euspen's 16th International Conference & Exhibition, Nottingham, UK, May 2016
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Implementation of a metrological UHV-STM

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Abstract
New nano length standards for the use in nanoscale metrology are currently being developed. These new standards are proposed to be based on certain invariants of nature such as the lattice spacing of the Si unit cell. An UHV-STM is being upgraded with interferometers in order to provide traceable measurements of lateral dimensions and step height. The design of the interferometers was adapted from an existing design developed at PTB and modified for operation under UHV conditions.

Keywords: dimensional standards, silicon lattice, traceability, interferometry

1. Introduction

Currently transfer standards for lateral dimensions and step heights are fabricated using methods from semiconductor manufacturing. Smaller feature sizes are achieved by downscaling, a so-called top-down approach, which happens on demand of customers. The smallest feature sizes of currently available commercial standards are 70 nm for lateral dimensions [1] and 6 nm for step heights [2]. Each fabricated standard needs to be calibrated using sophisticated metrological methods, which in turn leads to high costs of downscaling. Especially for the calibration of scanning probe microscopes, standards with much lower feature sizes than the ones currently available are desirable. In the context of a European joint research project a new bottom-up approach is proposed, which utilizes invariants of nature such as lattice spacing of the reconstructed Si(111) surface and principles of self-assembly. This approach has the potential to provide a method for cost-effective production of standards with very small feature sizes. For sample preparation and examination, ultra-high vacuum (UHV) conditions are required in order to keep the Si surface free of contaminations. To provide these conditions as well as direct traceability of these new standards to the definition of the metre, an existing UHV-STM, which can operate under pressures in the regime of 10^{-11} mbar, is being upgraded with interferometers. These interferometers are based on an existing heterodyne interferometer design developed at PTB [3], which was modified in order to account for the UHV conditions inside the STM as well as the limited space available. The completed setup is projected to achieve a resolution of better than 7 pm and 10 pm for lateral and vertical direction, respectively.

2. Implementation

2.1 The basis for the upgrade

An existing UHV-STM (Omicron STM-1) will be upgraded with interferometers. This instrument has been used in the characterization of comparable samples and has proved to be suitable for the task. It features a carrier ring which is suspended by coil springs and damped by eddy current technique. This ring will also need to hold the interferometer components, which thus had to be designed with consideration of total mass and centre of gravity of the whole system. These requirements, together with the very limited space made precise planning using 3D CAD software a necessity. A very precise 3D model of the STM was needed in order to make this possible. As no complete 3D data of the STM assembly existed, it had to be constructed from scratch. An optical 3D-scan of the STM components with a resolution of 0.05 mm was decided to be the most effective option and was used as the basis for a comprehensive 3D model.

2.2. The interferometer design

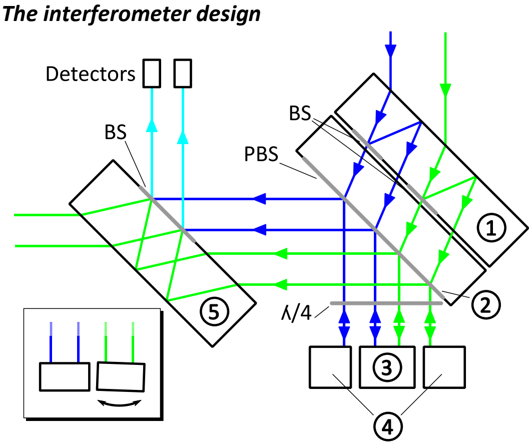

Figure 1. Schematic of a single axis interferometer configured for measurement of displacement. The inset shows mirror configuration for angle measurement. BS – beam splitter, PBS – polarizing beam splitter, λ/4 – quarter wave plate.

The light source used for the interferometers is a frequency-doubled Nd:YAG laser with a wavelength of 532 nm, which is frequency-stabilized on a hyperfine structure of iodine. The light passes through a beam splitter to be divided into two beams of equal intensity. Both beams are frequency-shifted by one acousto-optic modulator (AOM) each, both frequencies different by ca. 2 MHz. Afterwards the beams pass through

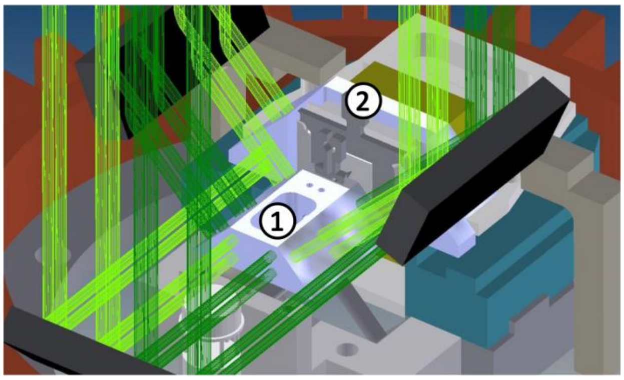

Figure 2. Detail showing the central STM with the mirrors attached to tip and sample holders. Also depicted are all 24 laser beams.

