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Review of reference metrology for nanotechnology: significance, challenges, and solutions

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Abstract. Metrology and control of critical dimension (CD) are key to the success of nanotechnology. Modern nanotechnology and nanometrology are largely based on knowledge developed during the last 10 to 20 years of semiconductor manufacturing. Semiconductor CD metrology entered the nanotechnology age in the late 1990s. Work on 130-nm- and 90-nm-node technologies led to the conclusion that precision alone is an insufficient metric for the quality assessment of metrology. Other components of measurement uncertainty (MU) must also be considered: 1. sample-to-sample measurement bias variation, 2. sampling uncertainty, and 3. sample variation induced by the 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 subnanometer MU for a number of nanometrology applications. Significant challenges of CDAFM remain, such as the following: 1. the finite dimensions of the probe are limiting characterization of narrow high-aspect spaces, 2. the flexibility of the probe complicates positioning control, 3. the probe apex sharpness limits 3D AFM resolution, 4. the lifetime of atomically sharp probes is too short, and 5. adsorbates change properties and dimensions of nanometer-sized objects considerably. We believe that solutions for the problems exist; therefore, we will discuss the role of RM in nanometrology, current RM choices, and the challenges of CDAFM as well as suggest some potential solutions. [DOI: 10.1117/1.JMM.11.1.XXXXXX]

Subject terms: accuracy; reference metrology; critical dimension; nanometrology; bias; critical dimension scanning electron microscope; critical dimension atomic force microscope; scatterometry; relative accuracy; absolute accuracy.

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1 Introduction

Gradually, the effects of poor metrology are being recognized in the semiconductor fabrication industry.[1–3] The term accuracy is used more frequently than ever before,[4–6] and there is a critical need to meet the challenges facing semiconductor metrology by confronting the costly and technically difficult solutions to more accurate metrology.[7] Semiconductor manufacturing engineers need fast and accurate measurements for their production lines as well as for advanced development. The objectives of this paper are to present the significance of reference metrology in supporting manufacturing and development of patterning technology to review existing reference metrology technologies, to explain why we think that there is significant leverage with scanning probe technology by considering its strengths and deficiencies, and to suggest potential solutions for reference metrology. This is primarily a review paper with some forward-looking speculation about how to solve the thorny problem of accurate metrology.

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2 Significance of Reference Metrology

Perhaps the best way to begin a discussion on the importance of reference metrology (RM) is to highlight a few recent examples of how workhorse metrology has shown deficiencies in important semiconductor applications. Workhorse metrology refers to the kinds of metrology technologies that are prevalent in the manufacturing setting such as the critical dimension scanning electron microscopy (CDSEM) and the growing implementation of scatterometry, also referred to as optical CD (OCD).

In a 2009 SPIE keynote paper by Rana et al.,[3] the dependence of CDSEM uncertainty on measurand complexity was demonstrated. This is dramatically illustrated in Fig. 1 (taken from Ref. 8) in which the total measurement uncertainty[4] (TMU) of the CDSEM is shown as a function of the feature-shape complexity that is caused by the scanner focus and the very short depth of focus of high numerical aperture scanners. The degree of scanner defocus is shown in the sketch at the right of Fig. 1. Note that it is the measurement of the isolated line that presents the most significant challenge for the CDSEM. TMU is an

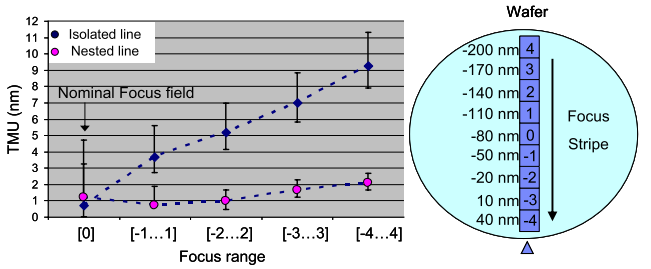

Fig. 1 The increased CDSEM measurement uncertainty as a function measurand complexity induced by scanner focus (courtesy of Rana et al., 2009).

