Development of a Scanning Probe Microscope for Traceable Nanoscale Length Metrology

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Abstract
We give an overview of the design and planned operation of the metrological Scanning Probe Microscope (mSPM) currently under development at the National Measurement Institute Australia (NMIA) and highlight the metrological principles guiding the design of the instrument. The mSPM facility is being established as part of NMIA's nanometrology program and will provide the link in the traceability chain between dimensional measurements made at the nanometre scale and the realization of the SI meter at NMIA. The instrument will provide a measurement volume of 100 µm × 100 µm × 25 µm with a target uncertainty of 1 nm for the position measurement.

1 Introduction

The National Measurement Institute Australia (NMIA) operates a nanometrology program with the aim of supporting research, development and commercial application of nanotechnology in Australia, and to assist in assuring the safety of applications of nanotechnology for Australian consumers, workplaces and the environment.

To provide a link in the traceability chain between dimensional measurements at the nanoscale and the realization of the SI metre at NMIA, a metrological Scanning Probe Microscope (mSPM) is currently under development. This instrument utilizes laser interferometers to monitor the displacement of the sample stage along three perpendicular axes of motion. The wavelength of the laser used with the interferometers will be calibrated against NMI's optical frequency comb which is the

Australian realization of the SI metre. The aim is for the mSPM to provide this traceability with a total uncertainty of ≤1 nm.

Here, we give an overview of the design and operation of the mSPM, and highlight the metrological principles guiding the development of the instrument.

2 Main components and design principles

The mSPM will provide a measurement volume of 100 µm × 100 µm × 25 µm with a target uncertainty of 1 nm for the position measurement. Its main components, illustrated in Figure 1, are a metrological frame that defines the reference coordinate system; a translation stage to implement the displacement between the probe and the sample; sensors to measure the displacement; a probe head and a sensor to quantify the interaction between probe and sample; and a feedback system to control the relative position between probe and sample, i.e., the scanning motion.

Laser interferometry is used for traceable measurement of the displacement between the sample stage and the metrological frame along the three perpendicular axes of motion. Experience in designing ultra precision mechanical stages and instruments [1] and in operating mSPM instruments at other metrology institutes [2–6] has shown that there are many potential contributions to the uncertainty of the displacement measurements. These include alignment errors, particularly Abbé errors; deformations of the mechanical structures, for instance due to thermal expansion; motion errors of the translation stages; form errors of the measurement mirror body; figure errors of the mirror surfaces; interferometer nonlinearities; and fluctuations in the refractive index of air. The instrument design follows a number of principles that are aimed at minimizing the magnitude of these uncertainty contributions.

To minimize Abbé offsets, the probe head is fixed with respect to the metrological frame, and the beams of the interferometers are aligned such that they virtually intersect at the contact point between probe and sample. The flexure design of the three-axis translation stage minimizes cross-talk between perpendicular degrees of freedom as well as out-of-plane motion and tilting errors. The stage carries the sample as well as the measurement mirrors for the interferometry system and features an aperture in the *z*–axis for optical access. The design of both the sample holder and the mirror assembly minimizes their respective masses while maintaining mechanical integrity and stiffness.

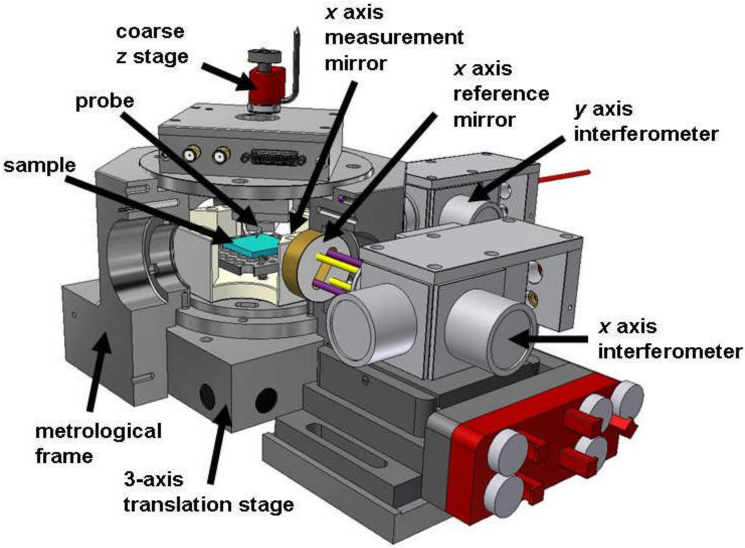

Figure 1: Partial design view of the mSPM. Some of the key components are identified by the labelled arrows.

Reducing the mass load on the translation stage aids in keeping the mechanical resonance frequencies of the translation stage as high as possible, thus reducing the coupling of the scanning motion to the vibration modes of the stage.

The interferometers are plane mirror heterodyne differential interferometers with the laser light provided by a Zeeman-split frequency stabilized HeNe laser with a wavelength λ=632.8 nm and a wavelength stability $\Delta\lambda/\lambda$ better than 10^{-9}. The phase of the heterodyne interferometer is measured using a phase meter that is based on a phase locked loop and implemented on a field programmable gate array platform. The phase meter achieves a noise floor of 30 pm $Hz^{-1/2}$ and a signal bandwidth of 8 kHz, thus allowing use of the interferometer signals for closed-loop position control during the scanning motion.

To minimize tip wear and sample damage while maintaining high sensitivity, the mSPM operates in non-contact atomic force microscope (nc-AFM) mode utilizing a quartz crystal tuning fork. Due to the low electrical currents involved in the excitation and detection of the fork vibration, power dissipation is minimized.

To minimize thermal expansion effects, the metrological frame, the translation stage and the mirror components are manufactured from low thermal expansion coefficient materials. The design of the metrological frame is axially symmetric around a vertical axis that runs through the probe to maintain its axial position when the frame expands or contracts. Coarse translation stages that could contribute to thermal expansion are disabled during mSPM operation. Several instrument components aid in aligning the interferometers and in characterizing the motion errors of the flexure stage. Position-sensitive detectors help with locating the interferometer beams. The form errors of the measurement mirror body are characterized separately so that they can be corrected for.

Variations in environmental parameters such as temperature, operating atmosphere and ambient vibrations are mitigated by means of enclosures that allow operation in a controlled atmosphere, by seismic isolation and anti-vibration measures and by physical separation of heat sources from the instrument. Multiple temperature sensors and heaters are embedded in the instrument body to allow for the detection and active compensation of residual thermal gradients.

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