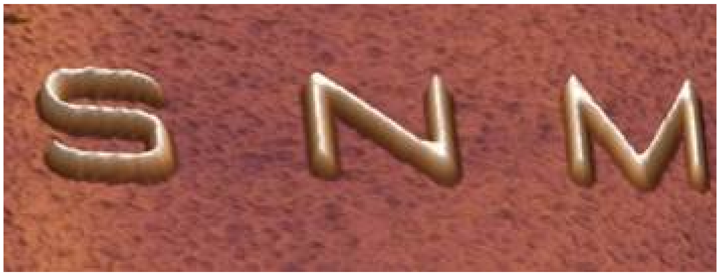

Collaborative project*

Project acronym: SNM

Project full title: "**Single Nanometer Manufacturing for beyond CMOS devices**"

Grant agreement no: 318804

Deliverable: D7.7 (“Performance demonstration of high resolution 3D-AFM”)

Name of the coordinating person: Prof. Dr. Ivo W. Rangelow, Email: ivo.rangelow@tu-ilmenau.de

List of participants:

Participant no.	**Participant organisation name**	**Part. short name**	**Activity Type**	**Country**
1 (Co)	Technische Universität Ilmenau	**TUIL**	HER	Germany
2	EV Group E. Thallner GmbH	**EVG**	IND; End-user	Austria
3	IMEC	**IMEC**	RES	Belgium
4	Mikrosistemi Ltd	**µS**	SME; End-User	Bulgaria
5	Universität Bayreuth	**UBT**	HER	Germany
6	Technische Universiteit Delft	**TUD**	HER	Netherlands
7	Spanish National Research Council	**CSIC**	RES	Spain
8	IBM Research GmbH	**IBM**	IND; End-user	Switzerland
9	École polytechnique fédérale de Lausanne	**EPFL**	HER	Switzerland
10	SwissLitho AG	**SL**	SME; End-User	Switzerland
11	Oxford Instruments Nanotechnology Tools Ltd	**OINT**	IND; End-user	UK
12	Imperial College London	**IMPERIAL**	HER	UK
13	The Open University	**OU**	HER	UK
14	Oxford Scientific Consultants Ltd	**OSC**	SME	UK
15	VSL Dutch Metrology Institute	**VSL**	IND	Netherlands
16	University of Liverpool	**ULIV**	HER	UK

SNM
Work Package 7
Deliverable: D7.7 (“Performance demonstration of high resolution 3D-AFM”)

Lead beneficiary number	15	**Nature**	R	**Dissemination level**	PU

Estimated Person-months	2.0

Person-months by partner for the Deliverable	VSL									
	2.0									

Estimated Delivery Date	M48: 12/2016	**Delivery Date**	30/03/2017

Author	• Arthur van de Nes
Reviewed by:	• WP7 Leader: Marijn van Veghel • Coordinator: Steve Lenk at behalf of Ivo W. Rangelow

Criteria and Achieved Results	**Criteria**	**Achieved result**
	Demonstrate high resolution 3D-AFM measurement capability	• Demonstrated the measurement performance and capabilities of the custom built 3D-AFM, and its potential to perform 3D measurements.

Description of the Deliverable

Introduction

Atomic force microscopy (AFM) is commonly used to image structures with dimensions ranging between tens of micrometers down to a few nanometer. However the measurement technique is generally unable to deliver a true 3D profile, as the applied method depends on a 2D-raster scan over the surface of the measured object. The obtained image can be de-convoluted for probe shape and scanning parameters to improve the accuracy of the measurement, but the limitations become apparent when considering structure profiles that are not one-to-one under the scanning conditions, such as complex features like undercuts, and bandwidth limited functions. Various methods have been proposed to increase the imaging capabilities of AFM by adding one or more degrees of control to the scan procedure, e.g. [1] and [2]. At VSL a 3D-AFM is being developed, which is designed to perform traceable dimensional measurements of small structures within a measurement domain of 1 mm^3, with added 3D capabilities that allow for vector approaches and probing in multiple directions.

