Accuracy Considerations for Critical Dimension Semiconductor Metrology

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ABSTRACT

Due to greater emphasis on precision than accuracy, many of the measurements made in semiconductor fabrication facilities are not traceable to the SI (*Système International d'Unites* or International System of Units) unit of length. However as the feature sizes of integrated circuits decrease and the use of lithography models becomes more prevalent, the need for accuracy cannot be overemphasized. In response, the National Institute of Standards and Technology (NIST) in conjunction with SEMATECH has developed a reference measurement system (RMS) that can be used to provide accurate measurements for inline metrology tools. The RMS is a critical dimension atomic force microscope (CD-AFM) with traceability to the SI meter.

In this paper we present a set of strategies for achieving accuracy for different types of measurands within an RMS and examine several important factors when selecting reference instruments. We also present results of a recent evaluation of linewidth and height using two CD-AFMs and a calibrated AFM with displacement interferometry in all three axes. We further look at the stability of tips such as carbon nanotubes.

Keywords: CD-AFM, Accuracy, reference measurement system, critical dimensions

1. INTRODUCTION

Due to greater emphasis on precision than accuracy, many of the measurements made in semiconductor fabrication facilities (fabs) are not traceable to the *SI* (*Système International d'Unites* or International System of Units) unit of length. Precision as used in this paper refers to measurement variation or closeness of agreement between measurements. However as feature sizes decrease and the use of lithography models becomes more prevalent, the need for accuracy cannot be overemphasized. Accurate measurements are needed to verify results produced by optical proximity correction (OPC), which play a big role in lithography modeling. Results linking parameters such as line edge roughness to device performance [1] also highlight the need for accurate (i.e., traceable) measurements of device geometry. Other reasons for accurate measurements include the need for consistency when results produced by different instruments or at different locations are evaluated and when new parameters or architecture are needed.

The semiconductor industry's emphasis on precision is slowly changing; the metrology chapter of the International Technology Roadmap for Semiconductors (ITRS) [2] has a new definition of uncertainty that takes into consideration error from sources other than precision. This implicitly recognizes that there are certain errors of a measurement system or process that cannot be adequately captured or identified by precision alone. This is a step in the right direction. Ultimately, what is needed is a harmonization of the ITRS definition with those outlined in the *Guide to the Expression of Uncertainty in Measurement* (GUM) [3]. Other techniques used by the semiconductor industry to achieve process control include tool matching and fleet matching [4,5], wherein the performance of instruments is compared and harmonized.

The nascent nanotechnology industry does not have the luxury of de-emphasizing accuracy and traceability. At the nano-scale, physical dimensions play a great role in determining natural phenomena. In some cases, to get a complete answer to a characterization problem, instruments based on different technologies are used. The only way to ensure the validity of such results is through direct traceability to the *SI* or through the use of a common instrument that is traceable to the *SI.* A concept that could be applied to non-semiconductor fab based nanometrology is that of the reference measurement system (RMS) [6]. The National Institute of Standards and Technology (NIST) in conjunction with SEMATECH has

developed an RMS [7,8] that is used to provide traceable measurements for inline metrology tools. This implementation is a critical dimension atomic force microscope (CD-AFM) with traceability to the *SI* meter.

The system has since supported numerous applications, among them instrument evaluation and parameter verification [9-11]. Details of the RMS implementation and performance are well documented [7,8,12-14]. In this paper we will focus on some of the strategies used to achieve accuracy for different types of measurands within an RMS and examine some important factors when selecting reference instruments. These strategies are important not only for inline metrology tools in the semiconductor fab, but for non-fab nanoscale instruments as well. We present results of a recent evaluation of linewidth and feature height using two CD-AFMs and a calibrated AFM with displacement interferometry in all three axes.

2. CD-AFM RMS OVERVIEW

The RMS implemented by NIST and SEMATECH works as follows: a set of samples, which could be from a national measurement institute or internal to the organization, is used to calibrate one of the better performing instruments, which is designated as the reference instrument. This instrument is then used to calibrate a set of wafers that is used to monitor inline tools. Overall, the system includes the instrument, the calibration samples, the metrology transfer methods, and the uncertainty analysis techniques used to ensure traceability to the SI. A key criterion for selecting a CD-AFM as a reference instrument is the relative insensitivity of measurement results to different materials. Figure 1 shows a schematic of the RMS strategy as implemented by NIST and SEMATECH.

