0.1-nanometer resolution positioning stage for sub-10 nm scanning probe lithography

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ABSTRACT

High Performance Single Nanometer Lithography (SNL) is an enabling technology for beyond CMOS and future nanoelectronics. To keep on with scaling down nanoelectronic components, novel instrumentation for nanometer precise placement, overlay alignment and measurement are an essential pre-requirement to realize Next Generation Lithography (NGL) systems. In particular, scanning probe based methods for surface modification and lithography are an emerging method for producing sub-10 nm features. In this study, we demonstrate nano-scale lithography using a scanning probe based method in combination with a Nanopositioning and Nanomeasuring Machine. The latter one has a measuring range of 25 mm x 25 mm x 5 mm, 0.1 nanometer resolution and outstanding nanometer accuracy. The basic concept consists of a special arrangement allowing Abbe error free measurements in all axes over the total scan range. Furthermore, the Nanopositioning and Nanomeasuring Machine is able to store the exact location that can be found again with an accuracy of less than 2.5 nanometers. This system is also predestinated for critical dimension, quality and overlay control. The integrated scanning probe lithography is based on electric-field-induced patterning of calixarene. As a result, repeated step response tests are presented in this paper.

Keywords: Nanopositioning and Nanomeasuring Machine (NPM), Abbe error free measurement, Nanolithography, Scanning Probe Lithography, Maskless Patterning, Closed Loop Lithography

1. INTRODUCTION

The state-of-the-art optical lithography approach is designated for high-volume production that incorporates highly sophisticated and carefully maintained fabrication equipment. Regarding the trends of the International Roadmap of Semiconductors (ITRS), fabrication facilities and processes currently become orders of magnitude more complex and expensive. This is especially true in the case of nanoscale optical masks, where costs can be as much as a million dollars per mask set.

For future nanoelectronics and beyond CMOS applications alternative technologies of nanofabrication are coming more and more in focus of attention. Alternative nanofabrication technologies have facilitated the development of many new fields, e.g. nanoplasmonics, nanophotonics, and nanomedicine. Novel functionalities and unique characteristics, increasing optical resolution, and raised potential for energy harvesting are some important goals. In the field of nanomedicine early disease diagnosis and monitoring, personalized medicine, protein and peptide delivery, nanorobots and nanoprobes, antibody therapeutics, and even cell repair are important keywords. Additionally, nanofabrication includes the ability to integrate such nanoscale components and devices into systems spanning nanoscale to macroscale dimensions.

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These kinds of new applications are still in their infancy state. More development iterations or product revisions are necessary in order to decrease nanofabrication costs and enable more flexible and reconfigurable processes. This is particularly important for rapid nanoscale prototyping.

Amongst others, high performance Single Nanometer Lithography (SNL) is an enabling technology for nanoelectronics. Scanning probe-based methods for surface modification and lithography are an emerging method of producing sub 10-nm features for future nanoelectronic and beyond CMOS applications [1].

Today's Scanning Probe Lithography (SPL) approaches are based on atomic force microscopes, characterized by highly restricted positioning ranges in the order of 100 µm x 100 µm [2]. The quality and productivity of the nanostructures created by SPL strongly depend on the capacities of equipment and instruments used, and the extent to which the tip can be precisely controlled. To keep on with shrinking feature sizes of nanoelectronic components the precision of SPL control must be enhanced, allowing sub-nanometer positioning accuracy range for all three axis, minimized nonlinearity errors and high tip speeds for precise traveling of up to mm/s. In addition, SPL for beyond CMOS applications require positioning and placement systems providing repeatability and uncertainty in the range of nanometers in combination with x-, y- travel ranges of millimeters [3].

To fulfill such requirements it is necessary to apply new positioning and measuring concepts providing minimum errors in large geometric areas. The Nanopositioning and Nanomeasuring Machine (NPM) developed at Ilmenau University of Technology with a measuring range of 25 mm × 25 mm × 5 mm and sub-nanometer resolution allows the application of the most diverse optical, tactile and atomic force probes. Various commercial and home-developed AFM's where integrated into the NPM Machine, tested and evaluated. Based on the NPM technology the ability of Scanning Probe Lithography (SPL) can be extended far beyond the state-of-the-art.

In this paper we describe the combination of the NPM Machine with SPL, enabling high precision large area pattern generation in closed loop lithography fashion [4]. Herein, the area of interest is imaged before and after lithography by the same tool enabling precise pattern overlay alignment and in-situ inspection. We address the different aspects related to system resolution, system noise, internal number representation and limited output resolution at Digital-to-Analog Converters (DAC). As one result, repeated step response tests are presented. In general, SPL resolution can be tuned mainly by tip bias and applied electron dose, determined by current set point and scanning speed. [4, 5, 6] Its capabilities include high resolution patterning, low energy operation preventing substrate damage and proximity interactions, high resolution alignment and direct inspection [4]. Employing parallel, self-actuated cantilever arrays can significantly increase the "writing" speed and provides a novel technology capable of high throughput patterning of future nanoelectronic devices [7].