Metrological 3D-AFM

The metrological 3D-AFM currently being developed at VSL is a custom instrument using components developed in other projects in collaboration between the Technical University of Eindhoven [3], Entechna, Xpress Precision Engineering, MI partners, and VSL. It consists of a sample stage controlled by three Lorentz motors in combination with three interferometers and fast control electronics. Additionally, a stationary AFM head is used to hold the AFM probe, and incorporates the capability to thermally actuate the cantilever. The deflection of the cantilever is measured optically using a fast quadrant detector. The stage is designed to have its thermal center at the AFM probe, and a minimal Abbe-error for the displacement measurements. A stiffness and weight compensation mechanism helps to reduce the heat load from the Lorentz actuators to a minimum. The sample can be moved in a highly symmetrical rotated configuration, allowing for displacement within a 1 x 1 x 1 mm range (x, y, z). The maximum diameter of the sample is limited to approximately 15 mm diameter. The metrological 3D-AFM is depicted in Figure 1.

The 3D-AFM has been positioned on top of an active vibration isolation system (Herzan TS-150) and placed inside an acoustic enclosure (Herzan Silencer). The laser light required for the interferometric position measurements, as well as the resultant return beams, are delivered to the AFM and their detectors using optical fibers fed through the enclosure. The two lasers required for driving the cantilever modulation, and for detecting the cantilever deflection, are also fiber coupled and fed through the enclosure. A CMOS-camera is used to provide visual feedback of the sample and cantilever.

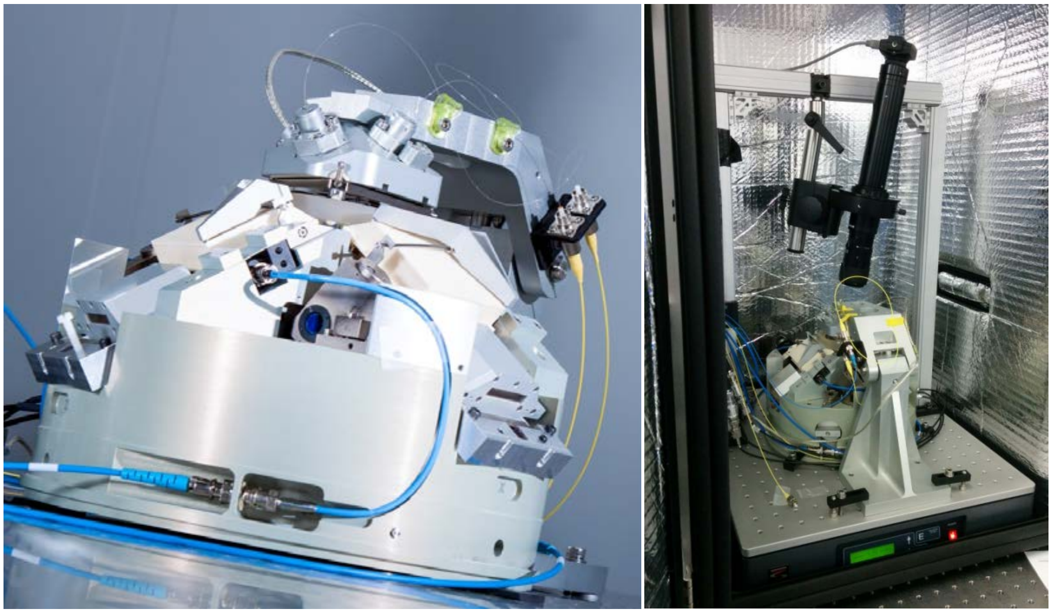

Figure 1 Metrological 3D-AFM (left), and in its enclosure (right).

The control system of the AFM consists of a user PC, a real-time PC and a dedicated FPGA-card and the programs are written in LabVIEW. The FPGA (NI PXIe-7962R) determines the position of the sample stage based on the signal of the four detectors connected to a 4 channel 120 MS/s ADC add-on (NI 5734). The four signals are derived from the interferometers and correspond to the reference signal and the three independent axes. Additionally, the FPGA receives the cantilever signal, as well as operating instructions from the real-time PC. In return, the FPGA determines the driving current to be applied to the Lorentz-motors based on the measured position and the deflection of the cantilever, checks the system-health of the instrument by means of a state-machine, and reports back to the real-time PC. The real-time PC (NI PXIe-8820) controls the multi-purpose DAQ card (NI PXI-6230) that drives the Lorentz-motors, and receives the cantilever deflection signals from the Lockin amplifier (Zurich Instruments HF2LI). Furthermore, it communicates with the user PC to stream the collected measurement data, and transmit operating instructions at a sample rate of 10 kS/s. The control algorithm is schematically depicted in Figure 2. The lasers used to monitor the deflection and photo-thermally actuate the cantilever are controlled with the Lockin amplifier.

