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- Ndubuisi G. Orji: Performed the measurements, simulation and wrote the initial manuscript.
- Hiroshi Itoh: Designed and fabricated the comb characterizer, developed the procedure for comb based characterizer analysis, and prepared some of the images.
- Chumei Wang: Worked on the design and fabrication of the comb characterizer, and prepared some of the images
- Peter S. Walecki: Implemented some of the MATLAB code used in the analyses.
- Ronald G. Dixon: Provided CD-AFM data interpretation, tip simulation information, and revised the initial manuscript.
- Sebastian W. Schmidt and Bernd Irmer: Developed and manufactured all the tips used in the experiment.

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Tip Characterization Method using Multi-feature Characterizer for CD-AFM

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Abstract

In atomic force microscopy (AFM) metrology, the tip is a key source of uncertainty. Images taken with an AFM show a change in feature width and shape that depends on tip geometry. This geometric dilation is more pronounced when measuring features with high aspect ratios, and makes it difficult to obtain absolute dimensions. In order to accurately measure nanoscale features using an AFM, the tip dimensions should be known with a high degree of precision. We evaluate a new AFM tip characterizer, and apply it to critical dimension AFM (CD-AFM) tips used for high aspect ratio features. The characterizer is made up of comb-shaped lines and spaces, and includes a series of gratings that could be used as an integrated nanoscale length reference. We also demonstrate a simulation method that could be used to specify what range of tip sizes and shapes the characterizer can measure. Our experiments show that for non re-entrant features, the results obtained with this characterizer are consistent to 1 nm with the results obtained by using widely accepted but slower methods that are common practice in CD-AFM metrology. A validation of the integrated length standard using displacement interferometry indicates a uniformity of better than 0.75 %, suggesting that the sample could be used as highly accurate and *SI* traceable lateral scale for the whole evaluation process.

Highlights

- We describe a multi-feature AFM tip size and shape characterizer and method, and apply it to critical dimension AFM tips.
- We report feature size results that are within 0.5 nm compared with existing methods, and require fewer measurement steps.
- A comparison of a length standard built into the multi-feature characterizer shows a uniformity of less than 0.75 %, indicating that the characterizer could be used as nanoscale *SI* traceable length artifacts.
- We implement a simulation using morphological operators that helps determine and specify what range of tips sizes and shapes the characterizer can measure.

Key Words: critical dimension atomic force microscope; tip characterizer; tip dilation

1. Introduction

In atomic force microscopy (AFM) dimensional metrology, the tip is a major source of uncertainty. Images taken with an AFM show an apparent broadening (or geometric dilation) of the feature size due to the finite size of the tip. In critical dimension atomic force microscopy (CD-AFM), this is a bigger problem because of the high aspect ratio (HAR), and sometimes undercut nature of the features being measured. In addition, CD-AFM applications mostly involve nanoscale width measurements, where any tip dilation directly affects the measurand.

This dilation could be corrected if the size and shape of the tip are known. From the earliest days of probe microscopy, the problem of tip induced feature dilation has been recognized as a key limitation to using the instrument for accurate metrology. This geometric dilation is present whether the measurand is surface roughness, nanoparticles, or HAR integrated circuit (IC) features. Figure 1(a) shows a schematic of a tip and a surface, and the resulting dilation from the tip. Figure 1(b) shows the dilation introduced by the tip when measuring a HAR feature using conical and cylindrical tips. Such geometric dilation complicates the process of obtaining accurate dimensions of the features being measured.

Over the years, several techniques have been presented to address this problem. They include the use of physical artifacts that are measured a priori and blind reconstruction techniques among others [1-4]. Methods for reconstructing the shape of re-entrant topologies (such as features encountered in integrated circuit manufacturing) have also been proposed and demonstrated [5-7]. Although some of the techniques use procedures that do not require physical artifacts (tip characterizer), methods used for highly accurate and traceable dimensional measurements do. One such characterizer is a multi-feature sample known as the comb tip characterizer [8-10]. Multi-feature refers to the presence of multiple tip characterizer features on the sample. The comb characterizer and the accompanying procedure have been proposed as an effective and accurate method to determine tip shape and size. We evaluate the use of this characterizer for HAR tips used for CD-AFM. These include both non-flared tips and flared tip used for re-entrant features. The goal is to determine if the comb characterizer could be used to extract key tip parameters that affect measurements of HAR features. We use the extracted tip parameters to evaluate a series of HAR features and compare the results from those obtained through other methods. We also evaluated an integrated grating on the sample that could be used as a traceable scale calibration of nanoscale measurements.