2. NANOPOSITIONING AND NANOMEASURING MACHINE (NPM)

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 [3]. 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. At first, fiber coupled laser interferometers with highest precision are used. To avoid geometrical errors, the basic concept of the NPM machine is based on a special arrangement allowing Abbe error free measurements in all measurement axes over the total measurement range.

$$\Delta l_i = l_{off_i} \cdot \sin\alpha_i \rightarrow 0 \quad \forall i \in x, y, z \tag{1}$$

To realize such a set-up, which is schematically outlined in figure 1, the nanoprobe is defined as a null indicator and its scanning point is located in the intersection of the three coordinate measuring axes. Thereby, the co-ordinate measuring axes are defined by the laser beams of the three high precision fiber coupled miniature plane mirror interferometers. The laser beams are reflected on a so-called "mirror corner". This system, which carries the measurement object, forms the orthogonal coordinate system.

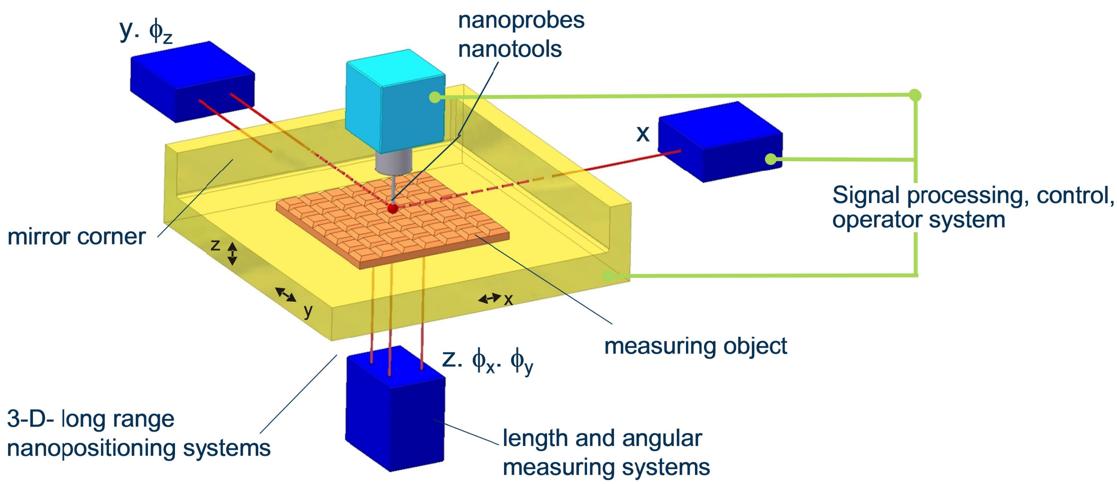

Figure 1. Basic concept and main components of the Nanopositioning and Nanomeasuring Machine (NPM Machine).

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

$$\alpha_i \to 0 \qquad \forall i \in x, y, z \tag{2}$$

In this way the Abbe error is minimized:

$$\Delta l_i = l_{off_i} \cdot \sin \alpha_i \to 0 \quad \forall i \in x, y, z \tag{3}$$

The pitch, roll and yaw deviations (Φ_x, Φ_y, Φ_z) of the 3D stage can be measured by three additional laser interferometers (Fig. 1) or by additional angular sensors, used in NMM-1 set-up (Fig. 2).

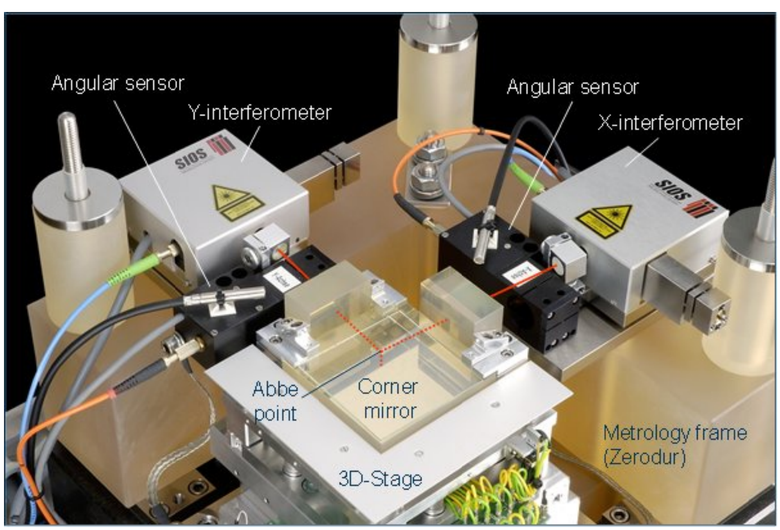

Figure 2. Basic components of the NMM-1.

