Accurate and traceable calibration of critical dimensions based on CD-AFM and TEM

G. Dai, K. Hahm, J Fluegge, H Bosse
Physikalisch-Technische Bundesanstalt (PTB), Bundesallee 100, 38116 Braunschweig, Germany
mailto:Gaoliang.Dai@ptb.de

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Abstract

A highly accurate and traceable critical dimension (CD) reference metrology with a preliminary estimated standard uncertainty *u* of 0.81 nm has been recently developed at the PTB. The new reference method combines two technologies: transmission electron microscopy (TEM) and atomic force microscopy (AFM). State-of-the-art aberration corrected TEM technique offers smallest uncertainties in measuring the CD of crystalline nanostructures, where the atomic spacing of the crystal lattice in the feature can be used as an internal ruler. CD-AFM has been applied to measure the CD difference of a reference and the TEM target structure before the TEM investigation. In such a way, the TEM results can be disseminated to the reference structure, as the sample preparation for TEM measurements is destructive. The estimated measurement uncertainty has been confirmed by five investigations of the CD of a reference structure which were carried out independently of each other by using different TEMs.

1. Introduction

Progressive miniaturization of the manufacturing processes, in particular in the semiconductor industry down to structure sizes of about 22 nm and below using cutting-edge EUV (extreme ultraviolet) lithography, puts increasing challenges for metrology of Critical Dimension (CD) and feature shapes both on silicon wafers and photomasks with more stringent measurement accuracy (< 1nm).

To meet these challenges, the PTB – the national metrology institute of Germany – has recently developed a highly accurate and traceable CD reference metrology method by combining CD-AFM (critical dimension atomic force microscope) and TEM measurements. State-of-the-art aberration corrected TEM is capable of measuring structures with atomic resolution, thus offering the capability in calibrating the width of a feature made of single-crystalline material by using the atomic lattice spacing as an internal ruler, especially in the case of Silicon material. As the preparation for the TEM measurement is destructive, a strategy consisting of three steps by complementarily use of CD-AFM and TEM is applied to disseminate its results. In the first step, two groups of specimens are selected, one as the reference structures and the other as the TEM target structures. Both groups of specimens are measured by a CD-AFM using the same flared AFM tip under the same measurement conditions. The CD differences between the reference and TEM target structures are registered. In the second step, the TEM target structures are prepared by FIB (Focused Ion Beam) and measured by TEM to determine their CD values. In the third step, the determined TEM results are transferred to the previously measured CD-AFM results, and in such a way, the “effective” tip geometry of the CD-AFM measurements can be evaluated to determine the CD of the reference structures.
The combined standard measurement uncertainty of the reference CD values obtained using the above mentioned strategy is preliminary estimated as 0.81 nm. Five independent investigations were carried out to determine the CD of a selected reference structure. The obtained CD values agree well within the estimated uncertainty level.

2. Traceable measurements of the CD using TEM

Two methods have been applied for achieving highly accurate and traceable measurements of the CD, as shown in figure 1. The first method applies the silicon crystal lattice as an internal ruler. As shown in figure 1(a), the structure geometry can be calculated by counting the number of the crystal planes inside the structure, N, and the silicon crystal constant d_{111}, which was determined traceably as 313.560 11(17) pm by combined x-ray and optical interferometry from bulk silicon material [1]. This method is highly accurate, however, it demands that the sample material is a single crystal. To solve this problem, an alternative method has been developed, as shown in figure 1(b). Using this method, the pitch L of line features was accurately and traceably calibrated in advance, for instance, by a metrological AFM [2]. After the line features were imaged in a TEM, the pitch (M) and width (N) of the feature pair could be determined in pixel units. Thus, the scaling factor of the TEM image could be calculated as $K = L/\mathrm{M}$ nm/pixel and the width of the structure could be evaluated as $W = \mathrm{N}\times L/\mathrm{M}$. An important idea underlying the proposed method is that unlike the CD metrology the pitch calibration using AFMs is independent of its tip geometry. Two methods are compared with each other showing an excellent agreement better than 0.3 nm for the measurements of structures with a nominal CD of 100 nm.