Figure 1: (a) schematic diagram of a tip apex and a surface, and the resulting dilation from the tip. (b) schematic diagram of the dilation introduced by the tip when measuring a high aspect ratio feature using conical and cylindrical tips.

2. Materials and Methods

2.1 CD-AFM and CD-AFM Tips

The CD-AFM [11, 12] is a specialized AFM that can directly access and measure feature sidewalls. The key differences with conventional AFM are the tip shape and scanning algorithm that allows it to dither in the lateral axis in addition to vibration in the vertical axis. During measurement of vertical surfaces, the two dimensional scanning algorithm tracks the sample slope and continuously adjusts the scanning and servo directions so the flared tip is in near-contact with the surface. For top down measurements, the instrument operates like a conventional AFM. Figure 2 shows a schematic diagram of a CD-AFM tip, when it is at the top of the sample and when it is at the sidewall. The flat shape of the tip means that high resolution surface detail cannot be obtained on horizontal surfaces; however, the lateral apex (with a radius of 15 nm or more) produces a profile used to estimate low frequency sidewall roughness, sidewall angle, in addition to lateral dimensions such as width.

Two types of CD-AFM tips were used in the evaluation, a flared tip and one without flare. Both tips were made by electron beam deposition, where a defined precursor is deposited on the very end of a Silicon Nitride AFM tip by means of a directed and focused electron beam [13]. In order to ensure process stability and tip parameter consistency, deposition steps are conducted in an automated scanning electron microscope. The tip parameters are width and effective tip length (both non-flared and flared tips), vertical edge height (VEH) and tip flared overhang (flared tips only). The VEH is the vertical distance from the bottom of the tip and the end of the flare. The tip flare overhang is the protruding lateral end of the tip that is in contact (or near contact) with the sidewall, and the effective tip length is the maximum depth the tip can measure. Although flared tips are generally associated with CD-AFM, they are only needed for re-entrant features. Figures 3(a) and 3(b) show schematic diagrams of the flared and non-flared tips with the parameters respectively. Figure 3(c) shows the profile caused by the size of the tip, and how the offset VEH is determined.

Figure 2: Schematic diagram of the CD-AFM operation. The tip vibrates in the Z direction and dithers in the lateral direction. The tip is able to track both the vertical and lateral surfaces by adjusting the servo direction when a change in slope is detected by the sensor.

Figure 3: Profiles of (a) non flared and (b) flared tips (c) The apparent profile produced by tip dilation.

2.2 Tip Characterizer

The tip characterizer is made up of comb-shaped lines and spaces, knife-edge shaped features, and includes a series of gratings that is used as an integrated nanoscale length reference standard. It is fabricated by magnetron sputtering of multiple alternating layers of Si and SiO₂ on 4-inch (101.6 mm) Si wafer. Two wafers are bonded using a surface activated bonding method [8, 9]. This increases the number of layers available. The bonded wafer is cut perpendicular to the layers, and polished. The SiO₂ layers are selectively etched by dipping HF solution (HF:HCl=1:19). The lattice-plane selectivity of the etchant is greater than 100. Consequently, the edges of the lines are quite sharp and have sidewall angles of $90^\circ \pm 0.5^\circ$ and corner radii of 1.5 nm.