Here, we have implemented two fiber coupled autocollimators with a resolution of 0.001 arcseconds. Four z-drives compensate the angular deviations applying a closed-loop control. The measuring systems are mounted on a mechanically and thermally stable metrology frame manufactured by Zerodur.

The mirror corner and the object to be measured are moved by the 3D-precision stage in closed-loop control while the nanoprobe interacts with the surface of the object. The x-y-z data are gathered from the x-, y- and z-interferometers. Thereby, the data of the probe are regulated to be of zero value. Several tactile and non-tactile probes with nanometer z-resolution capability were developed and integrated into the NPM Machine [8]. This arrangement forms a universal and advanced basis for high precision measurement tasks with several nanoprobing systems. Two measurement examples are shown in Figure 3. Real 3D measurements are realized, for example, with tactile 3D microprobes [9]. Herein, the unique combination of: (1) high precision 3D-fiber coupled laser interferometers; (2) a long-term stable mechanical arrangement; (3) an Abbe error free arrangement; (4) an advanced voice coil based feedback control; and (5) high speed embedded signal processing enables a measurement uncertainty within the total measurement volume of 25 x 25 x 5 mm³ in the range of 5 nm.

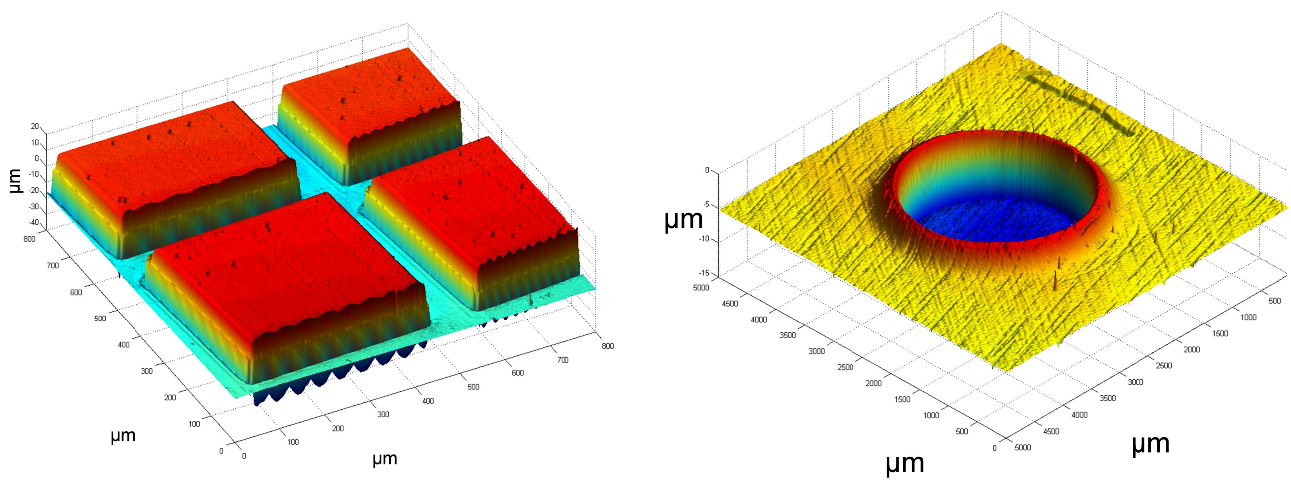

Figure 3: Si test structure (left) and etching crater in sheet metal measured with the NPM Machine

3. SCANNING FORCE PROBES

To be able to scan real micro- and nanostructures the scanning radius regarding conventional stylus probes (2 µm) must be reduced considerably. This could be achieved by integration of the scanning force probe technique using tip radii of less than 10 nm into the NPM Machine. Up to now, various commercial AFM's with different metrological and technical properties and detection principles were integrated into the NPM Machine, tested and evaluated, e.g. Ultraobjective/SIS/Germany, DualScopeTM 95/DME/Denmark, NT-MDT/Russia, and DI/Veeco/USA. To achieve highest accuracy a metrological AFM was developed at the Institute Process Measurement and Sensor Technology on the basis of a miniature fiber coupled laser interferometer [11].