polarisers and are coupled into two polarization-maintaining optical fibres. Inside the vacuum chamber the beams are collimated with a beam diameter of ca. 1.4 mm. these beams are split up into six of each frequency, one of each frequency being used for each interferometer axis. Figure 1 shows the schematic of a single interferometer. In the top beam splitter plate (1) each beam gets divided into two. All four resulting beams pass a polarizing beam splitter (PBS) (2), which is aligned in order to let through the beams coming from the top. All beams pass a quarter-wave plate, which converts the linear polarization state into circular polarization. The beams are reflected by the moving (3) and reference mirrors (4). Afterwards they pass the quarter-wave plate for a second time, resulting in linear polarization rotated by 90 degrees compared to the input beams. These beams are now reflected at the PBS (2) towards the superposition plate (5), where they are brought into interference. The resulting two beams are focused by aspheric lenses onto photodiodes. The resulting signals are amplified by a transimpedance amplifier. Afterwards they are digitized and their phase relation analyzed by a lock-in based algorithm implemented on a FPGA. The phase relations between the two signals are a measure for the displacement of the two sub-interferometers and thus, depending on configuration, for the displacement or angles of the mirrors.

In order to cover all possible lateral and angular movements of the STM tip relative to the sample, six full interferometers are needed. Five interferometers are configured for displacement measurement and cover lateral movement in X, Y and Z direction as well as pitch and roll angle. The sixth interferometer directly measures the yaw angle. Figure 2 shows the core STM setup with the mirrors attached to the tip holder (1) and sample holder (2). The interferometers measure the position and angle of these mirrors relative to each other.

2.3. Adaption of the interferometer design to the measurement setup

Due to space constraints, the interferometer setup had to be distributed over three levels (See Figure 3). On the top level, the two beams enter the vacuum chamber in optical fibres, get coupled out of the fibre, collimated and separated into the twelve beams needed for all interferometers. The detectors and focusing lenses are also attached to the top level plate. On the second level, the beam splitter plates and superposition plates are situated. The lowest level houses the STM components with the attached mirrors. All components needed to be scaled down significantly in comparison to previous implementations of the interferometer design.

In order to achieve the necessary UHV conditions in the chamber, a bake-out procedure is necessary. During this procedure, the chamber and its contents are kept at a temperature of more than 120 °C for several days.

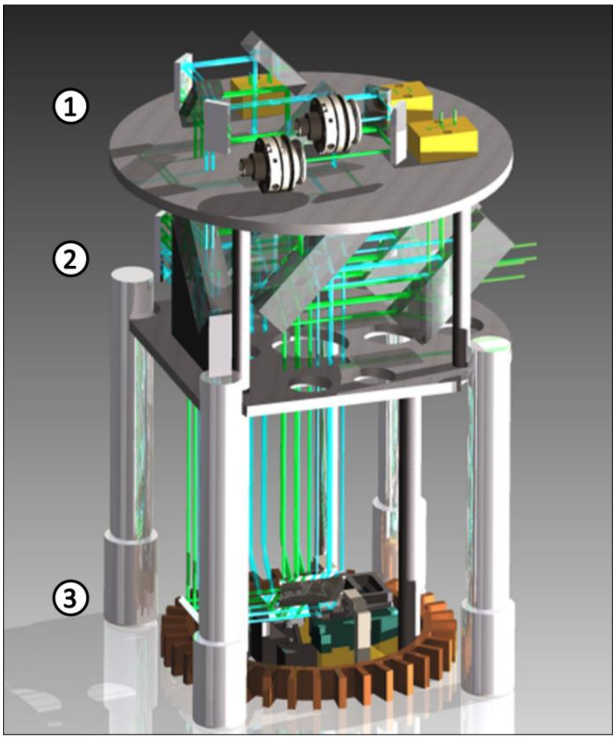

Figure 3. Overview over the whole UHV-STM setup, showing the distribution over three levels. (1) beam coupling, distribution and detection. (2) beam splitting and superposition. (3) STM and sample handling.

Opto-mechanical components utilizing flexure joints were designed and fabricated, with regard to long-term stability especially during the bake-out procedure required for ultra-high vacuum. Weight, space requirements and accessibility for adjustment were also taken into consideration. The polarization-maintaining optical fibres needed for the incoming beams were tested for their ability to retain their properties during bake-out. All components and materials were selected for their ability to operate under UHV conditions.

3. Current Status and outlook

As of January 2016 manufacturing of the mechanical components is completed and the fabrication of the custom-made optical components is nearing completion. All components needed for assembly of the core setup are expected to be available until early spring. By the time of publication results from measurements under atmospheric conditions are to be expected.

Acknowledgements

We gratefully acknowledge support by the Braunschweig International GraduateSchool of Metrology B-IGSM and the DFG Research Training Group GrK1952/1"Metrology for Complex Nanosystems"as well as the EMRP Project CRYSTAL.

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