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Investigations on the positioning accuracy of the Nano Fabrication Machine (NFM-100)

Untersuchungen zur Positioniergenauigkeit der NanoFabrikationsmaschine (NFM-100)

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Abstract: This contribution deals with the analysis of the positioning accuracy of a new Nano Fabrication Machine. This machine uses a planar direct drive system and has a positioning range up to 100 mm in diameter. The positioning accuracy was investigated in different movement scenarios, including phases of acceleration and deceleration. Also, the target position error of certain movements at different positions of the machine slider is considered. Currently, the NFM-100 is equipped with a tip-based measuring system. This Atomic Force Microscope (AFM) uses self-actuating and self-sensing microcantilevers, which can be used also for Field-Emission-Scanning-Probe-Lithography (FESPL). This process is capable of fabricating structures in the range of nanometres. In combination with the NFM-100 and its positioning range, nanostructures can be analysed and written in a macroscopic range without any tool change. However, the focus in this article is on the measurement and positioning accuracy of the tip-based measuring system in combination with the NFM-100 and is verified by repeated measurements. Finally, a linescan, realised using both systems, is shown over a long range of motion of 30 mm.

Keywords: Nano Fabrication Machine, extended working areas, planar nanopositioning, sub-nanometre precision, Atomic Force Microscopy (AFM).

Zusammenfassung: Dieser Beitrag beschäftigt sich mit der Analyse der Positioniergenauigkeit einer neuen Nano-Fabrikationsmaschine. Diese Maschine verwendet ein planares Direktantriebssystem und hat einen Positionierbereich von 100 mm im Durchmesser. Die Positioniergenauigkeit wurde in verschiedenen Bewegungsszenarien untersucht, einschließlich Phasen der Beschleunigung und Abbremsung. Auch die Positionsabweichung bestimmter Bewegungen wird bei unterschiedlichen Positionen des Maschinentisches betrachtet. Derzeit ist die NFM-100 mit einem spitzenbasierten Messsystem ausgestattet. Dieses Rasterkraftmikroskop (AFM) verwendet aktive Mikroantilever, die auch für die Field-Emission-Scanning-Probe-Lithographie (FESPL) geeignet sind. Dieses Verfahren ist in der Lage, Strukturen im Nanometer-Bereich herzustellen. In Kombination mit der NFM-100 und ihrem Positionierbereich können Nanostrukturen im makroskopischen Bereich analysiert und geschrieben werden, ohne jeglichen Werkzeugwechsel. Der Schwerpunkt in diesem Artikel liegt jedoch auf der Mess- und Positioniergenauigkeit des spitzenbasierten Messsystems in Kombination mit der NFM-100 und wird durch wiederholte Messungen verifiziert. Abschließend wird ein Linienscan, der mit beiden Systemen realisiert wurde, über einen großen Bewegungsbereich von 30 mm gezeigt.

Schlagwörter: Nano Fabrikationsmaschine, erweiterte Arbeitsbereiche, planare Nanopositionierung, subnanometer Präzision, Rasterkraftmikroskopie.

1 Introduction

Since some years now, it has become increasingly important to develop technologies for micro- and nanofabrication in a way to reduce the size of structures even further. For this purpose, different techniques, such as tip-based manufacturing, as well as optomechanical or optical manufacturing can be used [1]. Most lithographic processes show high accuracy and precision in small areas of a few micrometres. However, it is becoming increasingly necessary in semiconductor wafer-based manufacturing to ex-

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tend these ranges to large areas in the mm-range. In order to achieve the same precision and reproducibility in these areas, it is necessary to have a positioning system for investigation and verification of new lithographic technologies on large areas to check their suitability for wafer size applications. At the Technische Universität Ilmenau a new Nano Fabrication Machine (NFM-100) with a positioning range of 100 mm in diameter was developed. This machine with its attached tip-based measuring system offers the possibility to overcome the limitations of nanofabrication in large working areas. Currently, the tip-based measuring system, which is mounted, can be used for Atomic Force Microscopy (AFM) and especially for Field-Emission-Scanning-Probe-Lithography (FESPL). In this paper, the focus is on the positioning accuracy of the NFM-100 itself and the combined reproducibility of both subsystems. The deviations from ideal motion sequences are analysed in Section 4, which are recognised in the static as well as in the dynamic state. In addition, a linescan over a large distance in the mm-range is demonstrated by the combination of the systems.