The SPM-head consists of a deflection detection system including an interferometer and lever detection system. After the fiber coupled He-Ne laser beam has passed through the collimator, the beam is splitted by a polarizing beam splitter in a reference beam and a measurement beam. A focus lens focuses the measurement beam on the backside of the cantilever. There, the bending of the cantilever, described by the angle α, causes an angular deviation of 2α of the reflected measurement beam. Due to the fact that the reflected beam passes the focus lens again, the angular deviation turns in an offset r between the incoming measuring beam and the reflected one. The neutral beam splitter splits this reflected beam into two parts. One part interferes with the reference beam after passing the polarizing beam splitter again. The interference pattern is detected by an interference detection unit. The other part of the reflected measuring beam is detected by a quadrant photo diode to detect the torsion and the bending of the cantilever. This arrangement allows the usage of only one laser beam to determine the torsion and the bending of the cantilever as well as the position in z-direction (Fig. 4). The NPM Machine with integrated Scanning Probe Microscopy (SPM) head is shown in figure 5.

Based on the described NPM-SPM set-up excellent results in measurement of calibrated step height and lateral standards [12] were achieved. In fig. 6 (left) the measurement of a step height standard C12 R01, manufactured by the Fraunhofer Institute of Microstructure and calibrated by the PTB, is shown with an overall scan area of 100 µm x 100 µm. The step height of 782.42 nm was determined by 21 scan-repetitions with an expanded uncertainty of 0.54 nm (k=2). The pitch value of grating standards (fig. 6, right) where measured by 600 µm long line scans with an uncertainty of less than 30 pm (k=2).

For the vertical axis an additional high-speed piezoelectric drive is used to increase the measuring dynamics (fig. 4). The movement of the piezoelectric z-drive is controlled and traceable measured by the interferometer. Hence, nonlinearity and hysteresis of the actuator do not affect the measurement results. In conclusion, this set-up improves the bending control of the cantilever and allows much higher scan speeds of up to 200 μm/s [13].

Therefore, this arrangement of the NPM Machine with a measuring range of 25 mm x 25 mm 5 mm and a resolution of 0.1 nm in combination with the metrological SPM head is an outstanding basis for SPL, especially for SNL.

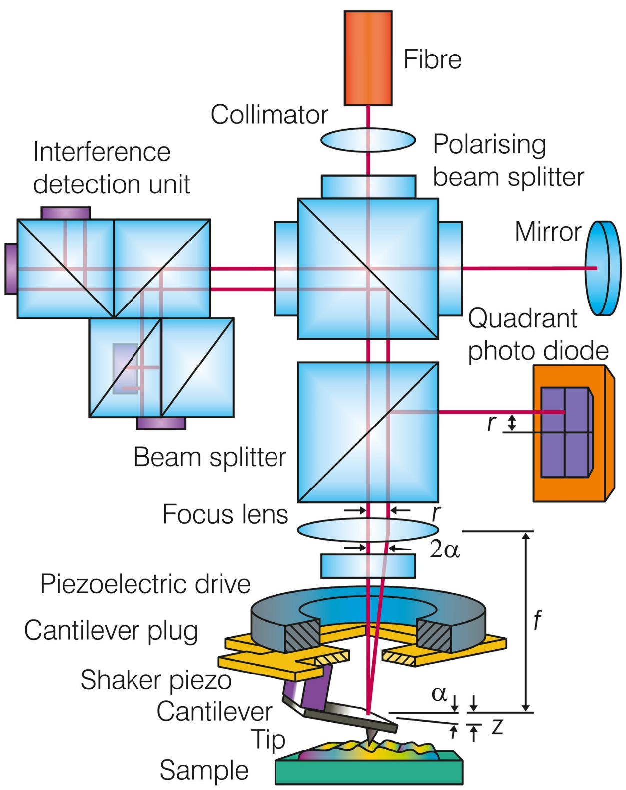

Figure 4. Optical design of the metrological SPM head.

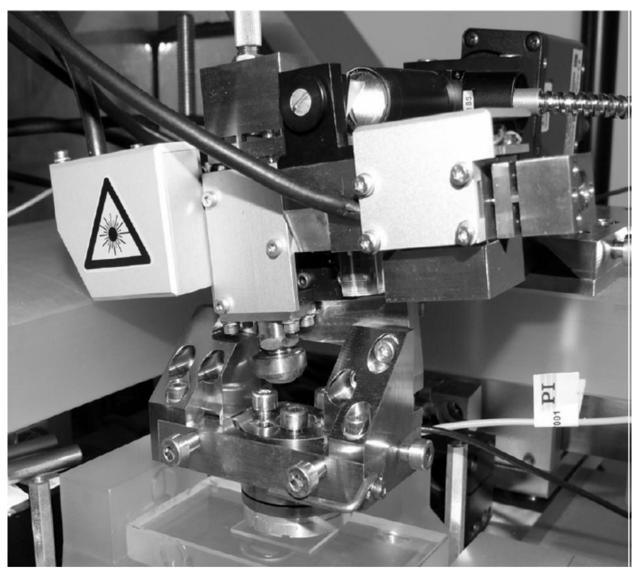

Figure 5. Metrological SPM head in the NPM Machine.

