CD-AFM Reference Metrology at NIST and SEMATECH

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ABSTRACT

The National Institute of Standards and Technology (NIST) and SEMATECH have been working together to improve the traceability of critical dimension atomic force microscope (CD-AFM) dimensional metrology in semiconductor manufacturing. A major component of this collaboration has been the implementation of a Reference Measurement System (RMS) at SEMATECH using a current generation CD-AFM. An earlier tool, originally used at SEMATECH, has now been installed at NIST. Uncertainty budgets were developed for pitch, height, and CD measurements using both tools. At present, the standard uncertainties are approximately 0.2 % for pitch measurements and 0.4 % for step height measurements. Prior to the current work, CD-AFM linewidth measurements were limited to a standard uncertainty of about 5 nm. However, this limit can now be significantly reduced. This reduction results from the completion of the NIST/SEMATECH collaboration on the development of single crystal critical dimension reference materials (SCDDRM). A new generation of these reference materials was released to SEMATECH Member Companies during late 2004. The SEMATECH RMS was used to measure the linewidths of selected features on the distributed specimens. To reduce the uncertainty in tip width calibration, a separate transfer experiment was performed in which samples were measured by CD-AFM and then sent for high resolution transmission electron microscopy (HRTEM). In this manner, CD-AFM could be used to transfer the HRTEM width information to the distributed samples. Consequently, we are now able to reduce the limit on the standard uncertainty (k = 1) of CD-AFM width measurements to 1 nm.

Keywords: CD-AFM, metrology, CD, linewidth, reference measurement system, standards, calibration, traceability

1. INTRODUCTION

The National Institute of Standards and Technology (NIST) and SEMATECH have been working together to improve the traceability of critical dimension atomic force microscope (CD-AFM) dimensional metrology in semiconductor manufacturing. A major component of this collaboration has been the development of a CD-AFM Reference Measurement System (RMS)[1-3] at SEMATECH using a current generation CD-AFM (the Veeco Dimension X3D)[†]. The concept of a RMS has been previously advocated by others, such as Banke and Archie.[4,5] In prior descriptions of our work, we have explained the implementation of a CD-AFM RMS in more detail.[1-3] Our discussion here will focus primarily on CD-AFM linewidth metrology and the reduction in uncertainty that is now possible as a result of the NIST/SEMATECH single crystal critical dimension reference material (SCCDRM) project.

In late 2004, a new generation of SCCDRM samples was released to the Member Companies of SEMATECH. The background and history of this project has been described elsewhere.[6-8] Features on the SCCDRM samples are preferentially etched into a {110} silicon-on-insulator (SOI) substrate, so the sidewalls are near-vertical. Due to the crystalline nature of these features, it is possible to use the silicon lattice constant as a source of width information when the structures are measured using high resolution transmission electron microscopy (HRTEM). Since HRTEM is destructive, we used the X3D to transfer the information from the HRTEM samples to those that were distributed. Ultimately, we were able to deliver structures with expanded uncertainties (k = 2) of less than 2 nm. The overall results

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[†] 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 or SEMATECH, nor does it imply that the equipment identified is necessarily the best available for the purpose.

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of the SCCDRM project are being described elsewhere.[9] Our discussion of the project will focus on the AFM methodology that was used for the project, and the application of the samples to AFM linewidth metrology.

1.1 RMS Implementation with CD-AFM

The operation of CD-AFM is more sophisticated than conventional or top-down AFM. Some unique aspects of CD-AFM operation are that force sensing occurs along both lateral and vertical axes and flared tips are used. This allows imaging of vertical sidewalls, as illustrated in Figure 1, and also allows some degree of undercut to be measured.

Initially, the RMS at SEMATECH was implemented using a Veeco SXM320[†] - the previous generation CD-AFM. However, this instrument was subsequently replaced with the current generation X3D. After decommissioning at SEMATECH, the SXM was then installed at NIST where it is also used as an RMS to support NIST standards projects and continuing collaboration with SEMATECH.

Uncertainty budgets were developed for pitch, height, and CD measurements using both tools.[1-3] At present, the standard uncertainties are approximately 0.2 % for pitch measurements up to several micrometers and 0.4 % for sub-micrometer step height measurements. Initially, the standard uncertainty of CD-AFM linewidth measurements in the deep sub-micrometer range was limited to about 5 nm. As a result of recent progress on the SCCDRM project, however, this limit can now be reduced to about 1 nm.