2.1 Accuracy and Traceability

According to the Vocabulary of Basic and General Terms in Metrology [15], traceability is defined as "the property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons, all having stated uncertainties."

In lithography metrology, in addition to the issues of device performance listed above, there are other reasons why accuracy and traceability are needed. When evaluating the consistency of measurements made by different instruments or at different locations, it is critical to make sure that all the measurements are based on the same stated reference value.

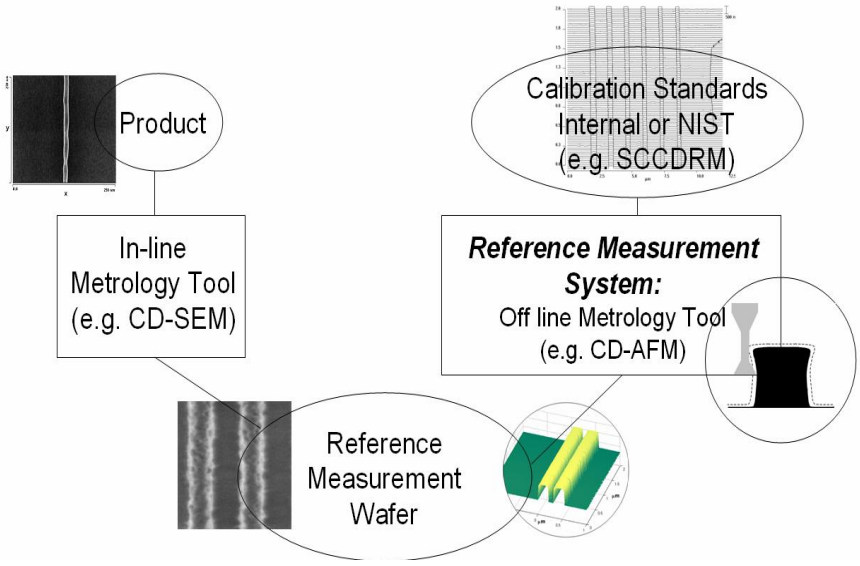

Figure 1: A schematic of the CD-AFM based RMS as implemented by NIST and SEMATECH.

This is the only way to verify that one is actually comparing measurements of the same thing. Accurate and traceable measurements are also needed when evaluating the performance of different high volume measurement instruments, when verifying the reliability of lithography models such as optical proximity correction (OPC), and when evaluating new instruments or verifying the usefulness of new parameters or new architectures.

2.2 Calibration Samples

The CD-AFM-based RMS provides rigorously traceable measurements for linewidth, height, pitch, and sidewall angle. This set of measurements lends SI traceability to a wide range of production relevant samples. To achieve the "unbroken chain of comparisons," a series of samples and analysis techniques are used. In the RMS, one of the samples used is the single crystal critical dimension reference material (SCCDRM). The features on the SCCDRM samples are preferentially etched into a (110) silicon-on-insulator substrate. This produces sidewalls that are close to vertical, which helps minimize the uncertainty of the measurements. The features on the SCCDRM range from 250 nm to less than 20 nm, ensuring that the calibration is useful for different purposes.

The sample derives its traceability from images taken with the transmission electron microscope (TEM). TEM is currently the preferred method for imaging the SCCDRM because some of the imaging modes can produce lattice-resolved images that have scale traceability to the SI definition of length. Our approach is to obtain an image of a cross-section of the crystalline lattice of these features and use them for calibration. The characterization approach is as follows. A series of samples are measured by the CD-AFM, a few of these samples are cross-sectioned and imaged with a TEM, and the widths are determined by counting the lattice columns. The vertical sidewalls ensure that the atoms across the width are relatively uniform.