2 State of the art

Until now, the high-precision positioning of the NFM-100 has been demonstrated through different movement scenarios, as well as its suitability for different tools, such as tip-based systems, optical and optomechanical systems [1]. In [2], the first results in terms of measuring and fabricating nanostructures were shown by the combination of the nanopositioning machine and its tip-based system. However, the accuracy of the two systems has not yet been demonstrated, so this is a particular focus for further characterization of the systems.

2.1 Nanopositioning and -measuring machines

Based on decades of research in this field, the Institute for Process Measurement and Sensor Technology developed the Nano Measuring Machine (NMM-1) and the Nano Positioning and Measuring Machine (NPMM-200) [3]. With these Nano Measuring Machines it could be demonstrated that the working principle of these 3D-coordinate measuring machines can be especially used to measure 3D-objects [4, 5]. Also, nanofabrication could be demonstrated in a macroscopic range with the NMM-1 [6]. Based on the experience from designing and operating these machines, the Nano Fabrication Machine was developed. As with the NMM-1 and the NPMM-200, the machine table of the NFM-100 is moved, while the measuring tool of these machines is at a fixed position. However, this machine is optimised for tasks in two dimensions and therefore especially wafer-based tasks.

2.2 Tip-based measuring system

As the machine table has no option for movement in the third dimension, the movement in z-direction has to be realised by the mounted measuring tool. At the moment, a tip-based measuring system is attached, which uses self-sensing and self-actuating microcantilevers.

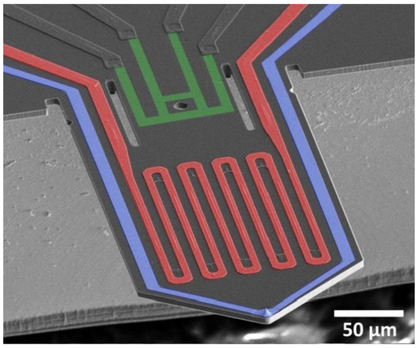

Figure 1: SEM image of the active cantilever integrating thermal bimorph actuation (colored red), piezoresistive readout (colored green) [7, 9].

On the one hand, these microcantilevers, shown in Figure 1, allow the use in AFM mode for the detection of surface topology and associated surface properties. The microcantilevers, which are used in this tip-based measuring system, utilise a wheatstone measuring bridge to detect the deflection of the beam at the clamping point. To induce oscillation, this type of microcantilevers use a thermomechanical actuator. This actuator consists of two different materials (silicon and aluminium) with different coefficients of thermal expansion in shape of a meander [7] (see Fig. 1). Furthermore, these active microcantilevers can be especially utilised for nanofabrication. This novel lithographic technology based on a Fowler-Nordheim type electron emission from a nanotip is called FESPL, which enables cost-effective technology for nanodevices [8]. Nanostructures in the range of sub-10 nm can be realised with this lithography technique and the described tool, which could be successfully demonstrated in [10]. This system also offers more advantages like closed-loop lithography, which includes pre-imaging, overlay alignment, exposure and post-imaging for feature inspection, and also sub-5 nm lithography resolution with sub-nm line edge roughness [8].

3 Design of the NFM-100 and its tip-based measuring system

The NFM-100 serves an important platform for high resolution nanopositioning over long ranges. Simultaneously, the tip-based measuring system offers high resolution with regard to fabrication of micro- and nanostructures. The combination thus opens up new possibilities for the fabrication of structures in the sub-10 nm range on wafer size with high precision.

3.1 Set-up of the NFM-100

For positioning, this machine uses a planar direct drive system [11]. There, the movement of the machine table is realised by linear actuators, which are arranged in a single plane and consist of two fixed flat coils which act on a magnet array. By using three planar air bearings as guiding system, a nearly frictionless motion of the table is possible. With the use of three laser interferometers the position of the slider can be tracked, which are fibre-coupled to one stabilised He-Ne-laser. To enable higher stability in terms of thermal stability and noise, differential plane-mirror interferometers are used. For length measurement, two interferometers are arranged in such a way, that their axes intersect virtually in the tip of the tool to guarantee that the Abbe-principle is fulfilled in x- and y-direction [1], which leads to an Abbe-offset $l_{Abbe,i}$:

$$l_{Abbe,i} = 0 \qquad i \in x, y, z \tag{1}$$

Due to this mechanical set-up, there is no guiding of the slider for the rotation around the z-axis. Therefore, this rotation has to be closed-loop controlled. For that reason, a third interferometer is included, which is detecting the rotation of the slider around the z-axis. Both interferometer arms, the measuring and reference arm, directly probe the moving mirror. The rotation φ of the slider around the z-axis leads to an Abbe-error Δl_i, which can be described by the following equation

$$\Delta l_i = l_{Abbe,i} \cdot \sin(\varphi_i) = 0 \qquad i \in x, y, z. \tag{2}$$

