Reference metrology for nanotechnology: significance, challenges and solutions

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Abstract

Metrology and control of critical dimensions (CD) are the keys to the nanotechnology success. Modern nanotechnology and nanometrology are largely based on knowledge earned during the last 10-20 years of semiconductor technology development. Semiconductor CD metrology entered the nanotechnology age in the late 1990's. Work on 130 nm and 90 nm node technologies led to the conclusion that precision is an insufficient metric for metrology quality assessment. Other components of measurement uncertainty (MU) must be considered: (i) sample-to-sample measurement bias variation, (ii) sampling uncertainty and (iii) sample variation induced by probe-sample interaction. The first one (sample dependent systematic error) is common for "indirect" and model-based CD metrologies such as top-down and cross-sectional scanning electron microscopy (SEM) and optical scatterometry (OCD). Unless special measures are taken, bias variation of CDSEM and OCD could exceed several nanometers. Variation of bias and, therefore, MU can be assessed only if reference metrology (RM) is employed. The choice of RM tools is very limited. The CD atomic force microscope (AFM) is one of a few available RM tools. The CDAFM provides sub-nanometer MU for a number of nanometrology applications. Significant challenges of CDAFM remain: (a) probe finite dimensions are limiting characterization of narrow high-aspect spaces; (b) probe flexibility complicates positioning control; (c) probe apex sharpness limits 3D AFM resolution; (d) lifetime of atomically sharp probes is too short; (e) adsorbates change properties and dimensions of nanometer-sized objects considerably, etc. We believe that solutions for the problems exist. In this paper we discuss role of RM in nanometrology, current RM choices, challenges of CDAFM, and potential solutions.

Key words: accuracy, reference metrology, critical dimensions, nanometrology, bias, CDSEM, CDAFM, OCD, relative accuracy, absolute accuracy

1.0 Introduction

Slowly, the effects of poor metrology are being realized in the semiconductor fabrication industry[1,2,3]. While the term "accuracy" is seen more frequently than ever before[4,5,6], there must be a critical need to meet the challenges facing semiconductor metrology to confront the costly and technically difficult solutions for more accurate metrology[7]. Semiconductor engineering manufacturers need fast and accurate measurements for their patterning production lines as well as patterning development. The objectives of this paper are to present the significance of reference metrology in supporting manufacturing and development patterning, to review existing reference metrology technologies, explain why the authors think there is significant leverage with scanning probe technology by pointing out its strengths and deficiencies, and finalizing with a discussion of some reference metrology solutions. Thus, this paper is a hybrid of a review paper and containing new material. The review is helpful in developing new thoughts on how to

solve the thorny problem of accurate metrology. The most promising candidates for reference metrology and their challenges are considered.

2.0 The Significance of Reference Metrology (RM)

Perhaps the best way to begin a discussion on the importance of reference metrology is to show a few recent examples of how "workhorse" metrology has shown deficiencies in important semiconductor applications. The workhorse metrology refers to the kinds of metrology technologies which are dominant in the manufacturing setting, such as the CDSEM and the growing implementation of scatterometry, also referred to as optical CD (OCD). In a 2009 SPIE keynote paper by Rana, *et al.*[8] it is shown how the CDSEM experiences various degrees of uncertainty as a function of measurand complexity. Rana shows this dramatically in Figure 1

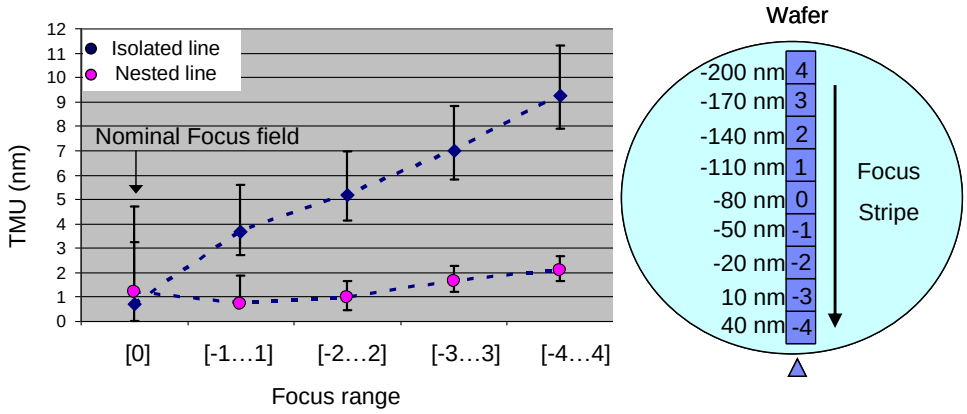

Figure 1. The increased CDSEM measurement uncertainty as a function measurand complexity induced by scanner focus.

where Total Measurement Uncertainty[9] (TMU) of the CDSEM is shown as a function of the feature-shape complexity caused by the scanner focus and the very short depth of focus of high numerical aperture scanners. The degree of out-of-scanner focus is shown in the sketch to the right of the graph in figure. Note that it is the measurement of the isolated line which presents the most significant challenge for the CDSEM. TMU is an IBM-defined metric in units of nanometers which captures additional (beyond precision) components of uncertainty of the measurement system under test, in this case the CDSEM. A RM is required to evaluate the TMU of a system under test. In this case the CDAFM was used as the trusted RM.