IBM-defined metric that uses units of nanometers to captures additional (beyond precision) components of uncertainty of the measurement system under test. RM is required to evaluate the TMU of a system under test. In this case, the CD atomic force microscope (AFM) was used as the RM.

Another example of the importance of RM comes from the evaluation of scatterometry. Fig. 2 shows results from an earlier IBM study[8] where the RM was a combination of the CDAFM and CDSEM to evaluate a scatterometer measurement system or OCD. The left graph shows the first stage of calibration where the suitability of the CDSEM was 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 Fig. 2 shows the subsequent use of the CDSEM as the reference metrology for the OCD under evaluation. Although this example represents an OCD evaluation in the early 2000s, it nevertheless reveals the limitations of OCD for measuring linewidth features at large pitch relative to those at smaller pitch.

Even though care was taken to mitigate the effect of nonuniformity within the OCD grating target by averaging 49 CDSEM measurements within each grating, the TMU analysis still resulted in a value of ± 4.7 nm. The larger scatter of the results on the grating with 595-nm pitch appears to be a significant contributor to the TMU value. The following two examples illustrate the use of RM for TMU evaluation of OCD measurements of CD and sidewall angle (SWA) of a nominal 40-nm wide poly-Si line.[2] Fig. 3 shows the correlation between OCD and reference data (CDAFM) for the gate-bottom CD and SWA of a structure with 260-nm pitch. The total number of precalibrated sites is 170. The total number of OCD measurements for the fleet of 3 baseline tools and 7 repeats is 3570. From the results demonstrated in Fig. 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 a process control perspective.

As a general rule, the measurement uncertainty should only consume a maximum of 20% of the process tolerance budget. The data from Fig. 3 also show that the OCD fleet TMU for SWA measurements is a nominal ± 0.8 deg. This level of uncertainty is not acceptable since SWA process tolerance for that technology was ± 1.6 deg. This leads to a U/T ratio of 0.5, which exceeds the required limit of 0.2 for the ratio. Fig. 3 shows that OCD single tool precision is ± 0.2 deg. 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 deg be considered, the OCD would be erroneously accepted as SWA control metrology. On the contrary, if TMU of ± 0.8 deg is estimated (using RM data), the OCD measurement would be rejected as a valid process control for SWA. This clearly shows the importance of considering uncertainty components beyond precision for evaluating a measurement technology's ability to control a process.

3 Choice of Reference Metrology

The proper choice of measurement techniques can be the most daunting part of implementing accurate reference metrology. In the example shown in Fig. 2, the reference metrology system was a combination of CDAFM and CDSEM. This added complexity was necessary because the evaluation of TMU in this application requires not only accurate measurements, but accurate measurements in sufficient quantity. Furthermore, if the features to be measured are sufficiently complex, the CDSEM, and possibly the CDAFM, could be challenged as a valid RM. Historically, the top contenders for RM have been the classical high-resolution laboratory instruments such as cross-sectional SEM, transmission electron microscope (TEM) and scanning TEM, 1D-AFM, and CDAFM. The field of RM candidates is rounded out by the focused ion beam (FIB), the dual-beam FIB, and a relative newcomer, the helium-ion microscope.

