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Construction and Evaluation of a traceable metrological long range Scanning Tunneling Microscope

Albert Weckenmann [1], *Jörg Hoffmann* [2]

[1] Chair Quality Management and Manufacturing Metrology, University Erlangen-Nuremberg, Germany,
weckenmann@qfm.uni-erlangen.de
[2] hoffmann@qfm.uni-erlangen.de

Abstract: Based on a commercial laser interferometrically controlled long-range nanopositioning unit a traceable metrological STM with a range of 25 mm · 25 mm · 5 mm and a resolution up to 0.1 nm has been designed, set-up and tested. Design objectives of the custom made STM probing system were low noise and high thermal and mechanical stability to enable for time consuming large area scans.
As the nanopositioning stage is capable of traceable position measurement the probing system is used in compensation method, i.e. minimizing the effective measuring range of the sensor so that the length measured untraceably by the sensor is negligible compared to the lengths measured traceably by the interferometers.

Keywords: STM, coordinate metrology, multisensorics, nano technology.

1. INTRODUCTION

Conventional scanning tunneling microscopes (STM) are capable for imaging with even atomic resolution, but are not suitable for dimensional measurements 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]. As the scan bow is caused to a large extent by hysteresis effects, it is not constant over time and cannot be compensated for efficiently by calibration.

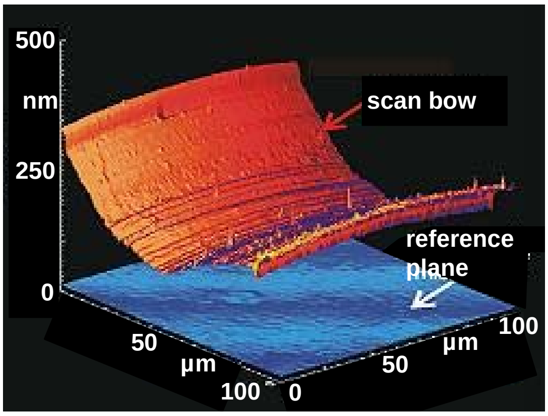

Fig. 1. Scanbow of a piezo tube scanner [1]

Measurement results of such instruments 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 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 the high resolution of a scanning tunneling microscope could also be beneficially used for precision measurement of distances between remote micro 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 millimeters and (sub-) nanometer resolution.

Recently promising advances were made in the field of long range metrological scanning stages with nanometer resolution [3] that could act as basis for dimensional measuring instruments with a ratio of measuring range to resolution comparable to large CMMs. These stages can be used to overcome the metrological deficiencies of conventional STMs. Because of the vast measuring range compared to resolution, additional overview systems are needed for the navigation of the relatively slow STM sensor, which is not able to scan the whole measuring range in acceptably short time.

The paper describes the design of a special STM without piezos, its integration into the nanopositioning unit SIOS NMM-1 [4], [5] and the operation and evaluation of the combined system.

2. DESIGN OF THE SYSTEM

To achieve best metrological properties (i.e. repeat-ability, linearity, traceability) of the measurement system, piezo actuators for the STM scanner had to be avoided completely due to the poor repeatability of piezo scanners. 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 alternative actuators, electrodynamic drives could be used, featuring very long travel and a linear relationship between driving force and current. For the present work the sub-nanometer resolution three DOF scanning stage SIOS NMM-1, based on electrodynamic drives is used. It is additionally equipped with a fast focus probe [5], [6] which can be used as overview system.

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 low measuring speeds and thus needs very high stability. On the other hand the moving sample configuration has considerable advantages in terms of accuracy and the use of several sensors in the same coordinate system resulting in a multisensor 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 mm · 25 mm · 5 mm and a resolution of 0.1 nm [5]. The specimen carrier of this stage is a mirror with three perpendicular faces (so called corner mirror) made from zerodur that is acting also as moving mirrors of the three HeNe Laser interferometers used for position measurement and control. The interferometers are attached to a thermally 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 measurement area.

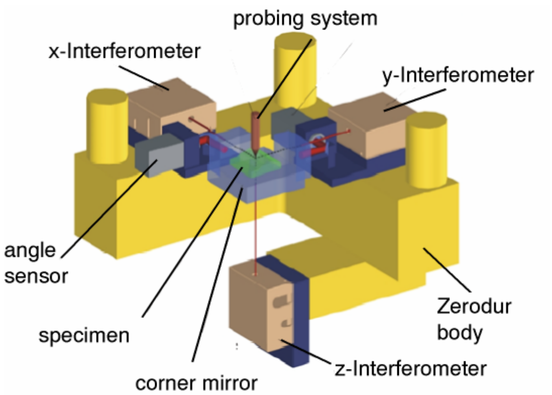

Fig. 2. Set-up of the nanopositioning unit SIOS NMM-1 [4]

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. To improve dynamic behavior of the measuring system, however, the actual probed specimen surface point is allowed move a small measurable distance in z-direction around the nominal probing point. This distance is controlled towards a set point of zero and also evaluated to get the local specimen height. With this approach, the positioning stage has only to follow low spatial frequency height variations of the work piece. High spatial frequencies are rather measured by the sensor than compensated for and thus have to be limited to the small measuring range of the sensor by adjusting the scanning speed. The height measured by the sensor can be calibrated with the help of the z-interferometer of the nanopositioning unit.