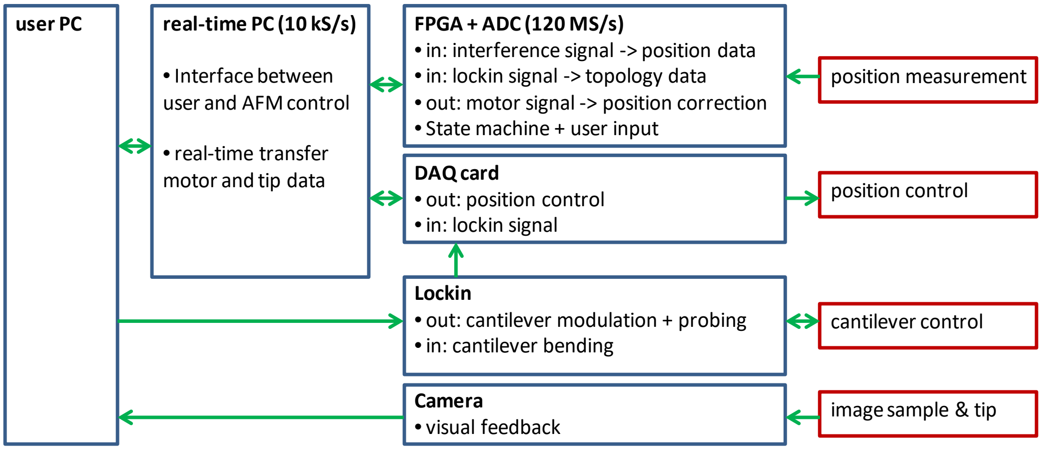

Figure 2 Schematic representation of the control software.

3D-AFM performance

The position of the sample stage is controlled based on the read-out of the interferometers and has a root mean square (RMS) deviation of approximately 0.1 nm, as shown in Figure 3. A position error is introduced by the residual non-linearities of the interferometers, and can be minimised by careful alignment of the laser beam and position of the interferometers, as well as providing an excellent polarization control. The interferometers were equipped with additional optical elements to correct for misalignments experienced during assembly, however a residual non-linearity of the order of a nanometer remains. The tilt of the sample stage has been measured using an autocollimator while the sample was moved over part of the measurement range. The observed tilt angle is less than 5 arcsec, and when required, the effect of the tilt on the position can be corrected in an additional post-processing step. A pitch measurement was performed using a calibration test grating (NT-MDT TGG1), as depicted in Figure 4. The measured period of 2.996 μm is in good correspondence with the 3±0.05 μm specified by the manufacturer.

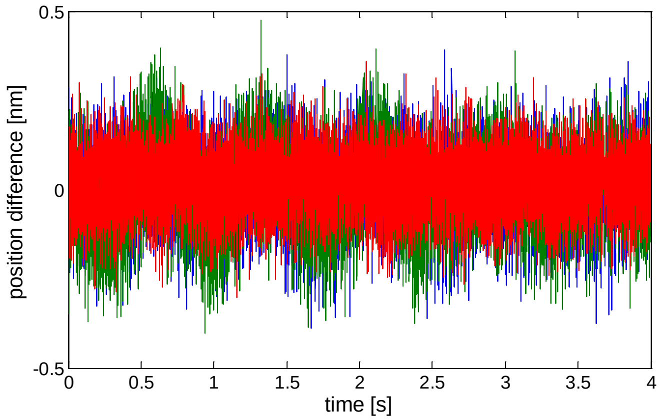

Figure 3 Positional noise of the 3D-AFM for 3 axes while in control and at standstill.

