The data from the profilometer were fitted with cylindrical or/and parabolic functions ($y=ax^2$). The correlation coefficients at parabolic function were in the range 0.999 - 0.9999 indicating that the shape of the foils can be represented by the above function. The parameter was dependent on the temperature and time of the forming and varied from 4.12×10^{-3} to $4.15 \times 10^{-3} \text{ mm}^{-1}$. For short heat treatment time the parameter a reached the highest values that raised with the increasing temperature indicating the most curved shapes. For longer forming times the shape of the foils became more opened and we observed a decrease with time. The shape of all the foils prepared by this procedure was more closed than when we applied pressure on the top of samples^{20, 21}.

The inner surface quality was determined using an optical interferometer (Zygo). The micro-roughness represented by the parameter R_a was around 0.3 nm. The surface had better quality than in the case of our previous experiments when we slump the glass foil with a composite mould that touched the inner surface^{20, 21}.

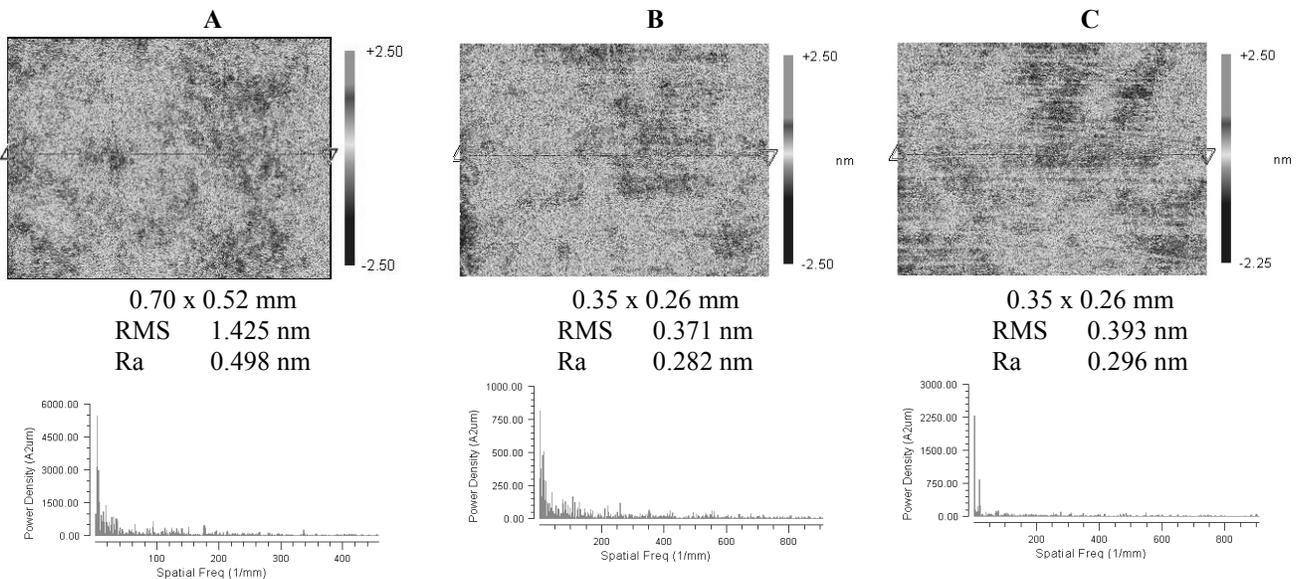


Fig. 14: Surface roughnesses of glass were measured by Zygo interferometer before (A) and after (B – concave side, C – convex side) GTF. Power Spectral Density (PSD) functions from these data were calculated.

