New Traceable Atomic Force Microscope for Dimensional Measurements

New developments in nano- and micro-technology impose challenging requirements for nano-dimensional measurements on technical components. For such applications, the Federal Office of Metrology (METAS) has built a dedicated atomic force microscope (AFM) with direct 3D traceability which can accommodate even large objects. The AFM design is based on three differential Jamin type interferometers and a commercial six axis flexure stage having a range of 800 µm x 800 µm. The AFM can operate in static or dynamic mode whereby height and deflection or height, amplitude and phase data are acquired synchronously. Instrument characteristics and first applications are presented.

Felix Meli

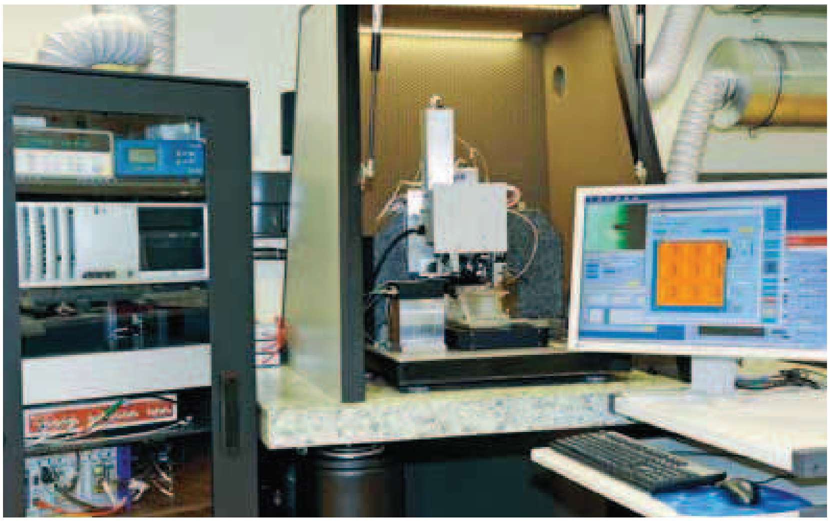
In the past years nanotechnology was pushed forward through huge research programs. Today first industrial applications are appearing. Nanomaterials, particles and powders are increasingly used and safety aspects have become a major concern requiring traceable measurement methods. Also the more classical but rapidly progressing field of micron and sub-micron technology is entering into the nano-range. Structure distances on data storage devices such as Blu-ray Discs are already as small as 150 nm.

Today's semiconductor devices have structures in the range of 45 nm and the trend goes down beyond 10 nm in a few years from now. Similar trends towards smaller structures can also be found in the field of micro electro-mechanical devices (MEMS), in micro-optics and for classical micro-objects such as small precision spheres, knife edges or diamond tips where the expected shape deviations are smaller than a few nanometres. Engineered areal surface roughness and treatments for super smooth surfaces require accurate measurements for their characterisation.

Atomic Force Microscope, a Basic Tool for Nanometre Measurements

A powerful metrology tool for the nanoworld is the atomic force microscope (AFM) whose origins go back to the invention of the scanning tunnelling microscope (STM) by Heinrich Rohrer and Gerd Binnig in 1981 at the IBM Research Center in Rüschlikon [1]. Since then a variety of scanning probe microscopes (SPM) were developed among which the AFM has the broadest industrial application. An AFM is a basic tool for imaging, measuring, and even manipulating objects at the nanometre scale (box 2).

AFMs used for traceable dimensional measurements, so called metrology AFMs, need to be specially designed. Today many national metrology institutes (NMIs) have projects running in this field [2–5]. METAS had built its first instrument in 1996 [6]. This first AFM profiler, with a 400 µm linear stage and an interferometer, was successfully validated in several international comparisons and was frequently used for customer services, but later on, the manufacturer has stopped any support for the AFM head and the lack of simultaneous 3D interferometric traceability required time consuming measurement strategies.



1 3D-AFM set-up in the clean room laboratory of METAS with electronic rack (left), AFM in the opened acoustic box (centre) and control screen (right).

In 2007, METAS started a project with the goal to develop a new, fully traceable metrology AFM. The design targets were specifically set in order to obtain a flexibly usable instrument fully based on in-house knowledge. In contrast to existing projects at other NMIs, the new AFM should be able to accommodate also larger technical objects maintaining at the same time an easy sample access [7].

