INFORMATION AND MEASUREMENT TECHNOLOGIES IN MECHATRONICS AND ROBOTICS

NANOPOSITIONING AND NANOMEASURING MACHINE FOR MULTI-SENSOR APPLICATIONS

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Abstract. In micro- and nanotechnology, the demands placed on measurement technology are increasing. The structures to be measured are becoming more complex with smaller structure widths, increasingly larger surface regions, and thousands of inspection features. To solve the problems, it has become desirable and even necessary to combine multi-sensor technology with high precision nanopositioning and nanomeasuring technology. The Nanopositioning and Nanomeasuring Machine NMM-1 with a measuring range of 25 mm × 25 mm × 5 mm and sub-nanometer resolution allow the application of several optical, tactile and atomic force probes. The combination of several sensor technologies in a multi-sensor approach for application with the NMM-1 is demonstrated.

Key words: Nanopositioning and Nanomeasuring Machine; multi-sensor technology; Probe; Nanotechnology.

1. Introduction

The range of measurement tasks in micro- and nanotechnology is becoming more varied and multifaceted, due to continual progress in manufacturing and production capabilities. The 2½ dimensional structures found in silicon technology are becoming more complex, with smaller structure widths and increasingly larger surface regions. The current demands for structure widths in the semiconductor industry are 45 nm according to the International Technology Roadmap of Semiconductors (ITRS). The prognoses for future years are described as follows: “Metrology methods must routinely measure near and at atomic scale dimensions” [1]. Similar tendencies can be observed in micro-systems technology, precision optical manufacturing, or micro-processing technology. Here, the micro- and nanogeometries produced are becoming more complex, and the aspect ratios are becoming larger.

This paper describes a machine that enables the large-area measurement of micro- and nanostructures with sub-nanometer resolution. To solve the problems arising within the widespread nanometrology application spectrum, this machine combines nanopositioning and nanomeasuring technology with multi-sensor technologies.

2. Nanopositioning and Nanomeasuring Machine

The Ilmenau University of Technology together with SIOS Meßtechnik GmbH has developed a Nanopositioning and Nanomeasuring Machine (NPM Machine) with a measuring volume of 25 × 25 × 5 mm³ and a resolution of 0.1 nm [2]. This NPM Machine has been manufactured for several years under the name NMM-1.

To achieve nanometer precision, it is necessary to apply a set-up that provides minimum errors. Therefore, the basic concept of the NPM machine consists of a special arrangement that allows Abbe error-free measurements in all measuring axes over the whole measuring range. This means that the Abbe offset should be zero in every axis.

$$\forall i \in x, y, z \qquad l_{off_i} \to 0 \tag{1}$$

By expanding the Abbe comparator principle, not only will the length offset between the measuring axis and the normal axis be minimized, but also an active measurement and correction of all angular deviations will be carried out.

$$\alpha_i \to 0 \qquad \forall i \in x, y, z$$

In this way the Abbe error can be minimized:

$$\Delta l_i = l_{off_i} \cdot \sin\alpha_i \to 0 \quad \forall i \in x, y, z \tag{2}$$

Such a set-up can be realized with an arrangement where the nanoprobes work as null-indicators and whose scanning point lies in the intersection of the three coordinate measuring axes of three laser interferometers (Fig. 1).

The laser beams are reflected on a so-called “mirror corner” that represents the orthogonal coordinate system and which carries the object to be measured. The mirror corner and the object to be measured are moved in a closed-loop control by a 3D-precision stage (Fig. 2).

Additional angular sensors measure the angular deviations of the 3D stage. Four *z*-drives compensate these angular deviations in closed-loop control. The measuring systems are mounted on a mechanically and thermally stable metrology frame manufactured by Zerodur. This arrangement forms a universal and advanced basis for high precision measurement tasks with several nanoprobing systems.

Due to this approach the nanoprobes (Fig. 1) work as zero indicators. The *x*-*y*-*z* data are gathered from the *x*-, *y*- and *z*-interferometers while the data of the probe are permanently controlled to be zero. The nanoprobes, described in more detail below, work only in the *z*-direction. Therefore, only surface measurements can be carried out. Real 3D measurements can be realized for example with tactile 3D microprobes [6].