While the SCCDRM serves as the primary calibration sample, the AMAG sample [10] is the main transfer metrology sample for in-line measurements. The sample has a series of features with different widths and pitches. Usually, the features are printed in a focus-exposure matrix (FEM), thus providing a range of linewidths from several hundred nanometers to less than 20 nm. A key benefit of this fabrication strategy is that the sample has a wide range of feature sizes that represent different measurement conditions. In addition to metrology transfer, the AMAG serves as an evaluation sample for other instruments such as CD-SEM and optical critical dimension instruments [11]. Here, selected features with known uncertainties are used to evaluate production instruments to see if they meet performance specifications [16]. Figure 2 shows some of the features on the sample.

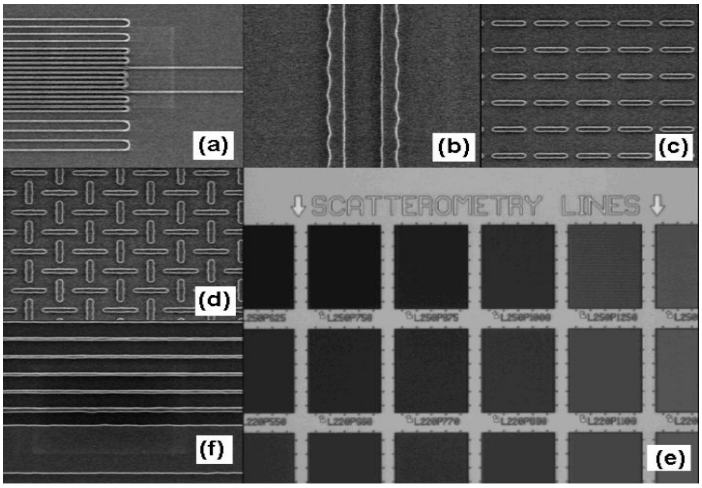

Figure 2: Images of some of the test structures on the AMAG sample (a) Isolated width features: multiple pitches and widths, (b) LER test patterns, (c) and (d) Line end and line pullback features, (e) and (f) Line gratings: multiple pitches and widths.

2.3 Error Sources

To evaluate the uncertainty of the instrument, we look at all possible sources of error. For the TEM measurements, these include the location of the TEM cross-section and edge detection of the line. The AFM value is an average of several scan lines that overlap the TEM location. If the sample exhibits line edge roughness (LER) the uncertainty in linewidth due to uncertainty of this location increases. LER also increases the uncertainty of determining the edge. The lattices on

a TEM image show a view of the average column information of several planes rather than the top plane. Depending on the angle of the cross-section, all of the lattice information may not necessarily be on the same plane. The effect of this is usually more pronounced at the edges where some of the lattice positions may appear faded, making it difficult to determine the exact edge location. Figure 3 shows a TEM micrograph that helps illustrate this. The error associated with the above two issues can be substantially reduced by using the average of several measurements rather than one [7,17]. Other sources of error include spherical aberration of the optics [18].

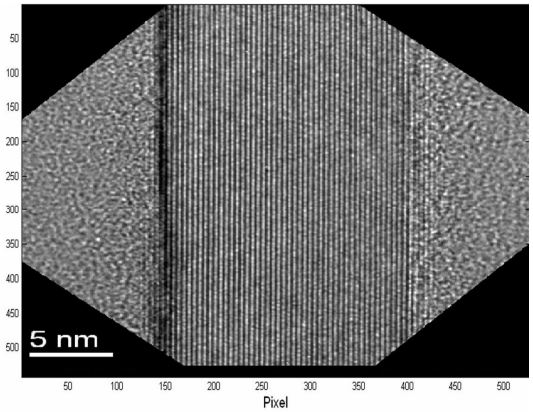

Figure 3: A TEM micrograph of a width sample. The poorly defined edges of the feature make it difficult to determine the width of the feature. This could be because some of the lattices are from a different plane or from beam damage at the edge of the feature. The (111) planes are imaged as lines, rather than as individual atoms, to facilitate counting the lattice.