General Design Concepts

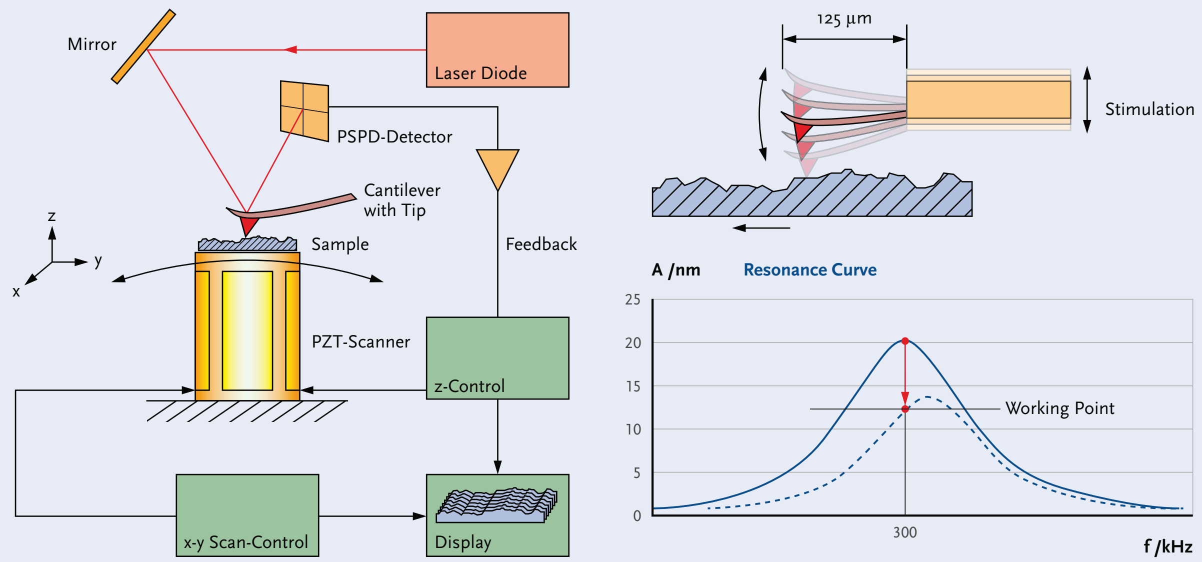
To obtain high quality traceable dimensional measurements, some basic principles have to be followed: The most important is the Abbe principle which says that the measurement scale, in this case the interferometer beam, has to be co-linear with the spatial dimension or displacement to be measured. The main goal of this principle is to avoid errors induced by unwanted rotational motions of the translation stages which are always present.

Besides a very stable temperature and low vibration environment, a stable metrology loop built from low expansion material is important to reduce drift. The use of differential interferometers provides the required traceability and additionally shortens the metrology loop (illustration 3).

AFM Realisation

To accommodate large samples in a metrology AFM, a corresponding large reference mirror frame is required. Using simple Zerodur elements, a light weight carrier structure for the three reference mirrors was built which can accommodate samples up to 90 mm x 60 mm x 60 mm (picture 4). This reference frame with the sample is moved by a commercial 6-axis piezo driven stage with a range of 800 µm x 800 µm x 200 µm [8].

The three rotational axes are mainly used to improve the quality of the linear scan movements by actively compensating



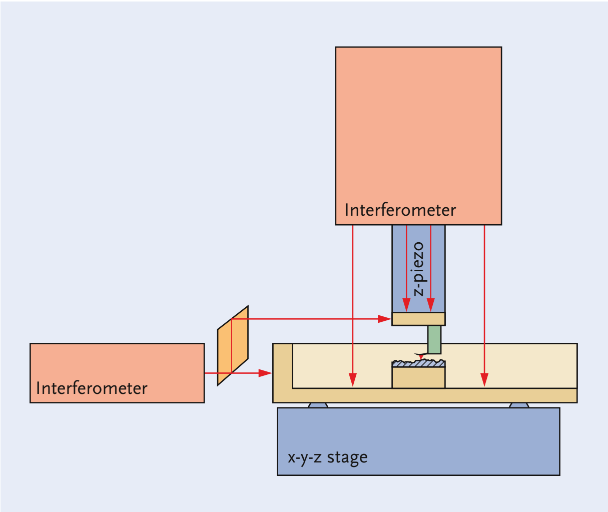
An atomic force microscope (AFM) is an instrument which can measure surface topographies with nanometre resolution. The measurement is performed with a very sharp tip which is held at a constant distance from the sample surface through the detection of very small atomic forces. Scanning the tip over a certain surface region using piezo driven x-y-z actuators produces a 3D surface data set called an «AFM image».

To measure the bending of the cantilever induced by the tip sample interaction forces, a laser beam is focussed on its back side and the reflected beam angle is measured with a differential photo detector (figure on the left). The tip and the cantilever are usually made out of mono-crystalline silicon.