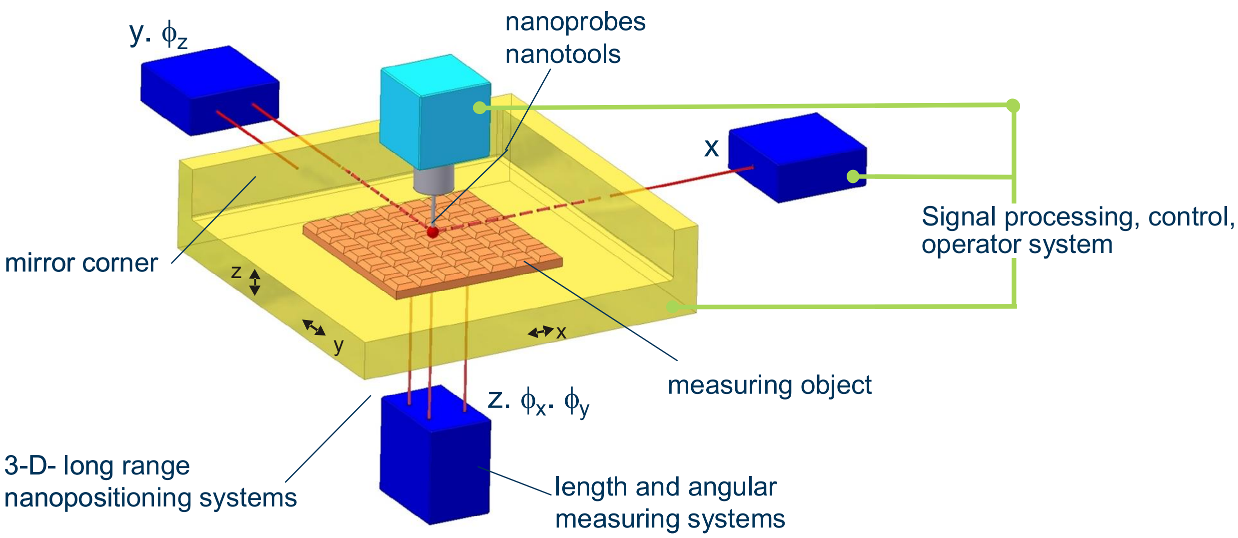

Fig. 1. The basic concept and main components of the NPM-machine

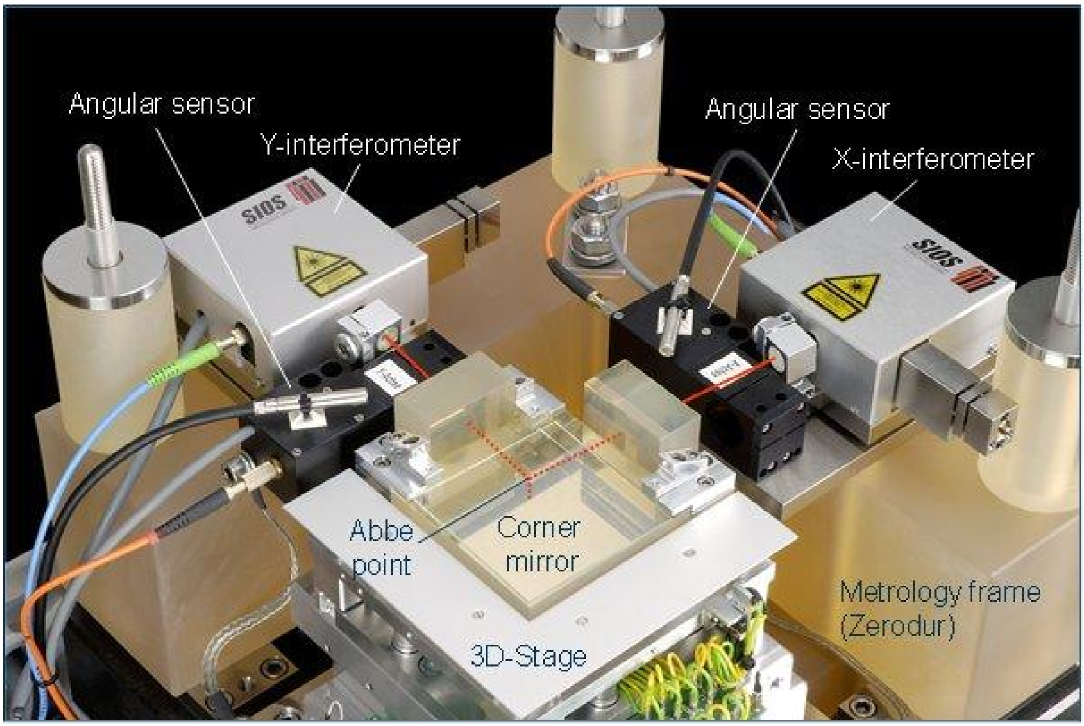

Fig. 2. Basic components of the NMM-1

3. Optical, Tactile and Atomic Force Probe Systems

A multi-sensor concept was developed based on an optical laser focus sensor (Fig. 3). The upper part is based on a so-called hologram-laser-unit and a CCD camera with illumination [3].

