FABRICATION AND CHARACTERIZATION OF STANDARDS FOR ATOMIC FORCE MICROSCOPE TIP WIDTH CALIBRATION

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INTRODUCTION

The National Institute of Standards and Technology (NIST) has been developing methods and standards for traceable critical dimension atomic force microscopy (CD AFM). The CD-AFM technique involves flared tips and two-dimensional surface sensing to enable scanning of features with near-vertical sidewalls. [1]

A major source of uncertainty in metrology with CD-AFM is the calibration uncertainty of the tip width. With a new generation of the NIST single crystal critical dimension reference material (SCCDRM) project, we are targeting expanded uncertainties in linewidth (k = 2) below 1 nm.

TIP WIDTH CALIBRATION AND THE SCCDRM PROJECT

The interaction of a CD-AFM tip with the imaged surface is very complex.[2-4] However, for many purposes a simplified, two-dimensional model is useful. In this basic view, the effect of the tip is represented as a simple offset, which must be subtracted from the apparent feature width to obtain an accurate measurement. This offset is referred to as the tip width correction, and there is an uncertainty component that represents the uncertainty in the value of this correction. As a result of the NIST SCCDRM project, which is discussed in the next section, it is possible to calibrate the tip width with a combined expanded uncertainty (k = 2) of less than 2 nm. [2,4] Beyond this correction are the shape-dependent details of the interaction, which are highly specific to each measurement.

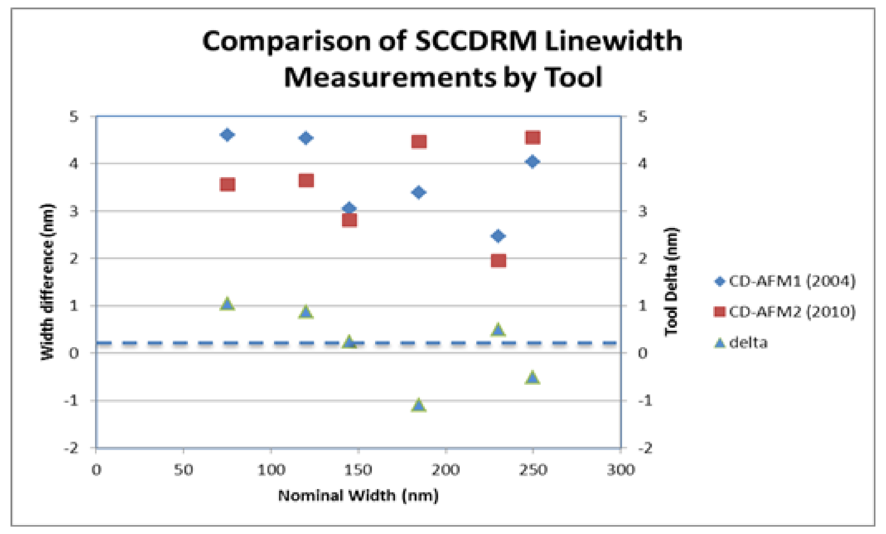

FIGURE 1. Measured line widths of six SCCDRM linewidth features with two generations of CD-AFM.

Figure 1 shows a comparison of linewidth measurements obtained with both our current and prior generation CD-AFM instruments. In both cases, the CD-AFM essentially functions as a width comparator between the target sample and the master/monitor sample – through which the traceability is established.

The average difference between measurements of the same features as measured six years apart by two generations of CD-AFM is 0.18 nm. The agreement represented by this average difference is very good, but there were approximately 1 nm deltas for half of the individual features. These were larger than expected, and are not attributable to trivial error sources such as a simple bias in the tip calibration. Our hypothesis is that these differences are due to secondary tip effects (e.g. shape and dither-related contributions). Reducing tip calibration uncertainties below the 1 nm level will require more investigation of such observations.

THE SCCDRM PROJECT

The SCCDRM features have near-vertical sidewalls. This is accomplished using preferential etching on {110} silicon-on-insulator (SOI) substrates.[4] As such, these structures are particularly useful for CD-AFM tip width calibration. The most recent generation has structures with linewidths ranging from 50 nm to 240 nm–and expanded uncertainties (*k* = 2) of 1.5 nm to 2 nm.