A typical cantilever has a length of 125 µm and a width of about 20 µm. The tip radius can be as small as 1 nm.

For many applications and especially for dimensional metrology it is advantageous to operate the AFM in «dynamic mode». The cantilever is excited at its resonance frequency of approximately 300 kHz. A tip height regulation circuit maintains a constant amplitude damping and thereby a constant tip surface distance (figures on the right). Through the cantilever oscillation, lateral tip forces are minimised and additionally, certain sample material properties can be determined using the amplitude and phase information from the measured tip oscillation.

2 Schematic principles of an atomic force microscope (figure on the left) and illustration of the dynamic AFM mode operation (figures on the right).



3 Differential interferometer beam configuration with main beams measuring the sample movement respecting the Abbe principle and reference beams monitoring the AFM tip position using a small mirror cube fixed to the end of the fast z-stage piezo.

all unwanted rotations. This 6-axis stage has its own built in capacitive measurement system. However, the stage controller allows also the use of external sensors such as the interferometer signals.

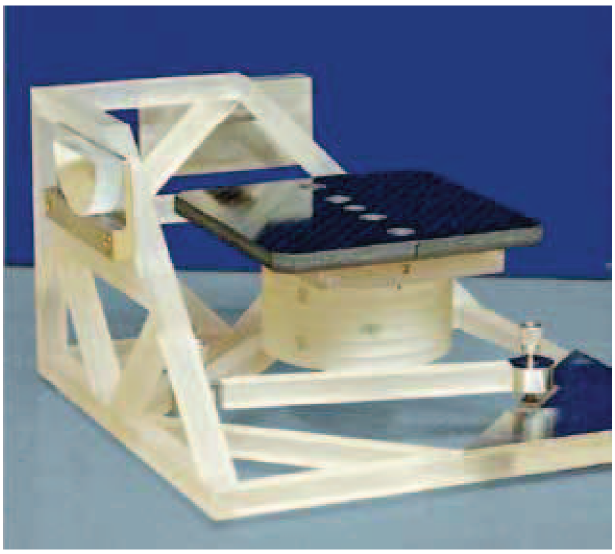
The sample position is measured with respect to the AFM tip by means of three differential Jamin type interferometers. The measurement beams fulfil the Abbe condition and the differential measurement shortens the metrology loop considerably. The METAS built interferometer system acquires all metrologically relevant information with high data synchronicity and is therefore a key component of the AFM.

To follow the sample topography, the AFM tip is actuated with an additional fast 12 µm piezo stage which is placed outside the metrology loop because the fast z-stage moves not only the AFM tip-holder but also the small reference mirror. Integrated in the tip holder is a small bimorph piezo which serves an activator for the cantilever oscillation. The cantilever bending is measured using the laser beam deflection method. A diode laser beam is focussed on the back side of the cantilever and the reflected beam angle is measured with a four quadrant photo detector (picture 5).

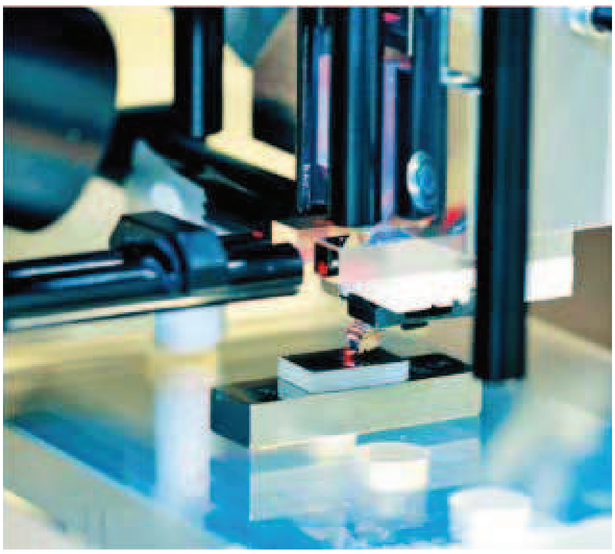
Contact and Dynamic Mode Operation

The AFM can operate either in contact or in dynamic mode. For contact mode measurements, the vertical and the lateral deflections of the tip are acquired synchronously with the x-y-z-position data, while in dynamic mode position, oscillation amplitude and phase are acquired synchronously. A commercial oscillation controller is used for the amplitude and phase measurements in dynamic mode [9]. This controller could be easily integrated into the main METAS LabView AFM control software.

