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Manufacturing of lamella of monolithic single crystal silicon X-ray and neutron interferometers

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Abstract

Monolithic silicon single crystal interferometers are used to determine the lattice constant of silicon for the definition of the unit kg. Both X-ray and neutron beams can be used in the experiments. In this study, the lamellae of such interferometers are produced from an oriented silicon blank. As a challenge for the manufacturing processes, the 40 mm high and 40 mm wide lamellae have a thickness of 2 mm for the neutron beam and must subsequently be reduced to a thickness of 1 mm for the X-ray beam. It is shown that these sensitive structures can be machined with form errors in the single micrometre range and average roughness values below 0.5 µm.

Silicon, Single crystal, Surface, Grinding

1. Introduction

X-ray and neutron interferometers are used for high-precision experiments [1,2,3,4]. Nuclear, electromagnetic, gravitational or topological interactions can be investigated [4]. The lattice spacing of a single crystal can be determined together with optical interferometry [2]. X-ray interferometry utilises the refraction of high-energy radiation at the crystal lattice. The interactions take place on specially designed lamellae. These can even be part of a monolithic structure, see figure 1.

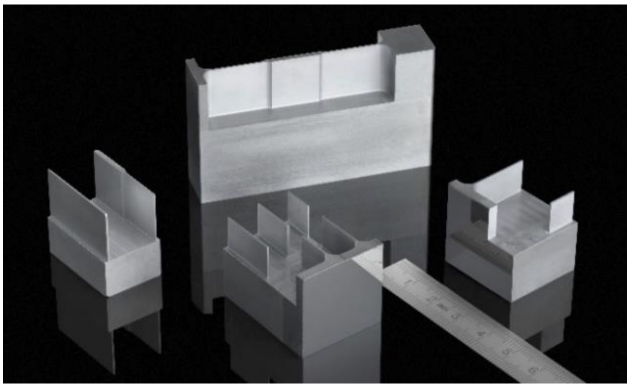

Figure 1. Monolithic silicon structures for the x-ray interferometers in [2,3], as manufactured at PTB

Such lamellae can have a thickness of several millimetres down to what is technically feasible. It could be shown that the lamella thickness can be reduced to 80 µm while maintaining the structural stability. The sub-surface damage of the conventional grinding process is very low. Thus the grinding parameters are fixed and their development is not part of this study.

Usually, a cutting and grinding process is followed by an etching process in order to remove or minimise the lattice distortions of the mechanical processes [1, 2, 3]. More recent approaches attempt to avoid such etching processes in order to better preserve the geometry [4]. However, form deviations may only be a few micrometres. This is essential for the functionality in the experiments with neutron- and X-ray beams.

As part of the present study, lamellae with an initial thickness of 2 mm are to be produced in order to use them in the neutron beam. Subsequently, these lamellae are to be worked to a thickness of only 1 mm in order to be able to carry out further experiments with the monolithic structure using the X-ray beam. An etching step is planned after both grinding processes.

The particular challenge in the production of these lamellae is the second step of reworking by grinding, as the lamellae are already very sensitive and flexible and they are excited by the rotating tools. The block also must be reclamped and realigned in machine. The requirements for shape and position must be met.

The flatness and parallelism of the individual surfaces of all lamellae must be below 10 µm in total. All distances of the interacting surfaces of the lamellae on the ingot must also be equal in that range. Ideally, all distances between all free surfaces in a plane parallel to the base surface (i.e. a beam plane) are the same within a single micrometre for corresponding lamellae.

2. Methods

Monolithic silicon interferometers have been manufactured at PTB for over 30 years. While a jig grinder SIP AFX was still used in [1], the Moore Jig Grinder 500 CPWZ was already used in [2,3].

In contrast to the production variants listed in [4], a traverse grinding process is used this study. Toric metal-bonded D46 diamond tools with the diameter of 8 mm are used for finishing on the Moore machine. The rotational speed is set to 23,000 rpm. The feed rate varies in a range from 1000 mm/min to 2000 mm/min, depending on the variable acoustic feedback of the process. Vertical infeed and pitch are then in the range from 1 µm to 5 µm.

The focus of the investigations is the strategy for thinning the 2 mm thick lamellae. As the interferometer has to be clamped and machined repeatedly, it may be useful to machine both mainplanes of a lamella in the second work. The depth of the removal will contribute to the stability and thus dimensional accuracy of the remaining structure. The selected thinning strategies are shown in figure 2.

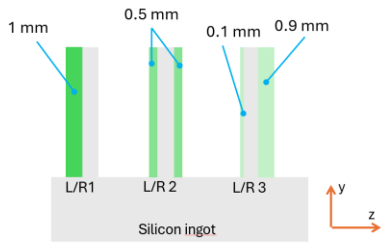

Figure 2. Selected strategies for thinning (green) the lamellae of the sample, whereby the side with 0.1 mm removal is ground first for lamellae L/R 3

As no suitable measuring equipment for determining the thickness and position of the lamellae is available at the time the study is carried out, the lamellae produced are cut from the block using a wire saw and their thickness is then measured using a tactile measuring device. The good resulting parallelism and flatness values of the process are already known from other work with this machine and this process. However, both should be measured in a next pass on the intact silicon structure in process.