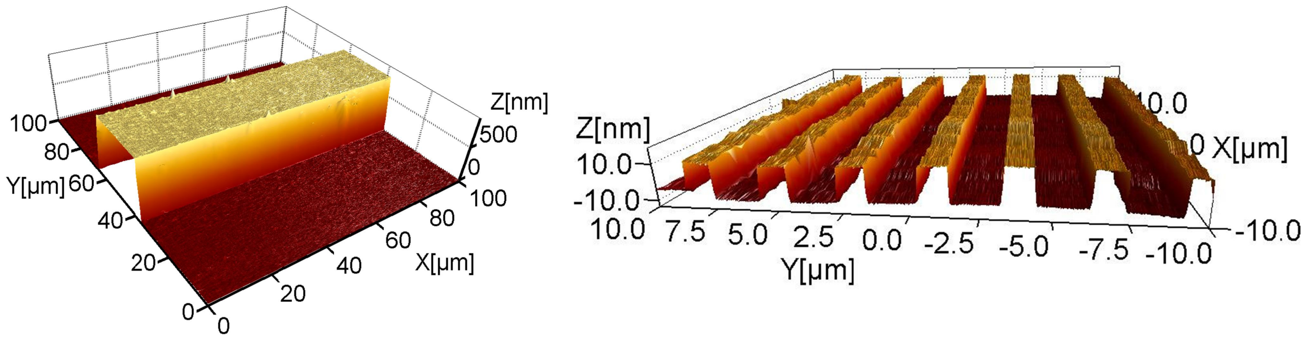

Fig. 6: High-precision measurement of a step height standard (h=782.42±0.54 nm, k=2) and a grating standard (p=3000.19±0.026 nm, k=2)

4. FAST SCANNING TECHNOLOGY

The Scanning Probe Microscopy (SPM) is limited by the speed of the scanner-unit and SPM-cantilever. In order to address these problems, several methods have been developed. In the last decade, Ando et al. [14] reported significant achievements in high-speed AFM. We have developed a scanning stage based on quasi monolithic integration of x, y, z piezoelectric actuation system and Silicon MEMS-unit. Herein, we have incorporated a new scanner design based on compact stack-piezos allowing the construction of a scanner with 10 µm scan range at high frequencies (> 5kHz). We have implemented high quality piezo stacks as coupled actuators to form a stiff 2D scanner made of silicon flexures (fig. 7). Herein, two piezos per axis (pull-push principle) are actuated by matching high voltage signals. The outer ends of the piezo stacks are attached to a micro-machined bulk silicon support frame, while the inner side of the piezo-actuators is attached to a partially flexible inner silicon omega-frame. The stage includes four piezoresistive “L”-shaped beams that bend in the direction of actuation when the piezo-actuator expands. The scanner is also equipped with integrated silicon-crystal strain gauge sensors that measure the position of the stage with nanometer resolution. To achieve an optimum performance we have designed and realized both high speed self-actuated, piezoresistive scanning probes [15] and high speed closed-loop silicon scanners [16].

The significant difference of our technology to the well-known fast scanning technology [17] is the capability to scan highly topographic semiconductor wafers. Using small cantilevers [18], we increased its thermal bandwidth and mechanical resonance frequency of up to 600 kHz [15]. The use of the piezoresistive SPM cantilever (fig.7) with integrated actuator provides the best solution to realize high speed noncontact-AFM. In general, piezoresistive detection is an attractive technique compared to conventional optical beam deflection methods. The cantilever is used for imaging samples in non-contact dynamic mode yielding significant higher scan rates. In combination with the fast scanning stage and a custom-build AFM controller we were able to achieve an imaging-rate of up to one image per second.