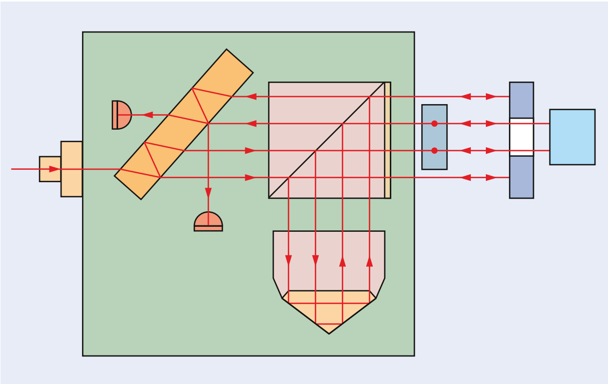
The upper part of the AFM is mounted on a coarse approach stage which can move the tip upwards by 50 mm. This stage facilitates tip replacement and sample exchange. Also the coarse sample approach is fully automatic once the tip and the surface position are determined by the focus of the video microscope. Furthermore, the built in top view zoom video microscope allows to position the AFM tip exactly above the location of interest on the sample. This concept offers a good sample visibility and an easy sample access. Finally, good laboratory conditions, electronics with direct heat evacuation, vibration damping, acoustic isolation box and low power dissipation help to reduce noise and drift (picture 1).



4 Zerodur carrier structure for the three interferometer mirrors which can accommodate also larger samples.



5 Interferometer beams monitoring the AFM tip motion by means of a small reference mirror.



6 Schematic of the differential plane mirror Jamin type interferometer. The METAS built interferometers have an optical fibre input and quartz beam benders at the exit for the required special beam geometry.

Interferometer Design

The METAS built interferometer system with the incorporated Field-Programmable Gate Array (FPGA) data acquisition is the most important component in order to fulfil the metrological traceability requirement. The three differential plane mirror interferometers of the Jamin type are based on a previous development at NPL [10]. This special interferometer configuration provides very stable, differential measurements.

It is a two pass interferometer with the four measurement beams placed symmetrically with respect to a centre reference line which must fulfil the Abbe condition. The Jamin plate made from quartz is the only component inside the interferometer which determines its stability. The homodyne interferometer produces sine and cosine signals with a period of 158 nm by the use of special surface coatings on the Jamin plate. Sub-nanometre resolution is finally obtained through accurate phase interpolation.

The METAS version of the interferometer has optical fibre input for the laser and quartz beam benders at the exit for the specially required beam geometry. The fast synchronous FPGA data acquisition includes signal corrections, fringe counting, phase interpolation as well as digital and analogue signal outputs in various forms (illustration 6).

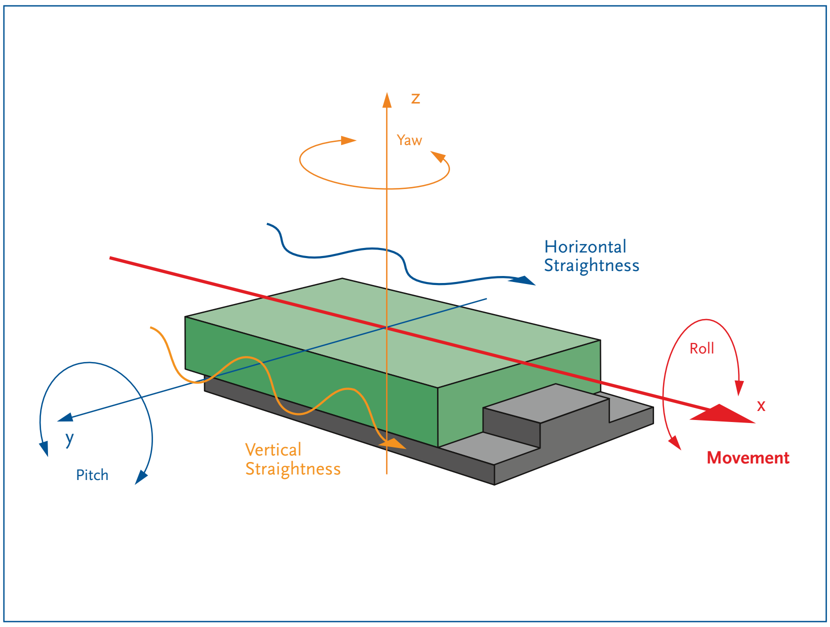
The interferometer noise is sensitive to the beam path length in air. To minimise the effect of air turbulences, all beams are guided inside black aluminium tubes. At 40 mm distance, the position noise at 10 kHz bandwidth is 0.2 nm p-p. The phase interpolation is improved using an online Heydemann signal adjustment [11] resulting in a phase interpolation non-linearity below 0.05 nm. The dead path correction requires an accurate tracking of the refractive index of the air. This is achieved by measuring temperature, humidity, pressure and CO_2 content as input parameters for the refractive index calculation using Edlén's equation.