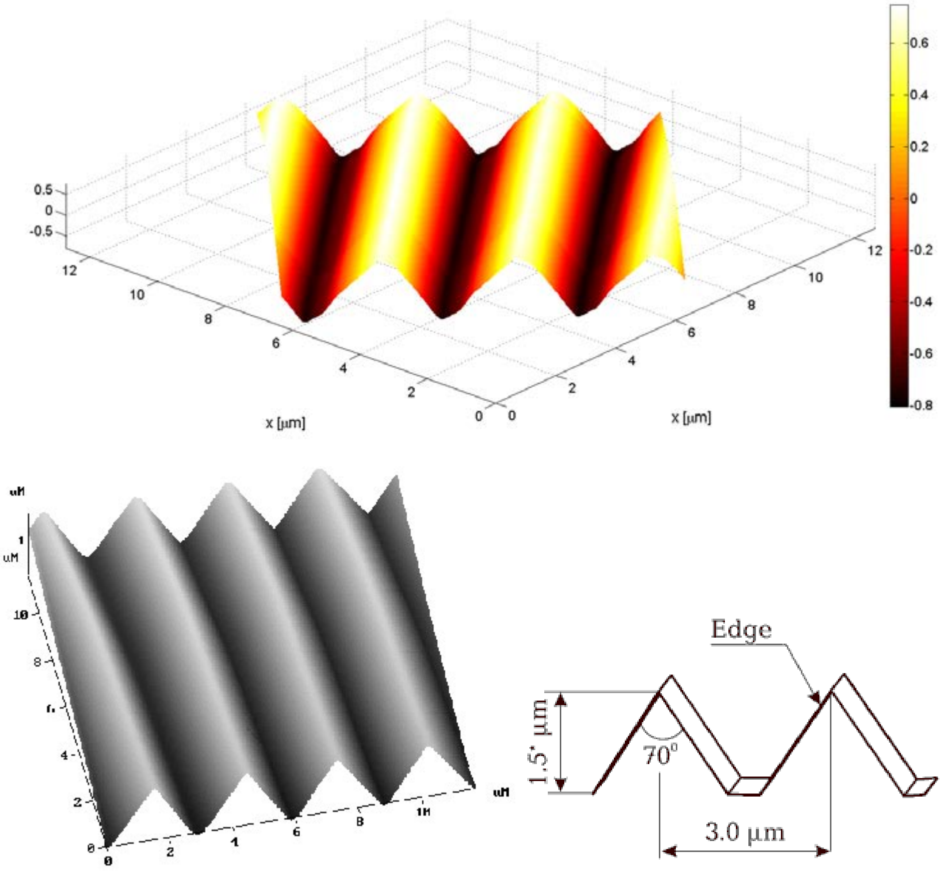

Figure 4 Height measurement of a calibration grating using the 3D-AFM (top). Reference picture of the grating and its dimensions as specified by the manufacturer (bottom). The scales are in micrometers.

The sample provided by IMEC used for the benchmark measurements of deliverable D7.8 [4] was used to demonstrate the measurement capabilities of the 3D-AFM further, since it was determined to have excellent stability and wear resistance. On the sample a two terraced structure was encountered and measured, depicted in Figure 5. Since the 3D-AFM has no preferential scan direction, the scan direction was programmatically aligned approximately orthogonal to the step. The larger step width is approximately 1180 nm wide, and has a 72 nm height. The smaller step has a width of approximately 200 nm and a height of approximately 23 nm Note the effect of the residual non-linearities of the interferometers due to imperfect alignment during the measurement, visible as a periodic height modulation of several nanometers. The line edge roughness of the larger step has been determined as well, resulting in a standard deviation of 5.1 nm, which is partially a result of the residual alignment error of the interferometers and partially due to manufacturing.

