Silicon Pore Optics: novel lightweight high-resolution X-ray optics developed for XEUS

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ABSTRACT

The next generation astronomical X-ray telescopes (e.g. XEUS) require extremely large collecting area (10 m^2) in combination with good angular resolution (5 arcsec). The existing technologies such as polished glass, nickel electroforming and foil optics would lead to excessively heavy and expensive optics, and/or are not able to produce the required large area or resolution. We have developed an entirely novel technology for producing X-ray optics which results in very light, stiff and modular optics which can be assembled into almost arbitrarily large apertures, and which are perfectly suited for XEUS.

The technology makes use of commercially available silicon wafers from the semiconductor industry. The latest generation silicon wafers have a surface roughness that is sufficiently low for X-ray reflection, are planparallel to better than a micrometer, have almost perfect mechanical properties and are considerably cheaper than other high-quality optical materials. The wafers are bent into an accurate cone and assembled to form a light and stiff pore structure with pores of the order of a millimeter. The resulting modules form a small segment of a Wolter-I optic, and are easily assembled into an optic with large collecting area.

We present the production principle of these silicon pore optics, the facilities that have been set up to produce these modules and experimental results showing the excellent performance of the first modules that have been produced. With further improvement we expect to be able to match the XEUS requirements for imaging resolution and mass.

Keywords: X-ray optics, X-ray astronomy, XEUS, Wolter, conical, silicon, wafer, stack, pore optics

1. INTRODUCTION

The optics for XEUS are a serious challenge when compared to the current state-of-the-art large area X-ray telescope XMM-Newton[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 but at very high cost in terms of weight and aperture. Using existing technologies for this resulution 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.
- 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.

It is obvious that XEUS requires a revolution instead of evolution from existing technologies. The technology for XEUS should best not be based on replication and/or floppy plates, and not use epoxy or glue.

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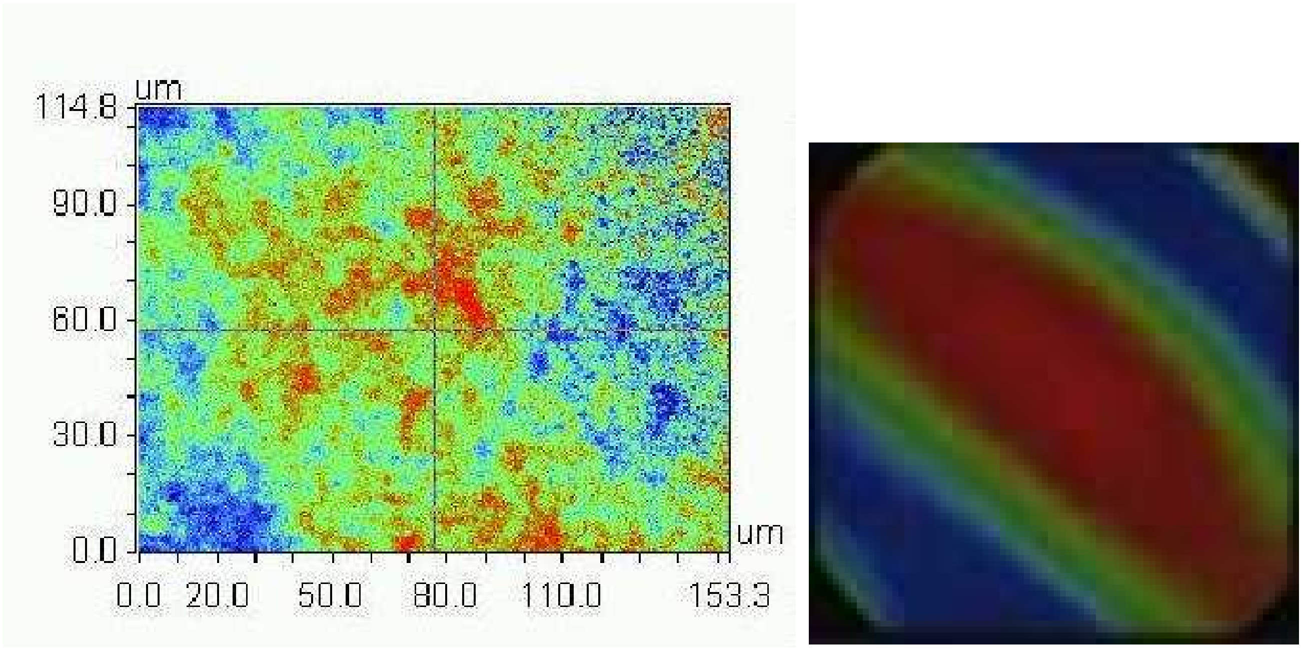

Figure 1. The surface roughness of high-grade commercial wafers is measured to be between 0.4 and 0.5 nm RMS between 5 and 500 mm^{-1} (left, 5 nm peak to peak). An interferogram of a sliced wafer (right) shows that it is dominantly cylindrically curved, however by no more than 1.5 μm peak to peak, corresponding to an image resolution of 1 arcsec.