Stage Characteristics

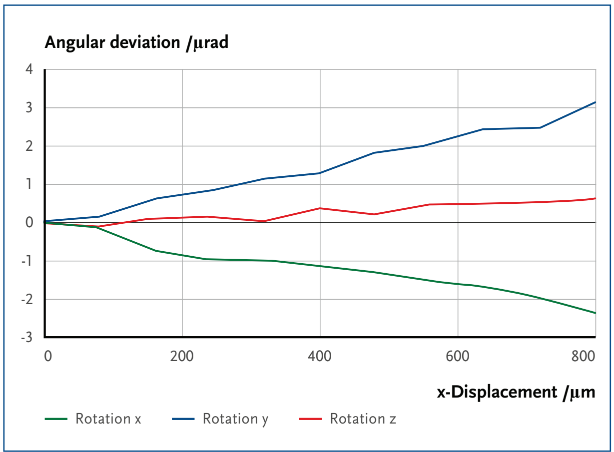
Although the AFM design nominally fulfils the Abbe principle there is always a small remaining offset to the Abbe reference line. With a non-ideal stage behaviour this can easily create large uncertainty contributions. The main 6-axis AFM stage uses its built-in capacitive sensors to adjust the rotational deviations to a minimum. Verification measurements with an autocollimator showed remaining, mainly linear, deviations below 4 µrad. For a maximum assumed Abbe offset of 1 mm the estimated uncertainty contribution remains below 0.6 nm/100 µm scan length (illustration 7 and diagram 8).

Distributed AFM Control

The main AFM control and data evaluation is performed by a METAS control software written in LabView. To reduce the load on the main controller PC, other decentralised dedicated sub-



7 All possible motion errors of a linear stage.



8 Autocollimator measurements showing the rotational deviations of the main 6-axis AFM stage.

systems are involved. The intelligent 6-axis stage controller generates also complex scanning motions according to a set of a few simple parameters. The dedicated controller of the fast z-piezo does the tip sample distance regulation according to the given amplitude setpoint and the feedback parameters.

The AFM tip oscillation controller uses a second FPGA board inside the main control PC and provides analogue amplitude and phase signals. Finally, two additional stage controllers are used for the video microscope and one for the coarse approach stage of the AFM head.

Data Acquisition

The most crucial data acquisitions with respect to timing and throughput are performed entirely FPGA based. An FPGA is an integrated logic circuit designed to be software configurable by the user after manufacturing. After programming it behaves like a huge electronic circuit with several million logic gates. The FPGA board used here features additionally eight synchronously sampled analogue input channels. Six channels are used for the interferometer signals and two for amplitude and phase of the tip oscillation.

Interferometer fringe counting is possible up to 10 MHz while all analogue signals are sampled and processed at a rate of 160 kHz. The sine and cosine signals of the three interferometers are corrected and the phase is interpolated by a large tangent lookup table resulting in digital position resolution of 20 pm.

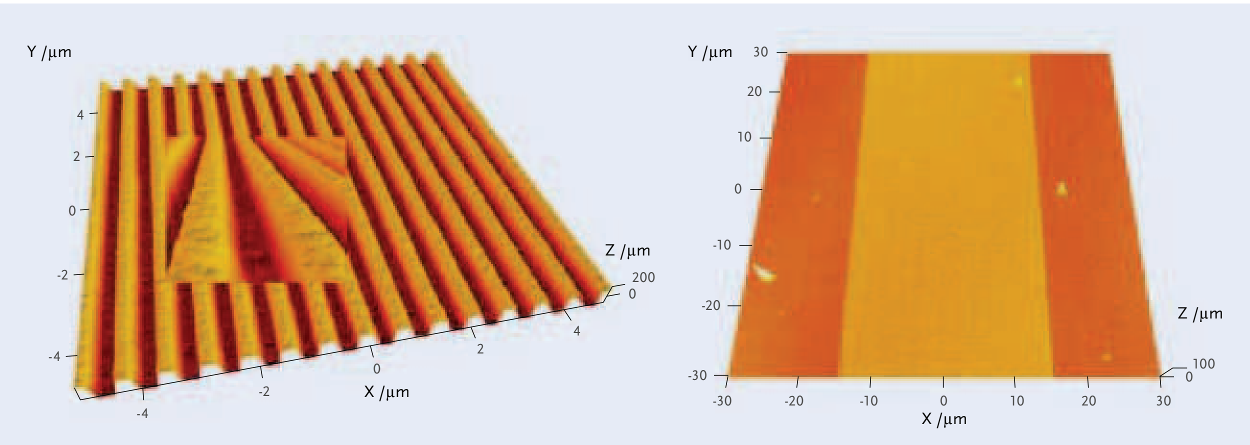
The 3D position data as well as the other signals from the tip oscillation controller are online averaged to 10 kHz and then directly transferred into the computer by means of Direct Memory Access (DMA). At the same rate, the interferometric position data is transmitted over a digital parallel port interface to the 6-axis stage controller. This results in a five times reduced positional noise compared to the original 16 bit capacitive sensor control.