The outcome is a series of comb-shaped lines and spaces with widths that correspond to the thickness of the deposited Si and SiO₂ layers respectively. The linewidths range from 15 nm to 60 nm and the line spaces from 10 nm to 50 nm. The multiple lines and spaces allow the capture of several tip/feature profiles for tip shape and size extraction. Figure 4(a) shows a schematic diagram of the tip characterizer, and figure 4(b) shows an AFM image of the tip characterizer. Figure 4(c) shows a representative TEM image of some of the features. The image in figure 4(c) was taken by an Insight CD-AFM[†]. Scan range is 4 μm by 1 μm , with a z-scale of 90 nm. The width value (including Si and SiO₂ layer) are determined from TEM images such as the one in figure 4(c). The scales of the rulers are obtained from imaging a small portion of the silicon, and using the lattice as transfer. The size of the SiO₂ layer, linearity, and the edge location are sources of uncertainty. We have previously demonstrated TEM width transfer uncertainty as low as 0.6 nm ($k=2$) through the use of multiple transfer features [14].

[†]Certain commercial equipment is identified in this paper to adequately describe the experimental procedure. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology nor does it imply that the equipment identified is necessarily the best available for the purpose.

Figure 4: (a) Schematic diagram of the comb tip characterizer, (b) CD-AFM image of the characterizer. Instrument: Insight CD-AFM, scan size: x:4 μm , y:1 μm ; z-range: 90 nm. Tip: 50 nm cylindrical CD tip (non-flared); average scan speed: 0.477Hz (c) TEM image of some of the features

3. Theory and Calculations

3.1 Tip Characterization Method and Analysis

Samples of the same batch of characterizers are measured with an AFM to determine batch consistency. If the consistency is adequate, one sample is cross-sectioned and imaged with a high resolution transmission electron microscope (HRTEM) to determine the size and shape.

The evaluation procedure works by determining the probe width W and probe length L as shown in figure 5. For example in figure 5 the W_1 is the probe width at probe length L_1 . This information is obtained at different probe lengths for each side of the probe, and at different length locations. The aspect ratio (A) of the tip at different lengths provides a good indication of the overall shape. The resulting plot is the probe characteristic, and provides size and aspect ratio information. The known value of the comb feature is subtracted to get W at each L . This procedure is shown in figure 6, where L_0 is the full length of the feature, W_0 is the feature width, and r_r is the corner radius of the feature. The evaluated portion of the feature excludes the corner radius and 10% of the feature length at the bottom, which could contain non-tip artifacts. When the probe width information is divided into left and right with respect to the vertical axis (as

shown in figure 7), a more detailed shape of the tip is obtained. The difference of the two halves (W_a and W_b) indicate the asymmetry of the tip. This is shown in figure 7. The tip width is given by subtracting the apparent width (W') [$W=W'-W_0$] from the *a priori* determined TEM width.

Figure 5: Definition of probe width (W_1 , W_2) and probe length (L_1 , L_2)

Figure 6: Probe shape characteristic determination using the narrow ridge structure.

(a) Profile of the probe feature. (b) Profile of the probe feature showing the portion attributed to the feature width. (c) Profile of the feature after subtracting W_0 . (d) Truncated profile of the comb feature showing 90% of the profile. The bottom portion of the profile could contain non tip artifacts. (e) Inverted version of the figure 4(d). (f) Probe profile used for analysis.

Figure 7: (a) Profile of a comb feature with width (W) measurements at specified L locations. (b) Probe asymmetry against x-y plane determined from (a).

3.2 CD-AFM Tip Evaluation

We obtained scans of the comb features using both flared and non-flared CD-AFM tips. Each feature in the image is isolated, and the probe characteristic is determined. Figure 8 shows plots of the line features obtained using a non-flared (cylindrical) tip. Figure 8(a) is the average profile, and figures 8(b) to (e) show a close-up view of select features. Probe profiles were extracted from each of the features using the method outline above and shown in figure 6. The extracted probe characteristics are shown in figure 9. Some of the profiles in figure 9 are longer than others and depends on how deep the features are. The information is then assembled and averaged. This allows for a more consistent and stable determination of tip parameters than would be obtained when only one feature is used. These plots are averaged to produce a more consistent plot. Note that averaging values from several lines and spaces works well for parameters such as tip width and VEH. A parameter such as the effective tip length is estimated by measuring the deepest trench the tip was able to measure. A similar analysis was performed for the flared tips.

Figure 8: (a) average profile of the CD-AFM image in figure 4(b) including the effect of tip dilation. The image was produced by a 50 nm cylindrical CD tip (b) to (e) close-up plots of select features. For each feature, a probe

characteristic (shown in figure 9) is developed.