We introduce and demonstrate here a technology that deals with these problems in the following way:

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

Pore optics for Wolter-I imaging already exist using micro-channel plate technology in glass,[3] but this technology is not expected to result in a resolution close to the required 5 arcsec. It has been proposed and tested to use silicon wafers before, but without the pore structure the imaging quality is not sufficient.[4] The XEUS mission and general aspects of the optics are published elsewhere in these proceedings[5,6]; in this paper we present the production method and facilities, and the results that were obtained.

2. BASE MATERIAL

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 (Fig. 1) 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 (Fig. 2(left)), and treating the back side with a chemo-mechanical process such that ribs remain with a very accurate height and a highly polished surface (Fig. 2(right)).

3. ASSEMBLY

The ribbed plates are then stacked onto a cylindrical mandrel, forming a pore structure (Fig. 3). The wafers can only be bent in one direction, leading to conical surfaces instead of the parabolic/hyperbolic surfaces required for optimal on-axis focussing. This effectively results in a conical approximation to a Wolter-I optic. However,

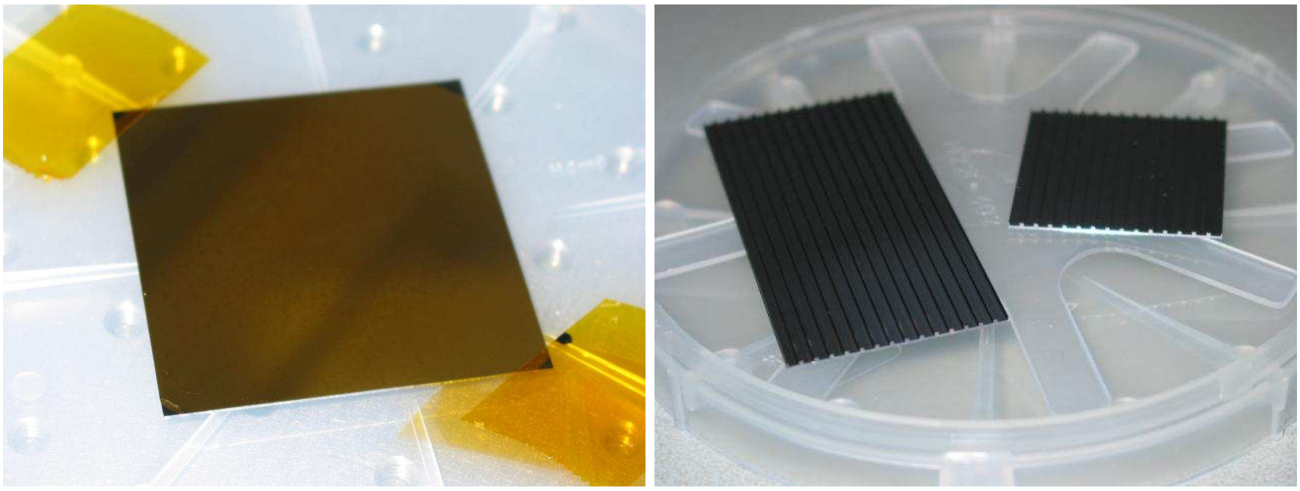

Figure 2. The optics are built up from rectangular cuts of commercial silicon wafers (left). The wafers are processed chemo-mechanically such that ribs remain, providing a thin membrane with ribs of very accurate height and highly polished surfaces (right).

