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Interferometer-based scanning probe microscope for high-speed, long-range, traceable measurements

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Abstract

The specialty of the metrological SPM-head is the combined deflection detection system for simultaneous acquisition of bending, torsion and position of the cantilever with one measuring beam. The deflection system comprises a beam deflection and an interferometer in such a way that measurements of the cantilever displacement are traceable to the SI unit metre. Integrated into a NPM machine scans with a resolution of 0.1 nm over a range of 25 mm × 25 mm are possible.

Keywords: nanopositioning and nanomeasuring machine, metrological scanning probe microscope, SPM, AFM.

Mikroskop z sondą skanującą na bazie interferometru do szybkich spójnych pomiarów małych przemieszczeń o dużym zakresie

Streszczenie

W artykule przedstawiono wyniki dotyczące opracowanej i zrealizowanej w Ilmenau University of Technology (Niemcy) maszyny Nano-pozycjonującej (NPM), która zapewnia nanometrową rozdzielczość oraz niepewność 3D pozycjonowania oraz pomiaru w zakresie 25 mm × 25 mm × 5 mm. Jednym ze składowych elementów tej maszyny, od którego zależą jej własności metrologiczne, jest mikroskop z sondą skanującą (SPM) na bazie interferometru, którego koncepcję przedstawiono na (rys. 1). Wykonana według tej koncepcji głowica metrologicznego SPM została zintegrowana z NPM maszyny (rys. 2). Osobliwością głowicy SPM jest system dla jednoczesnej akwizycji ugięcia, skręcania i pozycji belki wspornikowej tylko z jednej wiązki światła (rys. 1). Zostały wykonane badania dokładności pozycjonowania i pomiaru przy różnych szybkościach skanowania obiektu badanego od 1 µm/s do 1 mm/s. Przykładowe wyniki skanowania przedstawiono na rys. 3, 4. W celu wyznaczania jakości tych wyników oraz kalibracji SPM został wykorzystany zestaw wzorców wysokości skokowych z Physikalisch-Technische Bundesanstalt – PTB (rys. 6), oraz wykonane w specjalny sposób wzorce testowych wskaźników odniesienia rozstawionych na stosunkowo dużych odległościach (rys. 7). Uzyskane z SPM wyniki pomiarów wzorców wysokości oraz niepewności tych wyników wykazały bardzo dobrą zbieżność z wartościami wielkości tych wzorców (tab. 1). Wyznaczona powtarzalność wyników jest na poziomie poniżej 0.2 nm. Bardzo dobre wyniki uzyskano przy pomiarach testowych wskaźników odniesienia, powtarzalność wyników pomiaru centrów współrzędnych wskaźników wynosi poniżej 5 nm (tab. 2).

Słowa kluczowe: maszyna nanopozycjonująca i nanopomiarowa, metrologiczny mikroskop z sondą skanującą, SPM, AFM.

1. Introduction

For almost thirty years the scanning probe microscopy (SPM) has provided a view into the nano-world. The functional principle of SPM is based on observing the interaction over short distances between a very sharp tip (mounted on the end of a cantilever) and a sample surface. Forces between the tip and the surface cause deflection of the cantilever. By detecting the deflection of the cantilever, it is possible to determine the surface topography during the scan. Nowadays this special technique of investigation and imaging of surface properties is particularly important for the semiconductor industry, biotechnology, precision technology and many others fields. Progress in this key technology demands quantitative dimensional measurements with nanometre precision over large ranges.

In order to meet the described requirements, a nanopositioning and nanomeasuring machine (NPM machine) has been developed at the Institute of Process Measurement and Sensor Technology of the Ilmenau University of Technology with nanometre resolution and uncertainty over a positioning and measuring range of 25 mm × 25 mm × 5 mm [1]. Due to its structure, different probe systems, including SPMs, can be integrated into the NPM machine [2]. For metrological applications, a traceable, highly precise and stable SPM-head (probe system) is needed for the NPM machine. Such metrological interferometer-based SPM-head has been also developed at the Institute of Process Measurement and Sensor Technology [3].