Figure 9: Probe Characteristics of all the features shown in figure 8(a). The length of the profile depends on the depth of the feature.

Figure 10: A schematic diagram of a HAR feature, showing where the top, middle, and bottom CDs are calculated, and the sidewall angle.

After obtaining the tip parameters, a series of width features were measured, and the top, middle and bottom widths were determined. Figure 10 shows a schematic diagram of the locations on the feature used to determine width. The top width is measured at 80 % of feature height, and the bottom width at 20 %. This reduces the influence of top and bottom corner rounding on the results.

3.3 Nanoscale Grating Characterization

To obtain accurate information from the characterizer, the instrument needs to be calibrated and checked for scanner linearity. This ensures that scale errors are not transferred to the image. The comb characterizer has an integrated grating that could be used as a nanoscale length reference standard. In essence, the same profile used for tip characterization also contains length calibration information. The grating validation measurements were performed with the NIST

traceable atomic force microscope (T-AFM). The T-AFM is a metrology AFM with traceability to the *SI* (*Système International d'Unités* or International System of Units) unit of length, the meter. The traceability is achieved through the use of displacement interferometry, with a frequency stabilized 633 nm HeNe laser. A description of this type of metrological AFM is contained in Dixon et al. [15] and Kramar et al. [16]. The power spectral density of the grating portion of the data was calculated using the approximation in equation 1. Figure 11 (a) shows a profile of the comb characterizer, with the gratings highlighted in figure 10 (b). A power spectral density profile of the grating (shown in figure 11 (c)) in frequency domain shows the periodicity of the gratings.

$$S_1(f_j) \approx \frac{\Delta x}{N} \left| \sum_{k=1}^N z_k \exp[(2\pi i)jk/N] \right|^2, j = 1, 2, \dots, N/2 \quad (1)$$

Figure 11: (a) Profile of the comb characterizer. (b) Close-up view of the grating portion of the sample. (c) Power spectral density profile of the grating in frequency domain.

3.4 Geometric Tip and Characterizer Simulation

When considering using a characterizer, it would be helpful to know if a particular characterizer is suitable for the task. To do this we simulated the AFM scanning process using a range of tip parameters. The goal is to be able to specify what types of tips could be used on a specific characterizer. This information will enable users to select appropriate characterizers for their needs. Note that this only works if the user has some nominal information about the tip from the manufacturer.

We use a simulation method based on morphological operators of dilation and erosion [4, 17]. Morphological operations require two items, an *object A* and a *structuring element B*. The interaction of these two items could be any of the following set operations: Union, intersection, complement, and translation. Different results can be obtained by varying the size and shape of the structuring element. An overview of morphological operators can be found in Dougherty et al.[4,17].

For our purposes, the *object A* is a profile of the tip characterizer, and the structuring element *B* is the tip. Two of the basic morphological operations we use are dilation and erosion. Dilation results in a new set of points represented by the maximum value of the profile within a region defined by the structuring element, while erosion results in the minimum value of the profile within a region defined by the structuring element. Equation 2 represents the dilation of *profile A* by *probe B*. With respect to our simulation, the dilation equation can also be expressed as outlined in equation 3, where $sim(x, y)$ is the simulated surface, $A(x', y')$ is the surface being measured, and $B(x, y)$ is the probe surface.

If a profile is dilated by a scanning tip, the result would be an apparent broadening (or geometric dilation) of the resulting profile. This will only occur at the sides of the features (as shown in figure 1) rather than on top. So the simulated output heights are translated by the tip width.

