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Ion beam figuring machine for ultra-precision silicon spheres correction

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ABSTRACT

In the framework of the Avogadro project, isotopically enriched ^{28}Si spheres had been manufactured as artifacts for the assessment of various physical quantities including the sphere volume which finally leads to a very accurate determination of the Avogadro constant N_A. The Avogadro constant is an important input datum for the redefinition of the unit of mass, the kilogram, on the basis of fundamental physical constants. During the recent measurement campaign, it has turned out that one of the main contributions to the overall uncertainty of N_A is the sphericity error and consequently the interferometric volume measurement. Since chemical–mechanical polishing has reached its limits with respect to form accuracy due to the sensitivity of material removal rate to crystal orientation, it has been proposed to use ion beam figuring for further reduction of sphericity error from currently 50 nm PV to values <10 nm PV. In this paper, a new concept and realization of a multi-axis ion beam figuring machine dedicated for deterministic correction of silicon spheres is presented. Aspects of long term tool stability and alignment procedures in order to relate the ion beam footprint to the sphere surface are covered. Furthermore, a process dwell time calculation and tool path generation method dedicated for spheres manufacturing will be presented and discussed.

1. Introduction

Isotopically enriched ^{28}Si single crystal silicon spheres with nearly perfect spherical shape have been identified as suitable artifacts for volume and mass determination in the course of the accurate measurement of the Avogadro constant N_A [1]. The Avogadro constant is an important input datum for the redefinition of the unit of mass, the kilogram, on the basis of fundamental physical constants. Since 2005 the Avogadro project aims at ultimate measurement accuracy of the physical quantities that are required for the determination of N_A [2]. During the recent measurement campaign in 2011, it has turned out that one of the main contributions to the overall uncertainty of N_A is the sphericity error and consequently the interferometric volume measurement [3]. Two of such spheres with diameter of approx. 93.7 mm and a mass of 1 kg have been fabricated so far. Final polishing has been recently conducted by PTB, Germany. The ultimate roundness achievable on such spheres depends mainly on the mechanics of the grinding and polishing process. It has turned out that crystal orientation finally determines the local material removal in polishing. Deviations from ideal roundness are in the order of 30–50 nm peak-to-valley. The sphere volume is determined by measuring diameters using a spherical Fizeau interferometer developed at PTB [4,5]. Those interferometer measurements contain systematic errors partly originating from retrace errors due to shape deviations of the sphere under test. Since the uncertainty of the volume measurement contributes to the overall measurement uncertainty of the Avogadro number u_{N_A} by nearly 60%, it is necessary to reduce the roundness error below 10 nm peak to valley in order to achieve the required relative uncertainty $u_{N_A} < 2 \times 10^{-8}$.

It has been shown in the past that ion beam figuring (IBF) is a technology capable to correct optical surfaces with very high accuracy and process convergence due to its low and thus well controllable local material removal. Nowadays, IBF processes are widely applied in manufacturing and finishing of ultra-precision optical elements [6–8]. Therefore, it has been proposed to use IBF process for further correction of residual surface topography errors on the Avogadro silicon spheres. Although IBF is one of the standard machining processes in Leibniz-Institute of Surface Modification (IOM), the main challenge of this task is the handling and deterministic machining of a body with such a high symmetry. Hence, new concepts for ion beam figuring of spheres are required. In this paper we present the newly developed IBF system. In particular, we discuss the aspects of stable tool operation, sphere

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alignment procedures as well as processing data and tool path generation, which are important prerequisites for deterministic surface processing.

2. Ion beam figuring machine

Ion beam figuring is an established machining technique for ultra-precision optics fine correction on nanometer scale. It is based on physical sputtering of surface atoms by low energy ions (500–1000 eV) accelerated to the workpiece surface. Material removal rate depends on several physical parameters, e.g. ion mass, ion energy, ion incidence angle, and surface atom species. Usually, inert gases like argon are employed for ion beam sputtering. In order to ensure a mean free path long enough for generating and accelerating ions, a high vacuum environment is necessary. Together with NTG GmbH, a new IBF machine has been designed and built dedicated for spheres corrections. The system comprises three linear stages (*X*,*Y*,*Z*) and three rotary axes (*A*,*B*,*H*) for computer-controlled coordinated motion that are mounted in a high vacuum chamber with a volume of approx. 1 m^3. Fig. 1 shows a sketch of the motion system. The silicon sphere to be corrected rests on the table top of stage *A*, a direct driven rotary table that rotates the sphere around its vertical axis, which is designated as *z*-axis. In order to prevent any contamination or scratching of the surface, the sphere is supported by three pins made of polyether ether ketone (PEEK).