This unit can be used together with all assemblies beneath alternatively as laser focus sensor, measuring microscope, white-light interference microscope, tactile stylus sensor, or as AFM probe. The basic functions and all probe systems will be described below (Fig. 4).

The hologram-laser-unit is used together with a focus lens (respectively an objective) and detects a focus error signal if the sample surface is outside of the focal plane of the focus lens. To measure the contour of a sample the NPM Machine scans the surface while the *z*-axis of the machine always is controlled in such a way that the focus error signal is zero. Then, the measuring result is represented by the *z*-interferometer value. Because the laser focus probe is a single point sensor the additional CCD-camera system is used for a quick orientation on the sample surface.

In combination with a long working distance (LWD) objective the focus sensor has a spot diameter of 0.6 μm, a numerical aperture of 0.55, a vertical resolution of < 1 nm, and a working distance of 10 mm. The sensor allows scanning speeds on moderate objects of up to 6 mm/s at reproducibilities of < 2 nm, which cannot be achieved using tactile sensors.

Because the laser focus probe is a single point sensor the measuring data are recorded sequentially and point by point. Thus, highly variable measurements can be performed, but the scanning of large surfaces with a high point density can be very time-consuming. Therefore, the focus sensor was modified into a white-light interference microscope (Fig. 5).

Here, the focus lens is replaced by a Mirau interferometer objective, and the viewing microscope now directly records the measurement data – while the hologram-laser-unit is switched off. Using a 20-fold objective, about 750.000 measuring points can be captured and processed in parallel and simultaneously in one field of view (0.8 × 0.6 mm) with a charge-coupled device (CCD) camera, with a pixel distance of 0.8 μm. On average, one *z*-scan takes about 20 s. Collecting the same amount of data with a single point sensor would take at least 30 minutes. In comparison with conventional white-light microscopes, the *z*-scan is performed at the interferometric precision of the NPM Machine. In principle, step heights of up to 5 mm can be measured (limited at the moment to 3 mm by the working distance of the Mirau objective). In contrast, conventional interference microscopes are limited to a measuring range of 100 μm. Furthermore, it is possible to measure larger surfaces by sequentially stitching together smaller surface profiles. In contrast to conventional stitching algorithms based on image processing strategies these individual "height maps" can be joined together geometrically exactly at the nanometer precision of the NPM Machine.