$$A \oplus B = \bigcup_{b \in B} (A + b) \quad (2)$$

$$sim(x, y) = \max\{A(x', y') + B(x-x', y-y')\}. \quad (3)$$

4. Results and Discussion

4.1 Tip Parameters

After the calculations described in the last section, an *a priori* determined value of 15.5 nm (from TEM) for the narrow ridge is removed from the width. The probe characteristic plots for both sides of the tip are shown in figure 12a. The final tip profiles are shown in figure 12c for the non-flared tip, and figure 12e for the flared tip. Table 1 shows results for flared and non-flared tip parameters obtained using the comb characterizer, and those obtained from another method which uses two samples called “vertical parallel structure” and “flared silicon ridge,” referred to in the rest of the paper as VPS/FSR [5]. The VPS/FSR procedure derives traceability through HRTEM, and can have uncertainty values of less than 1.5 nm ($k=1$) [11,14]. The VPS/FSR uses two separate samples, and requires an additional measurement step. Tip width results from the two techniques have a difference of less than 1.5 nm. The low standard deviation (less than 1 in most cases) reflects the uniformity of the features used. Table 2 shows additional comparison of flared tip parameters from the comb characterizer, VPS/IFRS and scanning electron microscope (SEM). The spread of the results for the VPS/IFRS and comb characterizer represent the standard deviation of 5 measurements, while that of the SEM indicate the size of the edge bloom. All the SEM width results were at least 3 nm less than the comb and VPS/IFRS values, and also had larger spreads. The comb and VPS/IFRS results are less than 1.5 nm apart for the results in table 2. The difference in the SEM width results could be attributed to edge bloom on both sides of the tip image in the SEM data, which reduces the accuracy of the edge location. The edge height results are within 1.5 nm for all three results. The closeness of the SEM edge height results comes from the way the measurand is defined, where the edge height is vertical distance from the bottom of the tip and the end of the flare. The width measurand, which was entirely in the lateral direction was more susceptible to SEM edge determination error. So although the SEM images give some indication of the parameters values, for this purpose the spread in the results makes it difficult to use as a characterizer for applications that require low uncertainty. Figure 13 shows SEM images of *Flared CD Tip2* and *Flared CD Tip3* in table 2. The

effective tip lengths reported for the comb characterizer is limited by the etch depth of the super-lattices during manufacture.

Figure12: Probe characteristic and reconstructed profiles for non-flared (a,b,c) and (d and e) flared tips.

Table 1: Tip Parameter Results

	Comb Tip Characterizer	VPS/IFSR
<i>Flared CD Tip1</i>		
Width	41.8 nm $\pm$ 0.6 nm	40.2 nm $\pm$ 0.4 nm
Edge Height	15.8 nm $\pm$ 0.7 nm	15 nm $\pm$ 0.56 nm
Effective Tip Length	$\geq$ 60 nm	175 nm
<i>Non Flared</i>		
Width	23.6 nm $\pm$ 1.1 nm	23.5 nm $\pm$ 0.9 nm
Effective Tip Length	$\geq$ 80 nm	175 nm

Table 2: Flared Tip Comparison with SEM

	Comb Tip Characterizer	VPS/IFSR	SEM
<i>Flared CD Tip2</i>			
Width	45.52 nm $\pm$ 0.9 nm	46.8 nm $\pm$ 0.6 nm	40.9 nm $\pm$ 3 nm
Edge Height	14.8 nm $\pm$ 1.2 nm	14.2 $\pm$ 0.48	13.4 nm $\pm$ 2.5 nm
Effective Tip Length	$\geq$ 60 nm	340 nm	356 nm
<i>Flared CD Tip3</i>			
Width	55.27 nm $\pm$ 0.74 nm	53.97 nm $\pm$ 0.4 nm	50.2 nm $\pm$ 3 nm
Edge Height	10.3 $\pm$ 1.34 nm	11.2 $\pm$ 0.83 nm	10.7 nm $\pm$ 2.5 nm
Effective Tip Length	>60 nm	342 nm	362 nm

Figure 13: SEM images of the flared tips in Table 2 (a) Flared CD Tip2 (b) Flared CD Tip3: Both images were acquired with landing energies of 5kV, with 43 pA. The images have magnification of 500 000x.