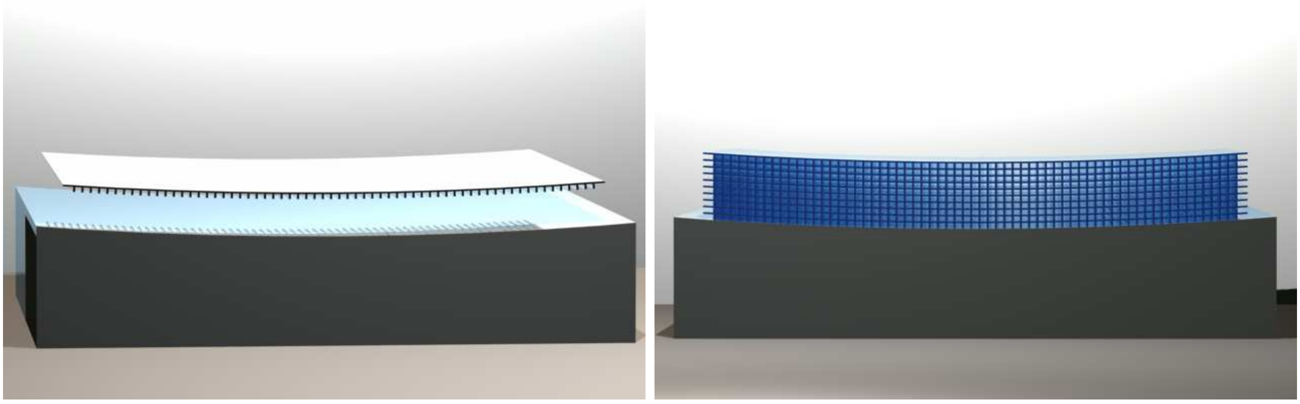

Figure 3. Ribbed plates are stacked onto a mandrel that provies the correct starting curvature.

the effect can be sufficiently small provided that the mirror length is small compared to the (long) focal length of XEUS.

To stack the plates they are bent into a cylindrical shape with the required radius, and then pressed onto the previous plate. 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 can be raised in temperature to turn it (partially) into a true covalent bond.

The radial ribs of the pore structure provide extreme stiffness and stability and therefore allow the walls to be thin. The accurate height of the ribs, a direct result of the good plan-parallelism of the wafers, ensures that the plates are accurately 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 laboraties. An automated optical assembly system was developed and placed in a class-100 clean room environment (Fig. 4). The system is fully computer

Figure 4. 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.

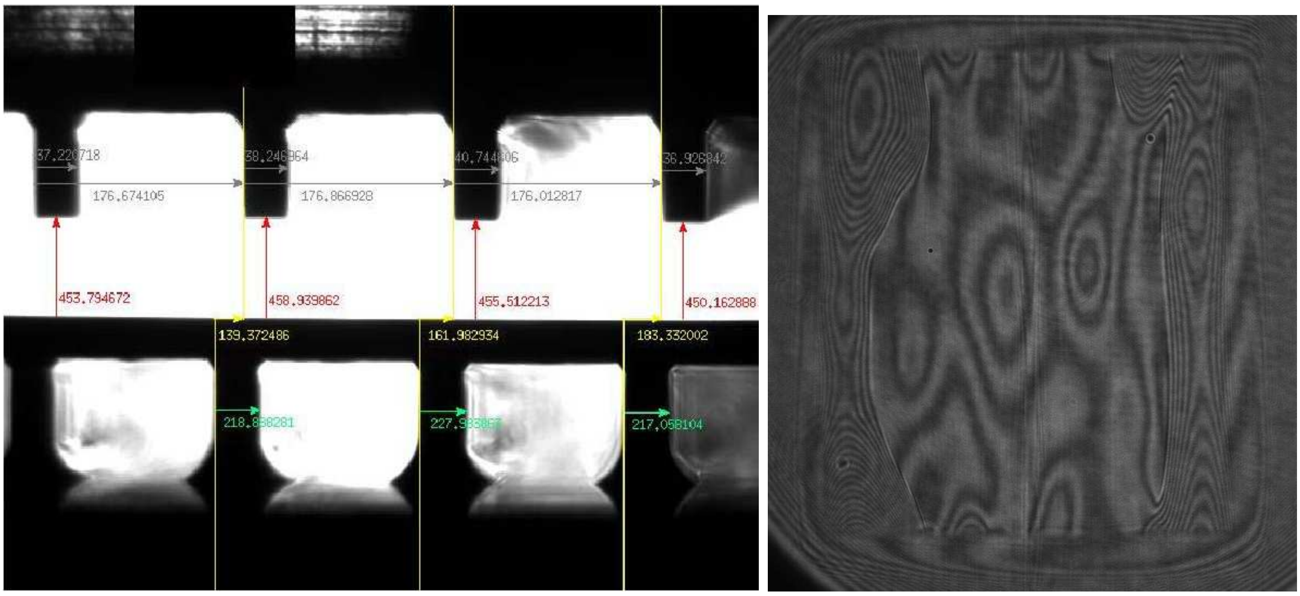

Figure 5. Real-time image analysis of digital microscope images provides alignment to μm accuracy (left). Interferometry is used to measure the shape of the plates to high accuracy during stacking (right).

controlled and has 16 actuators, some of them nano-actuators, an interferometer, digital microscopes with real time image analysis (Fig. 5), and force sensors.