This concept of interferometers offers the possibility to detect the rotation of the stage independently from the lateral movement [12]. The actuators as well as the interferometers for traking the position of the slider have an angle of 120° between each other (see Fig. 3), which leads to a circular positioning range of Ø 100 mm.

The slider of the nanopositioning machine is built on a granite base, which can be seen on the left side in Figure 2. Additionally, the slider and the mirrors of the interferometers are made of quartz. Thus, the thermal and mechanical drift can be reduced to a minimum. Due to the fact, that the granite base is not ideally flat, the deviation has to be compensated by the measuring tool. To allow ultra-precise positioning, the granite base is installed on a vibration-isolated base. In addition, an acoustic noise suppression enclosure is built around the complete machine. To avoid thermal drift, the entire set-up is located in an air-conditioned room.

Figure 2: Image of the nanopositioning machine and a mounted tip-based measuring system (left) and detail view of the tip-based measuring system (right) [2].

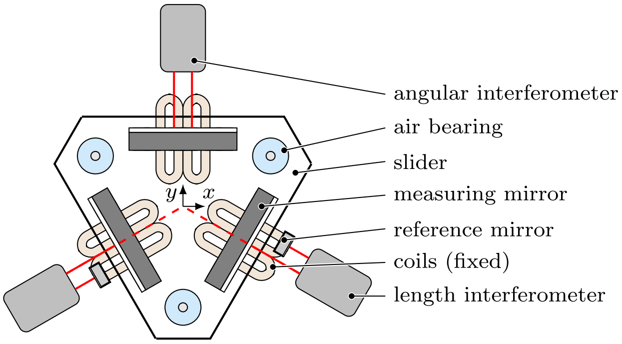

Figure 3: Mechanical and Interferometer set-up of the NFM-100. The position of the slider is tracked by three laser-interferometers in a 120° arrangement. The slider is driven by linear actuators, which consist of flat coils and a magnet array.

In order to be able to operate production and measurement processes flexibly and in a short time, control parameters must be readjusted quickly and therefore a rapid control system was applied [13]. This system can also be adapted with different plug-in cards for numerous purposes, so the system can be modified for optimisation, testing or adapting other measurement/fabrication tools [1].

3.2 Measurement and fabrication tool

Usually, a laser focus sensor is used as standard tool for large-area measurements in NPMMs [14], but there is a limit because of its lateral resolution. In contrast to this, tip-based measurement systems offer nanometre resolution. Currently, an AFM is installed as a measuring system, shown on the right side of Figure 2. For the realisation of large-area nanofabrication in the sub-10 nm range, this AFM-/FESPL-system with the nanopositioning machine represents an ideal possibility. The ability to measure and write with these microcantilevers also provides the opportunity to use this tool for both pre- and post-production inspection of structures. New lithographic technologies can be verified on large area to check suitability for wafer size.

4 Measurement results

To allow a positioning with high resolution and high accuracy, important parameters have to be investigated. Especially important for manufacturing, the trajectory has to be followed with nm-accuracy, which differs from measuring. There, deviations can be tracked and compensated for offline. But for nanostructuring, deviations of the trajectory lead to damages or errors, which usually cannot be corrected. To demonstrate the performance of the machine, different movement scenarios were conducted and investigated in the following.

4.1 Static operation of the NFM-100

First the position stability of the machine itself is investigated. To show the position stability, the position noise was recorded for a duration of 5 s with a sampling frequency of 10 kHz, which is depicted in Figure 4. The standard deviation of 0.2417 nm shows, that the NFM-100 in closed loop control mode has an outstanding position stability.