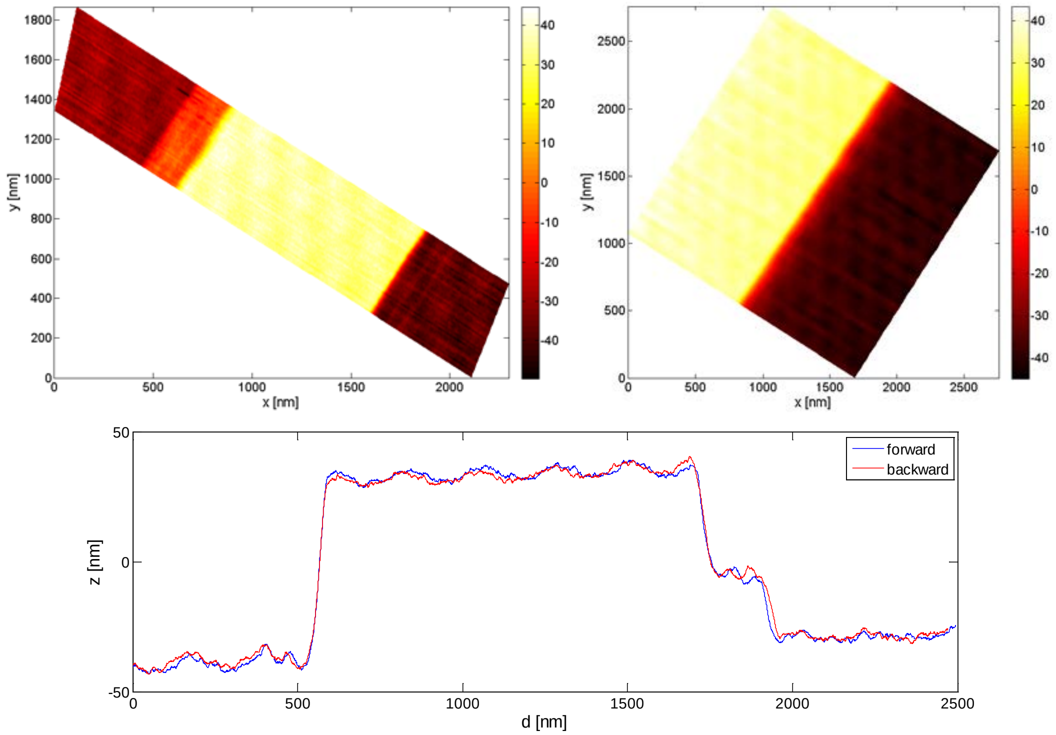

Figure 5 Height profile measurement of a two terraced step profile encountered on the sample used for the benchmark exercise (top). Section of the height profile along the forward and backward scan direction (bottom).

At a different location on the same sample, a shallow line structure was found and used to demonstrate the 3D-AFM measurement performance. Although the effect of the residual non-linearities on the measurement position is clearly visible, after averaging, the lines can easily be resolved and characterised, resulting in a pitch of approximately 85 nm, a line width of 37 nm, and a varying step height of maximally 11 nm.

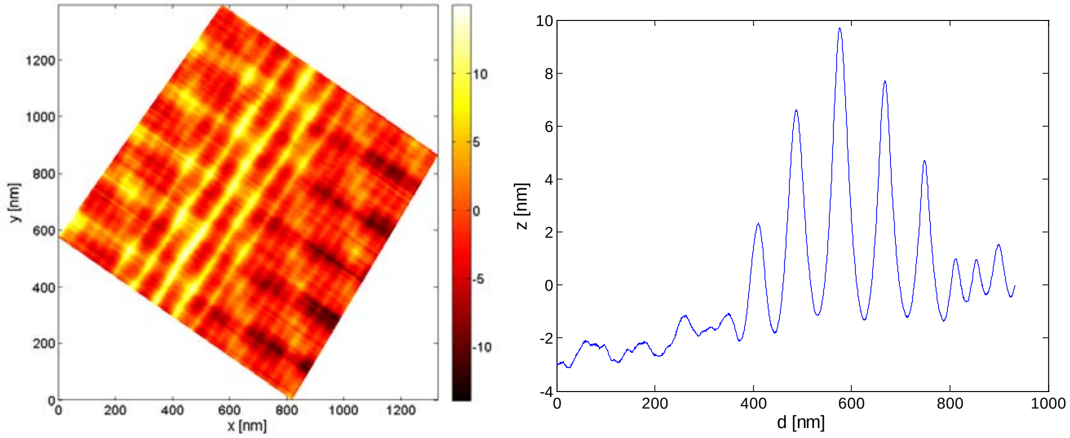

Figure 6 Height and line profile measurement of five lines with a pitch of 85 nm, a line width of 37 nm, and maximum height of 11 nm.