2. CD-AFM LINEWIDTH METROLOGY

There are many important metrology applications of CD-AFM in semiconductor manufacturing. However, the most common is linewidth metrology – for measurement of gate CD or as a reference tool for in-line critical dimension scanning electron microscopes (CD-SEMs). For this application, it is especially important to minimize the uncertainty of the CD-AFM width measurements.

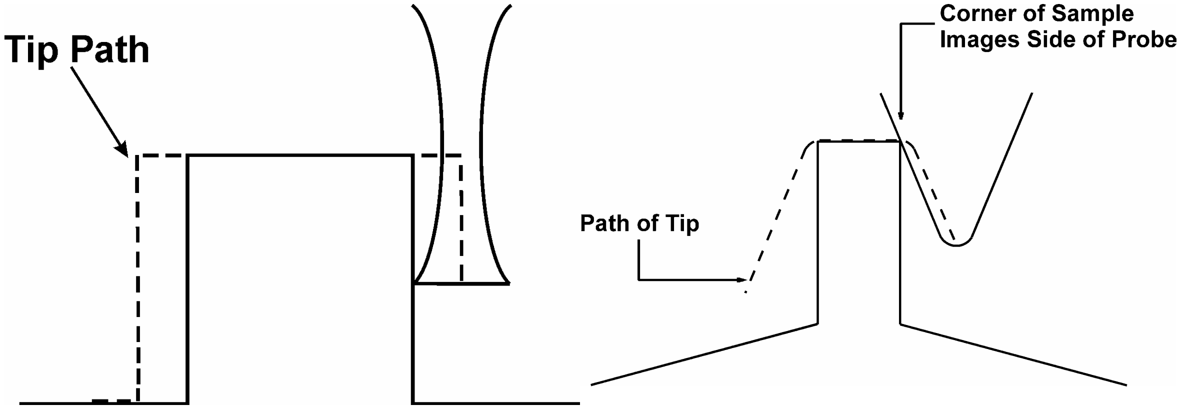
The standard approach to uncertainty budgets is to develop an estimated contribution for every known source of uncertainty in a given measurement, which includes terms pertaining to both the instrument used and the particular specimen measured.[10,11] Terms evaluated exclusively by statistical methods are known as type A evaluations. Other terms, known as type B evaluations, are evaluated using some combination of measured data, physical models, or assumptions about the probability distribution. All the terms are then added in quadrature to obtain a combined standard uncertainty for the measurement. This is usually multiplied by a coverage factor k to obtain a combined expanded uncertainty.[11] The most common coverage factor used is $k = 2$, which would correspond to approximately 95 % confidence for a normal (Gaussian) distribution.

Previous descriptions of our project included uncertainty budgets for CD-AFM pitch, step height, and linewidth measurements.[1-3] Although not identical, the uncertainty budgets for both the X3D and SXM are conceptually similar and contain most of the same terms. The current linewidth budget for the X3D is shown in Table I. Although there are eight terms in the uncertainty budget, the most significant source of uncertainty in many CD-AFM width measurements arises from the calibration of the tip width. We have been able to reduce this contribution to 1 nm.

2.1 CD-AFM Tip Width Calibration and Uncertainty

For deep submicron linewidth measurements, the dominant term in the current width uncertainty budget is due to the tip. We call this term the zeroth order tip width correction, and it represents the uncertainty in correcting the apparent width of an imaged feature for the effect of the tip. In turn, this depends primarily on the calibration of the tip width.

Although the interaction of an AFM tip with the imaged surface is complex, for many purposes a highly simplified and two-dimensional model illustrated in Figure 1 can be useful. In this basic model, the effect of the tip is represented as a simple additive offset which must be subtracted from the apparent width to obtain an accurate measurement. Hence, the zeroth order uncertainty component represents the uncertainty in the tip width value to be subtracted.



CD-AFM **1D AFM**

Figure 1. Illustration of differences between CD-AFM and conventional AFM using idealized geometries.

Since the tip width is determined from the apparent width of a reference structure, the zeroth order term is equivalent to the uncertainty in the width of the reference structure used for tip calibration. We have previously described several approaches to tip characterization and the origin of our original 5 nm estimate for the uncertainty of the zeroth order term.[1]

It is important to note that the standard uncertainty in the zeroth order correction represents an absolute uncertainty. For some applications, the absolute uncertainty is of less interest than the relative uncertainty between two given width measurements. This uncertainty can be significantly smaller than 5 nm. It is largely dependent on the stability of the tip width correction, the lateral precision of the tool, and on the higher order tip-related effects.