Another example of the importance of RM comes from the evaluation of scatterometry. Figure 2 shows results from an earlier IBM study[10] where the RM is a combination of the CDAFM with that of the CDSEM to evaluate a scatterometer measurement system, OCD. The left graph shows the 1st stage of calibration where the suitability of the CDSEM is evaluated by the CDAFM as the RM. This analysis resulted in a TMU estimate of ± 1.75 nm, which happened to be equal to the input uncertainties of the CDAFM and the CDSEM. The graph on the right in

Figure 2 shows the subsequent use of the CDSEM as the reference metrology for the OCD under evaluation. While this evaluation corresponds to an OCD evaluation in the early 2000's, the example shows inadequacies of the OCD measuring large pitch versus smaller pitched linewidth features. Even though careful attention was made to average the effects of the OCD grating variation by averaging 49 CDSEM measurements within each grating, the TMU estimate still resulted in a value of ± 4.7 nm. The increased scatter corresponding to the 595 nm-pitched grating seems to be a large contributor to the TMU value.

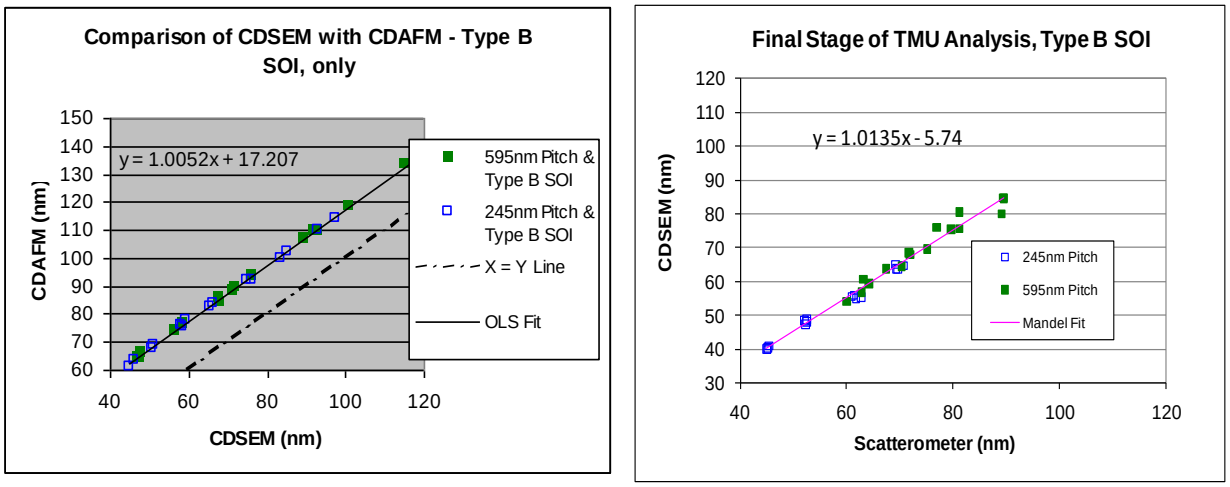

Figure 2. An example of using two stages of RM. First stage evaluating the CDSEM with the CDAFM as the RM, and the second stage using the CDSEM as the RM for the scatterometer.

The following two examples demonstrate employment of RM for evaluation of TMU of OCD for CD and sidewall angle (SWA) measurements of a nominal 40 nm wide poly-Si line[11]. Figure 3 presents the correlation between OCD and reference data (CDAFM) for the gate bottom CD and SWA of a 260 nm pitch structure. The total number of pre-calibrated sites is 170. The total number of OCD measurements for the fleet of 3 baseline tools and 7 repeats is 3570. From the results shown in Figure 3, TMU analysis shows that fleet measurement uncertainty (MU) for bottom CD measurement is about 2% of the nominal CD. For a process tolerance (T) of ± 4 nm, the U/T ratio is 0.2. This level of measurement uncertainty is acceptable from process control prospective. As a general rule of thumb, the measurement uncertainty should only consume a maximum of 20% of the process tolerance budget. The data from Figure 3 also shows the OCD fleet TMU for SWA measurements is a nominal ± 0.8 degree. This level of uncertainty (U) is not acceptable since SWA process tolerance for that technology was ±1.6 degrees. This leads to U/T ratio of 0.5 which exceeds the required limit of 0.2 for the ratio. Figure 3 shows that OCD single tool precision is ± 0.2 degrees. If this single tool precision estimate were used to estimate the U/T ratio, a result of 0.2/1.6 = 0.12 would significantly overestimate the SWA measurement capability of the OCD. There is a danger here. Should only a single tool precision of ± 0.2 degree be considered, the OCD would be erroneously accepted as SWA control metrology. On the contrary, if TMU of ± 0.8 degree is estimated (using RM data) the OCD measurement would

be rejected as a valid process control for SWA. Clearly, this shows the importance of using an uncertainty estimate instead of a precision estimate alone for estimating a measurement technology's ability to control a process.