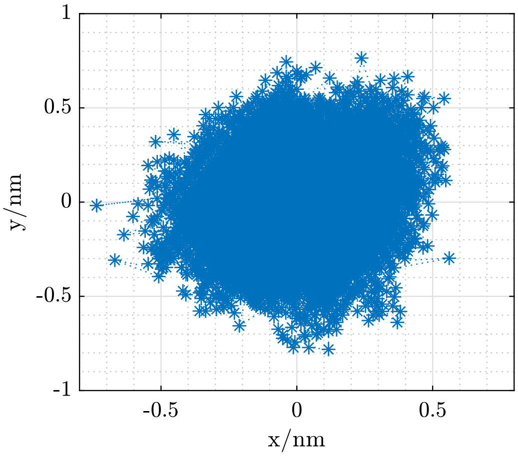

Figure 4: Position noise of the machine table with a sampling frequency of 10 kHz. The position was sampled for a duration of 5 s. The standard deviation of the position is 0.2417 nm.

4.2 Dynamic operation of the NFM-100

The resolution of the nanopositioning machine was investigated with steps in the picometre range. As shown in Figure 5 picometre steps were performed with a step distance of 100 pm in x-direction and a velocity of 500 pm/s. The steps in the pm-range can be made visible clearly by subsequent filtering of the measured data. A moving average filter of a length of 2500 is applied. For nanofabrication in the sub-nm range and also for measuring, it is of importance to position the slider with high precision.

Furthermore, it is particularly important in the manufacturing of micro- and nanostructures to guarantee a small deviation from the target position of certain movements over the entire range of motion. For this purpose, circles with a radius of 5 nm were driven at different posi-

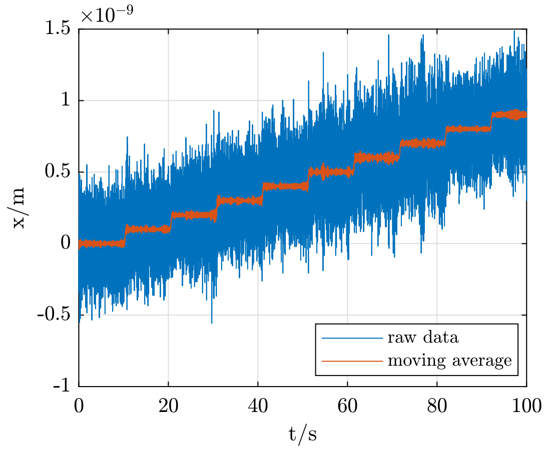

Figure 5: Positioning of the slider in 100 pm steps with a velocity of 500 pm/s with raw data and data filtered by a moving average filter of a length of 2500. The sampling frequency of the position is 10 kHz.

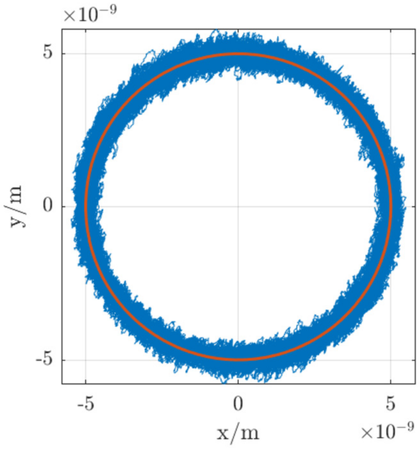

Figure 6: Plot of a circular trajectory with 10 revolutions with a radius of 5 nm driven by the machine table with a velocity of 10 nm/s and an acceleration of 200 nm/s^2 at position [0, 0].

Table 1: Standard deviation of driven circles (r=5 nm) at different positions with 10 revolutions.

Position [x in mm, y in mm]	Standard deviation in nm
[0, 0]	0.23614
[−40, 0]	0.27006
[40, 0]	0.27008
[0, −40]	0.25677
[0, 40]	0.26544

tions with the machine table. In Table 1 the standard deviation of circles at different positions with a velocity of 10 nm/s are shown. The measurements were repeated 10 times. In general, the standard deviations of the driven circles show, the motion of the nanopositioning machine is stable and below 271 pm over the whole range of motion. The investigations on the repeatability of measurements is important for further processes of nanostructuring on wafer size, such as mix-and-match [15], step and repeat [16] or for any change of tools [17]. In Figure 6 a driven circle at position [0, 0] is shown. Additionally, the ideal target circle is depicted in the figure. These results show, the resolution is adequate for sub-10 nm structuring.