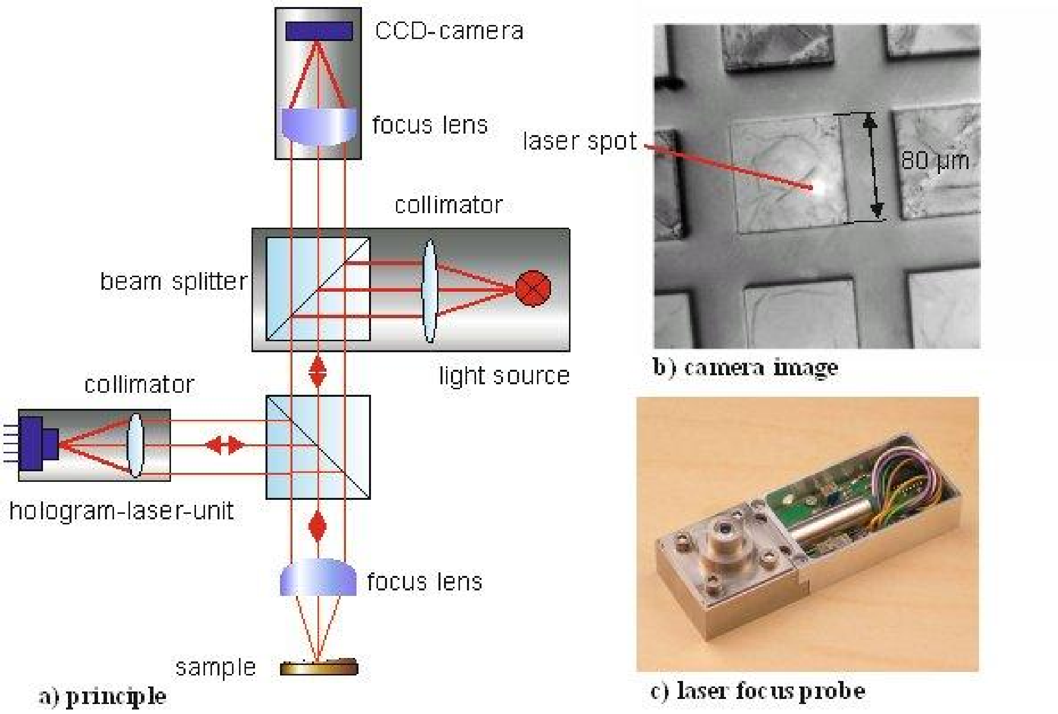

Fig. 3. Laser focus probe

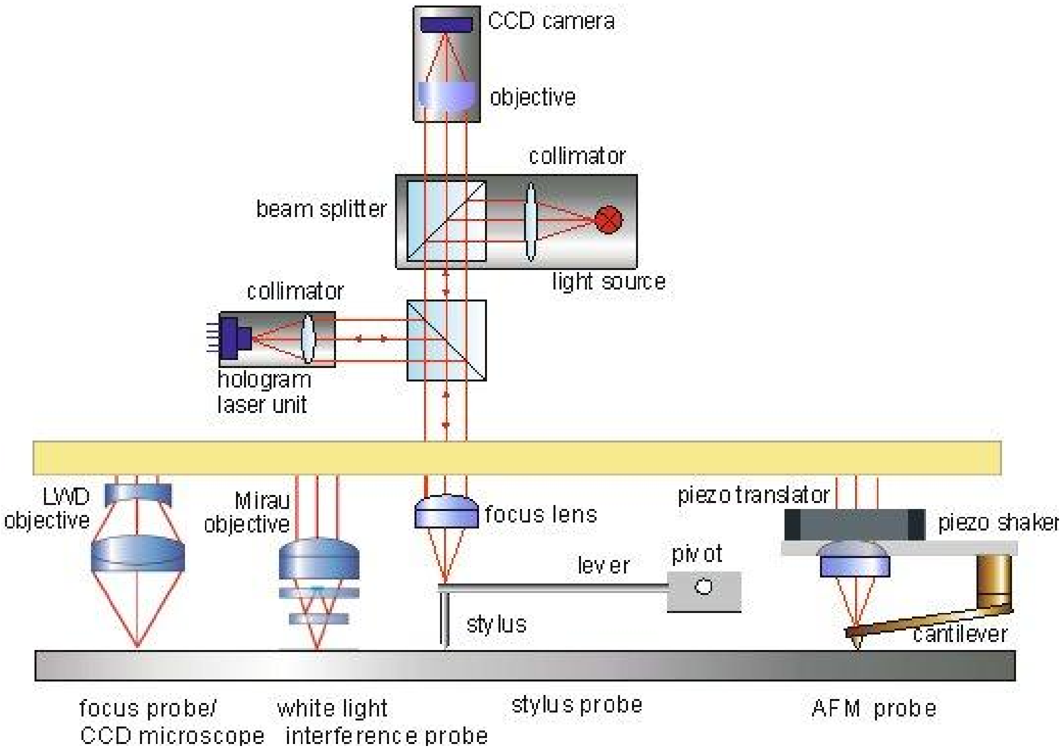

Fig. 4. Several probing systems based on laser focus probe

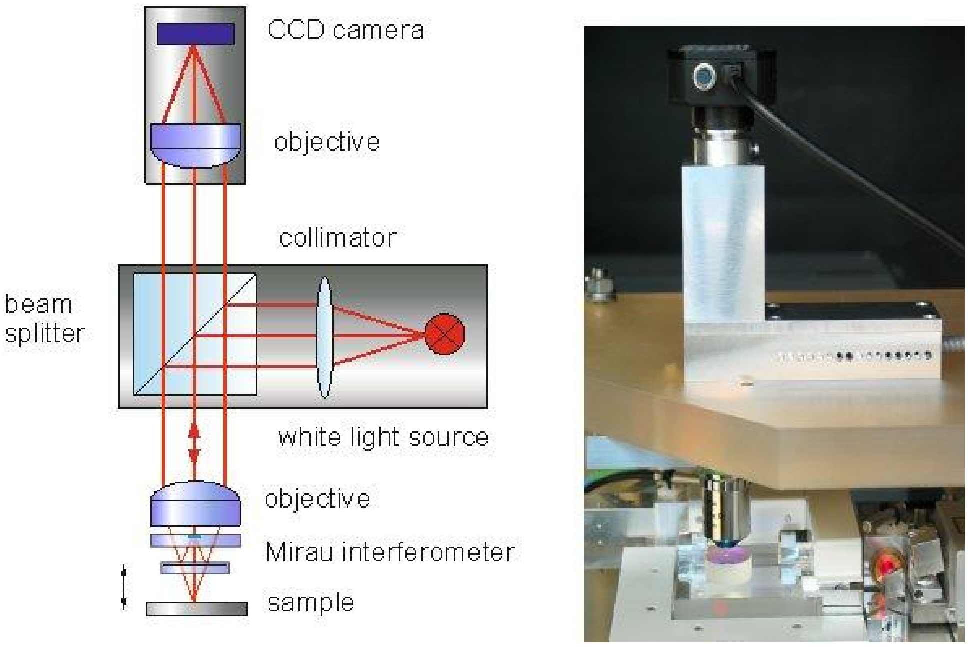

Fig. 5. White-light interference microscope

For example, a measuring surface of 4 × 4 mm consisting of 64 single maps and including 21 million data points can be measured in less than 25 minutes. Both probes the laser focus probe as well as the Mirau interference microscope have got their application fields together with the NPM Machine. While the focused probe can scan large lines or fields very fast the parallel data collection of the Mirau system is used especially for small areas very effectively.

The optical sensors offer the advantage of non-contact measurement but also presents the typical disadvantages of optical sensors, such as diffraction phenomena appearing on steep edges, and phase jumps on different materials. Also, the lateral resolution is limited by the diffrac-

tion-dependent spot diameter. Even so, we can use the high resolution of the laser focus sensor to assemble tactile probing systems. Therefore, the focus sensor was combined with the stylus of a tactile profilometer (Fig. 3, center and Fig. 5).

Here, the mechanical part of a pick-up MarSurf MFW 1250 was used (Fig. 6). The laser beam is focused onto the back of the stylus. The measuring surface is scanned with a conventional stylus having a diamond tip with a diameter of 2 µm and a slope angle of 90°. The tactile sensor works in a purely passive mode. The combined action of the integrated spring and the weight of the stylus results in a constant measurement force of < 0.1 mN. Unlike conventional tactile profilometer systems, this arrangement allows the sensor to work as a null indicator. Any measuring force fluctuations and measuring deviations resulting from the bearing clearance of the pivot are thus minimized. Depending on the type of surface of the probe, a scanning speed of 10 to 100 µm/s can be achieved in the scanning mode, with the uncertainty of measurement being < 1 nm. However, the lateral resolution of the sensor is again limited by the diameter of the stylus tip.