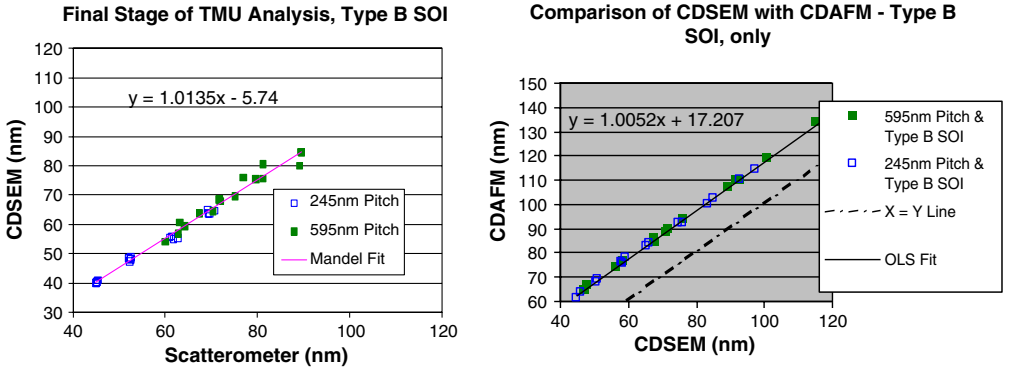

Fig. 2 An example of using two stages of RM. The first stage is evaluating the CDSEM with the CDAFM as the RM, and the second stage is using the CDSEM as the RM for the scatterometer (courtesy of Banke et al., 2004).

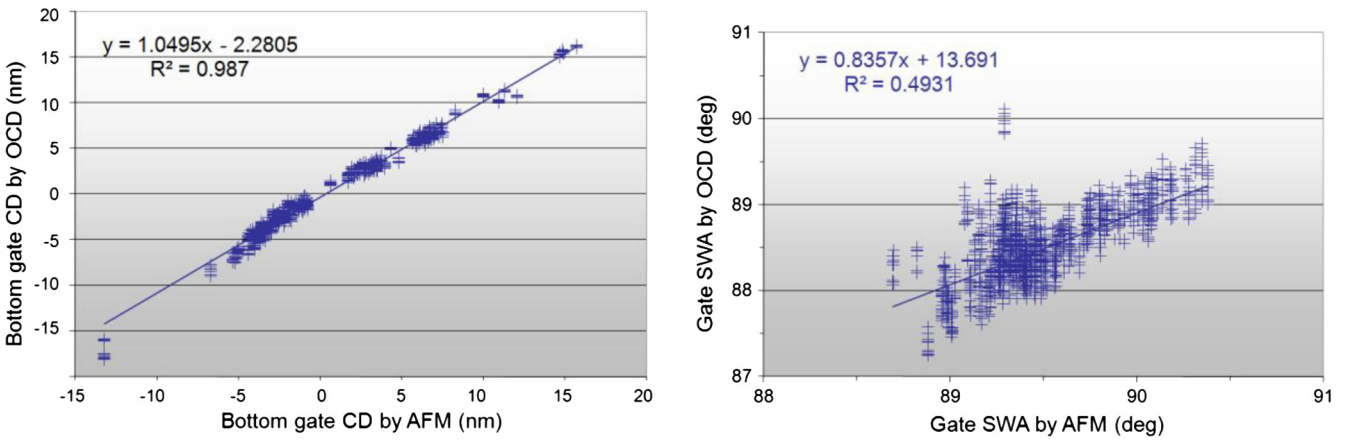

Fig. 3 The correlation between OCD and reference data for the gate bottom line CD (left) and SWA (right).

Every measurement technology has its strengths and weaknesses. This is qualitatively illustrated in Fig. 4, taken from a 2004 SPIE paper from IBM.[8] 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 information. Intrinsic relative accuracy refers to the amount of interpretation required, and 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 slice of the feature to be measured. Consequently, it takes considerable effort to acquire a sample set large enough to sufficiently represent the product variation for any type of cross-sectional measurement. It is noteworthy that the DBFIB technology represents an important first step in breaking away from this constraint by allowing a succession of cross-sections to be measured.

As also noted in the 2004 IBM paper, the CDAFM has a good balance of attributes showing a favorable combination of good intrinsic relative accuracy, sampling efficiency, and throughput. Table 1 below expands upon the three major attributes by taking account of relative versus absolute accuracy, measurement alteration (e.g., probe-induced damage to the measured feature), and navigational accuracy.

