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Construction and evaluation of a traceable metrological scanning tunnelling microscope

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ABSTRACT

Scanning tunnelling microscopy enables for imaging of conductive surfaces with a resolution down to the atomic level. However, virtually all commercial scanning tunnelling microscopes use piezo tube scanners and capacitance gauges what limits the operating range to typically less than 100 μm in the scanning axes and 10 μm in probing direction. Traceability of measured dimensions to the length unit metre can only be ensured by frequent calibration with the help of standards for pitch and step height. To improve the metrological characteristics of the measurement technique scanning tunnelling microscopy and to broaden its field of application, a directly traceable long range metrological scanning tunnelling microscope was set-up using a laser-interferometrically controlled nanopositioning unit with an operating range of $25 \cdot 25 \cdot 5\ mm^3$ as scanner and a passive tunnelling current measuring probing system as a null indicator. Line scan repeatability of 5 nm has been achieved at 1 nm vertical resolution.

1. Introduction

Conventional scanning tunnelling microscopes (STM) are capable for imaging with even atomic resolution, but are not suitable for dimensional measurements with low uncertainty due to severe non-linearity, hysteresis and the very short range of commonly used piezo tube scanners. Non-linearities of up to 10% lead to a heavily distorted scanning plane that is often described as scan bow, Fig. 1, [1]. Even in closed-loop operation non-linearities of 0.1% are state of the art [2], resulting in up to 100 nm deviations from ideal behavior at 100 μm scans.

As the scan bow is caused to a large extent by hysteresis effects, it is not necessarily constant over time and thus cannot be compensated for efficiently by calibration.

Measurement results of such STMs are always superposed with the shape of this scan bow and thus are not appropriate for precise quantitative evaluation.

Additionally the short range of commercial piezo tube scanners of maximal 200 μm (typically less than 100 μm) in the lateral plane and typically only 10 μm in vertical direction [2] is limiting the area of application to surface texture imaging of small spots on relatively flat parts. With much larger measuring ranges and appropriate dimensional measuring systems, the excellent resolution of scanning tunnelling microscopes could also be beneficially used for precision measurement of distances between remote micro or even nano sized structures. For this purpose the piezo tube scanner has to be replaced by a positioning system capable of traceable coordinate measurements with a range of several millimetres and (sub-) nanometre resolution.

In the past years promising advances were made in the field of long range metrological scanning stages with nanometre resolution [3] that can be employed as a basis for dimensional measuring instruments with a ratio of measuring range to resolution comparable to large range Coordinate Measuring Machines (CMMs) (e.g. 10^7). When applied instead of the piezo tube scanner of an STM these stages may help to overcome the metrological deficiencies of conventional STMs, if challenges concerning measuring speed, dynamic properties of the scanner, drift, hysteresis and repeatability of the approaching process can be solved.

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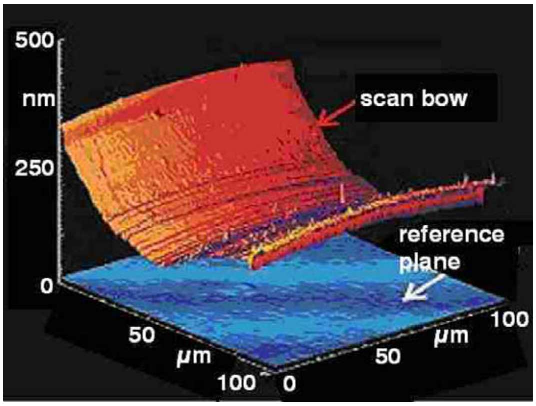

Fig. 1. Scanbow of a piezo tube scanner [1].

Additionally complex scanning patterns as well as evaluation and visualization of huge amounts of measured data (e.g. point clouds with 10^8 measured points) have to be managed.

The paper describes the design of a passive tunnelling current measuring probing system, its integration into the nanopositioning unit SIOS NMM-1 [4,5] and the operation and evaluation of the combined system using algorithms developed with matlab R2006b (www.mathworks.com).