The errors associated with the CD-AFM are mainly attributed to the scanning motions of the system and to the tip. These include the uncertainties associated with the scale calibration, scale non-linearity, and tip width calibration [12]. The non-linearity term comes from small changes in the scale factor when an instrument is measuring different ranges. The uncertainties associated with the tip are most important when measuring linewidth. These include the width and the shape of the tip.

3. UNCERTAINTY ANALYSIS AND SELECTING REFERENCE INSTRUMENTS

In general, the standard approach to uncertainty budgets adopted by NIST [3,19] is to develop an estimated contribution for every known source of uncertainty in a given measurement. Terms attributed to both the instrument used and the particular specimens measured are included.

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 of potential error sources in the measurement. All of these 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. A coverage factor of k =2 is used here and corresponds to approximately 95% confidence for a normal (Gaussian) distribution. Note that the combined uncertainty from each stage in the unbroken chain of comparisons is factored in when evaluating the uncertainty of any measurement. This is the propagation of uncertainties approach, where the errors include not only those of the current measurement but also uncertainties.

Important criteria for selecting a reference instrument are an unambiguous definition of the measurand, clear understanding of the error sources, and low measurement uncertainty. An instrument that produces measurements with the lowest Type A uncertainty may not necessarily be the best reference for a particular measurand. This is highlighted when several candidate instruments with similar standard uncertainties are considered for designation as a reference. In such scenarios, all of the individual uncertainty components play a key role. For each instrument, the uncertainty component that has the greatest effect on the measurand in question becomes the deciding factor. We refer to this error source as the major component (MC) [20]. This is illustrated with Table 1, which shows uncertainty sources for measurements by two instruments. Values for the uncertainty components are indicated with I and J, where I is smaller. The Type A uncertainty values for both instruments are the same, but some of the other components have different

values. In Table 1, if the measurand is width, then the tip calibration component would be an MC. In addition, if the range of required width measurements is large, then the linearity component is also an MC.

The flowchart in Figure 4 shows an outline of a procedure for selecting reference instruments using major components. It starts with specifying the parameters to be measured and identifying suitable test structures for those parameters. Next, the relevant uncertainty sources (major components) for the parameters are identified. The uncertainty budgets for the instruments are then reviewed and a selection is made based on the MC. When results are inconclusive, the suitability of the test structures is re-evaluated. Sampling plans and measurements then follow.

Table 1: Example uncertainty budgets for two different instruments

		Tool 1	Tool2
Type A			
	Repeatability, reproducibility, sample uniformity.	1SD	1SD
Type B			
	Tip - zeroth and higher order	I	I
	Scale factor (linear term)	I	I
	Non-linearity	I	J
	In-sample plane cosine error	J	I
	Out-of-sample-plane cosine error	I	I

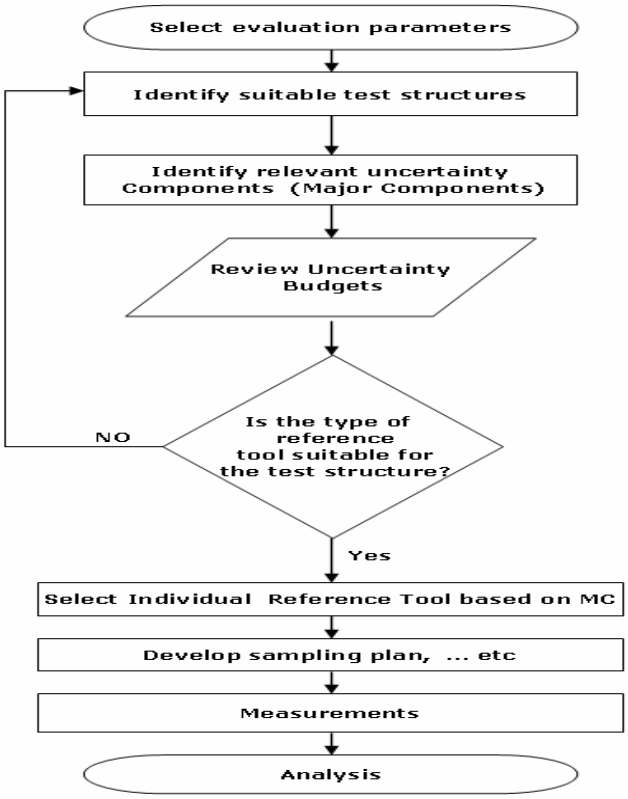

Figure 4: A flow chart for the general approach to using an uncertainty budget for deciding what reference measurement system to use.