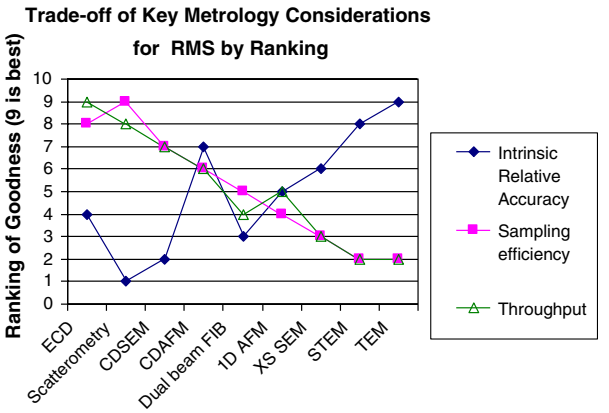

Fig. 4 Plot showing each potential RMS contender ranked by major attribute (courtesy of Banke et al., 2004).

A quantitative way to search for the best RM technique would be an attempt to estimate MU of various CD metrology techniques.[9] In Table 2, an updated version of MU estimates for five 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.

Any one of these RM candidates could be subject of a treatise. 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 low sample damage.

4 Unique Properties and Challenges of the CDAFM

In this paper, the CDAFM is defined as a scanning force microscope that has tip position feedback and servo simultaneously in both vertical and horizontal axes. 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 surface sensing. 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 responsible for both the advantages and disadvantages of AFM.

The first and the main advantage of AFM is the nanometer scale dimensions of the probe. The probe apex may have true atomic size (for example, in a scanning tunneling microscope). However, it is very challenging to keep the probe atomically sharp for a long time. All particle scattering-based metrology techniques have a rather large probe size (determined by the interaction volume size) of at least a few tens of nanometers (cloud of scattered electrons inside the sample). This 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 the probe and sample. In the ideal case, this is true subnanometer atom-to-atom interaction, yet this very local atomic interaction is strong enough to be detected by a

Table 1 Comparison of the top four reference metrology pros and cons.

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[b]	No	Unknown	Yes	Bad	Bad
CDAFM	Yes[a]	No	Yes	Slight	None	Ok	Ok
XS SEM	Yes	No	No	Some	Yes	Bad	Bad

[a]Must watch for tip artifacts.
[b]Can be irrelevant if product variation obscures the absolute accuracy acquired from the counting of lattice spacings (courtesy of Banke et al., 2004).

macro-world feedback system. In other words, the AFM sensor is a low-energy, electrically neutral, atomic-scale probe fully controlled in all three spatial dimensions. What could be better?

Having a mechanical probe of a nanometer or even atomic size introduces additional challenges affecting CDAFM accuracy. There are several aspects of the probe that 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 needs to be understood—both physically from a surface physics perspective as well as geometrically with respect to the probe shape and the feature shape—in order to extend the capability of a scanning mechanical probe. In this paper, we examine only some of the critical challenges for 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.[10] Therefore, one needs to know the exact shape of the probe to extract accurate feature dimensions from the AFM image. As shown in Fig. 5, there are three types of probes currently used with CDAFM: 1. flared, 2. cylindrical, and 3. *Y*-shaped probes. Critical probe parameters are the dimension in the fast scan, or *X* direction, and effective length in the *Z* axis. Carbon nanotubes (CNTs) mounted on Si cantilevers are often used as cylindrical probes. In this case, the deviation of CNTs from the vertical axis due to improper mounting of the CNTs to the cantilever is also a critical probe parameter. Today, 20-nm flared and 22-nm *Y*-shaped probes are commercially available. The effective length of the probes is limited to about 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, the optimal selection of probe coating will depend on the sample material.

A large variety of cylindrical probes are commercially available. The smallest possible diameter of c-Si probes is 15 nm with a length 150 nm due to the physical limitations of silicon. Carbon-coated 15 nm probes are commercially available.[11] The smallest diameter of CNT probes available today is 20 nm with a length limit of approximately 1 μm.