The new SCCDRMs are fabricated using electron beam lithography and a technique for auto-aligning nanostructures to slow-etching crystallographic planes in materials with a diamond cubic structure. A detailed discussion of the fabrication method and AFM evaluation has been published.[5] The method is schematically illustrated in Figure 2. Essentially, the use of offset notches in the drawn feature results in a final etched width that is not affected by small rotational misalignments between the crystal planes and the drawn feature.

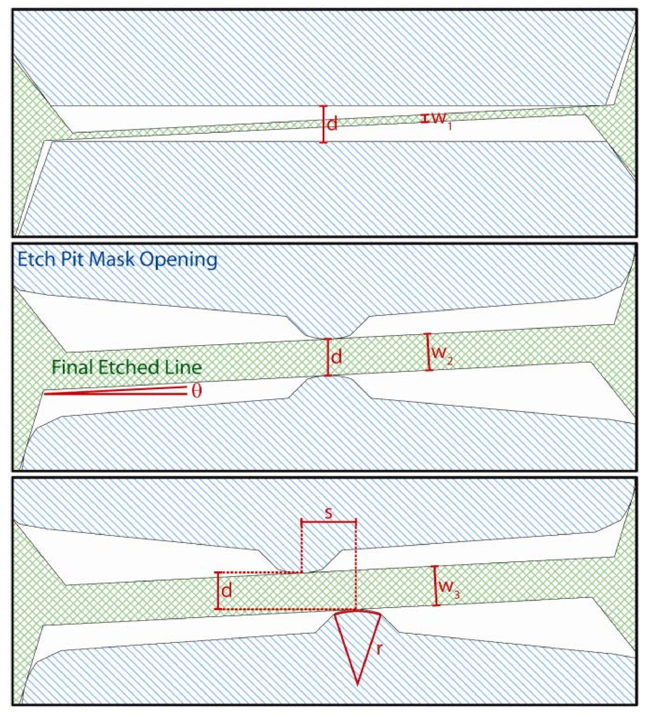

FIGURE 2. Schematic explanation of the auto-alignment method for SCCDRM fabrication. (d represents the drawn width, and $w_1 - w_3$ represent the final etched widths for different configurations of the as-drawn pattern relative to the crystal planes.)

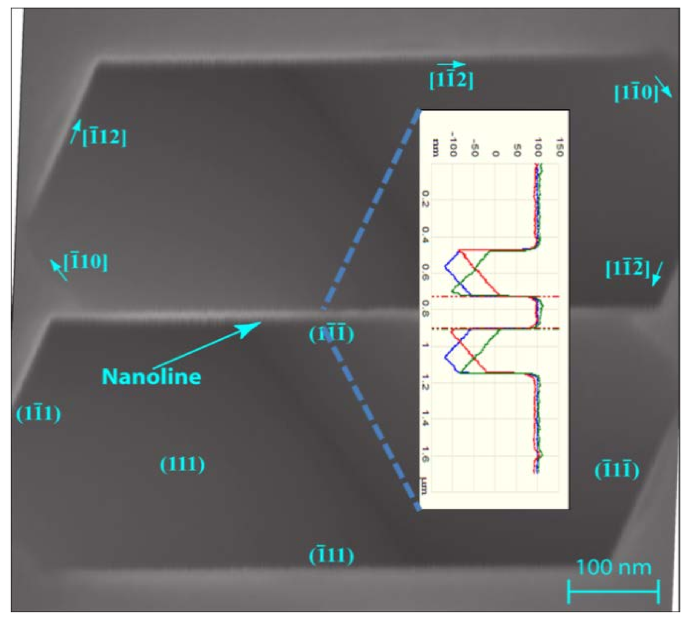

FIGURE 3. Top-down SEM image of a new SCCDRM feature with representative CD-AFM profiles inset.

In Figure 3 we show a scanning electron microscope (SEM) image of an etched SCCDRM feature with representative CD-AFM profiles in the inset. Note that the CD-AFM profiles are from a different feature and have not been corrected for the tip width.

During a recent fabrication run, we demonstrated line widths as small as 10 nm. Since the uncertainty of a width measurement is significantly affected by the sample non-uniformity, our priority in screening the SCCDRM features is non-uniformity rather than absolute width.

Figure 4 summarizes AFM line width observations on 29 separate SCCDRM features – indicating both small linewidths and local non-uniformity below 1 nm – as expressed by the standard deviation of width results from 256 linescans taken along the sampled length of each measured feature. A few outliers are present, but the observed non-uniformity is largely independent of feature width.