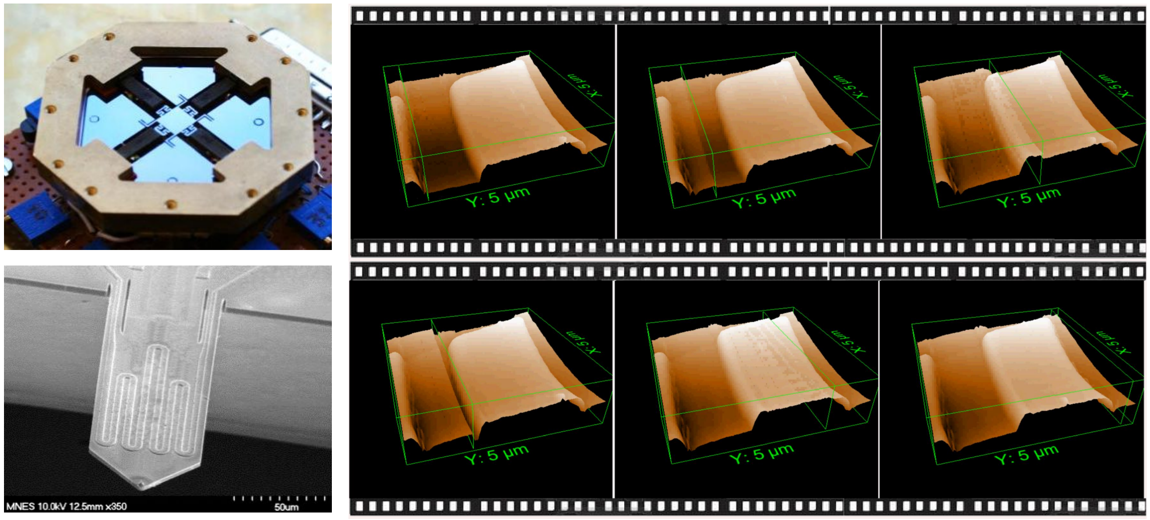

Fig. 7. Silicon scanner (top left); Self-actuated, piezoresistive cantilever (bottom left); and multiple screenshots of a video captured at 250 lines/second of a 20 nm high calibration grid (right).

5. SCANNING PROBE LITHOGRAPHY (SPL)

Scanning Probes are versatile tools capable to confine nanoscale interactions for imaging, probing of material properties as well as for nanolithography at the single nanometer scale or even smaller. The numerous tip-based nanofabrication methods [2] reveal its versatile maskless patterning capabilities for sub-10 nm resolution at relatively low cost and ease-of-use. Moreover, scanning probes provide a multi-nano-toolbox for closed-loop lithography [4], wherein the same nanoprobe is used for (i) AFM pre-imaging allowing inspection of the area of interest & ultra-high overlay alignment capability, (ii) direct writing of features using spatially extreme confined interactions between sample and resist or substrate, and (iii) AFM post-imaging enabling in situ inspection and analysis functions. In addition, in a second lithographic cycle the already generated features can be repaired, allowing a high degree of freedom for rapid nanoscale prototyping, fabrication of 1:1 masks for Nanoimprint lithography or creation of property-defining nanodevice features at the single nanometer digit level. However, throughput is the main limitation of this technique. Using already developed scale-up strategies of parallel probes, based on the self-actuation, self-sensing cantilever array technology [7] could overcome this problem.

The scanning probe lithography experiments were performed with a modified hybrid AFM set-up operated at ambient conditions and room-temperature. Herein, two feedback loops are installed, shown schematically in figure 8. Besides the standard AFM-AC feedback loop ("Force Feedback") for standard AFM-imaging, a second independent feedback loop for current controlled lithography is integrated. Within the lithography feedback loop a home-developed high precision IV-converter and preamplifier converts the Fowler-Nordheim field emission current into a voltage signal for feedback loop input (transfer function of 5 V/nA with 0.2 pA noise level). In summary, the Fowler-Nordheim (FN) current between AFM-tip and sample serves as both regulation signals for the Z-servo loop and/or DC-voltage for thermal actuator, and as local source to generate respective lithographic applicable interactions on the sample and/or resist surface. In the case of constant current mode lithography operation, applying a constant sample bias voltage on the sample surface, the FN current is held constant via adjustment of the tip–sample gap by Z-piezo feedback system. In conclusion, we take advantage of both AFM-AC-feedback for in-situ high resolution imaging for pattern alignment and inspection and constant current lithography feedback for high resolution, maskless pattern generation and reparation in true non-contact.

Within the tip-based nanolithography we investigate the patterning of molecular glass based resist materials (Fig. 8), especially calixarene and resorcinarene-based resist derivatives [1, 4 - 6]. Due to the small particle size (<1 nm) and truly mono-disperse nature of molecular resists, a more uniform and smaller lithographic pixel size can be defined in comparison to conventional polymeric resist systems. Thus, higher lithographic resolution and lower line edge roughness (LER) are expected.

Below the nanoprobe, a direct development-less patterning process in positive tone is triggered within the calixarene molecular resist film. This highly spatial confined nano-lithographic reaction is driven by a non-uniform electric field and an induced Fowler-Nordheim low-energy electron emission between AFM-tip and sample. Thereby, wide process latitude from sub-5 nm up to the µm-size was reliable achieved by variation of the line dose (determined by current set-point and tip speed) and bias voltage [4-6]. Further on, no development steps are necessary enabling the direct inspection after the lithography without any steps in between. Two test lithographic features are shown in figure 9 demonstrating the patterning of "L-corners" and short and long lines.