Accurate (SI-traceable) measurement of the diameter of a cylindrical probe is a challenge. Although TEM is commonly used, the measurement uncertainty of high-resolution TEM is unknown, and it can be particularly significant for

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

	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**
Dual Beam	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**			

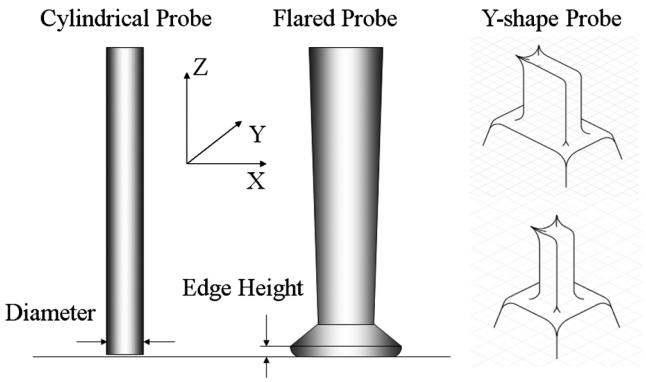

Fig. 5 Three the most common types of probes used with CDAFM.

measurements of a cylindrical object due to the edge contrast. Also, it is usually assumed that the CNT or c-Si probe is uniform. However, in reality, the probe can be covered by amorphous carbon, native SiO_2, or any other layer of adsorbates including H_2O. These additional layers are sensed differently by the TEM and CDAFM measurement systems. Most likely, such layers are transparent to the TEM but are definitely visible by AFM since they increase the effective width of the probe. However, accurate measurement of cylindrical probes using CDAFM is not trivial. Typically, a precalibrated vertical parallel structure (VPS) or linewidth standard is used to measure cylindrical probe diameter. There are commercially available VPS and linewidth standards for this purpose.[12] Several measurement uncertainty components should be considered in this case:

1. Probe or/and cantilever angular misalignment from the vertical axis (Fig. 6, left)
2. Probe slipping over the top corner of the VPS (Fig. 6, middle)
3. Probe snapping to the sidewall of the VPS (Fig. 6, right).

For thin and long probes, bending (slipping and snapping) can be as large as several nanometers. In many practical cases, the probe bending or snapping to the sidewall of deep and narrow structure (trench or hole) is, in fact, a major contributor limiting AFM capability.[13] Therefore, control of the probe-sample interaction becomes increasingly important during imaging of nanometer scale high-aspect ratio structures, where the probe stiffness can be overcome by the interaction forces.

4.2 *Probe Coating, Probe and Sample Adsorbates, and Scan Effects*

Coatings have been used effectively to minimize the chemical-mechanical wear of AFM probes. For example, carbon coating of flared Si probes improves their lifetime from tens to several hundred measurement sites.[14] Figure. 7 shows the wear of a carbon-coated flared Si probe as a function of number of measurement sites (which were etched trenches).

Carbon and Si nitride coatings are also known to reduce probe wear and improve the scanning speed on poly-Si lines due to a reduction of the probe-sample "sticking" caused by chemical interaction between the Si probe and poly-Si surface (the true nature of "sticking" is unknown, but some evidence exists that it is enhanced by the presence of adsorbed H2O as a fresh Si probe brought in contact with "sticky" poly-Si sample showed increasing signs of "sticking" over time and Poly-Si oxidation completely eliminates or prevents "sticking"). Very little is known about the exact mechanisms of probe protection since coating processes are usually proprietary. Nevertheless, some results have been recently published.[15]

There are several reasons why preconditioning of the sample and probe and imaging in controlled ambient may be necessary for optimal performance of a CDAFM. A single monolayer of adsorbates may cause a few angstroms per side change in the CD of a measured feature. Adding to this uncertainty is the potential variation of probe width caused by surface adsorbates. Together, these may result in a significant nanometer scale uncertainty in CDAFM linewidth measurements. Therefore, preserving the sample and probe surfaces in stable condition during the measurement process is becoming a must for achieving the desired subnanometer precision of CDAFM metrology. The routine practice of CDAFM provides many examples (unpublished for proprietary reasons) of systematic probe width and linewidth variations depending on the prehistory (over a few days) of the probe sample system. Imaging in a controlled ambient (temperature, humidity, chemistry, etc.) is also expected to bring additional tool calibration stability and reduced system drift. Another reason to control the surface condition of the probe and sample is the impact of the probe-sample interaction on probe "sticking," and, consequently, on CDAFM tip width calibration, resolution, scanning speed, probe wear, and the overall ability to image narrow high aspect ratio trenches. Therefore, probe and sample preconditioning and imaging in controlled ambient are expected to provide higher precision and better performance of CDAFM.