Besides the developed STM sensor, also the mentioned focus probe can be used in that way. The focus probe with fixed optics is evaluating the focus error signal and has been developed by technical university of Ilmenau [8]. It is based on a conventional DVD player pick-up and has already verified its performance at measurements of step height standards provided by PTB [5], [9]. The integration into the positioning stage is done mechanically on an invar plate being rigidly fixed to three zerodur pillars of the metrology frame of the NMM-1, Fig.2. Electronic integration is done via 16 bit analog-digital converters directly connected with the DSP unit controlling the entire system. The focus sensor has a resolution below 1nm and a maximum measuring range of a few microns, depending on reflectivity of the specimen and demands on linearity. Due to its high measuring speed of up to several mm/s this system can be used to scan large areas in relatively short time in order to locate features to be measured with the STM. Navigation is further enhanced by an optical microscope using the same objective as the focus probe.

2.2. STM probing system

The STM probing system consists out of the components tip holder, tip, grounding plate and electronics for voltage regulation, tip potential generation and signal amplification, Fig. 3.

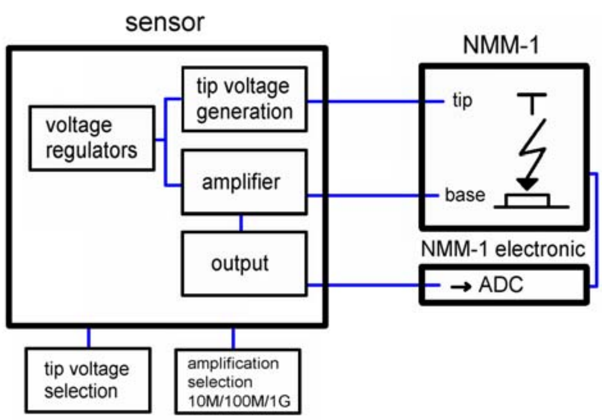

Fig. 3. Schematic of the STM electronics.

When a small voltage (0 - 2.5 V for the developed STM) is applied between tip and grounding plate and the tip is brought in close proximity (few nanometers) to a conductive work piece resting on the grounding plate, electrons may pass the gap without having enough energy to overcome that potential barrier (tunneling of electrons). The number of tunneling electrons per unit time, resp. the so-called tunnel current is then a very sensitive measure for the separation between tip and work piece surface, (1), [10].

The absolute value of this distance cannot be derived from the current signal, as the relationship between tunneling current and tip-sample separation is strongly dependent on material and geometry of tip and sample being reflected in constants A and k in (1).

$$I = A \cdot \frac{\sqrt{\Phi_{eff}}}{a} \cdot U \cdot e^{-k\sqrt{\Phi_{eff}} \cdot a} \qquad (1)$$

I: tunnel current a: tip-sample separation
U: tip potential ϕ_{eff}: effective work function
A, k: constants determined by tip shape and material, atmosphere and other details of experimental set-up

Mechanical and thermal stability of the STM is achieved by the use of high-strength but low expansion materials, like invar for tip holder and grounding plate and platinum-iridium for the tip. The mechanics of the STM include a stiff interface to the invar cross-head of the scanning stage realized by a 12 mm diameter invar rod with a radial arm being adjustable in height and orientation in order to adapt the sensor position conveniently for measuring work pieces of a wide range of dimensions (e.g. allowable thickness between 0 and 10 mm), Fig. 4.

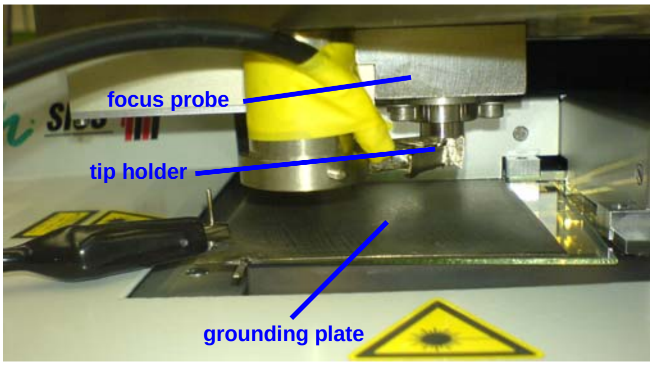

Fig. 4. Invar tip holder and grounding plate for specimen.