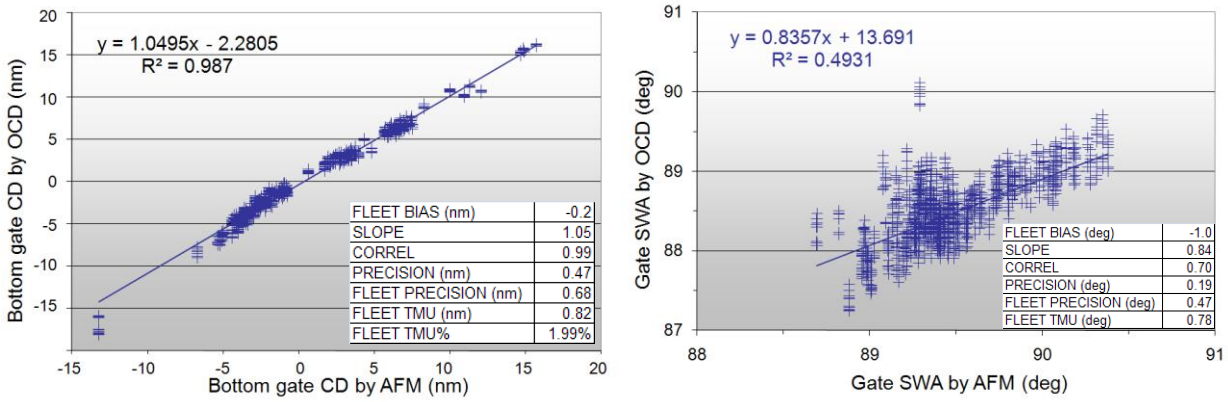

Figure 3. The correlation between OCD and reference data for the gate bottom line CD (left) and SWA (right).

3. Choice of Reference Metrology

The proper choice of a reference metrology can be the most daunting part of implementing accurate metrology. In the example shown in Figure 2, the complexity of the reference metrology *system* is shown as the combination of the CDAFM and the CDSEM to provide not only accurate measurements, but accurate measurements in sufficient quantity. If the feature to be measured is sufficiently complex, the CDSEM, and possibly the CDAFM usage could be challenged as a valid RM. Historically, the top contenders for RM have been the classical high-resolution laboratory instruments such as cross section SEM (XS SEM), transmission and scanning transmission electron microscope (TEM and STEM, respectively), and the 1D-AFM and CDAFM. The field of candidates are rounded out by the focused ion beam (FIB) and dual beam focused ion beam (DBFIB), and the newcomer helium-ion microscope (SIM). Every measurement technology has its strengths and weaknesses as qualitatively demonstrated in the graph from the 2004 SPIE publication[12] shown in Figure 4. The graph of this figure shows an arbitrary ranking from 1 to 9 of three important metrology attributes with 9 being the best: intrinsic relative accuracy, sampling efficiency, and throughput. The x-axis purposely lists the spectrum of measurement technologies from the most automated measurement to the most labor intensive measurement. Every measurement requires some amount of interpretation to yield the desired measurement. *Intrinsic relative accuracy* refers to the amount of interpretation required. *Sampling efficiency* refers to the amount of sample averaging built-in to a single measurement. For example, a single OCD measurement yields an averaged measurement over a region the size of the spot size, whereas a cross sectional measurement is contained within a single sliver of the intended feature to be measured. To take this a step further, it takes considerable energy to acquire a sample which sufficiently represents the product variation for any type of cross section

measurement technology. It is noteworthy that the DBFIB technology is an important step in breaking away from this constraint by allowing a succession of cross section cleaves to be measured. It is also noteworthy from the same 2004 paper from IBM, that the CDAFM has a good balance of attributes showing a strong combination of good intrinsic relative accuracy, sampling efficiency, and throughput. Table 1 below expands upon the three major attributes by considering relative versus absolute accuracy, measurement alteration (e.g. probe-induced damage), and navigation accuracy.

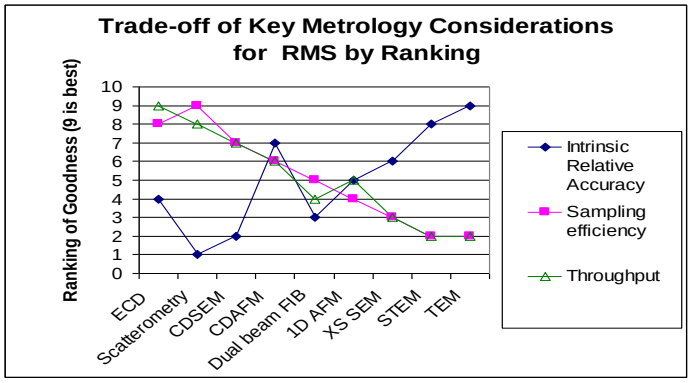

Figure 4. Plot showing each potential RMS contender ranked by major attribute.

Measurement technology	Important metrology aspects						
	Intrinsic accuracy		Multiple XS	Measurement alteration	Sample damage	MAM time	Navigation Accuracy
	Relative	Absolute					
Dual Beam FIB	Yes	No	Yes	Unknown	Yes	Ok	Ok
TEM	Yes	Yes**	No	Unknown	Yes	Bad	Bad
CDAFM	Yes*	No	Yes	Slight	None	Ok	Ok
XS SEM	Yes	No	No	Some	Yes	Bad	Bad

Table 1. Comparison of the top 4 reference metrology pros and cons. *Must watch for tip artifacts. **Can be irrelevant if product variation obscures the absolute accuracy acquired from the counting of lattice spacing.

A quantitative way to search for the best RM technique would be an attempt to estimate MU of various CD metrology techniques[13]. Below in Table 2, an updated version of MU estimates for 5 metrology techniques is shown. In brief, low sample-to-sample bias variation (intrinsic relative accuracy) and high sampling efficiency make CDAFM a good candidate for linewidth reference metrology.

	6S Scale Accuracy (%)	6S CD Repeatability (nm)	Bias Variation (nm)	6S LWR (nm)	Single Site 6S TMU (nm)	Gate CD Tolerance (%)	Single Site TMU/T	Typical Sample Size	Wafer Average 6S TMU
TEM	4	2.8	0	9	**9.5**	20	**1.49**	5	**4.41**
DualBeam	4	2.8	2	9	**9.7**	20	**1.52**	5	**4.84**
AFM	1	2.0	0.5	1.8	**2.8**	20	**0.43**	9	**1.08**
OCD	0	0.6	2	0	**2.1**	20	**0.33**	27	**2.00**
SEM	1	1.0	2	1.8	**2.9**	20	**0.45**	9	**2.14**
Gate CD	32			*LWR*		1.5			
				Number of scans		24			

Table 2. Estimated uncertainty of line CD measurement using 5 conventional metrology techniques.