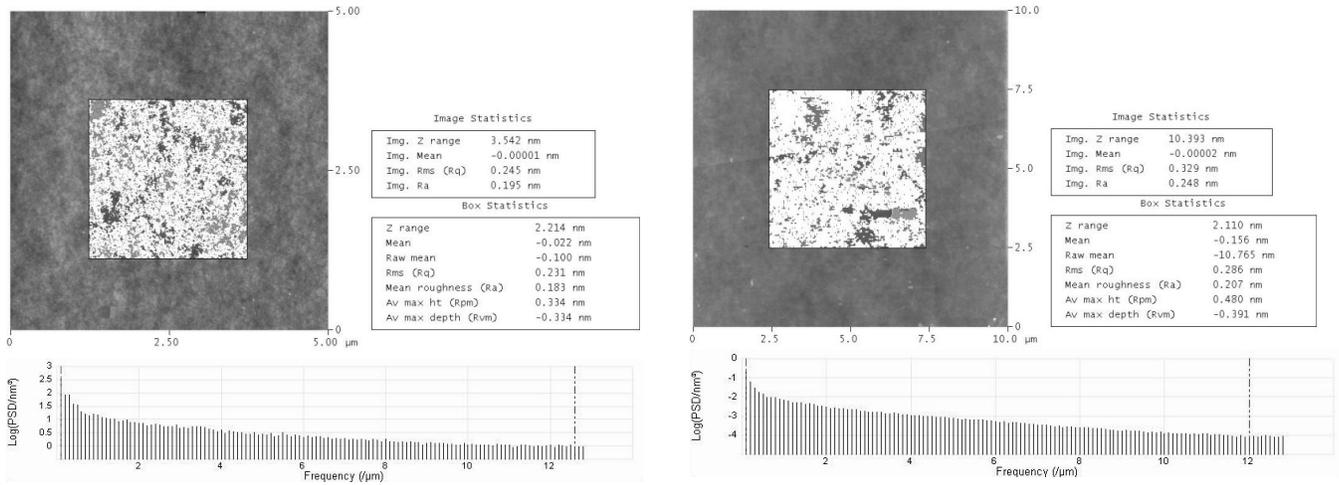


Fig. 15: Surface roughnesses of glass were measured by AFM microscopy. Left – GTF at T/Tg 1.13 and 45 min; right – GTF at T/Tg 1.21 and 15 min. Density (PSD) functions from these data were calculated.

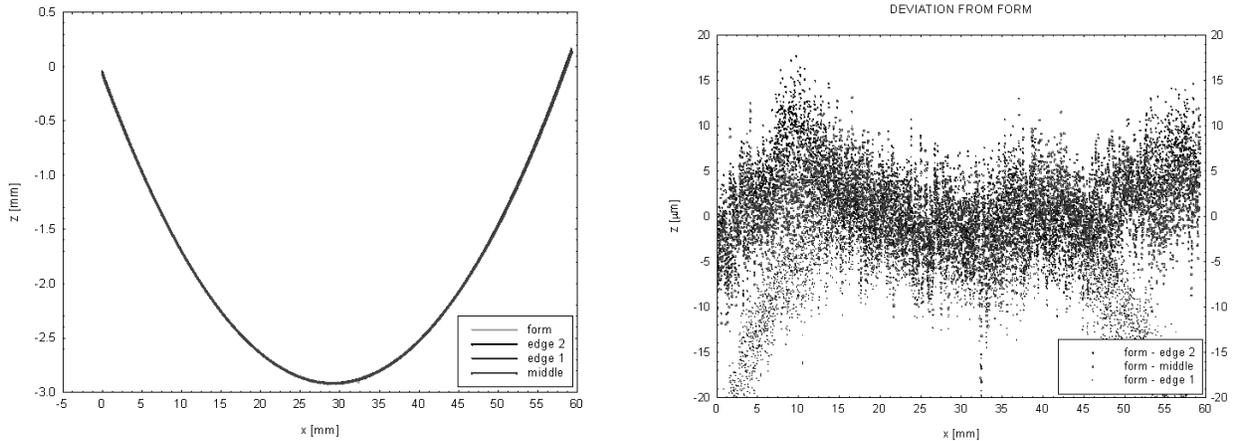


Fig. 16: Left: The glass bent mirror, cylindrical shape, 75 x 25 x 0.75 mm, comparison mandrel with formed glass. Right: deviation formed glass from mandrel, Taylor-Hobson profilometer.