Because of spatial restrictions and the possibility of changing the position of the tip holder, it is not feasible to install both sensors exactly in the Abbe-point of the system, so small Abbe-errors may be introduced when using the STM sensor, Fig. 5. As the positioning stage shows only very small parasitic angular movements of about 0.003 `` rms around x and y axis, Abbe-errors in the z-axis can be limited to about 0.15 nm rms for an Abbe offset of up to 10 mm.

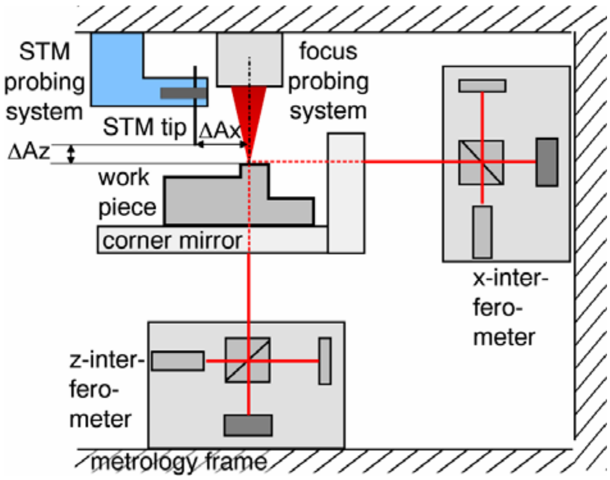

Fig. 5. Arrangement of interferometers and probing systems

ΔAx: Abbe-offset in x-direction
ΔAz: Abbe-offset in z-direction

Angular oscillations around the z-axis are not compensated for and thus are much higher. Due to the relatively high level of vibrations in the lateral plane (x-axis: 25 nm peak to peak) and the lower lateral resolution of focus probe and also STM however, Abbe-errors in the lateral plane are less critical in practice.

During the development different set ups of the electronics have been tested. In the first implementations a preamplifier of the STM with fixed amplification was placed close to the probe onto the invar plate of the NMM-1 so that the travel was short for the very low tunneling current (few nA) before amplification and transformation to a current proportional voltage signal. This was necessary to keep disturbances caused by external electric and magnetic fields as low as possible. After installation of electro-magnetic shielding and application of low noise op-amps (Burr Brown OPA129, noise 15 $nV/Hz^{0.5}$, bias current < 100 fA [11]) this turned out to be unnecessary and the preamplifier was also integrated into the main electronics. After pre-amplification the signal is transferred to the tunable main amplifier (amplification 10^7 - 10^9) to get the desired signal level. The sensor output signal is a voltage between zero and -10V, proportional to the tunneling current. The analog output of the STM electronics is connected with a 16 bit analog to digital converter of the NMM-1 DSP board.

As there is no piezo scanner, the measuring range of the sole STM sensor is very low in z-direction and virtually zero in the lateral plane. This abandons non-linearities and hysteresis effects being associated with commonly used piezo scanners and makes this sensor a so called null-indicator. On the other hand the very small range of the sensor of some ten nanometers depending on tip shape, work piece material and tip voltage [12] demands for very low measuring speeds in order enable the nanopositioning stage to compensate for height variations of the work piece with a residual high frequency variation of less than the sensor's measuring range.

2.3. *Software*

Measuring software for the system was custom made due to a lack of appropriate commercially available software. C++ DLLs were used for implementing the interface between machine controller and a PC. The graphical user interface was made using Labview. The software offers functionalities for conveniently controlling the machine, choosing and calibrating the desired sensor and saving the measured data. For data evaluation and visualization an interface to commercial scanning probe microscopy software was implemented using Matlab. The Matlab script also offers functionalities for diverse filtering operations, including adaptive filtering [6], [9].

2.4. Evaluation of system performance

The first step of evaluation of the system was to determine the characteristic curve of the sensor. As equation (1) shows, the characteristic curve will be strongly dependent on the probe tip, what could be confirmed by experiment. A typical curve when measuring a steel gauge block is shown in Fig. 6. The measuring range in z-direction is approximately 250 nm when measuring steel and using an effective amplification factor of 10^8 (10 nA input corresponding to 1 V output) and a tip potential of 0.3 V. In the actual stage, the curve shows a maximum deviation from an ideal exponential of about 8% (20 nm), demanding for further improvement. Room for improvement can be found in vibration isolation, as the actual positioning noise of the SIOS stage is in the order of 25 nm peak to peak in the x-axis (y- and z-axis below 3nm peak to peak). Clearly visible is the varying resolution due to the exponential interrelationship between tunnel current and tip sample separation, see (1).