For many circumstances, this relative uncertainty between two width measurements will be on the order of 1 nm or less. CD-AFM is thus an excellent width comparator. This means that if a more accurate tip width calibration standard were available, the uncertainty of linewidth measurements could be dramatically reduced. When combined with another technique for measuring absolute width, it also means that CD-AFM can be used as a powerful tool in measuring such a standard. This is the essence of the SCCDRM project described in the next section.

The finer details of the tip-sample interaction, pertaining to things like flare radius, feature sidewall angle, feature corner radius, and the three-dimensional nature of both the tip and sample (*i.e.*, shape in the axis not shown) are thought of as being higher-order tip effects. The idealized geometry of Figure 1 does not incorporate any of these considerations. In Figure 2, we illustrate a more realistic geometry, which gives some insight into the types of biases that can result from higher order effects.

The three higher-order effects that are typically most significant result from the tip flare offset height, the flare radius, and the flare overhang. Although the tip and feature geometries illustrated in Figure 2 are considerable simplifications, the potential impact of these higher-order characteristics on width measurements is apparent. In the figure, we have focused on the effect of the offset height, which is the most pervasive higher-order term – even if it isn't always the largest.

The offset height is of some significance in almost every CD-AFM measurement. Only on highly ideal structures, such as the SCCDRM features, is the impact typically negligible. It represents the height difference between the bottom of the tip and the flare apex. Because the offset height is non-zero, the very bottom of the structure (at heights equal to or less than the offset height) is inaccessible to the tip and cannot be measured. The figure illustrates how the apparent bottom width will be biased from the actual bottom width.

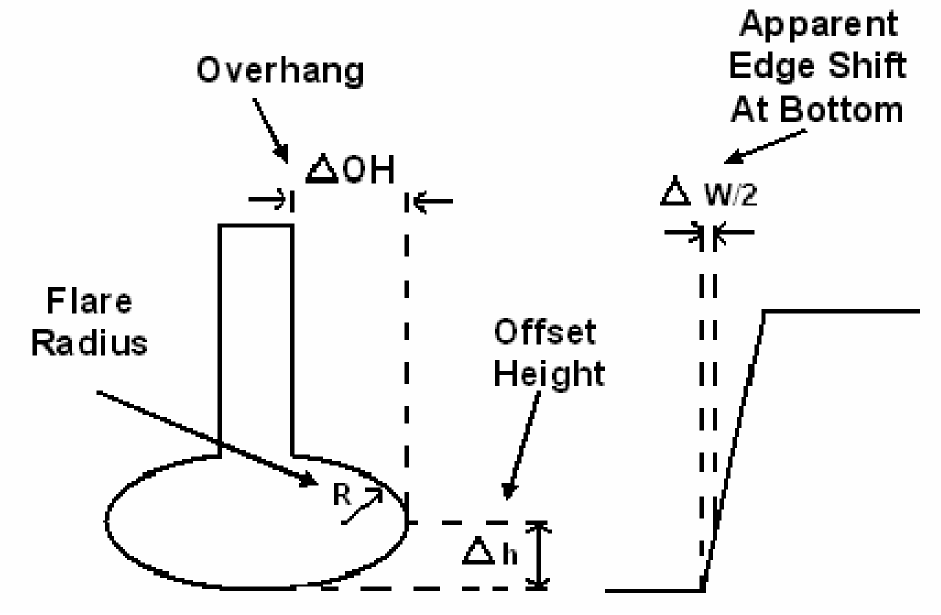


Figure 2. Illustration of higher order tip effects, using less idealized geometries than Figure 1. The offset height is the most prevalent effect and leads to a potential bias as illustrated in the figure.

The magnitude of the bias depends on the characteristics of the structure being imaged – primarily the sidewall angle and on the magnitude of the offset height for the specific tip. Significant tip to tip variations in offset height are observed, and the offset height also typically changes with tip wear. Accurate measurement of tip offset height is a challenging problem and requires the use of an undercut tip characterizer. Relative changes in the tip offset height can be tracked to about 1 nm using the undercut characterizer on the X3D. However, the uncertainty in the absolute offset height is somewhat larger – about 5 nm to 10 nm. Currently available tips for the X3D typically have apparent offset heights ranging from 5 nm to 20 nm – although badly worn or contaminated tips may have much larger values.