This approach of looking beyond the overall uncertainty value at the major components is motivated by the need to use and maintain multiple reference instruments. Some of these instruments may have implicit agreement but differ in their ability to measure specific parameters. This method of selecting a reference instrument is fully extendible to different instruments if the major uncertainty components of those instruments are well understood. Previous work has been done on how to use different metrologies in an RMS environment [21].

4. MEASUREMENT COMPARISONS

To ensure that the accuracy and traceability of the RMS is maintained, we periodically conduct comparison measurements with other traceable instruments. These measurements serve two main purposes: to ensure that the instruments that derive their calibration from the same samples are in agreement, and to crosscheck our measurements with samples that derive their calibration from independent sources. In this section, we present results of some of our comparisons using two different CD-AFMs for linewidth and a calibrated AFM for height.

Figure 5 shows results from a C-AFM [14], an instrument with direct traceability to the SI through displacement interferometry and CD-AFM. The samples have nominal 20 nm, 70 nm, and 300 nm step heights. The CD-AFM height measurements were obtained in 1D mode. The results show excellent agreement over a broad measurement window.

The width results shown in Figure 6 are from two different CD- AFMs and with samples that range in size from 18 nm to 140 nm. Width calibration is more complicated because it depends not only on the scale calibration but also on the tip sample interaction. The data show good agreement but also highlight some of the perils of width calibration. The features that show the smallest residuals have sidewall angles that are close to vertical [8]. In both CD-AFM and TEM measurements, non-vertical sidewalls contribute to the uncertainty of the width measurements [23]. The 18 nm feature was also measured using two modes of TEM (high resolution [HR]-TEM and annular dark field [ADF]-TEM), and the results are shown in Figure 7. This set of TEM measurements was carried out to see if there are variations when different modes of the TEM are used for dimensional calibration [22] and to continually refine our techniques with on-going research. The CD-AFM results shown in Figure 7 derive their tip width traceability from different TEM calibrations [22].

These comparisons are presented to highlight the types of activities that are needed to maintain reference instruments; these activities should not be limited to the same types of instruments.

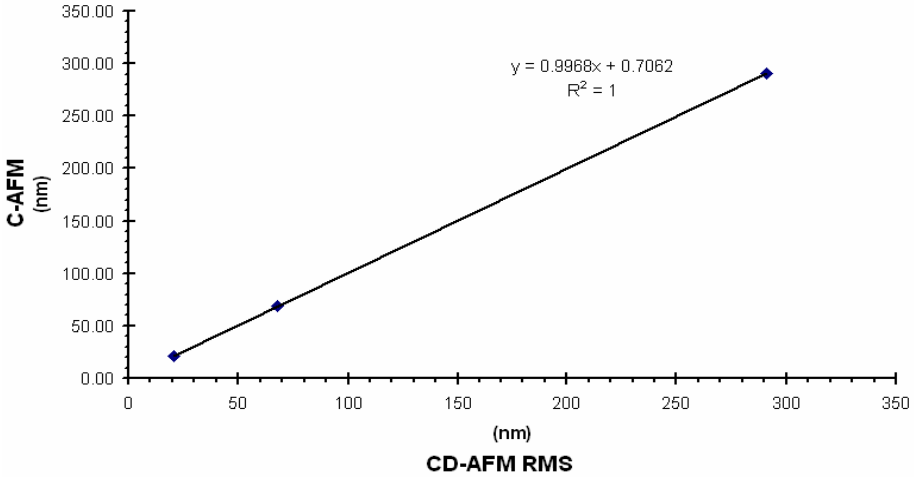

Figure 5: Height data for the CD-AFM RMS 1 and the C-AFM.