Any one of these RM candidates could be a treatise on their own. For purposes of this paper, the CDAFM is selected as a focus of further exploration because of the technology's promising properties of relative accuracy, sampling efficiency, navigation accuracy, and sample damage.

4. Unique properties and challenges of the CDAFM

In this paper, the CDAFM is defined as a scanning force microscope which has the ability to receive feedback and servo simultaneously in a combined vertical and horizontal direction. Of the four RM candidates listed in Table 1, the CDAFM is unique in its probe. It is the only mechanical probe measurement system and the probe is intimately connected to its method of sensing, or detection. The other three contenders are e-beam based probes. It is not surprising that the CDAFM mechanical probe is a very important part of the entire scanning system. This unique feature of AFM technology is simultaneously responsible for AFM's advantages and also its disadvantages. The first and the main advantage of AFM is a nanometer size of its probe. Probe apex may have true atomic size (example, scanning tunneling microscope). However, it is a real challenge to keep the probe atomically sharp for a long time. All particle scattering-based metrology techniques have a rather large probe (interaction volume) size of at least a few tens of nanometers (cloud of scattered electrons inside the sample). Large probe size makes particle scattering based methods sensitive to sample proximity effects.

The second significant advantage of the "mechanical" AFM technology is the extremely local (short range forces) interaction of probe and sample. In the ideal case, this is true sub-nanometer atom-to-atom interaction. And yet this very local atomic interaction is strong enough to be detected by macro-world feedback system. In other words, the AFM sensor is a low energy, neutral, and fully controlled in 3-dimensional space atomic probe. What could be better?

Having a mechanical probe of a nanometer or even atomic size introduces an addition layer of challenges affecting CDAFM accuracy. There are several aspects of the probe which require physical understanding. The movement of the probe and its feedback for sensing a feature surface and following the surface is one important aspect. Another aspect is how the probe moves in response to the driving force given its size, shape, and material. Lastly, the interaction of the probe with the sample surface both physically from a surface physics perspective as well as from the probe shape and the feature shape need to be understood to extend the capability of a scanning mechanical probe.

In this paper we examine only some critical challenges of the nanoscale CDAFM.

4.1 Probe size and composition challenges

An AFM image is always a dilation of the feature of interest and the probe shape[14]. Therefore, one needs to know an exact shape of the probe to extract accurate feature dimensions from the AFM image. Three types of probes are used with CDAFM today: (a) flared, (b) cylindrical, and

(c) Y-shape probes are all shown in Figure 5. Dimension in the fast scan, or X direction, and length (Z) are critical probe characteristics. Carbon nanotubes (CNT) mounted on a Si cantilever are often used as cylindrical probes. In the later case, deviation of CNT from the vertical axis due to improper mounting of the CNT to the cantilever is also critical probe parameter.

Today, 20 nm flared and 22 nm Y-shape probes are commercially available. Effective length of the probes is limited to 150 nm to maintain sufficient probe stiffness. Crystalline Si probes are available with silicon nitride or carbon coating. Chemical-mechanical wearing is the most common mechanism of AFM probe degradation. Therefore, probe coating should be selected depending on sample material.

Large variety of cylindrical probes is commercially available. The smallest possible diameter of c-Si probes is 15 nm with length 150 nm due to a physical limitation of silicon. Carbon coated 15 nm probes are commercially available[15]. The smallest diameter of CNT probes available today is 20 nm with length limit of about 1 micron.

Accurate (SI-traceable) measurement of the diameter of cylindrical probe is a problem. Measurement uncertainty of commonly used high-resolution TEM is unknown and can be significant for measurement of cylindrical object (edge definition is conditional). Also, it is usually assumed that CNT or c-Si probe is uniform. However, in reality the probe can be covered by amorphous carbon or native SiO_2 or any other layer of adsorbates including but not limited to H_2O. Two reference metrology instruments, TEM and CDAFM, treat these "additional" layers differently. Most likely they are transparent (invisible) for TEM but definitely "visible" by AFM. Recent studies[16] indicate that discrepancy in diameter measurements using TEM and CDAFM can be as large as 10 nm. The problem is not solved yet.

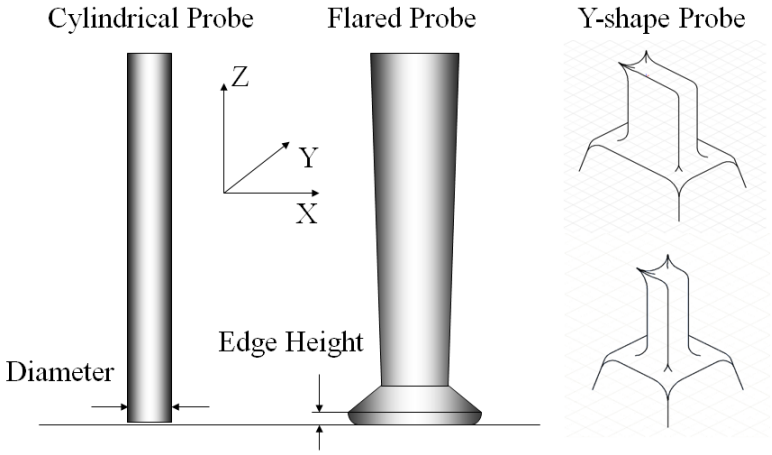

Figure 5. Three the most common types of probes used with CDAFM.