For features with sidewalls that are a few degrees from vertical and tips with typical offset heights, the bias can be on the order of 10 nm. It is particularly problematic for sidewalls that are not well described by a linear slope – such as for resist features having a 'foot' at the bottom. The uncertainty associated with trying to correct for the bias depends upon making assumptions about the feature shape. If a linear sidewall is assumed, a straightforward correction can be performed. If the linear model is a good fit to the actual feature shape, then this correction can be performed with relatively small uncertainties – on the order of 1 nm to 2 nm. But the appropriateness of the assumed geometry is often unknown. This is an excellent example of the need to use complementary metrology techniques to fully realize the RMS concept, as recently pointed out by Banke, *et al*.[4] It also underscores the importance of a careful definition of the measurand. This is the subject of a recent SEMI standard.[12]

For many of our RMS applications, this uncertainty has typically been smaller than the uncertainty in performing the zeroth order correction. Consequently, we focused our attention elsewhere. However, now that the zeroth order correction has been improved, the uncertainty due to offset height bias will no longer be negligible in many applications of the CD-AFM/RMS.

The effect of the flare radius, though usually of less significance than the offset height, is even more complicated to model. In essence, the flare and sidewall interact in the same manner as a conventional AFM tip imaging a horizontal surface. Consequently, the sidewall surface is distorted by the geometry of the flare. In terms of mathematical morphology, the imaging process is described as a dilation of the sidewall surface by the flare of the tip. The application of mathematical morphology to conventional AFM imaging and to reconstruction of surfaces and tip shape has been the subject of considerable investigation by Villarrubia.[13] A detailed treatment of this subject is outside the scope of this paper, and we will focus only a general discussion of the effect.

Although the image of the sidewall is always distorted by the flare shape, the significance of the resulting bias depends upon the measurand of interest. For a measurement of sidewall roughness it is of considerable importance. However, for width metrology, the flare shape is usually less important because the dilation of the surface does not typically introduce a significant bias in the apparent edge location. In other words, although the details of the sidewall are dilated, the shift in the average position of the surface is usually negligible. For very rough or highly irregular surfaces (such as sidewalls with defects or particulate contamination) this assumption will break down, and this should be kept in mind when interpreting CD-AFM data. However, for typical tips, features, and sampling areas, this effect will often be less significant than the bias due to the offset height.

The flare overhang is of importance primarily when measuring reentrant structures. If the feature reentrance exceeds the overhang, then the tip will be unable to image that portion of the structure. This results in a positive bias in the apparent width equal to the magnitude of the inaccessible reentrance. For highly undercut structures, this can become a substantial source of uncertainty. However, for features that don't exceed this reentrance limit, there is no bias from this effect. One caveat here is that for sharp undercuts the flare radius may limit the sensitivity to high spatial frequencies on the sidewall. However, the overall limit on observable reentrance is the overhang of the tip.

Because these effects have a strong dependence on the specific geometry of each tip and feature, it is difficult to make general statements about the resulting uncertainties, and it is necessary to make a specific assessment for every measurement. Prior to the present work, this was of somewhat lesser concern because these components were typically smaller than the uncertainty in the zeroth order correction. However, with reduction in uncertainty of the zeroth order term that results from the SCCDRM project, characterization and correction for these effects will become more important in CD-AFM width measurements. The X3D software includes utilities for tip shape deconvolution, and this will play a role in further investigation of higher order tip effects.

3. APPLICATION OF THE CD-AFM RMS TO THE SCCDRM PROJECT

NIST and SEMATECH collaborate extensively on linewidth metrology and standards development. There are several ongoing projects encompassing both wafer and photomask metrology using multiple methods – including AFM, SEM, and optical techniques. One component of this collaboration is the SCCDRM project.

The background, history, and prior rounds of this project have been described previously.[6-8] The current round of samples was released to SEMATECH Member Companies during October 2004. The SCCDRM features have near-vertical sidewalls; this is accomplished using preferential etching on {110} silicon-on-insulator (SOI) substrates.

In principle, it is possible to use the silicon lattice constant as a source of width information by using a lattice-resolving technique such as high resolution transmission electron microscopy (HRTEM). Due to the crystalline nature of the SCCDRM features, the HRTEM fringes can be counted across an entire structure for sufficiently small linewidths. However, to perform the HRTEM measurement, the feature must be cross-sectioned. Since this process is destructive, HRTEM cannot be used for direct calibration of SCCDRM features. Therefore, our strategy for the latest SCCDRM release, was to use the X3D as a comparator and then sacrifice some of the samples for HRTEM. In this manner, the HRTEM measurements effectively functioned as an elaborate tip calibration method, but with a lower uncertainty than previous methods using tip characterizers.

