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RECENT PROGRESS AND CHALLENGES IN AFM-BASED TRUE-3D MICRO AND NANOMETROLOGY

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ABSTRACT

In this paper, challenges of true-3D nanometrology are discussed on four fundamental aspects: probing sensor, measurement strategy, tip geometry and structure/tip deformation. Our research progress addressing these challenges is introduced.

Index Terms - Nanometrology, Atomic force microscopy (AFM), critical dimension (CD), tip characterization, 3D-Nanoprobe

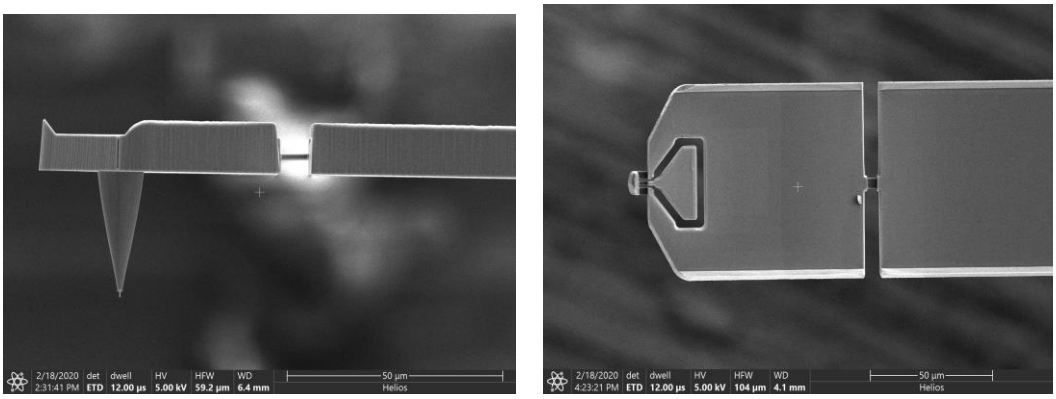
1. INTRODUCTION

True-3D metrology of complex micro- and nanostructures becomes increasingly important for advanced manufacturing, for instance, the developments of next generation integrated circuits (IC) with gate-all-around field-effect transistors (GAAFET) and/or 3D stacked (3D-SIC) architectures. However, most of the measurement techniques available today are not true-3D, despite their results often rendered as a 3D data map. In this paper, we discuss the challenges of true-3D metrology on four fundamental aspects: probing sensor, measurement strategy, tip geometry and structure/tip deformation, and introduce our research progress addressing these challenges.

2. 3D-NANOPROBE

Almost all AFM probes available today are in a cantilever form, where measurements are performed based on the bending and/or torsional deformations of the cantilever introduced by tip-sample interaction forces. Eventually there are two key facts which limit an AFM probe to become a true-3D probe. The first fact relates to the strong anisotropic stiffness of the AFM cantilever along three spatial directions. An AFM cantilever has much lower (>20 times typically) stiffness along the z-axis than that along the other two directions. Consequently, it shows a dominant probing sensitivity along the z-axis (i.e. 1D sensor). The second fact is that the AFM sensing techniques available today (such as the optical lever, interferometer or piezoresistive sensors) are a kind of 1D or 2D sensor only. They are thus incapable of sensing tip-sample interaction force in 3D.

To overcome the problem mentioned above, PTB has developed a novel and patented true-3D AFM probe, referred to as a 3D-Nanoprobe [1,2]. Such a probe can be realized by introducing flexure hinge structures to the cantilever of a conventional CD-AFM probe, as shown in figure 1. 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 tip diameter of nominal 70 nm is 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 an optical lever and a differential interferometer has been developed.