4.3 Combined measurement of NFM-100 and AFM

To show the performance of the combined measurement of the machine and the mounted AFM, a series of measurements of a holographic grating with a period of approximately 420 nm are made. The movement of the sample in *x*- and *y*-direction was realised by the slider of the NFM-100. The controlling of the *z*-direction was performed by the piezo-scanning unit of the AFM, while in *x*- and *y*-direction the microcantilever was in a fixed position. The holographic grating was measured 10 times over a length of 100 μm with a velocity of 1 μm/s. The results of these experimental investigations are shown in Figure 7. The standard deviation of these measurements is 2.7709 nm. Additionally, a section of 5 μm is shown. Furthermore, the movement of the slider during these measurements of the holographic grating was tracked by the differential length interferometers. The results of the driven lines are shown in Figure 8. As in Figure 7, the measurement was repeated 10 times. The standard deviation of the straight line movements of 100 μm is 1.0905 nm.

To demonstrate the performance over a long range of motion, a linescan of the holographic grating (same as in Figure 7) with a length of 30 mm and a velocity of 5 μm/s was measured without stitching in Figure 9. The tilt of the sample was removed from the original data. Additionally, a section of 5 μm of this linescan is shown (Fig. 9). These presented measurements show the capability of the combination of these systems.

5 Conclusion

To overcome the limits of nanofabrication in small areas, the NFM-100 acts as an important platform for basic research and training. This machine can be equipped with a large variety of tools like optical sensors [18], optomechanical processes [19] or a tip-based measuring system, which is currently mounted.

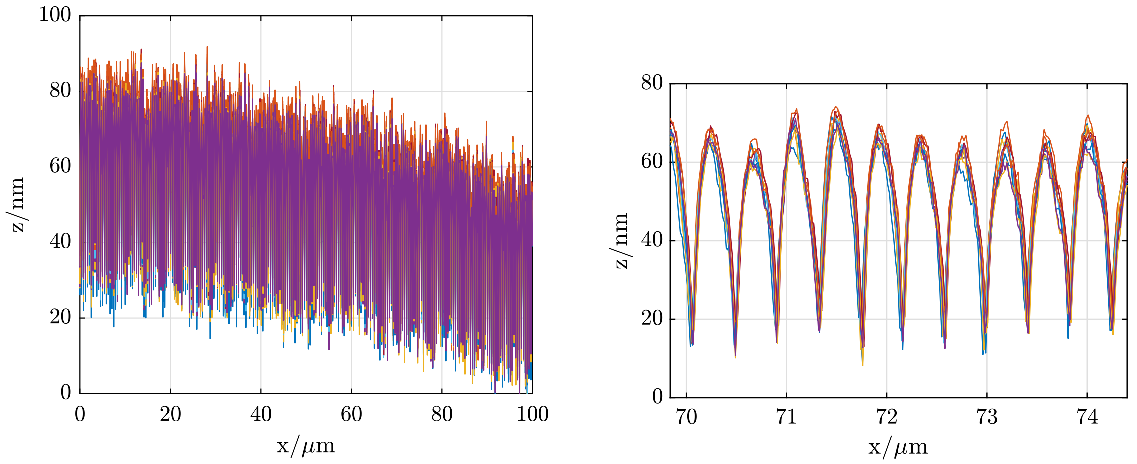

Figure 7: Linescan of a holographic grating with a structure depth of approximately 50 nm measured by the installed AFM in combination with the NFM-100. The *z*-signal was measured by the piezo-scanning unit of the AFM, while the sample was moved by the machine in *x*-direction. The measurement was repeated 10 times and results in a standard deviation of 2.7709 nm in *z*-direction. The left plot shows the complete scan over a length of 100 μm. In the right part, a detail of 5 μm is shown.

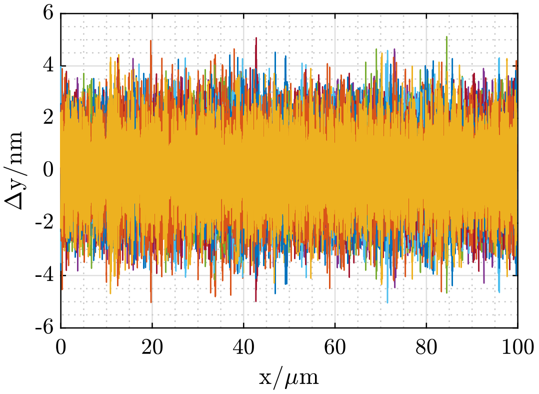

Figure 8: Line movement with signals of the x- and y-interferometers over a length of 100 μm in *x*-direction driven with the NFM-100 including acceleration and deceleration phase. The measurement was repeated 10 times and results in a standard deviation of 1.0905 nm. Sampling frequency of the position of the machine table is 10 kHz.