Ultimately, we were able to deliver structures with linewidths as low as 50 nm and expanded uncertainties ($k = 2$) of less than 2 nm. These overall results of the project are being described elsewhere.[9] Therefore, the rest of this discussion will focus on the AFM methodology that was used, and the application of the SCCDRM samples to AFM linewidth metrology.

3.1 CD-AFM Methodology for SCCDRM Measurements

As mentioned above, the X3D was used essentially as a width comparator for the SCCDRM project. The data were acquired in two major steps: (1) referencing of a monitor sample to the HRTEM results, and (2) referencing of the distributed samples to the monitor sample. The monitor sample serves two major functions. First, it is the transfer path for the HRTEM results. Second, it serves to maintain the same relative tip width calibration between the many measurements that are required for this work.

At the time of the SCCDRM measurements, the standard uncertainty in the absolute value of X3D linewidth measurements relative to the SI (*Systeme International d'Unites,* or International System of Units) meter was 5 nm. As discussed previously, however, it is possible for the relative uncertainty between any two width measurements to be much less than this. But, a lower relative uncertainty rests largely upon the stability of the tip width and the consistency of whatever tip width calibration method is used. Note that the method does not need to be accurate in an absolute sense. That is, a bias is acceptable, but it must be consistent from one measurement to the next. Our approach was to use the SCCDRM monitor sample as an anchor for the tip width calibration and to measure this monitor sample before and after every measurement of a target sample. In this manner, we could detect any change in the tip width and achieve internal consistency of our data set.

In the first step, the set of samples for HRTEM was chosen and these were measured relative to the monitor sample. Then, the samples for distribution were measured relative to the monitor sample. Once the transfer samples were cross-sectioned and measured by HRTEM, the linewidths of the remaining samples were then known relative to the TEM values. Although the silicon lattice constant is extremely well known relative to the SI meter, establishing traceability of linewidth results based upon HRTEM requires a careful and thorough methodology and validation from other metrology techniques, as discussed in the next section.

3.2 Traceability and Validating Metrology

The purpose of HRTEM in the SCCDRM project is to use the silicon lattice constant as a ruler for linewidth measurements. However, the issues of uncertainty in and traceability of these width measurements to the SI meter is complex. There are several possible effects that could lead to biased results and increased uncertainty. Ultimately, we were able to address these adequately with multiple HRTEM samples and with other results. While we do have a longer term goal of performing additional validation measurements and independently reproducing the results, we were able to establish the traceability of our results on the SCCDRM samples.

During the SCCDRM project, we used four HRTEM transfer samples – each having six features of different widths. The details of our analysis are being reported elsewhere.[9] The HRTEM fringes were counted manually and the images were analyzed in detail. Based upon this analysis, we concluded that most potential biases pertaining to sample preparation (*e.g.*, surface effects, membrane distortion, FIB-induced damage) were not a concern. However, we did conclude that there was a problem involving contamination and its removal during the HRTEM sample preparation.

The results of our analysis suggested that two of the HRTEM samples had been slightly contaminated, probably with hydrocarbon deposited during the prior SEM inspection, at the time of the AFM measurements. This caused a bias in the AFM/HRTEM comparison for those two samples. However, the results from the other two samples were in agreement and we concluded that these were not biased by contamination.

Another important internal check on our results was consistency of the scale calibration. The lateral scale of the X3D was independently calibrated during the development of the RMS, and traceability path and uncertainty budget has been previously described.[1,2] During the SCCDRM measurements, we monitored the scale calibration. Therefore, we did not need to rely on the TEM results to establish the scale calibration, but only to establish the value of the effective tip width during the measurements. Since the slope of the AFM/TEM regression curve was consistent with unity (*i.e.*, in agreement with the prior scale calibration), we were able to treat the HRTEM/AFM comparison data as a direct measure of the bias in the existing tip width calibration and calculate the offset between the HRTEM and the AFM results.

3.2.1 Comparison of Multiple Metrology Methods

For the current SCCDRM release, our results and uncertainties were derived strictly from analysis of the HRTEM and AFM data obtained on the SCCDRM samples. The results available to us from other methods were interpreted as a reality check on our derived result rather than being directly incorporated into the uncertainty analysis. This is appropriate since the HRTEM-derived result has a significantly lower uncertainty than the other results we had available. In principle, however, it is possible to formally combine such independent results, and this may be appropriate in the future when we obtain additional data or other results with comparable uncertainties.