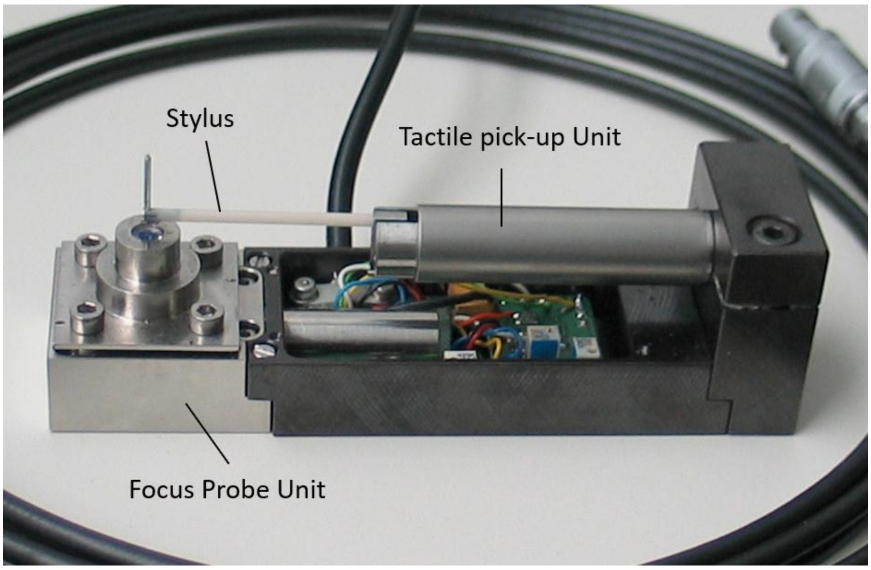

Fig. 6. Tactile stylus probe

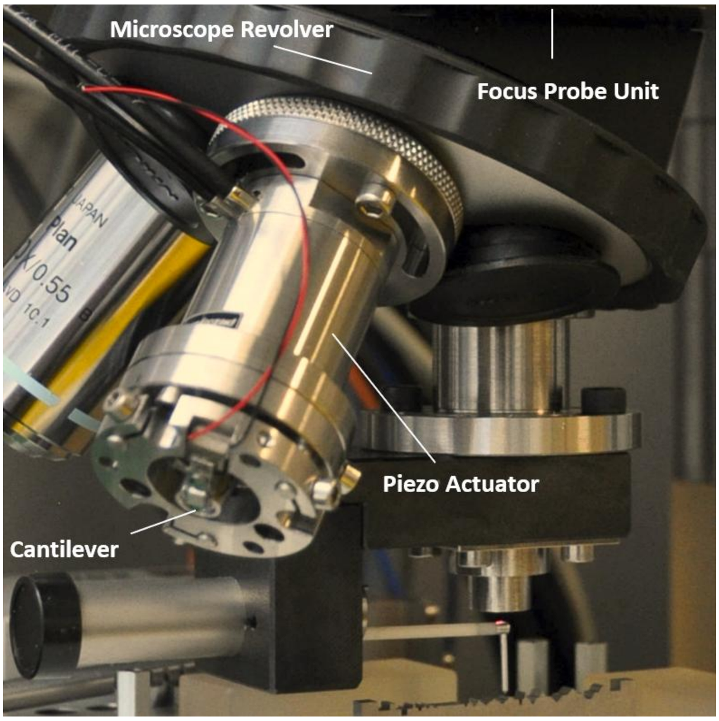

Fig. 7. Atomic force sensor in the NPM Machine

To be able to scan real micro- and nanostructures, the scanning radius must be reduced considerably. This is made possible by applying the scanning force probe technique with tip radii of < 10 nm. For this, an atomic force microscope (AFM) cantilever was again combined with the focus sensor (Fig. 7, right). Thus, this system operates as an atomic force sensor. The focus sensor detects the deflection of the cantilever due to atomic forces which become effective when the stylus is approaching the object to be measured. During the scanning force microscope (SFM) measurement, the force acting between the tip and the sample is weak, and even in the contact mode, it reaches only a few nanonewtons. This prevents the measured surface from being scratched during the SFM scanning process. In contrast, stylus profilometers may cause scratches on soft material surfaces. An additional piezoelectric element serves as a shaker for the dynamic scanning mode.

If this atomic force sensor is used in the nanomeasuring machine exclusively as a null indicator, the achievable scanning speed will be limited to a few micrometers per second by the high mass of the *x*-*y*-*z* table of the NPM Machine. Therefore, a further piezo translator with an integrated length sensor is employed to provide the quick *z*-movement of the cantilever and focus lens, which is rigidly connected. By combining the quick *z*-movement of the AFM-head with the slower movement of the heavy measuring table, a considerable improvement in scanning speeds is achieved. Depending on the surface structure of the object to be measured, scanning speeds of up to 100 μm/s were realized.

The probing systems introduced above enable a multitude of different measurement tasks. However, one crucial problem is that all probes fail at steep edges found in deep holes or grooves. In Fig. 8 this can be seen for the focus sensor as well as for the tactile stylus probe. The limitation angle of the focused probe with regards to the numerical aperture is 25°, and the limitation angle of the tactile probe with regards to the shape of the diamond tip is 45°. Thus, the big differences between both sensors regarding the PTB-measurements can easily be explained.

An alternative is to measure the height profile with the aid of the built-in CCD camera microscope by using the depth from focus (DFF) method [4]. Here, similar to the *z*-scan of the white light interference microscopy, a set of reasonably sharp pictures is captured in the *z*-direction with constant steps. Then, the position of the best focus for every pixel can be determined. This procedure can work up to more than an 80° inclination angle. Therefore, the complete micro contour standard could be measured (Fig. 9). The stitching capability of the NPM Machine can also be shown here. 9 shows the result of 90 single measuring fields (25 mm × 360 μm) stitched together with the nanometer precision of the NPM Machine. This method can measure steep edges, but its resolution is only 50 to 100 μm, and the method fails when measuring reflective surfaces.