2. System set-up

Systems for dimensional measurements of complex objects, e.g. coordinate measuring machines and profilometers, are usually combined of a device for detecting the surface of the specimen – the probing system – and axes systems for manipulating and measuring the relative position of the specimen to the probing system. To construct a versatile metrology tool with a very high ratio of measuring range and resolution and good metrological properties (i.e. repeatability, linearity, traceability) a combination of a traceably position measuring axes system and a probing system working as a null indicator is favourable, due to the fact that it is much easier to achieve a low relative measuring uncertainty when a known and stable reference structure (e.g. scale or plane mirror) is probed rather than an unknown and possibly irregular work piece surface [6].

Electrodynamic drives are an alternative to piezo actuators, featuring very long travel and a linear relationship between driving force and current, which enables for sub-nanometre resolution even at travel in the millimetre range. For position measurement helium–neon laser interferometers are appropriate due to the combination of sub-nanometre resolution even at measuring ranges of several millimetres. The traceability of the laser wavelength to caesium frequency standards simplifies traceability of the measured length to the definition of the SI length unit.

For the present work the sub-nanometre resolution three DOF scanning stage SIOS NMM-1, based on electrodynamic drives and laser-interferometric length measurement in all axes is used [4,5]. It is additionally equipped with a focus probe [5,6] which can be used as overview system to locate areas of interest on a specimen due to its measuring speed of up to 1 mm/s.

A moving sample configuration combined with comparably bulky serial kinematics of that system lead to a dramatically slower dynamic response than being achievable with piezo scanners, so the design of the probing system has to deal with relatively low measuring speeds (e.g. 1 µm/s) and thus needs very high thermal and mechanical stability. On the other hand the moving sample configuration has considerable advantages in terms of accuracy (Abbe principle can be hold in 3D) and the possibility of using several sensors in the same coordinate system resulting in a multi-sensor nano CMM [3,7].

2.1. Scanning stage and overview systems

Basic component of the system is the laser-interferometrically controlled 3D nanopositioning stage SIOS NMM-1 with a range of 25 · 25 · 5 mm and a resolution of 0.1 nm [4,5]. The specimen carrier of this stage is a mirror with three perpendicular faces (so-called corner mirror) made from zerodur that is also acting as moving mirrors of the three HeNe laser interferometers used for position measurement and closed-loop control of the stage. The interferometers are attached to a thermally and mechanically stable metrology frame also made from zerodur (Fig. 2) in a way that the virtual extensions of the three laser beams coincide in one point that is also the zero position of the installed focus probing system (nominal probing point), preventing first order (Abbe-) errors. The corner mirror is suspended by high precision roller bearings and driven by Lorentz actuators, closed-loop controlled with a frequency of 6.25 kHz. Additionally parasitic angular movements are monitored by two angular sensors and compensated for by the driving system [4]. The manufacturer SIOS claims a volumetric positioning uncertainty of less than 10 nm ($k = 1$) in the whole working range.

If probing occurs only in the point of intersection of the three laser beams, traceable measurements of work piece features are feasible without Abbe-errors. For optimizing measurement uncertainty the probing system is used as a null indicator [6], i.e. the position of the work piece is controlled in a way that measurement of each surface point is done at a constant position in the measuring range of the probing system. In that way non-linearity and lack of

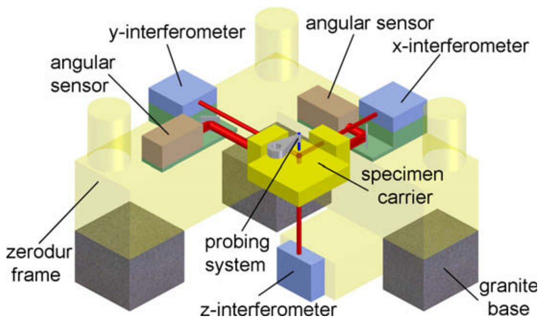

Fig. 2. Set-up of the nanopositioning unit SIOS NMM-1 (according to [4]).