DOI 10.5162/SMSI2023/D6.3

Recent progress on AFM techniques for traceable 3D nanometrology at PTB

Gaoliang Dai [1], Jan Thiesler [1], Johannes Degenhardt[1], Rainer Tutsch[2]*
[1] Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany
[2] Technische Universität Braunschweig, IPROM, Schleinitzstraße 20, 38106 Braunschweig, Germany
**) corresponding author: Gaoliang.Dai@ptb.de*

Summary:

This paper presents an overview on recent research progress achieved at PTB for reference 3D nanometrology: (1) development of a new low noise 3D-AFM, which has combined measurement modes of CD-AFM and tilting-AFM in one instrument; (2) accurate calibration of the tip form with a new traceability route using the silicon lattice parameter which is suggested by the *Mise en pratique* for the realisation of the *Metre* in nanometrology; (3) development of a novel true 3D AFM probe, referred to as a 3D-Nanoprobe, which has quasi-isotropic stiffness in three directions and is thus more powerful for detecting 3D tip-sample interaction forces in AFM measurements.

Keywords: Atomic Force Microscopy, dimensional nanometrology, traceability, calibration, critical dimension (CD), tilting AFM, tip characterization, 3D-AFM probe

Background and motivation

Progressive developments in nanomanufacturing, particularly in the nanoelectronic industry, pose increasing challenges in measuring nanostructures with ever smaller size and more complex three dimensional (3D) shape. Traceable metrology of nanostructures including measurands such as e.g. feature width, sidewall angle, line edge/width roughness (LER/LWR), corner rounding are essential tasks for quality assurance of process developments and process control in nano-manufacturing.

This paper will provide an overview of recent research progress achieved at PTB for reference 3D nanometrology.

Progress

The *first* progress concerns the development of a new low noise 3D-AFM, as shown in figure 1(a). The AFM offers two combined measurement modes in one instrument, referred to as the CD-AFM and tilting-AFM. When it is operated in the CD-AFM mode, a flared AFM tip which has an extension at the free tip end is applied. Such a flared AFM tip allows direct probing of vertical sidewalls or even undercuts in a single measurement. However, due to the complex shape of the flared AFM tip, it is difficult to measure dense nanopatterns. To solve this problem, the tilting-AFM mode is realized, as shown in figure 1(b). Using this technique, a nanostructure is measured by an AFM tip tilted in different angles, where the obtained AFM images will then be fused to derive the real 3D topography of the nanostructure. Owing to the sharp AFM tip applicable in the tilting AFM, it has the capability to measure patterns of high density, however, the uncertainty in data fusion will impact the measurement accuracy. The complementary application of two measurement modes thus offers an optimized solution for reference 3D nanometrology.

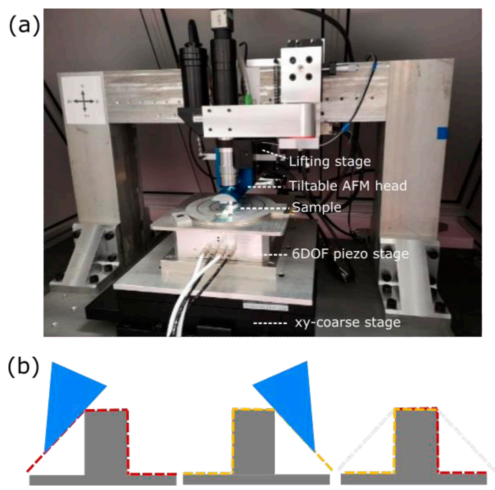

Figure 1. (a) Photo of the recently developed low noise 3D-AFM at the PTB; (b) schematic diagram showing the principle of the tilting AFM for true 3D metrology of complex nanostructures.

DOI 10.5162/SMSI2023/D6.3

The *second* progress concerns the accurate calibration of the tip form. A fundamental concern in AFM measurements is the influence of the AFM tip geometry on the measurement results. The tip-sample interaction represents the most critical challenge of AFM measurements. From the morphological point of view, the profile measured by an AFM is the dilated result of the real structure by the so-called effective tip geometry. At PTB, a new method for accurately characterizing the tip geometry has been developed. A sample type IVPS100-PTB whose line features have vertical sidewalls, round corners with a radius of approx. 5~6 nm and very low surface roughness has been applied as the tip characterizer. The geometry of the line features has been accurately and traceably calibrated to the lattice constant of crystal silicon. Detailed measurement strategies and data evaluation algorithms have been developed, particularly concerning several important influence factors such as the line width roughness of the tip characterizer, measurement noise, measurement point density, and the calculation of the averaged tip geometry. Thorough experimental studies have been carried out, indicating sub-nm measurement accuracy of the developed method. An example is shown in figure 2.

