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A bottom-up approach for traceable nano dimensional metrology

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Abstract
This paper presents a bottom-up approach which uses the transmission electron microscopy (TEM) and the reference value of the crystal silicon lattice constant as a pathway for traceability to the SI metre for applications in dimensional nanometrology. Compared to the traditional traceability approach based on optical interferometry, this bottom-up approach offers several important advantages: the atom spacing is much shorter than the optical wavelength, offering higher measurement resolution; it avoids a significant error source – the inherent nonlinearity error of optical interferometry; and more importantly its measurement results suffer much less from the probe-sample interaction for feature width metrology thanks to the true atomic resolution power of TEM. The bottom-up approach has been realised for the feature width metrology of nanostructures both at PTB and NIST. More recently, a comparison on a crystal silicon line width standard, referred to as the IVPS100-PTB, has been performed between two institutes. Excellent agreement has been achieved, which confirms the feasibility of applying the proposed bottom-up approach for traceable dimensional nanometrology.

Key words: dimensional nanometrology, traceability, crystal silicon lattice, feature width, transmission electron microscopy (TEM), atomic force microscopy (AFM), scanning electron microscopy (SEM)

1. Introduction

Traceability is identified as a fundamental task of nanometrology. The metrological traceability is defined in the International Vocabulary of Metrology (VIM) as "property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty" [1]. The lack of traceability in measurements inhibits the matching of the results of different tools and limits knowledge about the real size of fabricated features.

The traditional traceability approach for dimensional nanometrology is based on the optical interferometry which is usually built-in in metrological tools for instance metrological AFMs. AFM images of nanostructure measured in such tools are derived from the displacement of their scanner, which is precisely measured by nanometric laser interferometers. Thus the measurement results can be ultimately related to the wavelength of the laser source calibrated to the metre, the unit of length in the SI (International System of Units), by using either an optical frequency comb or an iodine frequency stabilised laser. However, the traditional traceability approach is not sufficient to satisfy the uncertainty requirements for calibration of probe/tip geometry, which is a crucial task in feature width metrology.

In this paper, we present a bottom-up traceability approach which uses the atom spacing as an internal ruler. It offers a complementary pathway for realising traceability in dimensional nanometrology.

2. The bottom-up traceability approach

A basic principle of the bottom-up traceability approach is illustrated in figure 1. Using state-of-the-art high magnification TEMs, it is possible to resolve the spatial periodicity of a crystal lattice. If a crystalline silicon structure is imaged in this manner it is possible to use the silicon lattice as an internal ruler for determining the magnification of the TEM images. Consequently, a traceable width measurement of the feature cross section is possible. In the simplified schematic shown in Fig. 1, for example, the feature width would be calculated as the number (N) of crystal lattice planes within the feature's cross section multiplied with the silicon crystal constant a_{111}. This constant has been traceably measured as 313.560 11(17) pm for bulk silicon through a combination of x-ray and optical interferometry.

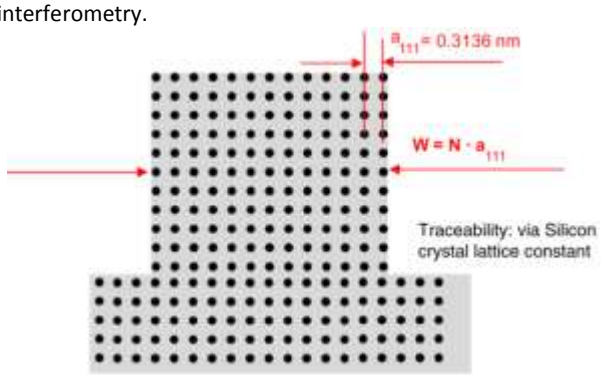

Figure 1. Calibration of the master CD standards were ultimately traceable to the SI metre through a constant of nature: the lattice parameter of silicon.

The application of this principle to actual measurements, however, presents several practical challenges. Some of these are: (1) TEM image interpretation and edge definition, (2) stability and detection of amorphous oxide layer, (3) transfer measurements to intact samples which is required by the destructive nature of the TEM cross-section process.

There are two advanced TEM methods that can be used for this type of lattice-resolving measurement: high-resolution TEM (HRTEM) and scanning transmission electron microscopy (STEM). Both methods are capable of generating atomic-scale images that resolve the lattice periodicity. Nevertheless, there are effects due to both instruments and the sample preparation that can result in reduced fringe contrast near the boundaries, resulting in ambiguity in the edge location.[2]

Additionally, when TEM is used to calibrate the width of silicon structures that are used with CD-AFM, the thickness of the native oxide layer must be accounted for because CD-AFM operates in the ambient environment where an oxide will always be present on silicon structures. This presents challenges both with respect to the visibility of the oxide layer in the images, as well as the possibility that the oxide layer could be altered during preparation of the lamella for TEM.

Furthermore, since the oxide layer is amorphous, there is a fundamental question about the definition of the oxide boundary in the TEM images. Our general conclusion was that the most physically suitable definition of the edge location for STEM images is the half intensity location. This definition corresponds with the location where the material occupation is approximately 1:1 and is analogous to the edge definition used for optical microscopy in the limit of low numerical aperture and incoherent illumination.