Accurate measurement of cylindrical probes using CDAFM is not trivial. Usually, a pre-calibrated vertical parallel structure (VPS) or linewidth standard are used to measure cylindrical

probe diameter. There are commercially available VPS and linewidth standards for this purpose[17]. Several measurement uncertainty components should be considered in this case:

- Probe or/and cantilever angular misalignment from vertical axis (Figure 6, left)
- Probe slipping over top corner of VPS (Figure 6, middle)
- Probe snapping to the sidewall of VPS (Figure 6, right)

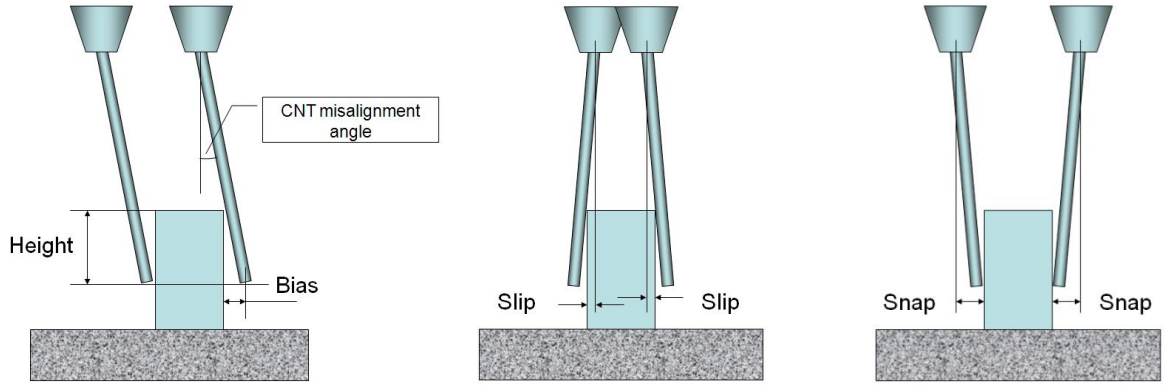

Figure 6. Impact of probe misalignment (left), slipping (center) and snapping (right) on diameter measurement uncertainty.

For thin and long probes bending (slipping and snapping) can be as large as several nanometers. In many practical cases probe bending or snapping to sidewall of deep and narrow structure (trench or hole) is, in fact, a major contributor limiting AFM capability[18]. Therefore, control of probe-sample interaction becomes increasingly important during imaging of nanometer scale high-aspect ratio structures, where the probe stiffness can be overcome.

4.2 Probe coating, probe and sample adsorbates and scan effects

Probe coating is used effectively in the past to minimize chemical-mechanical wear of AFM probes. For example, carbon coating of flared Si probes improves their lifetime from tens to several hundred sites measured[19]. Figure 7 shows probe wear as a function of number of etched trench measurement sites scanned with a carbon-coated, silicon-flared probe. Carbon and Si nitride coating is also known to improve probe wearing and speed of scanning of poly-Si lines through reduction of probe-sample "sticking" caused by chemical interaction between Si probe and poly-Si sample surface[20]. Very little is known about exact mechanisms of probe protection since most often processes of coating are proprietary. Nevertheless, some results have been published in the past[21].

Several reasons exist why pre-conditioning of sample and probe and imaging in controlled ambient may be required in the future for optimal performance of CDAFM. A single monolayer of adsorbates may cause a few angstroms per side change in line CD. Adding to this uncertainty, potential probe width variation caused by surface adsorbates may lead to significant, nanometer scale uncertainty of the linewidth CD measurement. Therefore, preserving sample and probe surfaces in stable, unchanged condition is becoming a must for achieving desired sub-nanometer

precision of CDAFM. Practice of CDAFM operation provides many examples (unfortunately undocumented) of systematic probe width and linewidth variations depending on pre-history (a few days) of probe-sample system. Imaging in a controlled ambient (temperature, humidity, chemistry, etc.) also is expected to bring additional tool calibration stability and reduced system drift. Another demanding reason to control surface condition of probe and sample is an impact of probe-sample interaction on probe "sticking" and, hence, on CDAFM calibration, resolution, speed of scanning, probe wear and overall AFM capability to image narrow high aspect ratio trenches. Therefore, probe and sample pre-conditioning and imaging in controlled ambient are expected to provide higher precision and better performance of CDAFM.

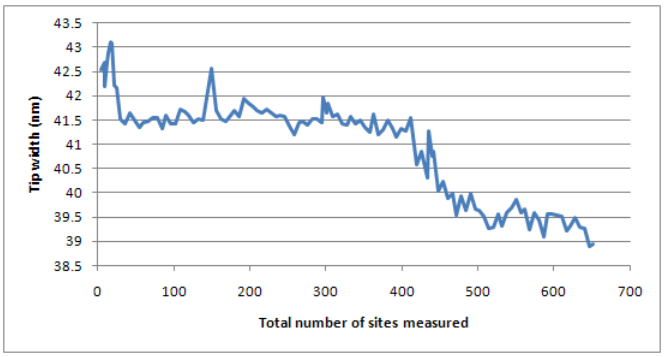

Figure 7. Wear of carbon coated flared probe during interconnect trench CD measurements.