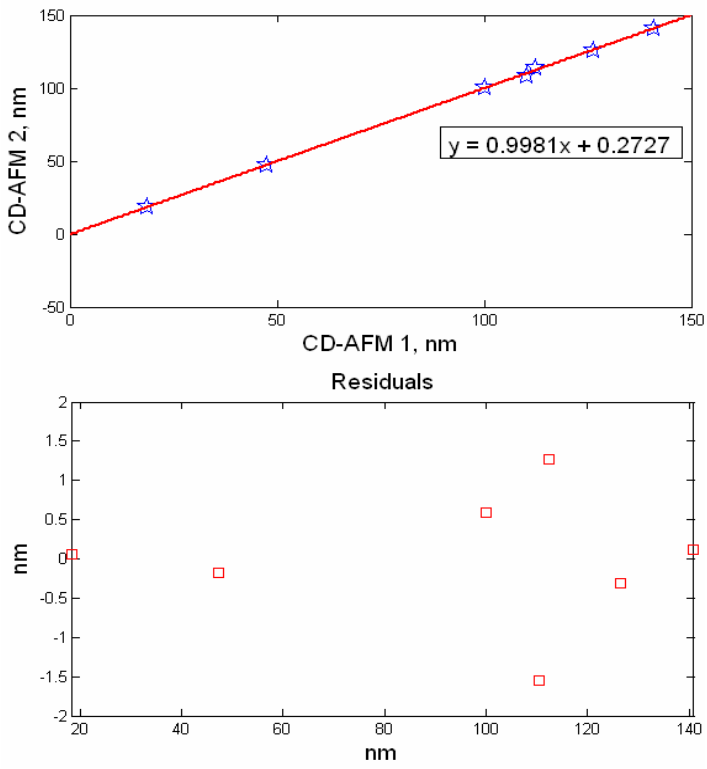

Figure 6: Width comparison data for two different CD-AFMs.

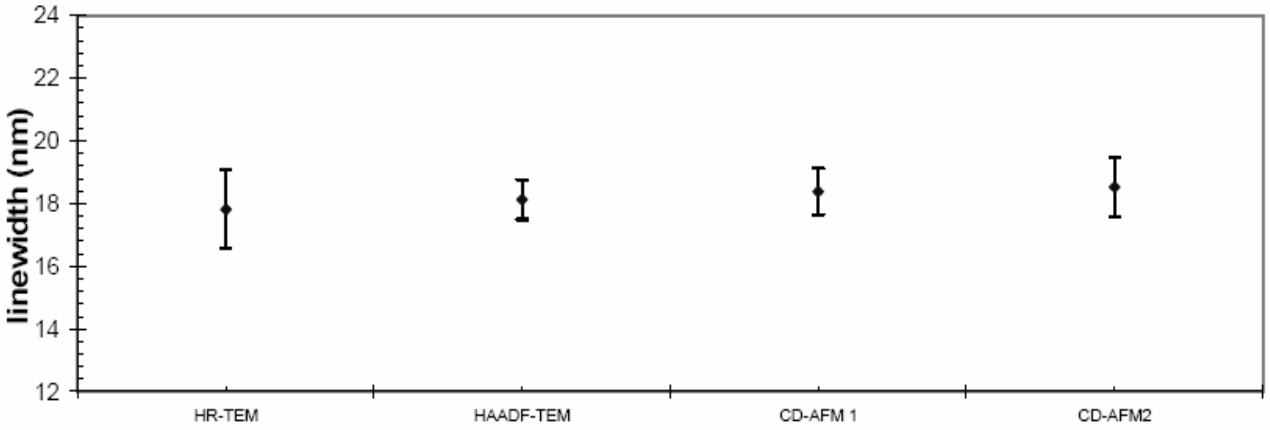

Figure 7: Preliminary results for measurements for HR-TEM, HAADF-STEM, CD-AFM1, and CD-AFM2. Notes: The uncertainties shown are all standard uncertainties $k = 1$. Those for the TEM results include only the uncertainty in edge determination. The uncertainties for the CD-AFM results include all components except for an LWR/navigation term for direct comparison with the TEM values. Note also that the CD-AFM results derive their tip width calibration uncertainty from the independent series of HRTEM samples used in the SCCDRM project [8].