A single measured AFM scan line can have up to 200 000 data points. To avoid too large data files, data reduction procedures are applied already online during the measurement. Finally, at the end of a measured AFM image the acquired 3D surface point cloud is resampled into the usual 2D height matrix which uses much less storage space and which can be evaluated offline using free or commercial AFM image processing software such as Gwyddion, WSxM or SPIP.

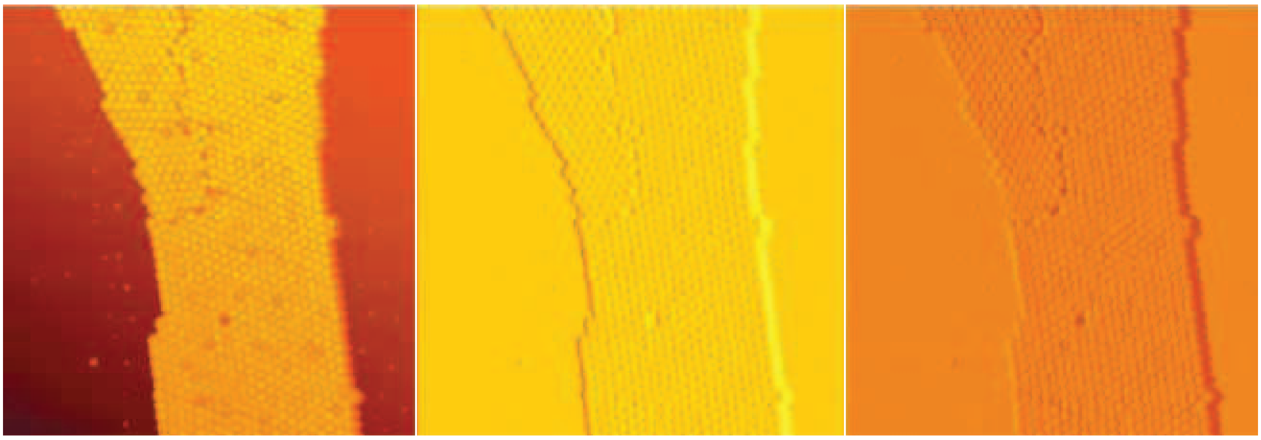
Applications

The typical application field of Metrology AFMs is to calibrate surface topography standards such as 1D or 2D gratings and step height standards which are themselves used to calibrate ordinary SPMs or other microscopes such as SEMs (picture 9). Further applications include the calibration of line width standards and tip characteriser shapes.

Besides these traditional tasks, the calibration of standard reference particle diameters is becoming more and more



9 AFM pitch and step height calibrations. Left: holographic grating with 700 nm pitch, image 10 µm x 10 µm. Right: 7 nm step height standard, image 60 µm x 60 µm.



10 200 nm polymer reference particles on mica. Raw data images showing height (left), amplitude (centre) and phase (right) of the AFM tip oscillation. Images 8 µm x 8 µm with 1024 x 1024 data points.

important [12]. METAS was participating in the EURAMET EMRP project «Traceable characterisation of nanoparticles» where traceable methods needed for particle size and size distribution measurements were developed (picture 10).

Technical applications such as the roughness of microparts, surface texture of precision balls, profiler stylus shape deviation, edge radius of cutting tools and diamond indenter shape deviation measurements are possible. Since the AFM is designed to accommodate also larger objects, it can also be applied for direct measurements of microstructures and surface roughness on technical objects such as gauge blocks, probing spheres, medical or watch parts. In the future, the implementation of improved 3D functionality is planned: nano coordinate measuring machine.

References

[1] G. Binnig, H. Rohrer, Scanning tunneling microscopy, Helv. Phys. Acta, 55(6), p. 726–735, 1982.