4.2 Linewidth Results

Using these tip parameters we measured a series of HAR width features and show these results on figure 14 alongside results obtained using tip parameters from VPS/FSR. Two of the samples are etched silicon features, and the other one is resist. Each mean value on figure 14 is an average of 10 measurements. For the non-flared CD tips, the mean values are consistent with those obtained from the VPS/FSR combo. This is encouraging since the tip characterization data were obtained in a single scan, whereas the VPS/FSR process involves two different sets of samples and measurements. The biggest difference in the results was 1.7 nm observed at the bottom width of the etched silicon feature measured with flared CD-tip. Results from the same bottom width also show higher standard deviations indicating that the bigger variations could be sample related rather than technique. The rest of the results were less than 1 nm of each other for the three samples measured.

Figure 14: (a) Linewidth results for the non-flared tip on (a) etched silicon and (b) resist. (c) Linewidth results for the flared tip on etched silicon.

4.3 Nanoscale Grating Characterization

The gratings contained in the characterizer scan could be used as a traceable lateral scale for the whole process. This is important because if the instrument used for the tip characterization is not well calibrated, the final tip parameters will include scale errors. The nominal pitch on the sample determined from deposition rate of the films was 28 nm, based on the total film thickness and numbers of the film layers. The total thickness of the film was determined by measuring the height difference between a masked and unmasked region on the Si wafer with a stylus profiler. The nominal pitch was then calculated by dividing total film thickness by the number of layers. Although the pitch of the grating could also be obtained from the TEM image, validating the sample using a metrology AFM allows us to develop uncertainty estimates for the mean value and also capture any instrument related deviations contained in the data. When this sample is measured by another instrument, this value is used to adjust the lateral scales, thus ensuring that scale deviations are not included in the tip parameters. Table 3 shows values of 28.03 nm for the gratings with a sample uniformity of 0.21 nm. This value is the standard deviation of the pitches across the grating (obtained using a peak to peak spatial domain analysis) from a single measurement and represents the local uniformity. The standard deviation of 0.09 nm reported on the same table comes from 10 repeated measurements of the gratings. This is an indication of the global uniformity. Note that this calibration process is similar to what users should do to regularly maintain their instrument; in this case the calibration image is acquired at the same time as the actual image. While this calibration exercise will enable the user to know the distance from one feature peak to another, it does not calibrate feature width.

Table 3 T-AFM Validation of Grating Pitch

	(nm)	Comment
Mean	28.03	<i>This is the mean value obtained from the displacement interferometry data.</i>
Sample Uniformity	0.21	<i>This is the standard deviation of the grating from a single measurement rather than from repeated measurements, and represents the sample quality.</i>
1 Standard deviation	0.09	<i>10 repeated measurements</i>

Overall, the hallmark of a good characterizer is the ability to obtain the desired tip parameters. For CD-AFM tips, these are the parameters shown in figure 3: VEH and flare size for flared tips, width and effective tip length for both flared and non-flared tips. The multi-feature design of the comb characterizer allows for a consistent and stable extraction of tip parameters. The main advantages of the comb characterizer are the presence of several features that could be used to extract tip parameters. The different spacing sizes, depths and shapes make it possible to collect independent information from individual features that are used in aggregate to determine a more complete tip shape. In essence this allows multiple features which may interact in slightly different ways with the tip to contribute to the analysis. One limitation of the comb characterizer is that it cannot be used to evaluate the flare size, so if the intention is to measure samples with re-entrant surfaces (undercut), this characterizer will not be suitable. For non-re-entrant HAR features, the comb characterizer is robust and stable enough. A possible improvement would be to provide certified reference values for the grating pitch.

4.4 Simulation Results

Using dimensions obtained from TEM micrographs (figure 15), we simulated a comb characterizer profile. With the profile as the object, and the tips as structuring elements, we evaluated the impact of measuring the characterizing with both non-flared and flared tips. For the non-flared tip we used 18 nm, 32 nm, and 46 nm tip widths to simulate new profiles. The widths for the non-flared tips are defined at 10 nm from the apex. The size of the tip above the cone is also larger as tip size increases, introducing an additional constraint. The results are shown in figure 16(a) and give an indication of what one might expect when characterizing similar dimensions. The key information is to what extent the tips were able to penetrate the trenches, and how many of the resulting profiles are suitable for analysis. Figure 16(b) shows a close-up view of the simulated profiles. As expected, the smaller tips were able to reach deeper into the trenches. The 18 nm width tip was able to obtain data from eight features, thereby providing not only width, but tip length information to the full extent the characterizer can provide. The 32 nm tip yields full profile information from only one feature and varying amounts from six more. One can still evaluate a 32 nm tip using this specific characterizer design, but would lose whatever advantage averaging would have provided. The 46 nm width tip, as expected, had the most problem reaching into the trenches. At the deepest, it reached less than 15 nm into the sample, and was not able to map the tip shank curvature shown in the tip profiles in figure 16 (d). In interpreting simulation results it is important to bear in mind that these are ideal conditions with only geometric influences. Figure 16(c) suggests that a 46 nm width tip would be able to measure 28 nm pitch gratings. This is because the width is not determined at the very apex of the tip, which is much smaller. Even under simulation conditions, the penetration depth is only 0.5