4.2.1 Discussion of future work needed for reducing tip to sample artifacts

Depending on the sample nature various flash desorption methods: microwave (RF), infrared, optical and ultraviolet radiation as well as conductive heating of sample could be employed to achieve the goal. Dry nitrogen, noble gases and buffer liquids could be used as an ambient media. The right combination of sample and probe pre-conditioning and ambient media should depend on specific application.

4.3 Probe tip radii and its lifetime

The best available CDAFM resolution in both XZ and XY planes (Figure 5) is about 5 nm and limited mostly by probe geometry and probe tip apex sharpness. Required semiconductor industry resolution of CD metrology is 1 nm or better. Transmission electron microscopy (TEM) and high-energy cross-sectional SEM are capable of such resolution. Figure 8 shows a to-scale comparison of a TEM image of a transistor gate structure and a sketch of an idealized flared probe with its finite vertical edge height (VEH). Clearly, the VEH of the probe limits the ability of the probe to scan the bottom of such a gate structure. To stay competitive, resolution of CDAFM probes need to be improved.

Y-shape probe design from Figure 5 is promising. Figure 9 shows two SEM images of two different Y-shaped probes at different magnifications. The probe manufacturer claims that 1 nm

(or even better) radius of Y-probe apex is achievable but preserving the sharpness is a challenge[22]. In support of the claim one may use counterintuitive data showing that coated probes as a rule show better resolution or vertical edge height (VEH). Indeed, one would expect larger radius of apex curvature for coated probes. However, in unpublished results by one of the authors, coated probes quite often show better resolution, which may be due to the improved wear properties of the coated probes[19]. The phenomenon can be explained if one assumes that during the first probe qualification the uncoated, unprotected probe almost immediately gets "blunt" and actual VEH of "fresh" probe is never known.

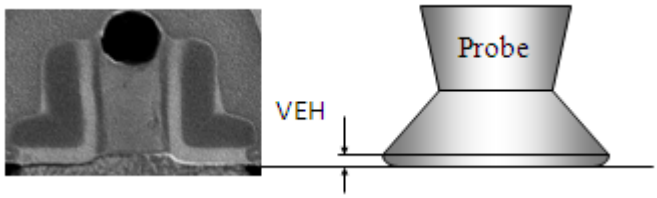

Figure 8. Comparison of TEM and CDAFM XZ resolution. Typical vertical edge height (VEH) of flared probes is 5 to 10 nm.

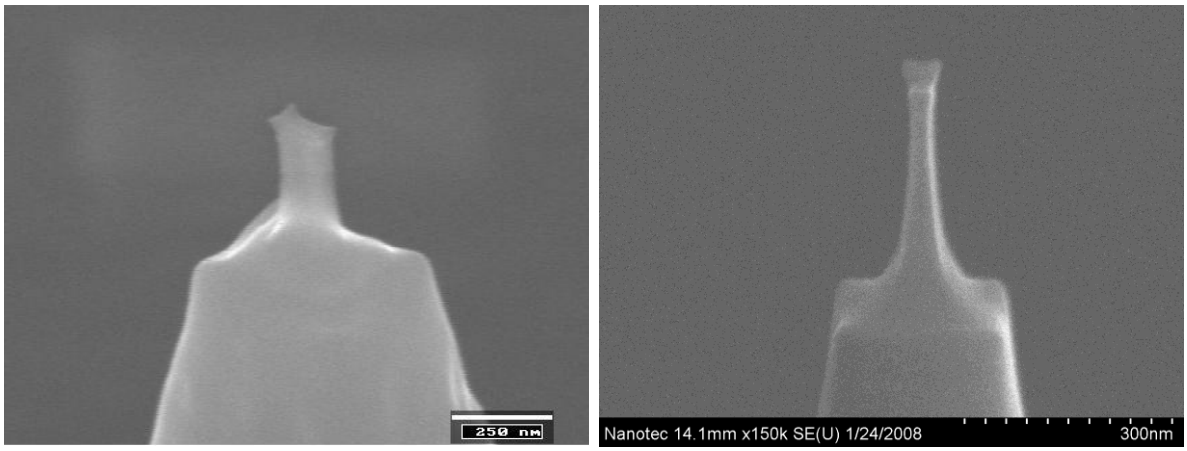

Figure 9. SEM images of Y-shape probe. Courtesy of Team Nanotec GmbH (Germany).

Therefore, to achieve required 1 nm XYZ resolution of CDAFM several challenging problems have to be resolved. First of all, surface sensing and probe control must be improved. We think that faster 3-dimensional probe position control is needed to avoid unintended "hard" contacts with sample. At the same time it is understood that chemical-mechanical contacts between probe and sample are almost unavoidable especially when nanometer size high-aspect ratio probes are employed in CDAFM. Secondly, lateral snapping of a flexible probe to the sidewall is almost impossible to avoid even with a very fast feedback, high-frequency servo, and a rigid cantilever. Therefore, chemical stability of probe-adsorbate-surface system must be achieved. Again, correctly selected probe coating, probe and sample pre-conditioning and AFM imaging in controlled ambient are believed to be the way to solve this complex problem.

Even if the above problem is solved, there will still be occasional probe-surface "crashes" or/and probe contamination through nanoparticle pick up. For example, it is quite common that during imaging of photoresist patterns or post-etching interconnect trenches and holes that nanoparticles of photoresist or post-etching debris will stick to AFM probe. An expensive state-of-the-art probe has to be replaced. On the other hand even the most stable coating will eventually wear out. The probe will become blunt.