5. OUTLOOK

Some of the key challenges facing CD-AFM based RMS metrology include the need for smaller tips and better tip reconstruction. Good progress has been made on both fronts through the introduction of new software [23], smaller tips such as carbon nanotubes (CNT) [24], and ways to validate tip reconstruction [25].

Carbon nanotube-based tips have the potential of becoming the tip of choice for AFM dimensional metrology. Their small sizes are suitable for tight trenches, and when mounted vertically, they can image features without introducing an apparent sidewall angle into the image. This is highlighted by the image in Figure 8, which shows profiles of a feature scanned by a CNT tip. The CNT tip was destroyed during measurement, allowing us to see the difference between portions imaged by the CNT and portions imaged by the silicon tip supporting it. The high aspect ratio of CNT tips should also be useful when imaging deep features. However, CNT tips can also flex during measurements, and the interaction of the tip with the sidewalls produces a range of measurement artifacts [26], is not yet well understood, and is an important subject for research.

We have been trying to determine the utility of CNT-based tips for critical dimensional metrology. To this end, we conducted a series of measurements using them. Our objective was to examine the type of variation that could be obtained using these tips. The focus was specifically on the stability of the CNT tips for features such as height, width, and sidewall angle. All the measurements were performed in 1D mode on a 2 μm tip sample. Here the focus was not on size, but on building some understanding of how the tips work.

Figure 9 shows one standard deviation results for height and width from 21 tips. Each value is from 10 separate images. For height, the standard deviation values range from 0.15 nm to more than 1.5 nm, for width they range from 0.5 nm to more than 6 nm. For height, all of the tips that produced a standard deviation of less than 0.5 nm were less than 400 nm long. For width, 90% of the tips that produced standard deviation values of 2 nm or less were also less than 400 nm. This strongly suggests that height is a key factor in the stability of CNT-based tips. In another set of measurements, we restricted all our measurements to tips less than 350 nm long. The results are shown in Figure 10, where all the standard deviations are less than 0.7 nm. Given the expectation that longer CNT-based tips will play a key role in imaging high aspect ratio features, more work is needed to determine if there are conditions where they can be imaged without large measurement variations. Note that while smaller variations are obtained with shorter tips, the values are still much larger than is needed for CD measurements.

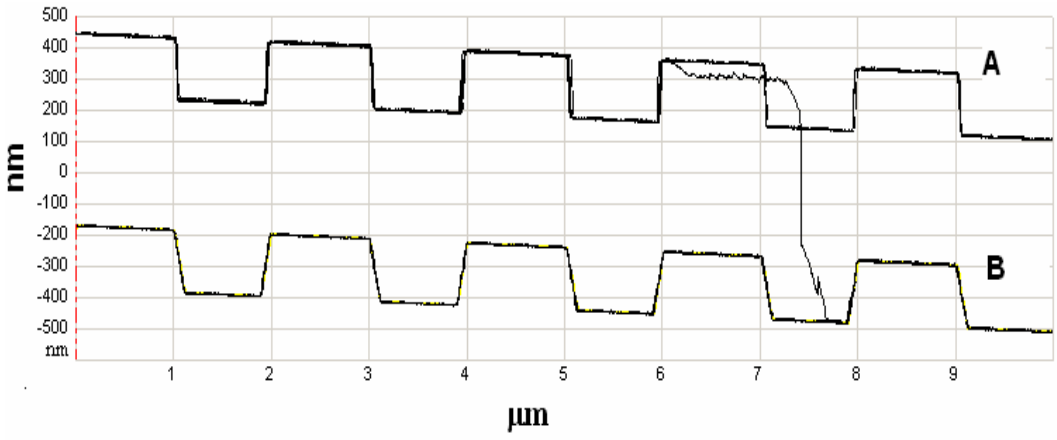

Figure 8: Profiles of a 2 μm pitch sample. The A profiles were imaged by a CNT tip, while the B profiles were imaged after the tip was damaged. Note the difference in sidewall angle.