nm. Under real measurement conditions, a 46 nm width tip would be unlikely to produce such a profile due to tip-wear, noise, and other tip-sample interaction details.

For the flared tips, the widths used are 10 nm (0 nm VEH), 15 nm (0 nm VEH), 15 nm (2 nm VEH), 18 nm (3 nm VEH), and 44 nm (9 nm VEH). The tip width is the distance from one lateral apex to the other. For a flared tip with zero VEH, as long as it is able to penetrate the trenches, dilation of a feature produces a profile whose apparent width includes the tip. This is reflected in the results on figure 17(a) where the output profiles show offsets depending on the tip width. A close-up view of the output profiles is shown in figure 17(b). However, the profiles produced by tips with VEH (15 nm, 18 nm, and 44 nm) show dilations at the top of the features. Under our idealized conditions, these dilations correspond to the VEH both in size and shape. This is clearly illustrated in figure 17(c) where the 15 nm tip with 2 nm VEH is distorted. It is interesting to note that although a 15 nm flared tip is not able to measure the gratings, the presence of a 2 nm VEH reduces the size of the tip apex that first contacts the surface allowing for some data to be acquired. This is shown in figure 17(d) and is similar to the observation in figure 16 (d). Figure 17(e) shows the flared tip models used.

Overall, the main take-away from the simulation is that it could be used to determine and specify the upper bounds of what a specific characterizer can measure. It can also be used as a pre fabrication design tool to determine the range of tips a particular characterizer can evaluate.

Figure 15: (a) TEM micrograph of the comb characterizer. (b) A close-up image of the comb features. (c) Close-up view of one of the features showing the sidewall angle and corner radius. (d) Close-up view of the narrow ridge.

Figure 16(a) Simulated profiles for the characterizer, with output for non-flared tips with 18 nm, 32 nm and 46 nm tip widths. (b) Close-up view of line space features. (c) Close-up view of the calibration gratings. (d) Profiles of tip shanks of the simulated tips. The tip width is defined at 10 nm from the tip apex.

Figure 17 (a) Simulated profiles for the characterizer, with output for flared tips with 10 nm, 15 nm, 18 nm, and 44 nm tip widths. (b) Close-up view of line space features. (c) Close-up of one of the features showing simulated profiles from a 15 nm tip (0 nm VEH) and 15 nm tip (2 nm VEH). (d) Close-up of the simulated profiles from the gratings for 15 nm tip (0 nm VEH) and 15 nm tip (2 nm VEH). (e) flared tip models. Only a portion of the 44 nm tip is shown.

4.5 Conclusions

We described a multi-feature characterizer for evaluating the size and shape of AFM tips, and applied it to critical dimension AFM tips. The tip parameter values extracted using the “comb” technique were consistent with another method currently used, but required fewer measurement steps. In addition, the sample includes a certified grating, so the instrument could be calibrated for scale using information from the same scan. Effectively, this provides a robust and stable tip characterization method for non-re-entrant surfaces. The absence of an undercut on any of the features precludes it from being used for re-entrant tips. The design of the characterizer determines what tip sizes could be used. In cases where only a few or one of the features produce a full profile, tip parameters can still be obtained. However, any advantage provided by averaging would be lost. An evaluation of the integrated grating, obtained in the same scan as the characterizer data, shows a pitch uniformity of 0.5 % from the mean. This indicates that the grating could be used to correct scale errors for the measuring instrument, as well as provide *SI* traceability. We also implemented a simulation using morphological operators that could be used to determine and specify what range of tips sizes and shapes the characterizer can measure.