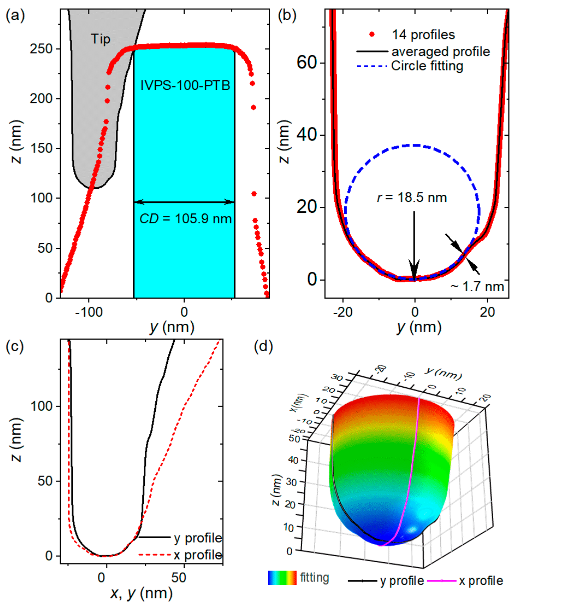

Figure 2. (a) a measured AFM profile (in red) together with the geometry of reference line feature of IVPS100-PTB standard. (b) 14 reconstructed tip profiles along the y-axis (red) and the averaged profile (black) of the tip. The blue dashed line denotes the fitting circle of the tip apex; (c) the averaged tip profiles along the x (red) and y (black) direction, respectively; (d) 3d fitting geometry of the tip according to reconstructed profiles.

The *third* progress concerns the development of a novel true 3D AFM probe, referred to as a 3D-Nanoprobe. Such a probe is realized by introducing flexure hinge structures to the cantilever of a conventional CD-AFM probe. It has quasi-isotropic stiffness in three directions and is thus more powerful for detecting 3D tip-sample interaction forces in AFM measurements. In addition, the stiffness of the 3D-Nanoprobe is balanced to the bending stiffness of slender CD-AFM tips, offering improved 3D sensitivity. In our study, a design example of a 3D-Nanoprobe based on a CD-AFM probe with a nominal tip diameter of 70 nm will be presented. The design parameters are optimized via theoretical modelling and finite element analysis (FEA) method. The simulation results indicate that the designed 3D-Nanoprobe has much better performance than that of the original CD-AFM probe, for instance, its stiffness' anisotropy ratio (including the tip contribution) has been improved from 7:7:1 (x, y, z) to 0.7:0.8:1 (x, y, z). The probing sensitivity is improved by a factor of more than 84, 128 and 1.5 in x-, y- and z-direction, respectively. In addition, the designed 3D-Nanoprobe has the first bending mode eigenfrequency of 46 kHz and the first torsional mode eigenfrequency of 177,6 kHz. The 3D-Nanoprobe has been manufactured by applying a focused ion beam (FIB) tool. Finally, to detect the full 3D interaction forces by the 3D-Nanoprobe, a new AFM-head prototype which consists of a dual optical lever and two differentially working interferometers has been developed.

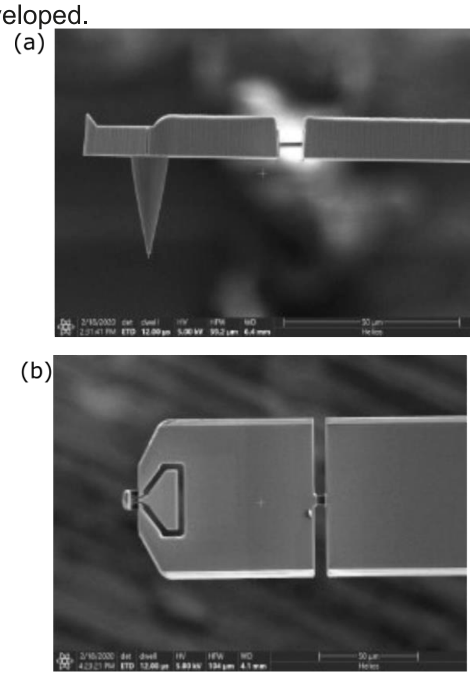

Figure 3. SEM image of developed 3D-Nanoprobe, shown as (a) a side view and (b) a top-down view.