A contribution to the investigation on the positioning accuracy of the machine could be shown in this paper. For a duration of 5 s, the position noise of the machine table features a standard deviation below 241 pm. By different movements like steps in the pm-range and circles with a radius of 5 nm at different positions of the machine table the positioning capability could be demonstrated. Over a wide range of motion it could be shown, that the standard deviation of circles with a radius of 5 nm are below 271 pm. In addition, investigations were carried out on the combined measurement of the two measuring systems, the nanopositioning machine and the AFM-system. The repeatability of the measurements in Figure 7 indicate, at a length of 100 μm and a repetition of 10 times, a standard deviation of 2.8 nm (Figure 7) in *z*-direction and 1 nm (Figure 8) in *y*-direction. It could also be shown, that it is possible to measure structures over large areas in the millimetre range. A linescan with a length of 30 mm could be demonstrated through the machine and its tip-based measuring system.

6 Outlook

Because of these remarkable results, this machine offers a possibility for high-precision positioning in nanometrology and nanofabrication for wafer-based manufacturing with high resolution and repeatability. However, the tilt or curvature of the sample is currently still a limiting factor with regard to measuring and structuring surfaces over large distances in the mm-range, as this must be compensated by the measuring tool. At the moment, an interferometer is installed to observe the movement of the slider in *z*-direction. However, this *z*-interferometer can only record the change in position, while there is no regulation of the *z*-axis of the slider. The next step is to investigate the *z*-noise of the machine table and also influences of the air bearings. Nevertheless, a system for controlling the *z*-axis of the planar machine could be developed in [20]. In principle, the machine can be extended with this concept to allow active control of the table in *z*-direction and to compensate tilt.

Moreover, with larger positioning range, the duration of nanofabrication processes will increase over the entire

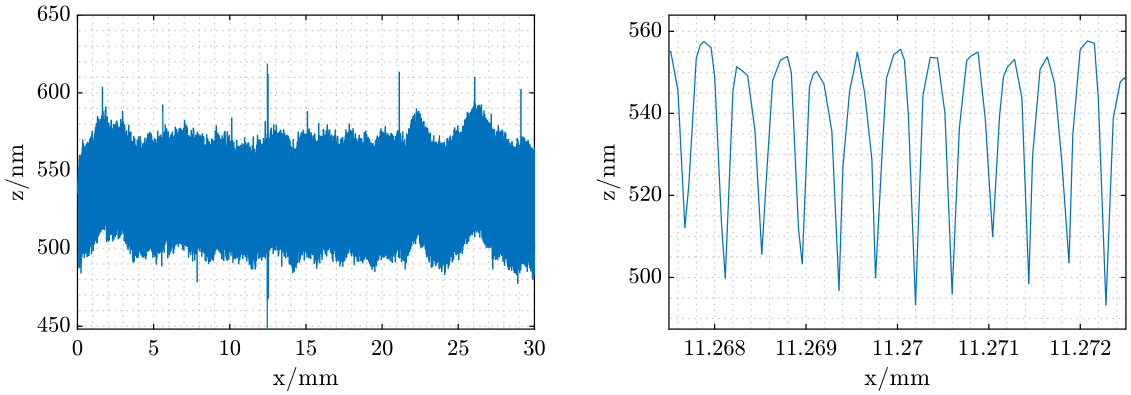

Figure 9: Linescan of a holographic grating (same as shown in Fig. 7) over a length of 30 mm measured by the NFM-100 and the tip-based measuring system (left) and section of 5 µm of the 30 mm-Linescan (right). Measured with a velocity of 5 µm/s.

area of motion, which leads to a tip wear and tip deformation after hours of processing. In [21], it could be shown, that a diamond tip shows good current emission stability and high resistance against mechanical stress. To increase the fabrication duration with low tip wear, a microcantilever with special deposited material like diamond can be used for nanofabrication over long ranges with the AFM-/FESPL-system in combination with the NFM-100. To get more information about the properties of the cantilever used, a special calibration device was developed and can be utilised for this reason [22]. In future work, the investigations on the new machine will focus on nanofabrication through the AFM-/FESPL-system over long ranges and large areas.

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