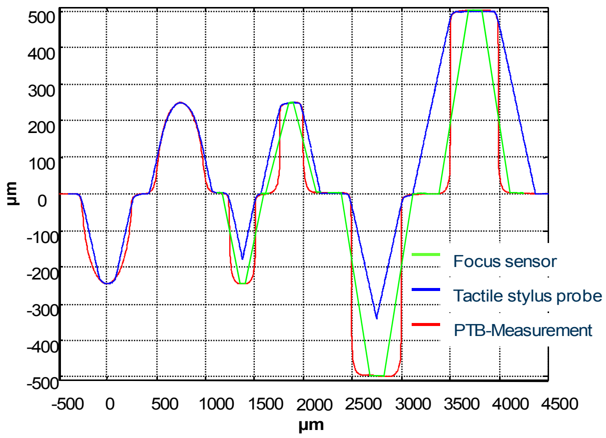

Fig. 8. Comparison of microcontour measurements

The four different probing systems (devoid of DFF method) have been compared using measurements of step height standards (from 7 to 700 nm). These measurements demonstrated very good agreement among all sensors in the order of 1 nm (at a step height standard of 70 nm) [8]. This is a very important pre-condition for a comparison of the measurement results of the different probes. Naturally, the probes differ in several parameters, such as lateral resolution, scanning speed, probing force. In Table 1 the several probes are compared regarding the main measurement properties. On this basis the probes can be chosen for different measurement tasks.

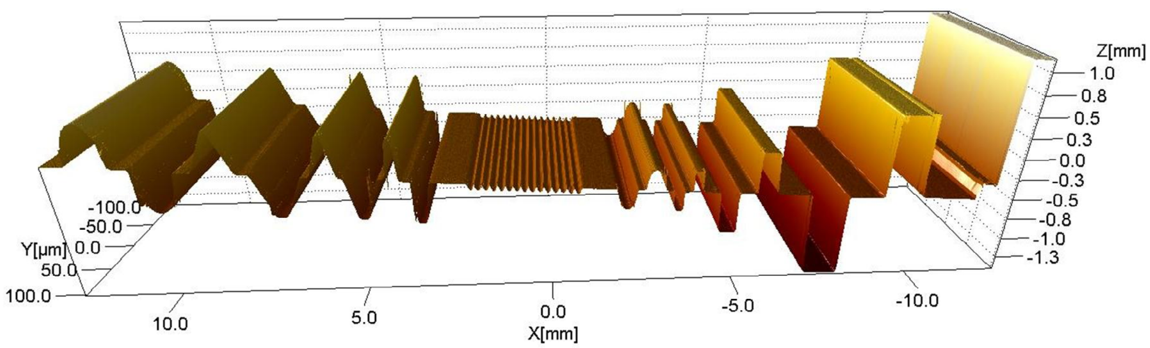

Fig. 9. Microcontour measured with the DFF method

Table 1

Comparison of measurement properties of the presented probes

	Focus probe	Stylus probe	AFM probe	White light interference probe	Depth from focus microscope
z-resolution	1 nm	1 nm	1 nm	< 1 nm	50–100 nm
probe diameter/ lateral resolution	0.6 µm	4 µm	20 nm	0.8 µm	0.8 µm
working distance	10 mm	10 mm	10 µm	3.5 mm	10 mm
scanning speed	up to 6 mm/s	100 µm/s	10 µm/s	> 20 µm/s	> 20 µm/s
aperture angle	33°	30°	10°	24°	33°
edge angle	25°	55°	65°	20°	> 80°
measuring force	0	0.9 mN	10^{-10}N	0	0
data collection	serial	serial	serial	parallel (2 mill.)	parallel (2 mill.)
path planning	flexibel	flexibel	flexibel	fixed area/ stitching	fixed area/ stitching
main advantage	high speed	no bat wing effects	lateral resolution	fast data collection	sharp edges
main limitations	sharp edges	lateral resolution	step height	sharp edges	vertical resolution

4. Multisensor Approach

The measuring tasks to be solved are often highly varied and present different requirements that can depend upon the size of the measuring field, the lateral resolution, the point density, whether an optical or tactile method should be applied, and other factors. For these reasons, the combination of the various sensor technologies seems to be desirable.