2. Metrological SPM-head as the probe system for the NPM machine

The heart of the developed SPM-head is the metrological deflection detection system (see Figure 1). A detection system is required for registration of the cantilever deflection (bending, torsion, oscillation amplitude, phase, frequency) caused by the interaction between the cantilever tip and the test surface. There are different techniques to capture the deflection of the cantilever. The most common and advantageous is the optical lever-detection. This detection system affords simultaneous registration of the cantilever bending and torsion and therefore normal, lateral and axial interaction forces [4]. For an accurate measurement, the position of the cantilever must be retrieved additionally to the torsion and bending. Such application of an interferometer for acquisition of the cantilever displacement makes the measurements traceable to the wavelength of the He-Ne laser and therefore to the SI unit metre.

The developed metrological deflection detection system comprises a beam deflection and a homodyne interferometer, and therefore enables simultaneous measurement of the bending, torsion and position of the cantilever. Due to the special combined optical arrangement, only one measuring beam is required, which is focused on the free end of the cantilever (see Figure 1).

Furthermore, the SPM-head includes an additional high-speed piezoelectric drive for controlling the cantilever deflection during the surface scan. At the same time the movement of the piezoelectric drive is interferometrically measured, using the metrological deflection detection system directly on the cantilever backside. Therefore, nonlinearity and hysteresis of the piezoelectric drive have no bearing on measurement results.

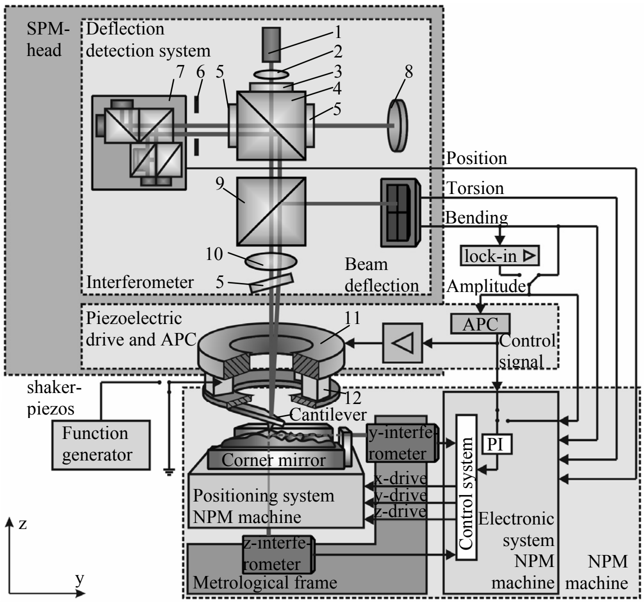

Fig. 1. Concept of the metrological SPM. 1 – fibre, 2 – collimator, 3 – polarizing filter, 4 – polarizing beam splitter, 5 – λ/4-wave plate, 6 – aperture, 7 - interference detection unit, 8 – reference mirror, 9 – beam splitter, 10 – focus lens, 11 – z-piezo, 12 – shaker piezo

Rys. 1. Zasada budowy metrologicznego SPM. 1 – światłowód, 2 – kolimator, 3 – filtr polaryzacyjny, 4 – polaryzacyjny dzielnik promienia, 5 – płytka ćwierćfalowa, 6 – otwór, 7 - interferometryczny układ detekcji, 8 – lusterko odniesienia, 9 – dzielnik promienia, 10 –soczewka ogniskująca 11 – z-piezo, 12 – piezo wibrator.

The metrological SPM-head is used as a probe system for the NPM machine. Due to the corresponding mechanical and electrical interfaces, the SPM-head is integrated into the NPM machine (see Figure 2). The measurement sample is placed on a movable corner mirror that is driven by a three-axis positioning system. The three fixed interferometers traceable measure the position of the corner mirror and the sample, respectively. The position measurements are used for closed-loop control. Three measurement axes intersect at one point, and in all axes the measurement sample and the interferometers are also in line at all times (i.e. Abbe comparator principle is realised in each measuring axis). This means the coordinate system is determined by the corner mirror.