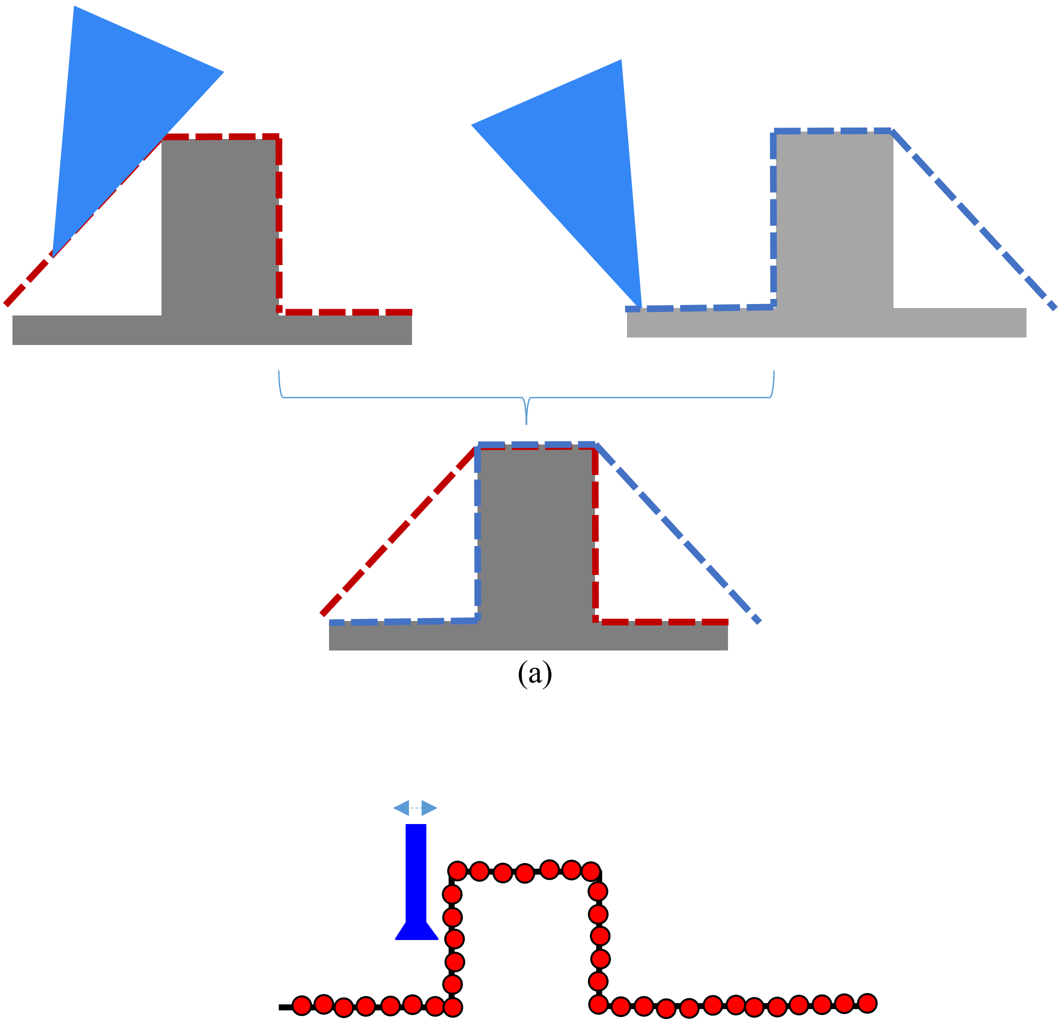
(a) (b)

Figure 1. SEM images of a developed true-3D probe shown as a side view (a) and a top-down view (b).

3. MEASUREMENT STRATEGY

Conventional AFM typically uses a pyramidal or conical shaped AFM tip for measurements. Vertical sidewalls of complex nanostructures are not measurable using such devices because the tip apex cannot get proximate to the sidewalls, despite how sharp the tip apex is.

To overcome this problem, PTB has applied two new measurement strategies. One is referred to as critical dimension AFM (CD-AFM), where a kind of flared AFM tip is applied instead of the pyramidal or conical shaped AFM tip. Such flared AFM tip has an extrusion at the end of the AFM tip, enabling the probing of vertical sidewalls, as shown in figure 2(a). The other is referred to as tilting AFM. The AFM head can be titled respect to the structure with a certain tilting angle in a tilting AFM. In such a way, (one) vertical or even undercut sidewall becomes measurable, as shown in figure 2(b). To realize true-3D measurements of nanostructures, however, the AFM images measured at different angles have to be stitched together. The stitching error thus becomes a critical issue.


(a)

(b)

Figure 2. Schematic illustration of (a) a tilting AFM and (b) a CD-AFM measuring using the vector approach probing (VAP) strategy.