4. PERFORMANCE

Over the last year we have produced and tested about 10 prototype stacks. They typically consist of 5 to 6 plates of 70x70 mm^2 (Fig. 6). These stacks were measured at a synchrotron facility using pencil beams with varying energy and diameter.

Measurements of the scatter distribution (Fig. 7 (left)) 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.

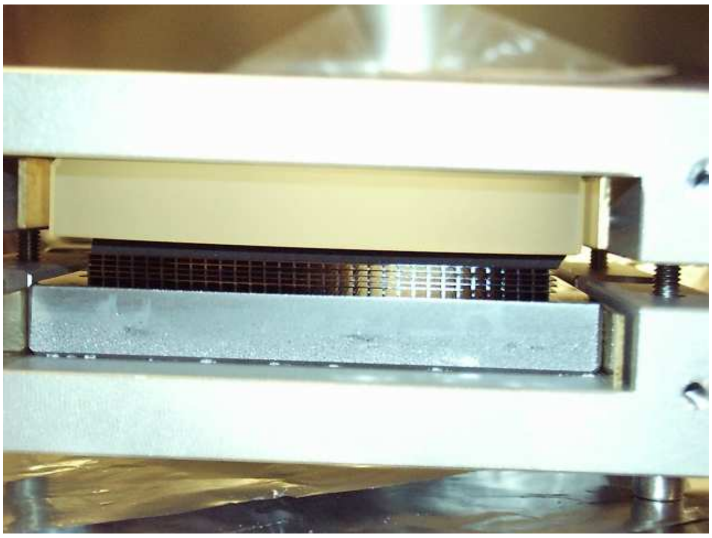

Figure 6. Front side of a prototype stack consisting of 6 plates of 70x70 mm^2, providing 5x31 pores with a total area of 2 cm^2.

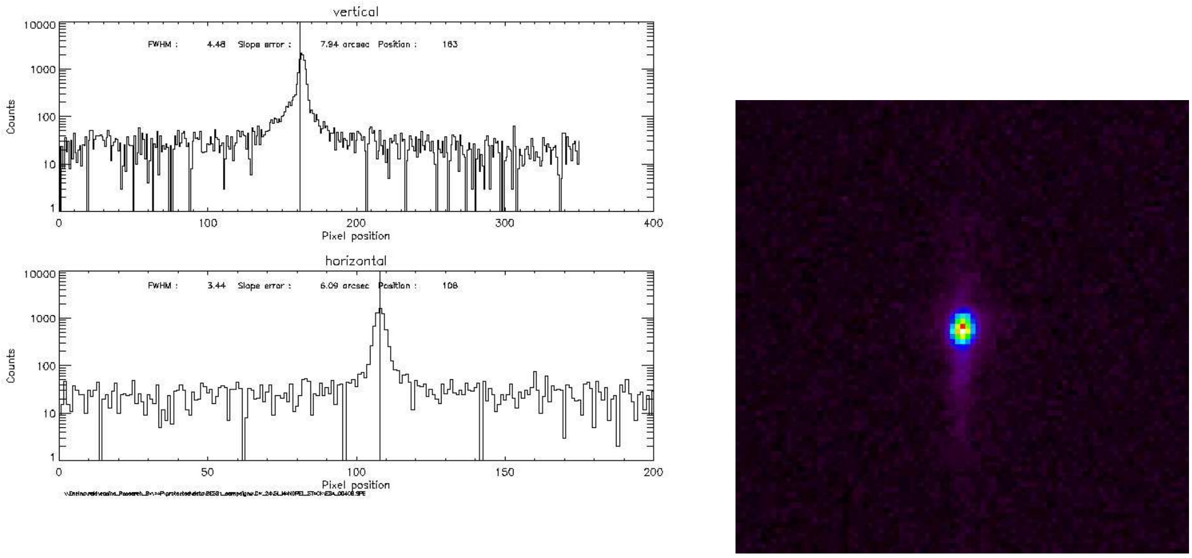

Figure 7. Measurements of the reflectivity and scattering confirm the excellent surface roughness of the wafers also after processing (left). The reflected spot with a footprint of 0.05x5 mm on the surface of the mirrors is not noticably larger than the incident beam, which has a divergence of 1.5 arcsec (right).