The NPM machine handles the entire measuring procedure, including the scanning motion, so that no additional scanner for the x- and y-axis is necessary for the SPM-head. Only the vertical adjustment (along the z-axis) during the measurement is performed with a combined movement of the piezoelectric drive and the positioning system of the NPM machine. The piezoelectric drive with its small motion range of 2 µm performs fine high-frequency movements, and the NPM machine is responsible for the coarse, low-frequency movements (because of the high mass of the positioning system and corner mirror of the machine) over the entire range of 5 mm. Thus the measurement result is the difference between the interferometer value of the deflection detection system from the SPM-head and the z-interferometer value from the NPM machine.

3. Application of the metrological SPM to high-speed measurements

The movement of the piezoelectric drive is controlled by a specially developed, based on a digital signal processor (DSP), active probe controller (APC) [5]. A different quasi-analog controller can by realized with the APC. Most commonly used (in SPM technique) proportional-integral (PI), proportional-integral-derivative (PID) feedback controllers as well as more sophisticated PI controllers with two notch filters (PI NF) are successfully implemented into the APC, optimised and tested.

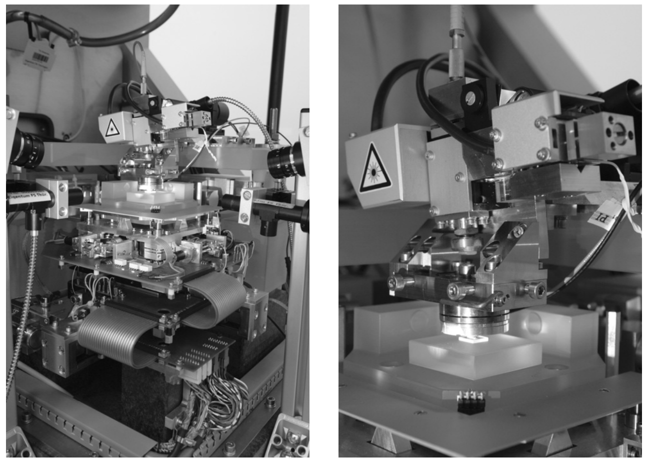

Fig. 2. Metrological SPM-head integrated into the NPM machine

Rys. 2. Głowica metrologicznego SPM zintegrowana z NPM maszyny

The best results are obtained with a PI NF controller. A new result is the increase in the scan speed up to 1 mm/s. The measurements are made in the contact mode (CM) of operation on the sample with ca. 120 nm deep trenches. The single line scans at different scanning speeds from 1 µm/s to 1 mm/s are shown (displaced for better representation) in Figure 3.

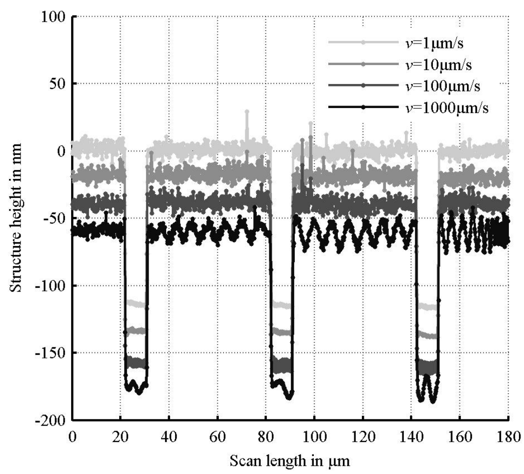

Fig. 3. Single line scan. Structure profile

Rys. 3. Wynik skanowania pojedynczego wiersza. Profil struktury

The control deviation during the line scans (Figure 4) is the difference e between the setpoint value (defined bending) and the bending signal (of the deflection detection system from the SPM-head). The control deviation for each scanning speed is also displaced plotted for better representation. Figure 5 shows the dependency of the control deviation on the scanning speed. The deviation is here calculated as the standard deviation of the control deviation e of scan line. The increase of the scanning speed under-standably induces the enhancement of the overshoots on the structure edges (Figure 4), and leading to an increase in the standard deviation of the control deviation (Figure 5), where the control deviation is interferometrically measured directly on the cantilever by the deflection detection system and is incorporated into the calculation of the structure profile. As of 200 µm/s speed, the relationship between the control deviation and the scanning speed is linear (Figure 5). The continuing increase in the scanning speed can lead to damage of the measurement sample (in particular on the structure edges) and the cantilever tip.