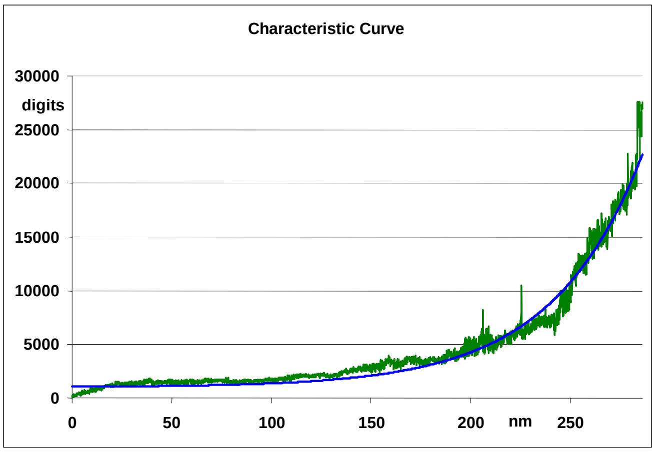

Fig. 6. Characteristic curve of the STM sensor on steel.

green graph: characteristic curve of the STM sensor
blue graph: $y = 40 \cdot e^{0{,}0022 \cdot z} + 1000$

First short line scans were disturbed by the influence of vibration, but also showed the principal functional capability and high resolution of the measuring system, Fig. 7. The scan was made 300 nm in x-direction and back at a speed of 5 µm/s. Due to the poor flatness of the worn gauge block slight changes in lateral position can have significant effects on the measured z-coordinate. Lateral resolution is enhanced by a factor of approximately 100 compared to the focus probe. Further improvement could be made by reducing lateral vibrations.

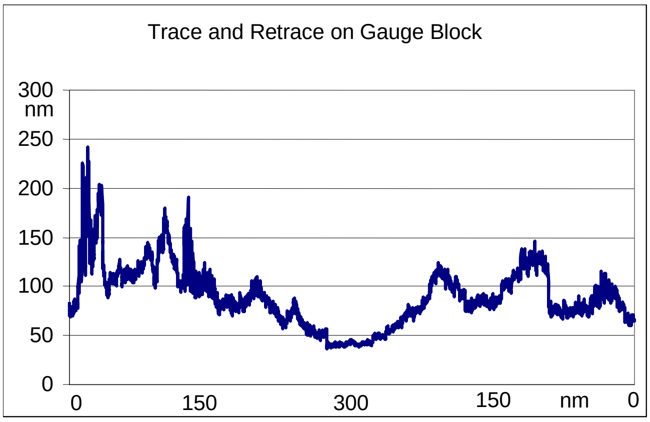

Fig. 7. Measurement of a worn steel gauge block.

Lateral vibrations, Fig. 8, are also a hazard for the delicate probe tip as they may lead to collisions due to the very low working distance of the STM probing system, so for further evaluation at 2 dimensional measurements, at first improvements of the vibration isolation system are to be made. For this purpose additional shielding is to be installed to protect the system from the turbulent airflow induced by the high performance air conditioning system in the precision metrology lab of QFM.

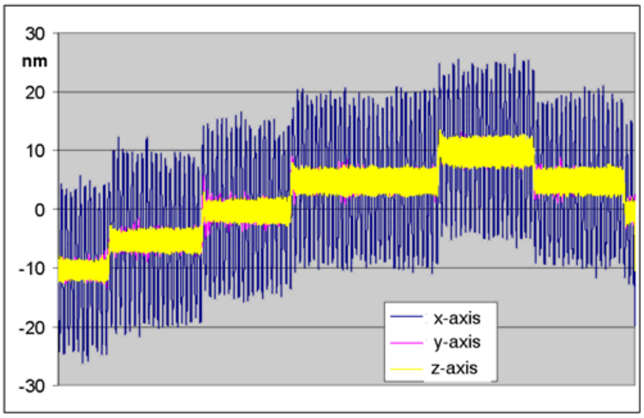

Fig. 8. Positioning noise at steps of 5nm.

For final characterization of the STM calibrated silicon lateral and step height standards will be measured with both probing systems and also different measuring systems like a white light interferometer and a commercial scanning tunneling microscope.

3. CONCLUSION

A traceable metrological STM with a principal measuring range of up to 25 · 25 · 5 mm^3 has been designed, implemented and tested. Visual and metrological overview systems enhance navigation on large samples and enable for distance measurements between small remote features on the sample. Operation of the system is convenient due to custom made measuring software and commercial evaluation software. For the improvement of system performance vibration isolation is a critical issue. Further evaluation of the system with the help of calibrated standards and comparative measurements is planned.

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