Another practical challenge to implementing this method for width calibration is that it is inherently destructive, since the target feature must be cross-sectioned for TEM measurement. In order to utilize the TEM results for subsequent CD-AFM calibration, it is necessary to implement some type of comparator measurements between samples prior to the TEM cross-section. Both NIST and PTB used a very similar approach to this problem, and the general strategy is illustrated in Fig. 2. Conceptually, there are three major components to this strategy. The first is to use CD-AFM as a comparator to measure the CD difference (δCD) of two groups of specimens (i.e. the master CD structures S_{ref} for subsequent transfer of calibration, and the target structures S_{TEM} for the destructive TEM measurements). In order to minimize any variation of measurement bias due in the response of the CD-AFM to the different targets, these two groups of specimens should be as similar as possible, and the CD-AFM measurements should be performed under the same measurement conditions (i.e., using the same tip and instrument parameters). Ideally, this would mean that the impact of the effective tip geometry on the apparent widths of all features would be the same, and thus the observed CD differences are nearly tip independent.

The second component is the actual cross-sectioning and measurement of the TEM target structures (S_{TEM}) using a lattice resolving TEM technique. Using the approach described above, traceable width values of the TEM features (CD_{s_TEM}) are determined based on the lattice parameter of silicon. The third component is using the observed values of δCD and the CD_{s_TEM} to determine the CD of the master standards. Through this procedure, it is possible to determine width values of intact standards that are traceable through the silicon lattice constant.

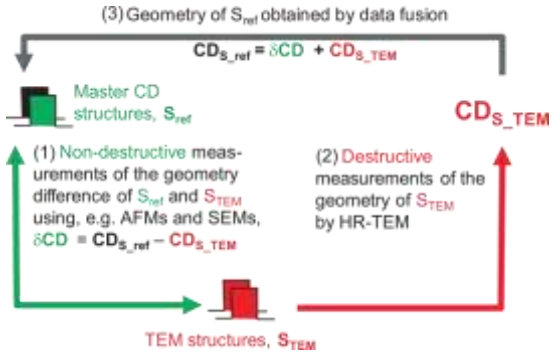

Figure 2. Conceptual strategy for realising non-destructive calibration of the master CD standard using TEM

3. PTB-NIST bilateral comparison on line width metrology

Recently, a comparison of the line width calibration of a crystalline silicon line width standard, referred to as IVPS100-PTB standard, had been carried out between PTB and NIST [3]. CD-AFM was the measurement method used for this comparison. Both institutes applied generally the same but independently developed traceability pathways: The scaling factor of the atomic force microscope (AFM) scanner was calibrated by a set of step height and lateral standards calibrated by metrological AFMs, while the effective tip width was calibrated using the bottom-up approach presented in this paper. The comparison result is illustrated in figure 3. Good agreement has been achieved in the comparison: For two groups of line features with nominal critical dimensions (CDs) of 50 nm, 70 nm, 90 nm, 110 nm and 130 nm that were compared, the observed deviations of CD results were between -1.5 nm and 0.3 nm. All En values of the comparison are well below 1, indicating that the deviations are well within the associated measurement uncertainty. This result confirms the feasibility of applying the proposed bottom-up approach for traceable dimensional nanometrology.

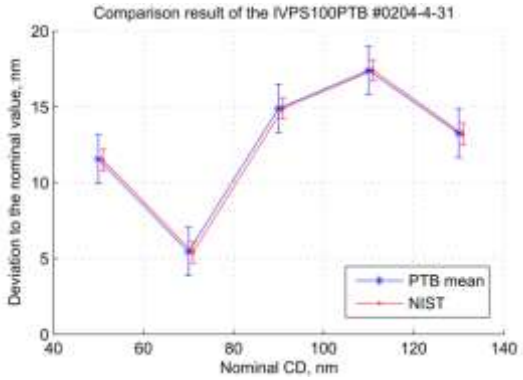

Figure 3. Comparison of the measured middle CD values of five line features of a IVPS 100PTB standard (S/N: 0204-4-31) with nominal feature width of 50 nm, 70 nm, 90 nm, 110 nm and 130 nm, respectively, between PTB and NIST. The error bar shown is the estimated expanded uncertainty at the 95% confidence level.

4. Conclusion

The presented bottom-up traceability approach is an important complementary pathway for the traditional optical interferometry approach. The bottom-up approach uses the atom spacing as a ruler which is much shorter than the optical wavelength, therefore, it is capable of much higher measurement resolution and accuracy. In addition, thanks to the true atomic resolution power, the measurement results suffer much less from probe-sample interaction than that of other measurement tools (for instance AFM, SEM and optical scatterometry). Using the proposed traceability approach, the line width measurement uncertainty may reach U = 0.7 nm (k=2). It is much smaller than the measurement uncertainty achievable using the traditional optical interferometry traceability approach, which is typically (much) worse than 5 nm due to the limited accuracy in tip characterisation.

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