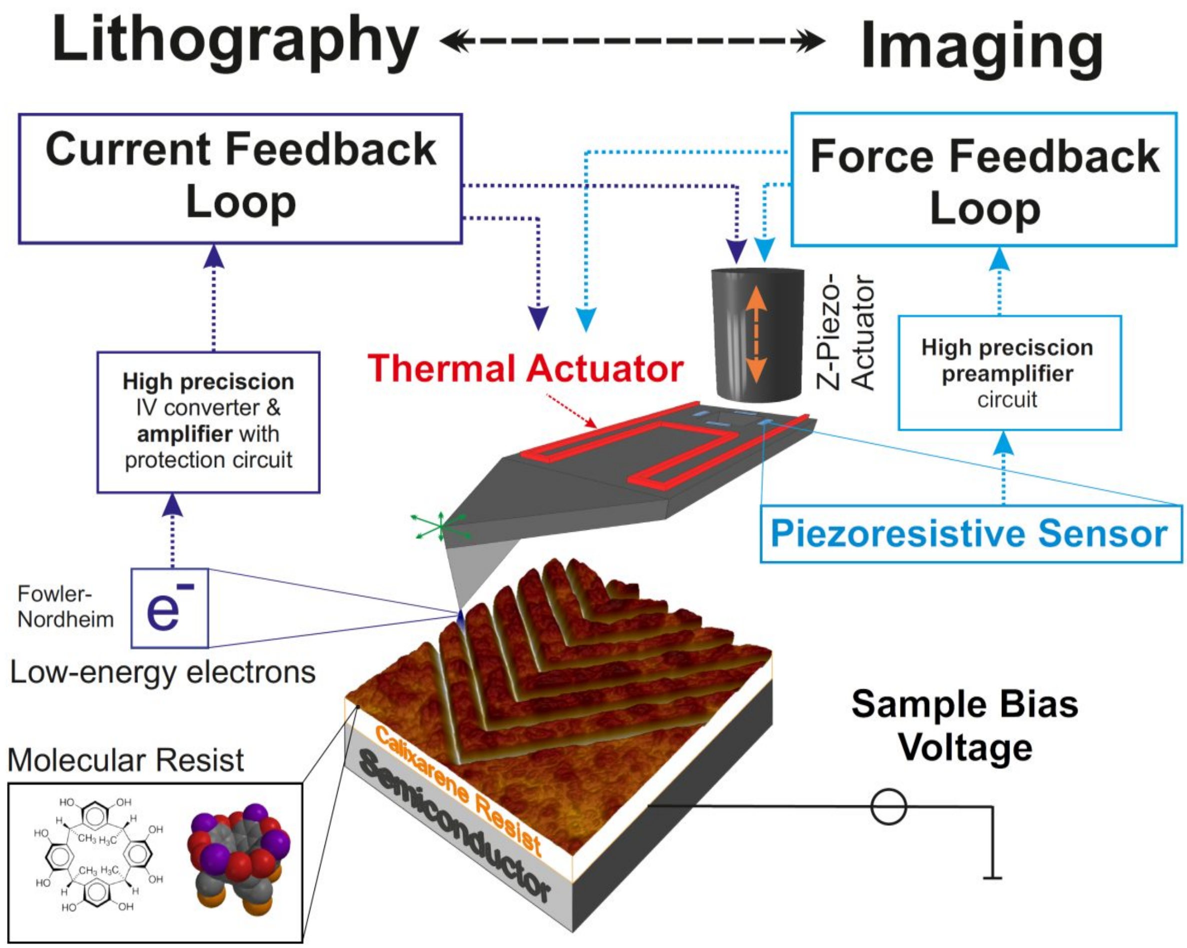

Figure 8. Schematic layout of the Imaging & Lithography system. The same nano-probe is used for both direct writing of nano-features using spatially confined low-energy electron emission from nano-probe-tip and AFM-imaging for pre- and post-inspection as well as for pattern overlay alignment [4]. Therefore, two independent feedback loops are integrated, one for AFM imaging and one for current controlled lithography.

The electric field required for Fowler-Nordheim electron emission is in the order of 10^9 V/m. This field can be easily achieved by using very sharp AFM-silicon tips, which significantly enhance the electric field at the tip apex, in close proximity to the sample surface. Thereby, silicon is an attractive material for building field electron emitters because its conductivity could be improved through doping or applied voltages and it has a well-developed MEMS-technology base.

Therefore, we have developed a SPL-cantilever process to obtain sharper silicon tips by employing anisotropic etching by SF_6 plasma etch and wet oxidation to obtain smaller curvature radii. With these tips FN field emission of low energy electrons (< 50 eV) can be obtained for nanolithographic applications.