AFM measurements are typically realized by scanning a tip/sample with a quasi-constant speed along lateral axes while keeping the tip-sample distance constant using a servo controller along the z axis. This measurement strategy is, however, no more appropriate for true-3D measurements. To overcome this problem, PTB has developed a new measurement strategy referred to as the vector approach probing (VAP) strategy [3], where the tip probes the structure surfaces along their normal direction point-by-point. The VAP strategy offers advantages such as higher 3D probing sensitivity, more measurement flexibility and lower tip wear.

The PTB has recently developed a new low-noise 3D-AFM which has both CD-AFM and tilting AFM (tilting range: -22°~22°) measurement modes. It is realized with both a conventional scan strategy with a z-servo controller, and a VAP measurement strategy. A photo of the low noise 3D-AFM is shown in figure 3.

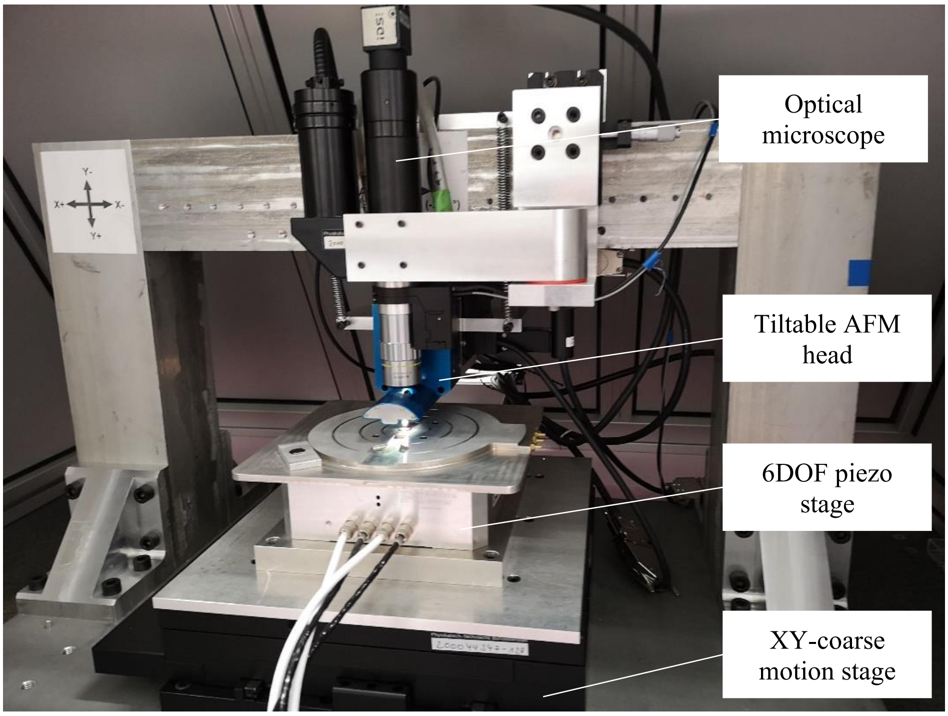


Figure 3. Photo of the newly developed low-noise 3D-AFM at the PTB which has both a CD-AFM and a tilting AFM measurement mode (tilting angle range: -22°~22°).

4. AFM TIP GEOMTRY

From the morphological point of view, the measured image by an AFM tip is the dilated result of the measured structures by the geometry of its tip. Consequently, the tip geometry is usually (one of) the most important error sources in true-3D metrology.

To overcome this problem, PTB has developed a new method for characterizing and correcting AFM tip geometry based on a bottom-up traceability approach. The method is realized based on a standard type IVPS100-PTB, jointly developed by PTB and the company Team-Nanotec. The standard consists of five line features having vertical sidewalls, round corners with a radius of approx. 5~6 nm and very low surface roughness, which can be applied as the tip characterizer. The geometry of the line features has been accurately and traceably calibrated to the lattice constant of crystal silicon. Together with a set of well-developed data evaluation algorithms and software, the AFM tip geometry can be calibrated with a measurement repeatability down to approx. 0.3 nm and an uncertainty down to approx. 1 nm. For more details of this part of research, please refer to [4].

Our recent research has further applied the accurate and traceable results of AFM tip geometry to the geometry of profilometric styli [5] and microspheres used as probing elements of micro coordinate measuring machines (micro-CMM) [6] for enhancing their 3D metrology accuracy as well.