4.3.1 Discussion of future methods for probe maintenance

One way to avoid losses of expensive CDAFM probes is to recondition contaminated or worn out probes using special in-situ, on-tool or off-tool methods of probe cleaning and sharpening. Various dry, wet, plasma- and field-assisted etching methods could be used to realize on-tool probe cleaning and sharpening[23,24]. One possible solution for on-tool or off-tool probe cleaning and sharpening is sketched in Figure 10. The ultimate goal is to achieve atomically sharp probes with an "infinite" lifetime. The prolonged lifetime would be achieved using periodic probe reconditioning. Of course, if this process is shown to be effective, it would have to be automated.

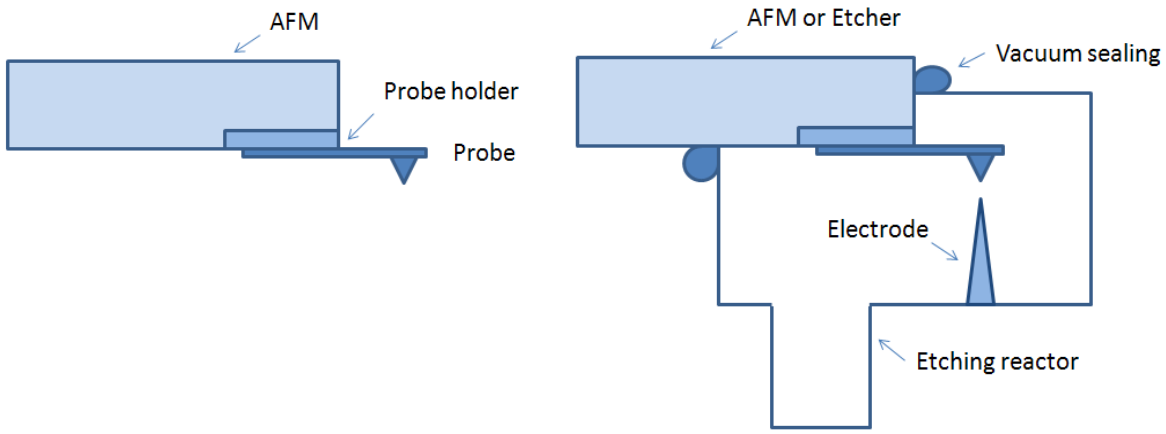

Figure 10. Sketch of possible on-tool or off-tool probe cleaning and sharpening solution.

4.4 Accounting for the probe shape in the CDAFM image

As mentioned in section 4.1, the CDAFM image is a dilation of the true feature shape and the true probe shape. The interaction forces tend to be short-range forces but their relative effect increases as features and probe sizes decrease[25]. Dahlen *et al.*[25] also point out that the CDAFM image is distorted as various points of the probe come in contact with the sample during the scanning process. Therefore, it is imperative that effects of the probe are removed from the CDAFM image to yield an accurate feature shape and subsequent measurement.

The probe shape is most commonly determined by the use of one or more tip characterizers[26]. The characterizers are designed and fabricated to reveal the probes general shape and to have well-defined sharp corners compared to the probe being investigated. The true probe shape is

reconstructed by "eroding", or removing, the effects of the probe characterizers' edge radii from the image of the probe scanning the characterizers. The result is a corrected image of the true tip shape as shown in Figure 11b. Figure 11a shows a sketch of a typical CDAFM flared probe along with its critical geometric parameters designed to scan vertical and undercut sidewalls of specimens. Figure 11b shows an overlay of a reconstructed probe scan with its corresponding TEM image. The true probe shape is determined by eroding out the known shape of the probe characterizer from the scan of the characterizer.

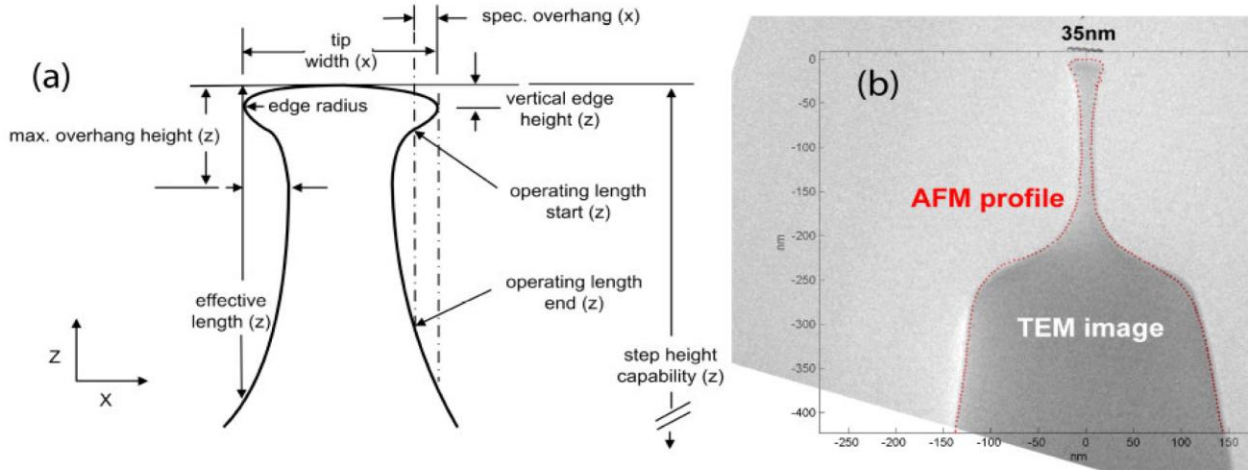

Figure 11. (a) shows the important dimensions of a flared probe. (b) shows the superposition of the eroded probe image (red) scan of a characterizer and a TEM image of the same probe. [Dahlen et al ref. 27]

The final step is to use the newly determined "true" tip shape and reconstruct the specimen surface from that information. An example of this exercise is shown in Figure 12 in an image taken from a subsequent publication from Dahlen *et al.*[27] in remarkable agreement of the eroded CDAFM (blue-colored scan) and the TEM image.