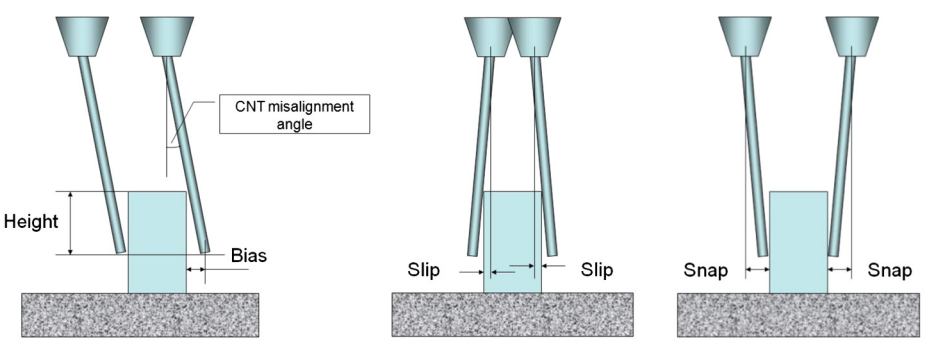

Fig. 6 Impact of probe misalignment (left), slipping (center), and snapping (right) on diameter measurement uncertainty.

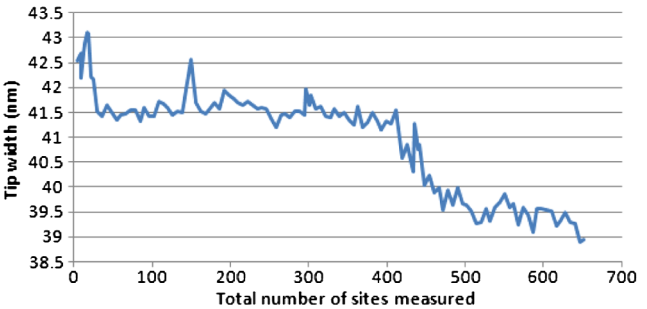

Fig. 7 Wear of carbon-coated flared probe during interconnect trench CD measurements.

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

Depending on the nature of the sample, various flash desorption methods could be used to achieve the goal including microwave, infrared, optical, and ultraviolet radiation as well as conductive heating of the sample. Dry nitrogen, noble gases, and buffer liquids could be used as an ambient media. The right combination of sample and probe preconditioning 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 (Fig. 5) is about 5 nm and is limited mostly by the probe geometry and probe tip apex sharpness. The resolution of CD metrology required by the semiconductor industry 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, the resolution of CDAFM probes needs to be improved.

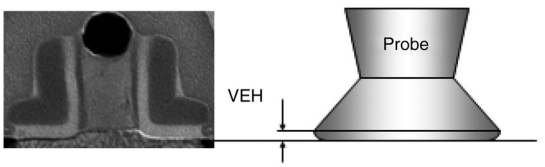

Fig. 8 Comparison of TEM and CDAFM *XZ* resolution. Typical VEH of flared probes is 5 to 10 nm.

The *Y*-shaped probe design shown in Fig. 5 is promising. Figure. 9 shows two SEM images of two different *Y*-shaped probes at different magnifications. The probe manufacturer claims that a 1 nm (or even better) radius of *Y*-probe apex is achievable, but preserving the sharpness is a challenge.[16]

In support of the claim, one may use counterintuitive data showing that coated probes typically show better resolution or vertical edge height (VEH). Indeed, one would expect coated probes to have a larger radius of curvature at the apex. However, an earlier investigation suggests coated probes often show better resolution, which may be due to the improved wear properties of the coated probes.[14] This observation could be explained if one assumes that during the first probe qualification, an uncoated, unprotected probe almost immediately gets "blunt" and the actual VEH of a "fresh" probe is never known.