In previous work[1,14], we have discussed how results from multiple metrology methods can be used to develop an estimate of the “true” value of the measurand, the linewidth in this case, and an associated type B uncertainty statement. Conceptually, the state of knowledge about the value of the measurand is represented by a model probability distribution. From the modeled distribution, a mean value and standard uncertainty can be derived. The characteristics of the modeled distribution, such as the shape and the range, are decided upon by consideration of the various experimental determinations of the measurand and the associated uncertainties.

At present, we have useful information available from two alternative AFM methodologies. First, we have the independent calibration of the tip width from characterizer samples. Second, we have preliminary results from an AFM image stitching methodology that is being developed at NIST.[15] Both of these methods have larger uncertainties than the HRTEM result, and we did not directly incorporate either one into our uncertainty analysis for the SCCDRM project. As illustrated in Figure 3, however, all three methods are in agreement.

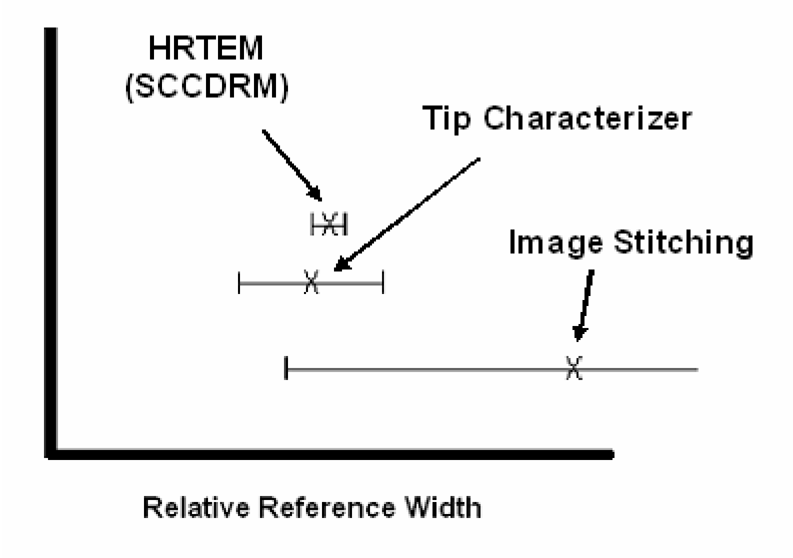


Figure 3. Conceptual illustration of multiple methods of determining a reference width. Our new result from the SCCDRM project is consistent with the older tip characterizer result and with the preliminary image stitching result. Although obtained using different samples, these results can be related to one another because the same tip and scale calibrations were used on the CD-AFM.

Prior to the SCCDRM project, the tip width calibration method on the X3D involved the use of a sharp ridge tip characterizer combined with a check standard having a rectangular cross-section. While this methodology has an undesirably large uncertainty, it is traceable. Therefore, the agreement between the width calibration from the AFM/HRTEM comparison and the width calibration derived from the characterizer method was a significant observation. Furthermore, this comparison also supports our conclusion that two of the HRTEM chips suffered from contamination. The two chips thought to be contaminated showed larger differences between the HRTEM result and the tip characterizer result. For some of the features, the difference was large enough to be in unambiguous statistical disagreement, while others were marginal.

In principle, it should be possible to refine the tip characterizer method by using additional samples and more sophisticated modeling. Since this could further validate our conclusions, we plan to pursue this in our future work. Since both the tip characterizer method and the HRTEM/AFM comparison are intended to represent the same physical measurand, the results should be consistent, and any observed discrepancies should be investigated and understood.

A complete description of image stitching is beyond the scope of this paper, but the method involves the use of correlation functions to match corresponding sections of a profile from different AFM images. The desired measurand can then be extracted from the composite image. For AFM width metrology, there are some circumstances in which this method can be particularly useful.

Carbon nanotubes have been mounted on conventional AFM tips by a variety of researchers, and mounted nanotube tips are also available from commercial sources. Although such tips are not free from imaging artifacts and limitations, there have been significant successes. For example, Zhao, et al. used nanotube tips to image an earlier generation of the SCCDRM samples.[16] One important limitation of nanotube tips, however, is that they are usually mounted at a significant angle with respect to the cantilever. Hence, the nanotube is not perpendicular to the surface when imaging. Consequently, when a structure with near-vertical sidewalls is imaged, only one of sidewalls is actually accessible by the tip. If the sample is then rotated by 180 degrees, the opposite sidewall is accessible. Separately, such images would not have much value for metrology. However, if the images can be joined with sufficient accuracy, then it may be possible to determine a value of the linewidth with sufficient accuracy to be useful.