The reflected spot size of a beam with a footprint onto the mirror of about 50x5000 μm (Fig. 7 (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.

Fig. 8 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.1(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.

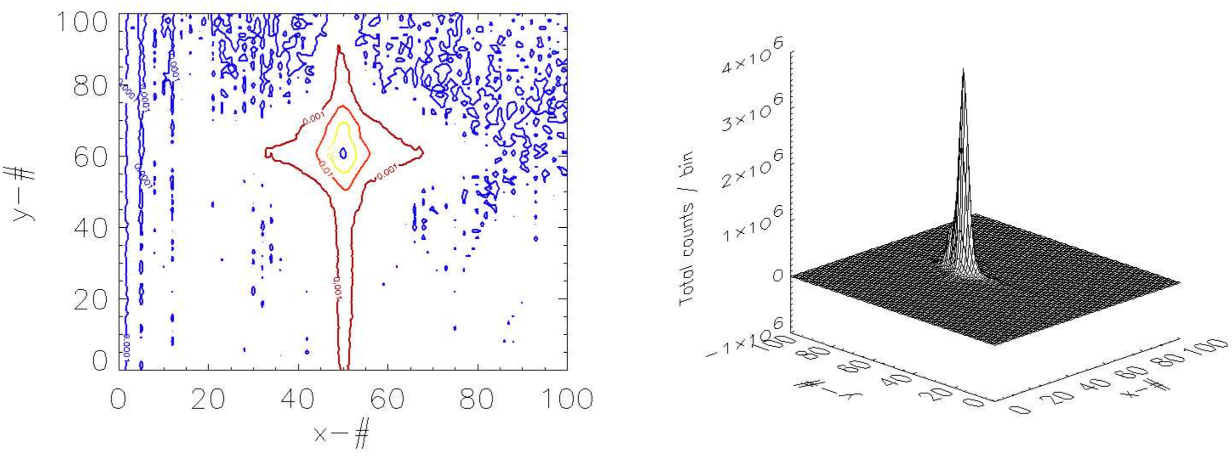

Figure 8. The point spread function of one of the measured stacks as constructed from pencil beam measurements over the central 70% of the aperture. The HEW is 5.3 arcsec. The FWHM of a single stack is 7.9 arcsec, which is large compared to the HEW due to the large asymmetry of the PSF.

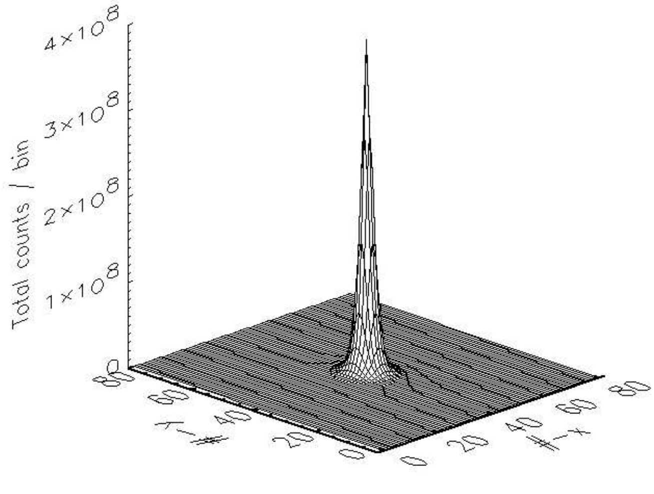

Figure 9. The point spread function of one of the measured stacks, taking into account the effect of placing the stacks along a full circle just as it would be in the final optic. The encircled energy is again 5.3 arcsec, but the FWHM is reduced to 3.1 arcsec.

Fig. 9 shows the result that is obtained when this stack is 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 $1/r$ effect from adding up an elongated PSF over all angles in a circle, which results in a circularly symmetric PSF.

5. CONCLUSION

We have developed novel silicon pore optics for XEUS. The technology is lightweight, resulting in optics of about 200 kg m^{-2} collecting area at 1 keV. It 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 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.

ACKNOWLEDGMENTS

We thank Kayser-Threde GmbH, Centre Spatial de Liège and TNO-TPD (Delft) for their contribution to this program, the Physikalisch-Technische Bundesanstalt at BESSY (Berlin) for their support of the testing, and SRON (Utrecht) and SenterNovem (NL) for financial support.

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