[2] H.-U. Danzebrink, F. Pohlenz, G. Dai, C. Dal Savio, Metrological scanning probe microscopes – instruments for dimensional nanometrology, Nanoscale calibration standards and methods, G. Wilkening and L. Koenders (Eds), Wiley-VCH Verlag, Weinheim, ISBN 3-527-40502-X, pp. 3–21, 2005.

[3] I. Misumi, S. Gonda, O. Sato, K. Sugawara, K. Yoshizaki, T. Kurosawa, T. Takatsuji, Nanometric lateral scale development using an atomic force microscope with directly traceable laser interferometers, Meas. Sci. Technol. 17, pp. 2041–2047, 2006.

[4] J. Haycocks, K. Jackson, Detecting and addressing the surface following errors in the calibration of step heights by atomic force microscopy, Meas. Sci. Technol. 18, pp. 469–475, 2007.

[5] B. Poyet, S. Ducourtieux, J. David, L. Lahousse, S. Leleu, Development of a new XY flexure translation stage with high guidance quality for the LNE metrological AFM, 10th Aniv. Int. Conf. of the European Soc. for Precision Engineering and Nanotechnology (euspen), Zurich, Switzerland, Proc. V2, pp. 375–379, May 2008.

[6] F. Meli, R. Thalmann, Long-range AFM profiler used for accurate pitch measurements, Measurement Science and Technology, 9(7), pp. 1087–1092, 1998.

[7] F. Meli, A. Küng, Realization of a large sample 3D metrology AFM with differential Jamin interferometers, 11th Int. Conf. of the European Soc. for Precision Engineering and Nanotechnology (euspen), Como, Italy, Proc. V1, pp. 203–206, May 2011.

[8] www.physikinstrumente.ch.

[9] www.specs-zurich.com.

[10] M. J. Downs, W. R. C. Rowley, A proposed design for a polarization-insensitive optical interferometer system with subnanometric capability, Precision Engineering, 15(4), p. 281–286, 1993.

[11] P. L. M. Heydemann, Determination and correction of quadrature fringe measurement errors in interferometers, Appl. Optics, 20(19) p. 3382–3384, 1981.

[12] F. Meli, Nanoscale Calibration Standards and Methods, G. Wilkening and L. Koenders (Eds), Wiley-VCH Verlag, Weinheim, ISBN 3-527-40502-X, pp. 361–374, 2005.

Felix Meli, Ph. D., Head of Nano- und Micro-Technology Laboratory,
direct phone +41 31 32 33 346,
felix.meli@metas.ch.

Neues Rasterkraftmikroskop für rückgeführte, dimensionelle Messungen

Neue Entwicklungen in der Nano- und Mikrotechnik stellen komplexe Anforderungen an die dimensionelle Messtechnik. Für die Messung von Nanopartikeln werden verlässliche Referenzpartikel mit kalibriertem Durchmesser benötigt. Digitale Daten werden immer dichter gespeichert: Auf einer Blu-ray-Disc haben die Datenstrukturen Abmessungen von nur noch 150 nm. Die Strukturen in integrierten Schaltkreisen haben heute noch eine Grösse von 45 nm, aber schon bald werden es weniger als 10 nm sein. Auch in der Mikrotechnik werden die Teile kleiner, feiner strukturiert und präziser gefertigt. Das Metrologie-Rasterkraftmikroskop (MAFM) ist das geeignete Messinstrument für diese neuen Aufgaben.

Am METAS wurde ein neues MAFM aufgebaut, das direkt rückgeführte Messungen auch an grösseren, technischen Objekten erlaubt. Das Gerät basiert auf drei differentiellen Jamin-Interferometern und einem 6-Achsen-Verschiebetisch mit einem Bereich von 800 µm x 800 µm x 200 µm. Der darauf befestigte Zerodur-Spiegelträger erlaubt Messungen an Teilen mit einer Grösse von bis zu 90 mm x 60 mm x 60 mm.

Ein Piezo mit 12 µm Hub bewegt die AFM-Spitze rasch in vertikaler Richtung, um exakt der Oberflächentopographie zu folgen. An dessen unteren Ende ist auch der Referenzspiegel für die drei differentiellen Interferometer befestigt, wodurch ein kompakter Messkreis entsteht. Die 3D-Positionsdaten werden synchron mit der Amplitude und der Phase der AFM-Spitze erfasst und ausgewertet. Dadurch wird der Einfluss von Vibrationen minimiert.