5. STRUCTURE/TIP DEFORMATION

AFM measurements are based on tip-sample interaction forces, which will inevitably result in structure/tip deformation and thus impact measurement results. Our recent investigation indicates that such deformation could be a significant error source, particularly, in measurements of small structures. As an example, figure 4 shows a simulated finite element analysis (FEA) result, indicating the deformation of the thinnest line of the IVPS100-PTB standard (width of 25.8 nm) under a probing force of 1 nN. It can be seen the deformation may reach approximately 1 nm, becoming a significant error source for CD metrology.

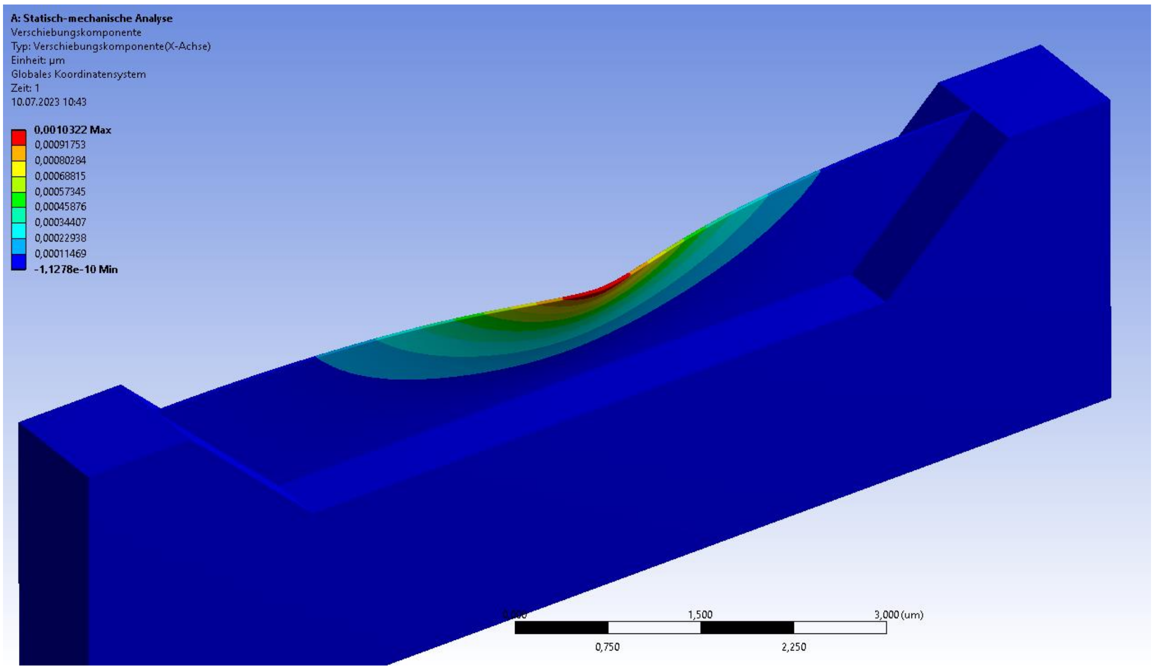


Figure 4. FEA analysis result showing the deformation of 25.8 nm line of the IVPS100-PTB under a probing force of 1 nN.

6. CONCLUSION AND OUTLOOK

True 3D nanometrology becomes increasingly important due to the application of more and more complex nanostructures in industry. This paper has given a brief overview on several challenging aspects in realizing reference 3D nanometrology: probing sensor, measurement strategy, tip geometry and structure/tip deformation. Our research progress addressing these challenges is introduced.

As an outlook, many research tasks are still to be carried out to achieve our ambitious goal, including:

(i) development of algorithm and software for stitching AFM images in the tilting AFM measurement mode;
(ii) comparison of metrology performance between different techniques developed, i.e. between the 3D-AFM and the tilting AFM modes, and between conventional AFM probes and 3D-Nanoprobes;
(iii) further development of the methodology for characterizing and correcting AFM tip geometry with a traceability route to the lattice constant of crystal silicon;
(iv) Further development of the bottom-up approach for the calibration of microscale geometries, such as microsphere probes of µ-CMMs and tip geometry of stylus profilometers, including the establishment of uncertainty budget;
(v) Further experimental and theoretical investigation of the structure/tip deformation issue.

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