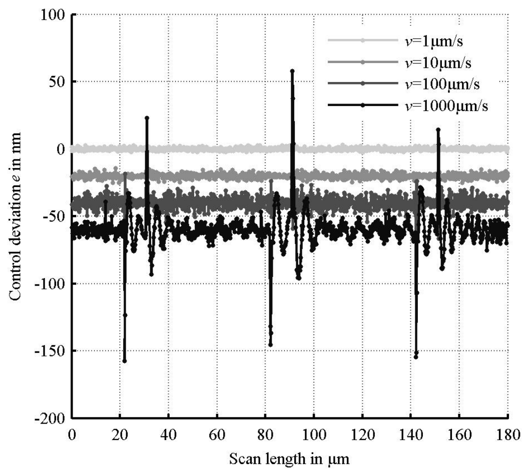

Fig. 4. Single line scan. Control deviation *e*
Rys. 4. Wynik skanowania pojedynczego wiersza. Rejestracja odchylenia *e*

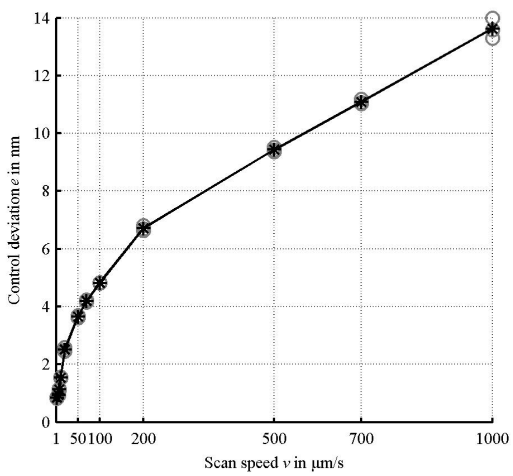

Fig. 5. The standard uncertainty of the control deviation *e* at different scanning speeds
Rys. 5. Niepewność standardowa odchylenia *e* przy różnych szybkościach skanowania

4. Key measurement tasks and results

The key measurement tasks of the metrological SPMs in national metrology institutes (NMI) are the certified calibration of transfer standards (lateral, step height standards) for other commercial SPMs. The lateral standards and step height standards are measured by the metrological SPM-head (in combination with the NPM machine) [6]. The one-dimensional (1D) calibration gratings (lateral standards) are scanned in the CM and intermittent contact mode (IM) of operation. The results – calculated mean - pitches are compared and discussed in [7]. Furthermore, the set of calibrated (by the Physikalisch-Technische Bundesanstalt - PTB) step height standards (Figure 6) are measured in addition to CM [6] in IM.

The calibrated fields R1 of each standard were scanned 30 times. Each measured line was processed according to EN ISO 5436-1 [8], then the average step height for each of the fields R1 was calculated. Finally, the mean step height *h* was determined as the average of all 30 step heights of the R1 field. The calculated results (height *h* and standard uncertainty *u*) for 7 nm, 20 nm and 70 nm standards and calibration values with expanded uncertainty *U* (*k*=2) are presented in table 1.

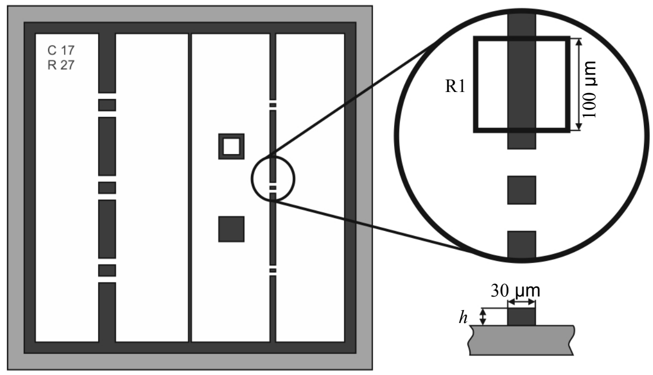

Fig. 6. Step height standard
Rys. 6. Wzorzec wysokości schodkowy

All the results from measurements in CM as well as in IM are within the uncertainty of the calibration values. The largest influence on the calculated step height came from the uniformity, roughness and cleanness of the standards. The deviation between the results from CM and IM is less 2 nm. The measurements in CM are taken any time earlier as measurements in IM; therefore, cleanness of the standards is very important. The repeatability of the results is less than 0.5 nm.