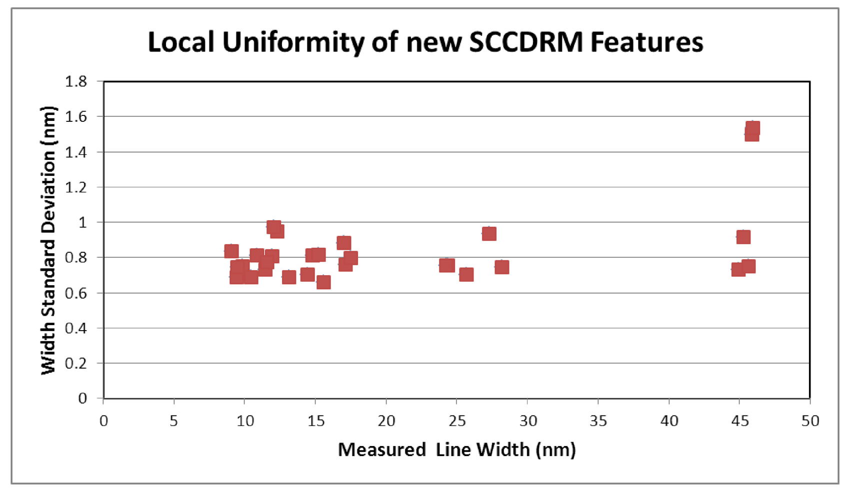

FIGURE 4. CD-AFM results on recent prototype SCCDRMs – showing both very small linewidths and sub-nanometer local non-uniformity.

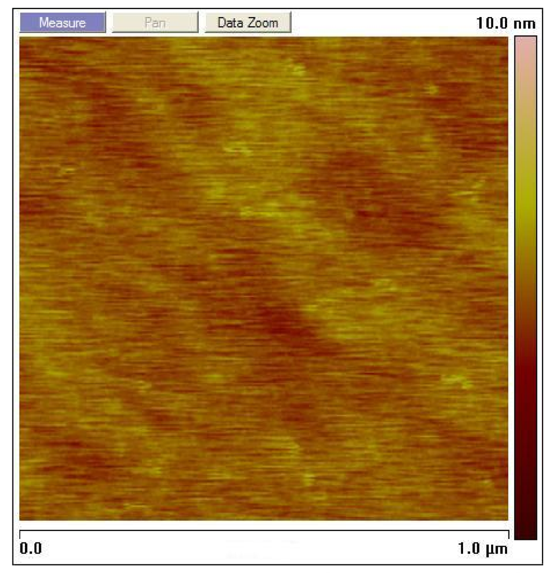

FIGURE 5. Tapping mode AFM image of an etched Si (111) surface. At 0.38 nm, the roughness average Ra is approximately twice the instrument noise floor.

For feature widths of 10 nm or larger, the new SCCDRM fabrication process works very well and we expect that conventional models of the AFM measurement process, with respect to the tip-sample interaction and behavior, are still valid. However, below the 10 nm level, some conventional assumptions, such as rigidity of the structure during imaging, may have to be refined.

The first stage of validating the structural integrity and quality of an approximately 10 nm wide feature was performed using high resolution transmission electron microscopy (HRTEM). Details of this work have been published. [2] In this initial evaluation, the feature remained intact during sample preparation, and the observed AFM and TEM linewidths agreed to within 1 nm – less than the combined uncertainty.

In performing such comparisons, a significant complication arises from the line width roughness (LWR) of the features due to uncertainties in the relative positioning of the AFM and TEM measurements. We have thus focused considerable effort on improving the etch process to reduce LWR. Since the sidewalls of the SCCDRM structures are Si (111) planes, we are performing an experiment to determine the dependence on etching parameters of the surface roughness in the bottom of etch pits on Si (111).

A recent example is shown in Figure 5. The roughness average Ra in this image is approximately 0.38 nm - about twice the instrument noise floor. This surface is very smooth – and better than most of the sidewalls we have previously etched. We expect to refine the process until the 0.3 nm atomic monolayer steps are clearly observable in our images. Surfaces of such quality have been observed after similar etching techniques. [6]

The goal of the SCCDRM effort is to develop a new NIST Standard Reference Material (SRM) for CD-AFM tip calibration. The new SCCDRM features must have width uniformity surpassing the previous generation, and the fabrication process must be consistent enough to yield samples in sufficient quantities for SRM production. These challenges are not trivial, but the current results suggest that our goals are realistic.

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