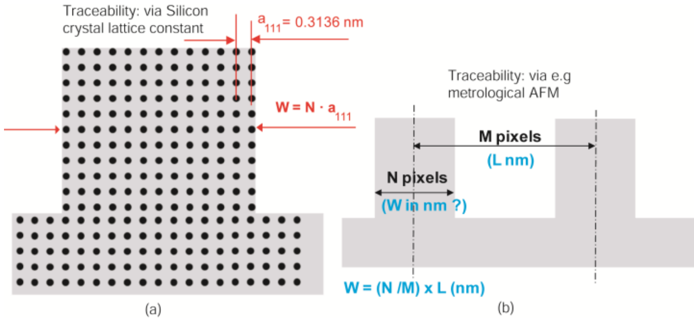

Fig.1 Two strategies applied in traceable calibration of the geometry of the reference nano structure based on its transmission microscopic images, (a) via silicon crystal lattice constant and (b) via metrological AFM.

3. CD measurements using the AFM technique

CD-AFM applies flared tips, which have an extended geometry near its free end. It is capable of probing steep and even undercut sidewalls. Compared to the tilting AFM, the CD-AFM technique has advantages of measuring both the left and right sidewalls of nanostructures in only one measurement. A new CD-AFM has been recently developed at the PTB [3]. To demonstrate its measurement capability, the profiles measured on a line structure of an IVPS Si sample using a CDR70-EBD tip with a nominal radius of 70 nm is shown in figure 2. Profiles of 4 repeated measurements are shown as raw data without data averaging or filtering. Part of the profile at the left sidewall, top region and right sidewall are zoomed in and shown in the insets. It can be clearly seen that the measured profiles repeat very well, and most of the data points agree with each other (much) better than 1 nm.

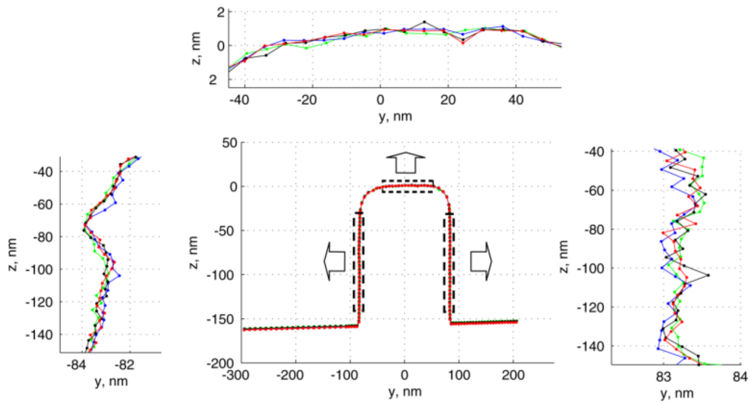

Fig.2 Measurement repeatability of the CD-AFM using a CDR-EBD tip with a nominal tip width of 70 nm.

4. Measurement uncertainty

The measurement uncertainty budget of the developed reference CD metrology method has been set up. Three important aspects, the uncertainty of the CD measurements using TEM, the uncertainty of the CD-bias measurement using AFM, and the uncertainty in matching the TEM and AFM results -- have been studied in detail. The preliminary standard uncertainty u is estimated as 0.81 nm (k=1), which has been confirmed by five investigations of the CD of a reference structure which were carried out independently of each other on different TEMs, as shown in figure 3.

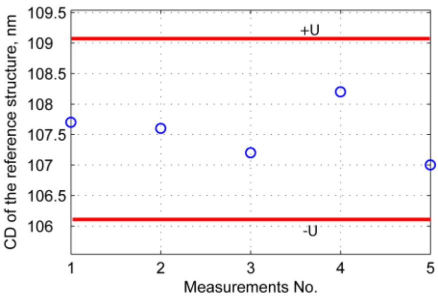

Fig.3 Measured CD values of the reference structure from five independent investigations. The values agree well with each other within the estimated uncertainty level metrological AFM.

References:

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