Using a prior generation of the SCCDRM sample, we have performed a preliminary comparison of the image stitching result with CD-AFM measurements using the tip characterizer method. At present, the uncertainties in the stitching result are relatively large and on the order of 30 nm. The uncertainties in the stitching process and in the bending and apex geometry of the nanotube are major components. We expect to considerably reduce the image stitching uncertainties in the near future and believe that this method will play an important role in supporting the results of the SCCDRM project.

Other metrology techniques such as SEM and optical metrology may be considered. In recent years, there have been advances in the modeling of the SEM edge-response and in the algorithms used for width extraction. By using physics-based models and library comparison methods, such as those developed by Villarrubia[17-19], it may be possible to obtain SEM width results on the SCCDRM samples with uncertainties less than 5 nm. At that level, the comparison to the AFM/TEM value could be useful.

3.3 Tip Width Calibration using an SCCDRM Sample

As part of the NIST/SEMATECH collaboration on the CD-AFM RMS, we installed one of the newly measured SCCDRM samples, which is identified as chip K143 L4, in the X3D to serve as a tool monitor and reference standard for tip width calibration. The calibrated feature widths on this chip ranged from 73.7 nm to 241.5 nm, and the expanded uncertainties ($k = 2$) for these features ranged from 1.5 nm to 2.0 nm. Consequently, this chip can now be used as a traceable source of tip width calibration with a standard uncertainty ($k = 1$) less than 1 nm.

Figure 4 shows the measurement history of six features on the SCCDRM sample which is now mounted in the X3D as a tool monitor. The first measurement in April of 2004 was part of the main body of measurements for the SCCDRM project. When it was decided to mount this chip in the X3D, the measurements were repeated. The history includes two different heads on the X3D and measurements that were taken when the chip was mounted on both the original carrier wafer and then subsequently on the sample pedestal in the X3D. All of the widths are measured relative to the same tip calibration: the SCCDRM monitor sample (chip K162 K) that was discussed in section 3.1. As would be expected, the measurements do not show dependence on the above factors. The standard deviation of repeated measurements was ≈ 0.5 nm for all six features in the target of interest. The observed residual variation largely reflects both the base precision of the X3D and relative variations due to the higher order tip effects.