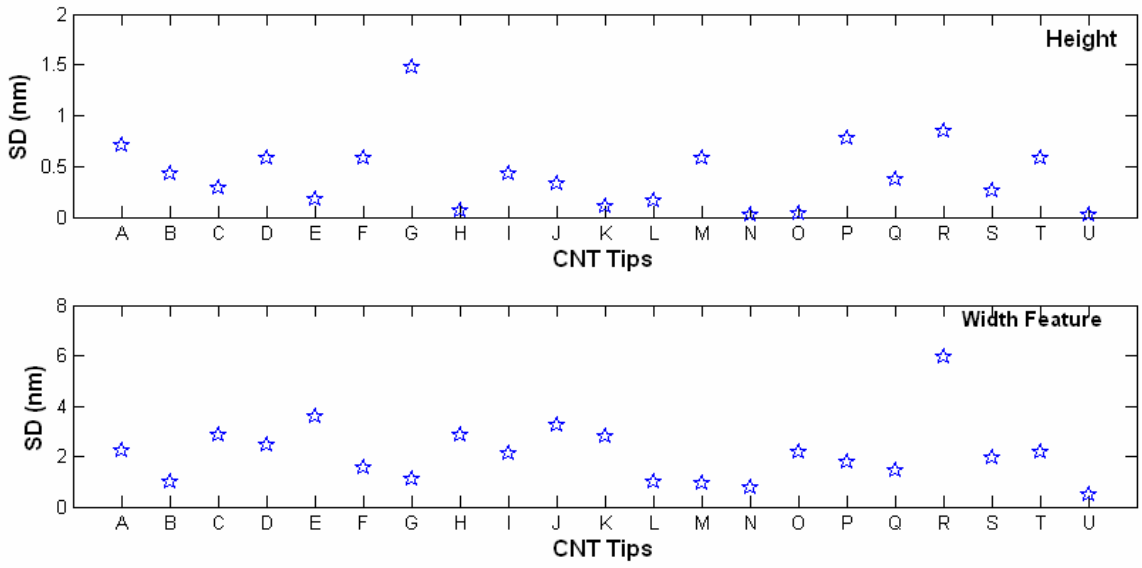

Figure 9: Standard deviation values from height and width measurements using a number of CNT-based tips.

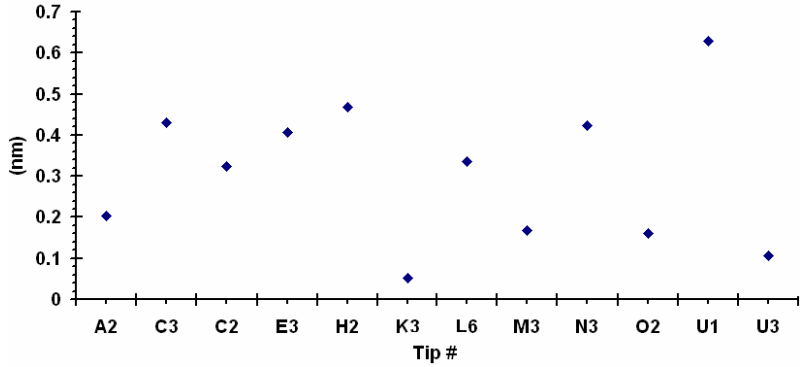

Figure 10: Standard deviation values from height measurements using a CNT-based tip. All the tips are less than 350 nm long.

6. SUMMARY

Semiconductor lithography metrology is at a stage where accuracy is becoming more important. One of the methods that could be used to introduce and maintain accurate measurements in a fabrication environment is a reference instrument. We described some of the accuracy considerations for an RMS, and some criteria for selecting one. This involves the use of uncertainty analysis and components to determine the most suitable reference instrument for specific measurements. We also examined some of the error sources in our implementation of an RMS, with emphasis on areas where more research is needed. We conclude by presenting recent results from our analysis of CNT-based tips for critical dimension measurements. Our results, while promising, show that more work is needed. Our current CNT-based tip research focuses on identifying measurement conditions that produce less variation in CD measurements.

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