The ion beam source is mounted on the *Y*,*Z*,*B* stage group which allows to conduct meridional movements with respect to the sphere surface. With this configuration, every point of the upper hemisphere can be reached by the ion beam under normal incidence angle. Furthermore, a voice coil driven lifting mechanism together with a 3-point roller stage *H* can lift the sphere vertically by approx. 0.35 mm from its pin bearings on the A table. The sphere then rests on the horizontal rollers driven by motor *C* which can turn it over around the *y*-axis by 180° to make the lower hemisphere accessible (see also Fig. 4). After this rotation the lifting mechanism lowers the sphere again on its bearings on the A table for rotation about *z*-axis. The spindle-driven *X* stage serves for aligning the sphere in *x* direction and for positioning of the attached Faraday cup with respect to the ion beam.

The positioning errors of the rotational axes are specified to be lower than 5 arcsec. The orthogonality errors of the linear axes system are specified to be lower than 5 arcsec, i.e. less than 3–5 μm on travel ranges of 150 mm. None of the linear axis has specified positioning errors larger than 2.5 μm peak to valley. Thus, hitting a point at the sphere is secure within less than 15 μm in the worst case.

3. Ion beam source and ion beam diagnostics

The argon ion beam is generated by a standard 40 mm diameter radio-frequency (13.56 MHz) inductively coupled ion beam source equipped with a multi-grid system for beam extraction [9]. The grid system shields the plasma while allowing the positive ions to be transmitted into the free vacuum. High voltages applied to the outer grids lead to focusing of the beamlets resulting in a spatially constrained ion current density at a distance of approx. 40 mm off the outer grid position. An annular graphite aperture with 4 mm diameter at this position masks the beam further to create a nearly Gaussian shaped ion current density distribution with a full width at half maximum (FWHM) of similar order. In order to generate a quasi-neutral particle beam that is emitted by the source, a ring-shaped neutralizer hot filament is located in the gap between grid and graphite aperture for injecting electrons radially into the positive space charge of the ion beam. Beam neutralization is important to maintain stable sputtering conditions on electrically insulating substrates, e.g. made from glass or non-doped silicon. The ion beam source is equipped with an electrical beam switch that allows the switching of the beam quickly on and off [10]. This feature is necessary for start and stop of the machining procedure, since the ion beam source must be moved from its wait position to the start position and back to wait position with beam off to prevent uncoordinated surface treatment.

An ion beam current probe (Faraday cup) for in situ beam diagnostics is attached to the *X* stage parallel to the A table (see Figs. 1 and 4). With this probe the position of ion current density

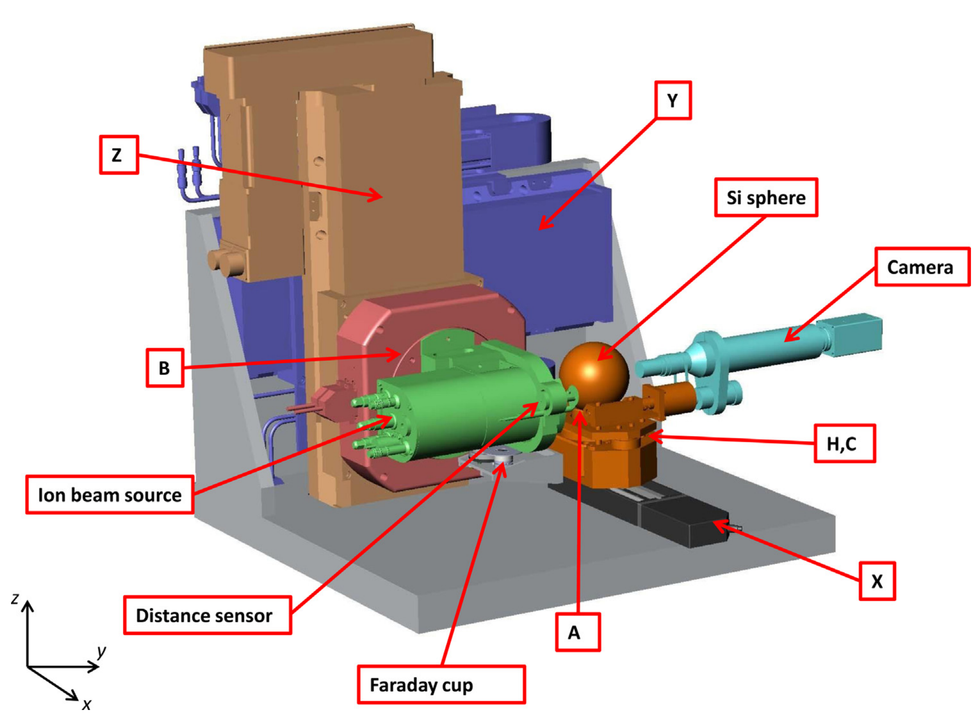

Fig. 1. IBF multi-axis motion system for Si sphere correction (courtesy of NTG GmbH, Gelnhausen, Germany).