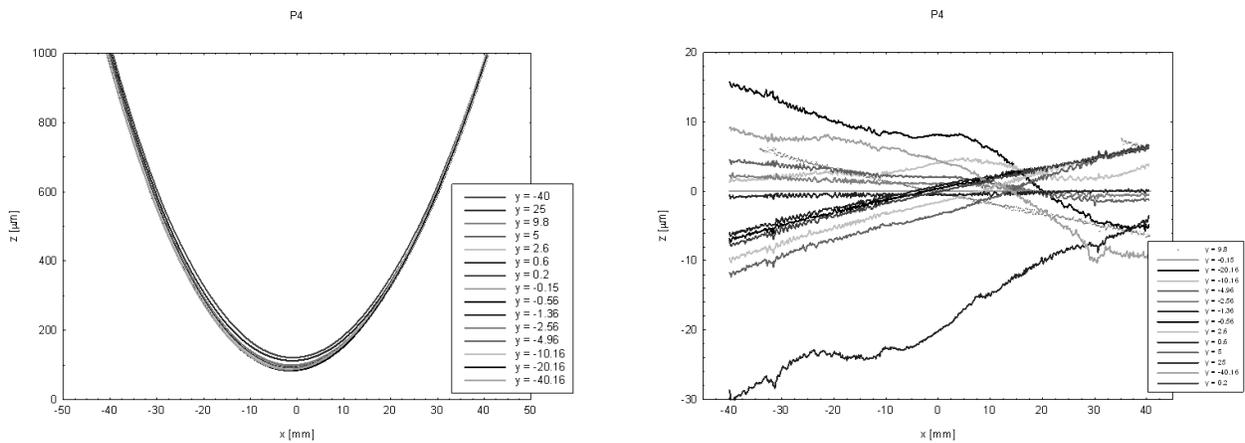


Fig. 17: Left: The glass bent mirror, 100 x 150 x 0.75 mm, parabolic shape (comparing profiles at various positions including both

edges and glass sheet centre). Right: deviation of the profiles at edges from the profile in the middle of the glass sheet ($y = 0 \Rightarrow$ middle of the sample, $y = 40 \Rightarrow$ edge of the sample and $y = -40 \Rightarrow$ second edge of the sample), Still optical profilometer.

4. CONCLUSIONS

New results in application of glass foils and Si wafers in future space projects with X-ray optics have been presented and discussed. The Glass Thermal Forming and Si wafer bending still belongs to the most promising technologies for future large space X-ray telescopes such as ESA/NASA/JAXA IXO. The results obtained and discussed are valuable also for efforts with active X-ray optics. While glass technology experiments with thermal forming continued with emphasis on repeatability of obtained results and also on alternative bending arrangements, development of Si wafers with improved parameters has been initiated, meeting better the requirements of high resolution X-ray optics and X-ray telescopes.

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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., X-ray Observatory, Study preparation activities status report, ESA SCI-A/2006/054/NR, 2006.

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.
20. Hudec, R. et al., Proceedings of the SPIE, Novel x-ray optics with Si wafers and formed glass, in Space Telescopes and Instrumentation II: Ultraviolet to Gamma Ray. Edited by Turner, Martin J. L.; Hasinger, Günther. Proceedings of the SPIE, Volume 6266, pp. 62661H, 2006.
21. Hudec, R. et al., Novel technologies for x-ray multi-foil optics, in 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.
22. Silicon, Evolution and Future of Technology, eds. P. Siffert, E. Krimmel, Springer-Verlag, 2004.
23. La Pedus, M., Debate rages over 450-mm wafer fabs, 04/28/2006, www.eetimes.com, 2006.
24. Montgomery, J., 450mm by 2012: Between the lines of PR lingo, 05/13/2008, Solid State Technology, sst.pennnet.com, 2008.
25. Kuramoto, M., Super Silicon Initiative and Future Large Wafer Size Diameter, in Semiconductor Silicon, Electrochemical Society Proceedings, p. 163-175, 2002..
26. Watanabe, M., 450 mm Silicon: An Opportunity and Wafer Scaling, The Electrochemical Society Interface, Winter, 28-31, 2006.
27. Fischer, A., Kissinger, G., Load induced stresses and plastic deformation in 450 mm silicon wafers, Appl. Phys. Lett. 91, 111911, 2007.
28. Lammers, D., 'Big Four' Talking 450 With Tool Vendors, Semiconductor International, 10/30/2007, Reed Business Information, 2008.
29. Yonegava, I., Activities of dislocations in heavily impurity-doped Si, J. Phys.: Condens. Matter 12, 10065-10069, 2000.
30. Patel, J. R., and Freeland, P. E., Change of dislocation velocity with Fermi level in silicon, Physical Review Letters 18, No. 20, 833 -835, 1967.
31. Patel, J. R., Testardi, L. R., and Freeland, P. E., Electronic effects on dislocation velocities in heavily doped silicon, Phys. Rev. B 13 No. 8, 3548 – 3557, 1976.
32. www.ntmdt-tips.com/catalog/test_s/products/STEPP.html, 2008.
33. Lanoo, M., J. Bourgoin, J., Point defects in semiconductors, Springer-Verlag Berlin, Heidelberg, New York, 1981.
34. Frank, H. et al., Studium vlivu jaderného záření na elektrické vlastnosti křemíku, research report (in Czech), FJFI Praha, 1977.
35. Frank, H. et al., Výzkum fyzikálních vlastností Si diod pro dozimetrii rychlých neutronů, research report (in Czech), FJFI Praha, 1977.
36. Alam M. S. et al., The Atlas silicon pixel sensor, Nuclear Instruments and Methods in Physics Research A 456, 217 – 232, 2001.
37. Gorelov, I. et al., Electrical characteristics of silicon pixel detectors, Nuclear Instruments and Methods in Physics Research A 489, 202 – 217, 2002.