Tab. 1. The measurement results from SPM
Tab. 1. Wyniki pomiarów z SPM

Standard	PTB		Metrological SPM				Deviation
			CM		IM		
	h (nm)	*U* (nm)	*h* (nm)	*u* (nm)	*h*, (nm)	*u* (nm)	h_{CM}-h_{IM}, (nm)
C26 R18	7.4	1.0	7.6	0.4	7.18	0.08	0.42
C18 R18	21.2	1.1	21.9	0.3	20.17	0.10	1.73
C17 R27	69.1	1.2	70.09	0.17	69.90	0.13	0.19

The next important application of the metrological SPM is long-range measurement. For navigation over the complete range of the NPM machine (up to 25 mm × 25 mm) and relocation of the cantilever tip after the replacement of the cantilever, special fiducial marks are developed [9]. The fiducial marks are designed as nested cross structures I and II sized from 40 µm to 800 µm located at each corner of the sample carrier (silicon wafer) within the measurement range of the NPM machine. The fiducial marks M1-4 are schematically illustrated in Figure 7. 4 fiducial marks are fabricated using UV lithography and reactive ion etching (RIE).

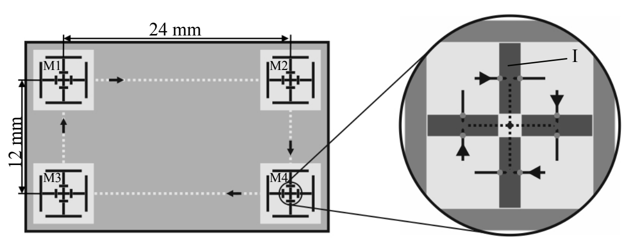

Fig. 7. Fiducial marks
Rys. 7. Wskaźniki odniesienia

The points of reference of the fiducial mark are determined as the centre of the cross structures I and II. To calculate this, the centres are not scanned completely across, and only 4 lines (per cross) are measured (Figure 7 right). Each line comprises the groove whose position is evaluated by the centre of gravity method. Then the centre of the cross structure is calculated as the intersection of two straight lines determined by the grove positions.

Tab. 2. Repeatability results of the determination coordinates of cross centres of fiducial marks
Tab. 2. Powtarzalność wyników wyznaczania współrzędnych centrów wskaźników odniesienia

Cross	*x*-coordinate (nm)	*y*-coordinate (nm)
I	5	1.4
II	4	1.3

All fiducial marks with nested crosses are consecutively measured. The coordinates of the cross centres of the fiducial marks as well as the distances between them are calculated. The complete measurement procedures were performed 25 times. The results, coordinates of the cross centres, and their repeatability (standard deviation) are determined and shown in table 2. Thus it appears that the relocation of the cantilever tip or measurement structure after the replacement of the cantilever can be better than 5 nm. Furthermore, the repeatability of the distances between the cross centres and between fiducial marks, respectively, (M1-M2, M2-M3, M3-M4 etc.) average 4 nm.

5. Conclusions

This paper shows the approach of the metrological SPM for high-speed, long-range, very accurate measurements. So the increase in the scanning speed up to 1 mm/s is possible. Very good results are achieved for step height and long-range measurements.

This research is supported by the Collaborative Research Centre SFB 622 "Nanopositioning and Nanomeasuring Machines" at the Ilmenau University of Technology and the German Research Foundation (DFG). Also, the authors wish to thank all those colleagues at the Ilmenau University of Technology who have contributed to these developments.

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otrzymano / received: 16.10.2013
przyjęto do druku / accepted: 01.01.2014 *artykuł recenzowany / revised paper*