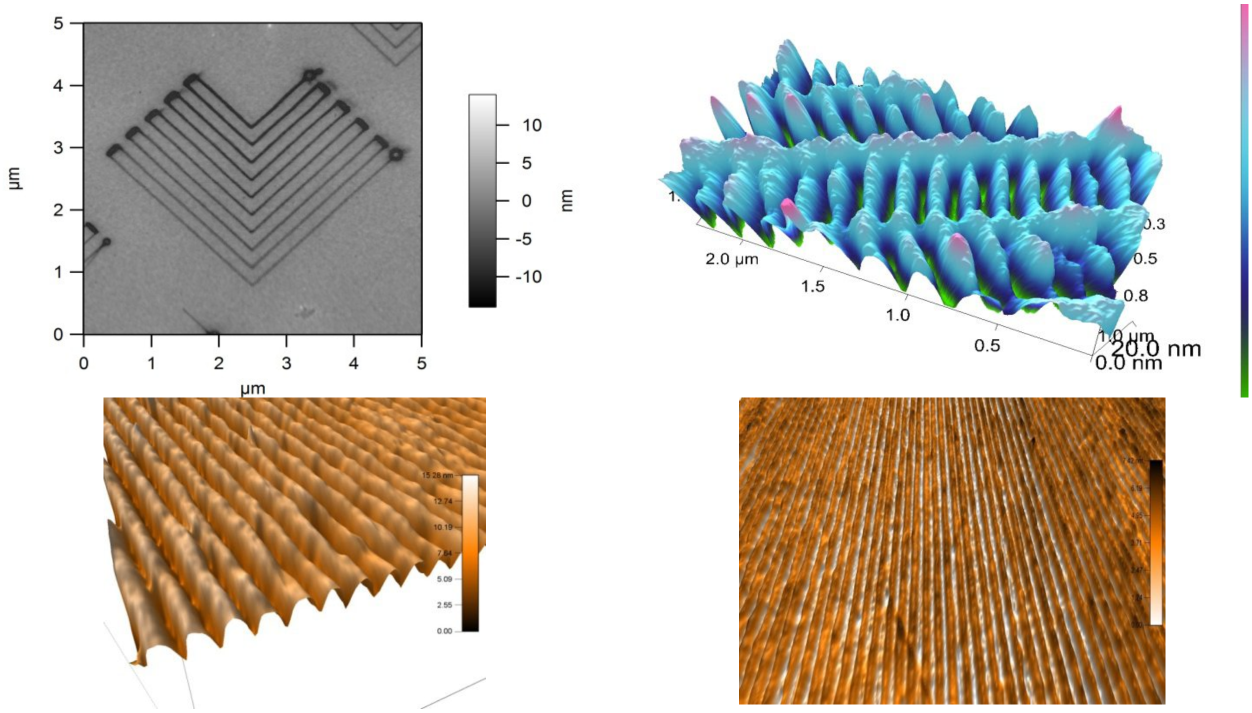

Figure 9. AC-AFM mode images of the SPL - structures generated in calixarene resist. All lithographic steps and AFM-images were done step by step with the same cantilever (and without any development steps). The two bottom AFM topography images show line pattern written with 45 nm half-pitch into 20 nm thick C-MC4R resist.

6. CONCLUSION AND OUTLOOK

The here presented development of fundamentally novel unconventional lithographic methods and their instrumentation basis for pattern placement, generation and inspection is a key technology enabler for nano-device fabrication in the sub-5nm scale regime. Scanning proximal probe techniques have been used to trigger highly localized interaction mechanisms. The integration of Scanning Probe Lithography (SPL) into the Nanopositioning and Nanomeasuring Machine (NPM) combines sub-nanometer exact positioning and measurement across an immense measurement area of 25 x 25 x 5 mm (XYZ) with nanometer lithographic resolution and sub-nm overly positioning accuracy capabilities. Moreover, the NPM is capable for high resolution non-destructive metrological CD measurements. In conclusion, the NPM is a robust platform for SPL, quantitative atomic force microscopy and single nanometer metrology tasks. For the scanning probe lithography adaption a development-less, positive-tone in-situ pattern generation process on calixarene-based molecular glass resist has been applied. This process is triggered below the scanning probe by the high electric field and induced Fowler-Nordheim field emission current. In addition, self-actuating & piezoresistive scanning probes can be employed, expanding the throughput capabilities by enabling cantilever array technology application for imaging and nanolithographic applications. Faster piezo-scanners [17] and regulation principles can be applied to increase imaging and writing speed.

7. ACKNOWLEDGEMENT

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