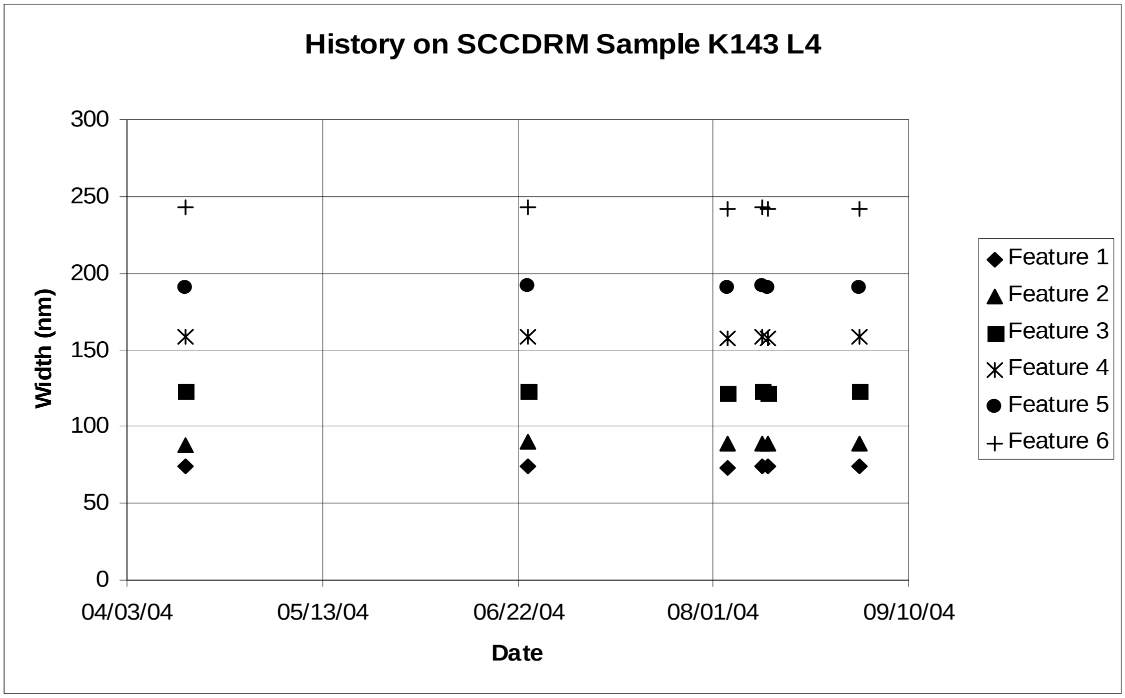


Figure 4. Measurement history on the SCCDRM chip now mounted in X3D. The feature widths are all measured relative to the SCCDRM monitor sample, and the standard deviations of repeated observations was ≈ 0.5 nm on all six features.

Although it is theoretically possible to reduce the zeroth order uncertainty component even further, it is no longer the limiting factor for most practical metrology applications. The uncertainty arising from higher order effects, as discussed in section 2, is now of equal or greater importance than the uncertainty of the zeroth order correction in most CD-AFM width measurements. Consequently, the opportunities to advance CD-AFM linewidth metrology in the near-term lie primarily in the quantification and correction of these effects.

4. SUMMARY AND PLANS

The National Institute of Standards and Technology (NIST) and SEMATECH are working together to improve the traceability of AFM dimensional metrology in semiconductor manufacturing through the development of a CD-AFM RMS at SEMATECH. The X3D has now been implemented as the RMS, and we have developed preliminary uncertainty budgets for pitch, height, and CD measurements. At present, the standard uncertainties are estimated to be approximately 0.2 % for pitch measurements, and 0.4 % for step height measurements. Recent progress on the SCCDRM project has allowed a reduction of the limiting linewidth standard uncertainty from 5 nm to 1 nm.

Ultimately, our goal in developing the CD-AFM RMS at SEMATECH is to improve traceability for measurements that occur in manufacturing. In addition to the major role it played in the SCCDRM project, the RMS at SEMATECH has been used extensively to support other metrology projects. These include serving as a reference tool for the CD-SEM benchmarking project[20-21], metrology on photomasks[22], and 193 nm resist shrinkage experiments.[23]

Future collaborations on the CD-AFM/RMS will be focused both on further validation of the SCCDRM results and on developing a more advanced treatment of the higher order tip related effects in CD-AFM width metrology. We also expect that the further development of the image stitching methodology will play an important role in validating the SCCDRM result.

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[†] 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 or SEMATECH, nor does it imply that the equipment identified is necessarily the best available for the purpose.

Table I. Preliminary Uncertainty Budget for X3D Width Measurements ($k = 1$)

Component		**Standard Uncertainty**
Type A		
(repeatability, reproducibility, sample non-uniformity, etc.)		Observed SD[a] or SDOM[a]
Type B		
Algorithm (edge/peak detection)/measurand definition		*
Tip width correction (zeroth order)	*Prior to SCCDRM:*	(5 nm)
	Current (using SCCDRM):	0.8 nm
Tip-related (higher order – e.g., offset height, overhang, corner rounding, tip wear)		‡
Scale Calibration (linear term)		$1.0 \times 10^{-3} W$[†]
Scale Non-linearity		$2.0 \times 10^{-3} W$[†]
Non-position-dependent motion errors (e.g., mechanical)		‡
Cosine Errors (in-sample-plane)		$0.15 \times 10^{-5} W$[†]
Cosine Errors (out-of-sample-plane)		$0.15 \times 10^{-3} W$[†]
Combined standard uncertainty, u_c (*width*)	=	$[(\mathrm{SD})^2 + (0.8\ \mathrm{nm})^2 + (2.2 \times 10^{-3} W)^2]^{1/2}$

[a] SD = standard deviation; SDOM = standard deviation of the mean

* Indicates that the major contribution is often included in the observed type A variations, and that the residual type B component may be negligible. But the contribution should be evaluated for each case. Note also that algorithm, measurand-definition, and tip-related terms are inter-related and not always easily partitioned.

‡ Indicates that contribution has not been thoroughly evaluated or is sample dependent and should be evaluated for every measurement – but is negligible in some cases.

[†] Indicates that the uncertainty is proportional to the measured value of linewidth *W*.

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