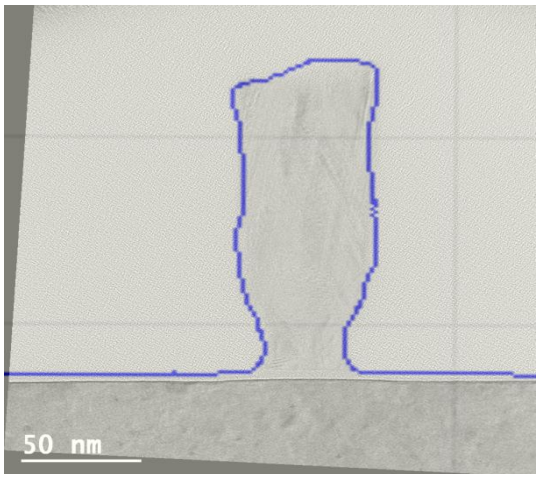

Figure 12. Superposition of a reconstructed CDAFM scan and a TEM image of the same sample scanned by the CDAFM. [Dahlen et al ref. 27]

Further work in this area of CDAFM image reconstruction has been extended to three dimensions[28]. This new methodology uses a concept of "dexels" to extend the principle of image reconstruction to 3-dimensional probe and specimen shapes.

These reconstruction models mentioned here all assume a "hard-sphere" model where there are no interactive forces assumed between the probe and the specimen. As discussed in section 4.1 and section 4.2, the reality can be somewhat different. That is, depending upon the probe and sample type, image reconstruction will need to take the probe and sample interactions into account.

5. The future of reference metrology

There are solutions for CDAFM technology specifically, but it is also important to discuss solutions on how to improve RM and ultimately the accuracy of workhorse[29] metrology. A workhorse metrology is the measurement system used most predominately in the semiconductor or nano fabrication facility for process control, but could also apply to a predominately used metrology for some aspects of process development. In today's setting the workhorse metrologies are the CDSEM and the OCD.

5.1 Is hybrid metrology a viable solution?

The idea behind a *hybrid* metrology is to improve the accuracy of a workhorse or a reference metrology by combining its measurement with that of another measurement. It doesn't have to be, but the complementary metrology could be another measurement technology. A recent example of this is from Silver *et al.*[30], where they supplement the OCD measurement with that of a CDAFM and significantly improve the OCD measurement uncertainty, while still able to maintain its high throughput. Table 3 taken from Silver's work shows the benefit of using the CDAFM in concert with the OCD measurement. The table shows the top, middle, and bottom linewidth measurement averages and standard deviations values from the OCD both with and without the supplemental CDAFM measurements. It is noteworthy that the top linewidth OCD average shown in the left matrix assisted by the CDAFM did not position itself *between* the separate OCD and CDAFM averages. It is also important to note that the uncertainties of all OCD measurements were significantly improved with the aid of the CDAFM, and surpassed the uncertainties of the CDAFM, itself!

	OCD fitting	AFM	OCD w/ AFM
Top	120	119.2	121
Middle	112	117.3	115
Bottom	143	132.8	141

	OCD fitting	AFM	OCD w/ AFM
σ_{Top}	1.05	0.75	0.35
σ_{Middle}	1.58	0.75	0.60
σ_{Bottom}	0.78	0.75	0.42

Table 3. Results from Silver *et al.*[30] showing OCD accuracy improvement when assisted by CDAFM measurements.

This is a convincing example of the benefit of combining metrology in new forms of a hybrid metrology.

6. Summary

This paper is predominately a compilation of prior work in the field of reference metrology and the CDAFM for the purpose of highlighting a major problem confronting the semiconductor and newly incoming nanotechnology industries, and to present paths for solutions to these problems. There are other reference metrology technologies which need similar analysis on the state of its metrology, because no single technology will provide all of industry's needs.

There is an urgency to address metrology accuracy deficiencies in nanoscale manufacturing. Specifically, the bias variation (relative accuracy) of the workhorse measurement systems is a major component of the measurement uncertainty, with the requirements for absolute accuracy as a close second place. Just as sometimes the lines between workhorse and reference metrologies are blurred, so too, the lines between manufacturing and development metrology are sometimes blurred. For example, many semiconductor fabricators are regularly feeding new products into their manufacturing by way of tight development cycles for optical proximity model construction. Many times workhorse metrology is called to support this model build cycle and conversely, demands are increasing for integrating once tried-and-true laboratory instrumentation into the manufacturing setting.

The case for reference metrology is strong. Reference metrology is the only way for engineers to assess process bias variation of the workhorse metrology. The authors have shown each of the reference metrologies along with their strengths and weaknesses, but none are adequate in their present state. This paper is a "call to arms" for suppliers and users alike for spending more resources on this poorly supported problem.

This paper points out the virtues of the CDAFM measurement technology as a good start and potential to be much better. It is also shown that the CDAFM has a lead on other measurement technologies in a couple of key metrics when combined together. The strengths and weaknesses of the CDAFM are pointed out by recalling good work by past research efforts and trying to encourage and focus future efforts. With this paper as a focus, there is significant promise if the technology deficiencies can be overcome, or at least made better, by novel and innovative work. This same effort needs to be encouraged for the other reference measurement technologies highlighted in section 3 of this paper.

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