The arrangement according to Fig. 3 can be used as a laser focus sensor, measuring microscope, white-light interference microscope, tactile stylus sensor, or as AFM probe. All arrangements based on the laser focus probe are combined with a CCD-camera microscope. A first step is the use of the microscope together with the focused probe for the various scanning systems by employing an additional revolver system (Fig. 10). Thus, it is possible to switch over mechanically to the different sensors in an easy way.

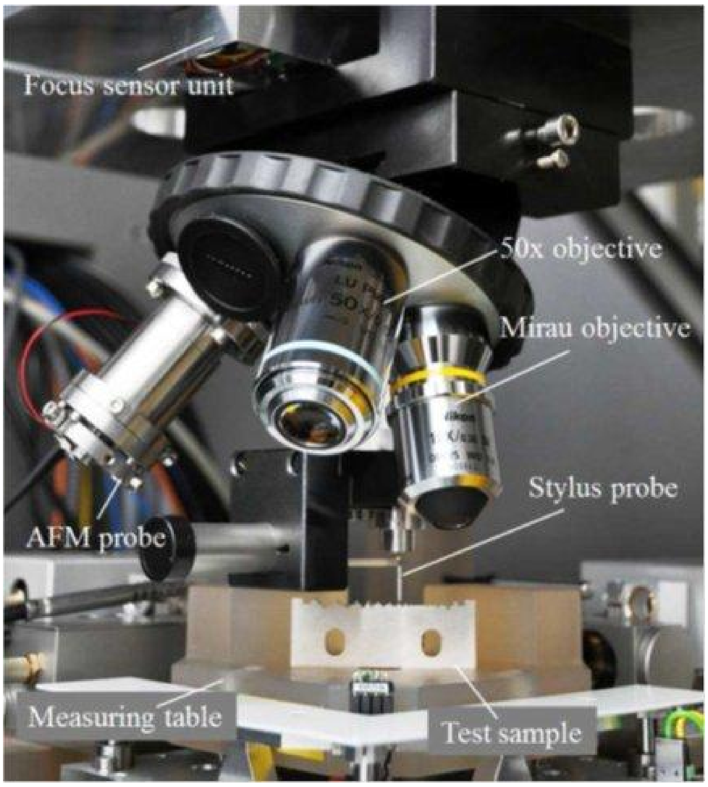

Fig. 10. Microscope revolver approach

Revolver systems of such kind are also available with a motor drive. However, these systems are not designed for high reproducibilities between the single revolver positions. To combine the measuring data gathered by different sensors on a measuring object, it is necessary to determine the exact relation between the single measurements. This shall be realized utilizing fiducial marks that are attached either to the measuring table or to the measuring object itself. The main requirement is that these fiducial marks can define a measurement point in 3D space with nanometer reproducibility for several optical and tactile probes. Here, for example, a new method regarding marker production by focus ion beam is presented by Ritter et al [7].

On this basis, various measuring strategies for specific measuring tasks are being developed and investigated by combining different sensors. Automatic probe selection as well as computer-aided inspection plan generation is a future challenge. However, if the topography or the structures are not known from the available computed aided design (CAD) data, this can be a real problem. In some cases, an automatic image capturing procedure of the full measuring area (e.g. 25 × 25 mm) can be carried out. These 2000 single images can be stitched together with the nanometer precision of the NPM Machine. Thus, an overall "map" of the surface including about 3 GPixel data is obtained, with the measuring resolution being 0.8 μm [5]. The whole image file can be segmented automatically and as a result, an overview of all areas that present certain surface characteristics is obtained. These areas will then be considered more closely for an AFM scan.

The NPM Machine is now able to navigate in real mode within this virtual map with nanometer precision. The fields of interest can be approached in a well-directed way and then scanned by the AFM. This allows measuring times to be drastically reduced, and in some cases allows measurements that were previously not even possible.

5. Summary and outlook

The NPM machine not only allows but even requires a multisensor set-up for making measurements on micro- and nanostructures. Based on a laser focus sensor, different optical, tactile and AFM measuring principles can be realized which operate with nanometer reproducibility and that c an be combined to form a unified multisensor system. At the same time, a large number of test features on micro- and nanostructures requires new measuring strategies so that measurements can be completed within an acceptable amount of time. Automatic probe selection and computer-aided inspection plan generation remain as challenges for the future. To improve this multisensor approach a tactile 3D microprobe is to be implemented as a next step.

6. Acknowledgments

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