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Reference

- [1] D.A. Grigg, P.E. Russell, J.E. Griffith, M.J. Vasile, E.A. Fitzgerald, Probe characterization for scanning probe metrology Ultramicroscopy, 42–44, (1992) 1616-1620
- [2] D. Keller, Reconstruction of STM and AFM images distorted by finite-size tip, Surf. Sci. 253, (1991) 353-364
- [3] E. E. Flater, G. E. Zacharakis-Jutz, B. G. Dumba, I. A. White, C. A. Clifford, Towards easy and reliable AFM tip shape determination using blind tip reconstruction Ultramicroscopy, (146), (2014) 130-143
- [4] J. S. Villarrubia “Algorithms for Scanned Probe Microscope Image Simulation, Surface Reconstruction and Tip Estimation, J. Res. Natl. Inst. Stand. Technol. 102(4) (1997) 425-454
- [5] G. Dahlen et al. Tip characterization and surface reconstruction of complex structures with critical dimension atomic force microscopy, J Vac. Sci. Technol. B. (23) 6 (2005) 2297-2303
- [6] F. Tian, X. Qian, J.S. Villarrubia, Blind estimation of general tip shape in AFM imaging, Ultramicroscopy 109, (1), (2008), 44–53
- [7] X. Qian, J.S. Villarrubia, General three-dimensional image simulation and surface reconstruction in scanning probe microscopy using a dixel representation, Ultramicroscopy 108(1) 2007, 29-42
- [8] H. Itoh, T. Fujimoto, and S. Ichimura, Tip characterizer for atomic force microscopy, Rev. Sci. Instrum. 77, 103704 (2006)
- [9] H. Takenaka, M. Hatayama, H. Ito, T. Ohchi, A. Takano, S. Kurosawa, H. Itoh, S. Ichimura, Development of Si/SiO₂ Multilayer Type AFM Tip Characterizers, J. Surf. Anal. 17(3), (2011). 264-268
- [10] M. Watanabe, S. Baba, T. Nakata, T. Morimoto, S. Sekino, H. Itoh, Atomic force microscope method for sidewall measurement through carbon nanotube probe deformation correction, J. Micro/Nanolith. MEMS MOEMS. 11(1), 011009 (2012).
- [11] Y. Martin and H. K. Wickramasinghe, Method for imaging sidewalls by atomic-force microscopy, Appl. Phys. Lett. 64(19), (1994) 2498–2500

- [12] N. G. Orji, R. G. Dixon, A. Martinez, B. D. Bunday, J. A. Allgair, T. V. Vorburger Progress on implementation of a reference measurement system based on a critical-dimension atomic force microscope, *J. Micro Nanolithogr. MEMS MOEMS* 6(2), 023002 (2007).
- [13] J. Foucher, P. Filippov, C. Penzkofer, B. Irmer, S. W. Schmidt, Manufacturing and advanced characterization of sub-25nm diameter CD-AFM probes with sub-10nm tip edges radius, *Proc. SPIE* 8681, (2013) 8681 -11
- [14] R. G. Dixon, R. A. Allen, W. F. Guthrie, and M. W. Cresswell, "Traceable Calibration of Critical-Dimension Atomic Force Microscope Linewidth Measurements with Nanometer Uncertainty," *J. Vac. Sci. Technol. B* Vol. **23**, 3028-3032 (2005).
- [15] R. G. Dixon, R. G. Koenig, V.W. Tsai, J. Fu and T. V. Vorburger, Dimensional metrology with the NIST calibrated atomic force microscope, *Proc. SPIE* 3677, (1999)
- [16] J. A. Kramar, R. D. Dixon, N. G. Orji, Scanning probe microscope dimensional metrology at NIST, *Meas. Sci. Technol.* 22 024001 (2011)
- [17] C.R. Giardina, E. R. Dougherty, *Morphological Method in Image and Signal Processing*. Prentice-Hall, Englewood Cliffs, NJ. (1988)