3 Results

The manufactured silicon structure with its 6 lamellae is shown in figure 3. The eigenfrequencies of the final lamella are in the range of 750 Hz ± 30 Hz. The grinding process itself leads to only minor sub-surface damage without macroscopic edge chipping.

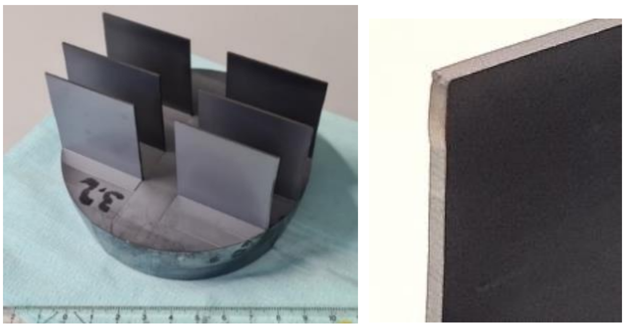

Figure 3. Left: Manufactured silicon sample, Right: Lamella 3.2/3R with thickness of 1 mm. Left face wavy as grown by Czochralski method, top face ground and free of macroscopic edge chipping

Natural oscillation of the free lamella is audible during processing. This become visible as patterns on the surfaces of lamellae of sample rows 1 and 3, for depth of cut see figure 3, but cannot be clearly quantified with the measuring equipment used. The natural frequencies change constantly during processing due to the continuously increasing free-standing thinned blade.

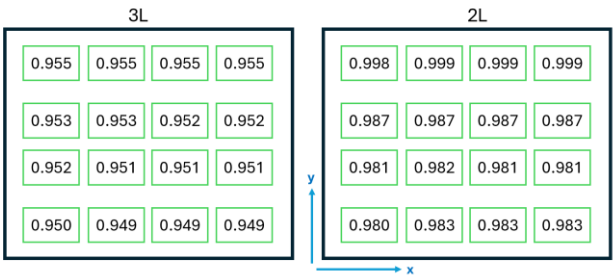

Figure 4. Thickness distribution of samples 3L and 2L; unit is **mm**

The variation of the thickness of the geometrically best lamella 3L and the geometrically worst lamella 2L is shown in Figure 4. A micrometre gauge Tesa micromaster 0-30 mm is used for the measuements. Sample 3L shows a maximum thickness deviation of 6 µm, in the x-direction the values lie in the interval [0, 1] µm, in the y-direction in the interval [5, 6] µm. Sample 2L shows a PV value of 19 µm. In the x-direction the values lie in the interval [0, 3] µm, in the y-direction the values of the thickness distribution lie in the interval [16, 18] µm.

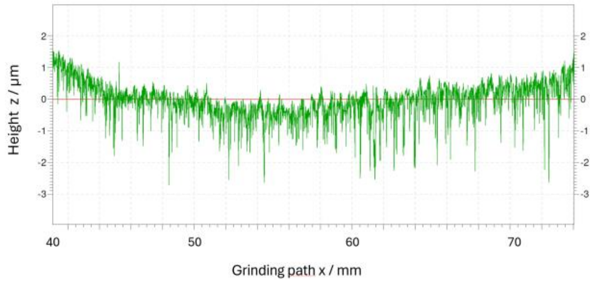

Figure 5. Linescan through centre of lamella 2L, x-direction

The Taylor Hobson Form Talysurf is used for form and roughness measurements. The central linescan of lamella 2L is shown in figure 5. The average roughness values Ra do not differ significantly for all samples, see table 1 and figure 6 for a typical plot. In future, optical measurement technology will provide more detailed information on the quality of the work results.

Table 1. Average Roughness values of samples 2L and 3L

Lamella	Average Roughness Ra_x /µm	Average Roughness Ra_y /µm
2L	0.329	0.314
3L	0.342	0.469

4. Summary, conclusion and outlook

Interferometers made of monocrystalline silicon are used for high precision experiments with X-ray and neutron radiation. The monolithic structures consist of several thin lamellae on a precisely oriented block with high dimensional and shape requirements.

This feasibility study introduces initial concepts for a two-stage production of such 40 mm × 40 mm large lamellae. In the first step, they are ground from the ingot to a thickness of 2 mm. A metal-bonded diamond tool is used for this. For the second step, three removal strategies are investigated for the same tool in order to achieve a lamella thickness of 1 mm. It is found that destabilisation of the lamellae during strongly minimizes the geometric accuracy. Thickness variations of less than 10 µm can be achieved with the most suitable process chain. Average roughness values are in the order of Ra 0.4 µm.

In the next step, the measurement technology must be expanded so that the challenging task of measuring the shape and position of the intact components is also possible, if possible in process. Damping and stabilisation strategies of the lamellae excited in the process must be investigated.

References

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