Typische Anwendungen des neuen MAFM sind die Kalibrierung von Oberflächen-Topographienormalen für die Mikroskopie wie 1D- oder 2D-Gittern, Stufenhöhen oder Linienbreiten. Daneben ermöglicht es auch direkte Messungen an technischen Teilen, um beispielsweise deren Oberflächentextur, den Radius einer Schneidkante oder die Geometrie von Tastspitzen und Eindringkörpern zu bestimmen.

Nouveau microscope à force atomique pour des mesures traçables

Les derniers développements en nano- et microtechnique imposent des exigences de plus en plus complexes pour la métrologie dimensionnelle. Pour la mesure de nanoparticules, il est nécessaire de disposer de particules de référence ayant un diamètre étalonné. Les données informatiques sont stockées de manière toujours plus compacte. Ainsi, la taille des structures sur un disque Blu-ray n'est que de 150 nm, tandis que la taille des pistes d'un circuit intégré, qui est actuellement de 45 nm, passera bientôt à 10 nm. En micromécanique aussi les pièces sont de plus en plus petites, plus finement structurées et plus précisément usinées. Pour effectuer toutes ces nouvelles tâches, le microscope à force atomique (MAFM) est un instrument idéal.

METAS a donc développé un nouveau MAFM qui permet des mesures traçables de haute précision aussi bien sur de petits objets que sur des objets de plus grande taille. L'instrument est composé de trois interféromètres de type Jamin et d'une table de déplacement 6 axes offrant un volume de mesure de 800 µm x 800 µm x 200 µm. La structure en zerodur supportant les miroirs permet cependant d'y placer des objets plus volumineux jusqu'à 90 mm x 60 mm x 60 mm.

Un actuateur piézo-électrique de 12 µm de course permet à la pointe MAFM de suivre rapidement la topographie de la surface à mesurer. Le miroir de référence pour les trois interféromètres y est directement fixé ce qui minimise la grandeur de la boucle métrologique. Les coordonnées en 3D ainsi que les signaux de phase et d'amplitude sont enregistrés de manière absolument synchrone limitant ainsi l'impact des vibrations.

Les applications courantes de ce MAFM sont l'étalonnage d'étalons de surface pour la microscopie tels que les réseaux de diffraction 1D et 2D, les étalons de hauteur et de largeur de ligne. L'instrument permet aussi la mesure sur des pièces de production, comme par exemple la texture d'une surface, le rayon de courbure d'un outil de découpe, la géométrie de pointes de stylets ou de pénétrateurs.

Nuovo microscopio a interazione atomica per misurazioni riferibili

I nuovi sviluppi nella nano e micro tecnologia pongono esigenze complesse alla metrologia dimensionale. Per la misurazione di nanoparticelle occorrono particelle di riferimento affidabili con diametro calibrato. I dati digitali vengono memorizzati in modo sempre più compatto: su un disco Blu-ray le strutture dei dati hanno dimensioni pari a solo 150 nm. Nei circuiti integrati le strutture sono attualmente di dimensioni pari a 45 nm, ma ben presto saranno inferiori a 10 nm. Anche nella microtecnica i componenti sono sempre più piccoli e fabbricati con maggior precisione. Il microscopio a interazione atomica per la metrologia (MAFM) è lo strumento di misura idoneo per questi compiti.

Presso il METAS è stato costruito un nuovo MAFM, che consente di effettuare direttamente misurazioni riferibili anche su oggetti tecnici di grandi dimensioni. L'apparecchio si basa su tre interferometri differenziali del tipo Jamin e una tavola a spostamento a 6 assi con un volume di misura di 800 µm x 800 µm x 200 µm. La struttura Zerodur che porta gli specchi consente di misurare componenti fino a 90 mm x 60 mm x 60 mm.

Un attuatore piezoelettrico con una corsa di 12 µm muove rapidamente la punta dell'AFM in direzione verticale, consentendo così di seguire esattamente la topografia della superficie. Alla sua estremità inferiore è fissato anche lo specchio di riferimento per i tre interferometri differenziali, per cui risulta un circuito di misura compatto. Le coordinate tridimensionali e i segnali relativi all'ampiezza e alla fase della punta AFM vengono rilevati in modo sincrono e interpretati. Ciò consente di minimizzare l'influsso delle vibrazioni.

Utilizzazioni tipiche del nuovo MAFM sono la taratura di campioni di riferimento di superficie per la microscopia quali i reticoli di diffrazione mono o bidimensionali, i campioni di altezze di scalini o di larghezze di linee. Esso consente anche misurazioni dirette su componenti tecnici, per determinare ad esempio la struttura della superficie, il raggio di utensili da taglio o la geometria di tastatori e di penetratori.