As demonstrated in deliverable D7.4 [5] and discussed in [6], using photo-thermal actuation in combination with a gold coated cantilever (Nanotools B20 with Au coating), the first bending- and torsion-modes can be excited and used to change the orientation of the AFM probe, schematically depicted in Figure 7. Currently, only the cantilever deflection based on the bending mode is implemented to be used for position control, however, the signal of the torsion mode is already available, and the program is prepared for combining or interchanging these information channels. In the future, using the position control based on the torsion mode signal will allow for straight forward line-edge and line-width roughness measurements. All presented measurement results were obtained using contact-mode AFM, as the non-contact mode AFM operation is currently still under development.

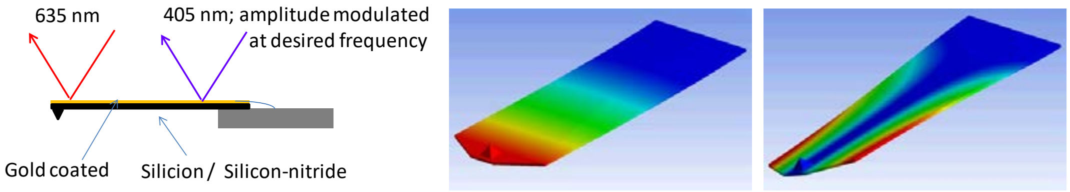

Figure 7 Schematic representation of the cantilever (left) modulated with a blue laser diode, and monitored using a red laser diode. Simulation of the displacement of the cantilever for the first order bending mode (center) and first order torsion mode (right).

Due to the incorporated traceable position determination using the interferometers, and as long as the stage is kept in control, the cantilever can be moved accurately to any desired position in the measurement domain. This allows for measurements of disjointed AFM scans while the positional relation between the various scans is known and can be related to each other. Additionally, it is possible to program the direction of approach of the sample as used by the scan stage, and single touch probing as is commonly done using conventional coordinate measuring machines.

In order to de-convolute influence of the AFM probe from the measurement results, the probe will need to be characterised as discussed in deliverables D7.3 [7] and D7.5 [8], and post processed using the corresponding probe model. In general, the uncertainty estimate in the probe characterization has a large contribution in the total uncertainty estimate for measurements in small domains. While in larger measurement domains, geometrical errors contribute significantly as well.

Conclusion

The current state and performance of the custom built 3D-AFM has been reported and demonstrated in this document. The position of the scan stage is traceable to the primary standard by means of the optical wavelength and using optical interferometers. The stand still performance while in control shows a RMS position error of approximately 0.1 nm. The tilt of the measurement platform has been determined, as well as the non-linearities of the interferometer to determine the positional uncertainty. Various measurements have been shown to demonstrate the capability to measure for example pitch, step height, line-width, line-edge roughness, and small features with high resolution. The 3D-AFM incorporates an additional degree of control of the cantilever by means of photo-thermal actuation, allowing for measurements requiring a rotated AFM probe, such as for measurements of undercuts and randomly orientated steep side walls. At its current state, the 3D-AFM operates in contact-mode, as non-contact mode AFM operation is still under development. The large measurement volume in combination with the absolute position knowledge allows for AFM measurement of disjoined regions while the position offset between the various regions can be related to each other. Finally, the 3D-AFM allows for vector approach and single touch probing.

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[8] A. van de Nes and R. Koops, “D7.5: Methodology for traceable characterization of probe-sample interaction and probe shape,” 2016.

Explanation of Differences between Estimation and Realisation	The deliverable has been achieved; the current performance has been demonstrated. Due to major changes to hard- and software of the 3D-AFM, the performance demonstration measurements for the deliverable were scheduled for the final stages of the project. To facilitate 3D-measurement capabilities, further improvements in algorithms and software were required resulting in a delay of the deliverable of two months.
Metrology comments	The deliverable discusses traceable AFM measurements using the 3D-AFM, and discusses the relevant metrology, please see the main text for more details.