Therefore, to achieve the required 1 nm *XYZ* resolution with CDAFM, several challenging problems have to be resolved. First of all, surface-sensing and probe control must be improved. We suggest that faster 3-D probe position control is needed to avoid unintended "hard" contacts with the sample. At the same time, it is understood that chemical-mechanical contacts between the probe and sample are almost unavoidable, especially when nanometer-size high-aspect ratio probes are used in CDAFM. Secondly, the 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 the probe-adsorbate-surface system must be achieved. Again, correctly selecting probe coating, probe and sample preconditioning, and AFM imaging in controlled ambient are expected to be the pathways to solving 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, nanoparticles of photoresist or post-etching debris will stick to the AFM probe. As a consequence, an expensive state-of-the-art probe has to be replaced. On the other hand, even the most stable coating will eventually wear out and the probe will become blunt.

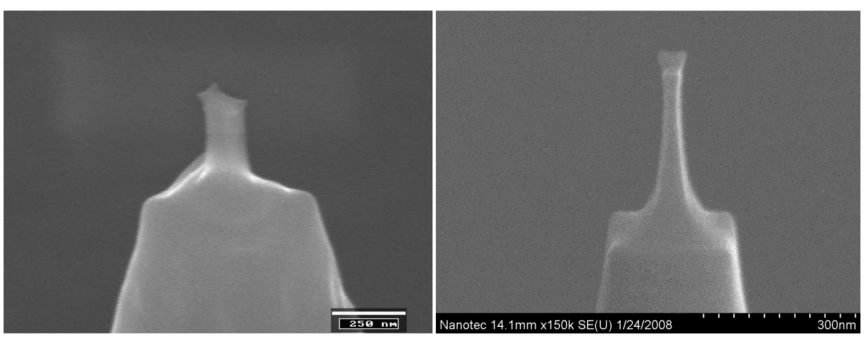

Fig. 9 SEM images of *Y*-shaped probe [courtesy of Team Nanotec GmbH (Germany)].

4.3.1 Discussion of potential 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-assisted, and field-assisted etching methods could be used to realize on-tool probe cleaning and sharpening.[17,18] One possible solution for on-tool or off-tool probe cleaning and sharpening is sketched in Fig. 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.

4.4 *Accounting for the Probe Shape in the CDAFM Image*

As mentioned in Sec. 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.[19] Dahlen et al.[19] 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.[20] The characterizers are designed and fabricated to reveal the probe's 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 edge radii of the probe characterizers from the CDAFM images of the characterizers. The result is a corrected image of the true tip shape as shown in Fig. 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 was determined by eroding out the known shape of the probe characterizer from the scan of the characterizer.

The final step is to use the "true" tip shape and reconstruct the actual specimen surface by eroding the tip shape from the image of the specimen. An example of this exercise is shown in Fig. 12, which was taken from Dahlen et al.[21] This image

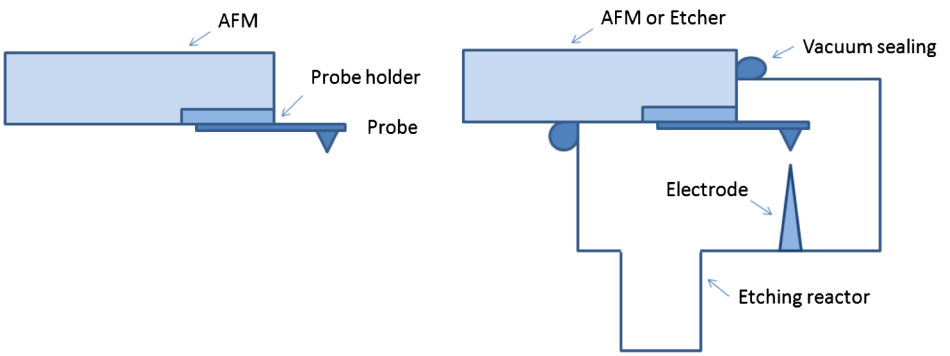

Fig. 10 Sketch of possible on-tool or off-tool probe cleaning and sharpening solution.

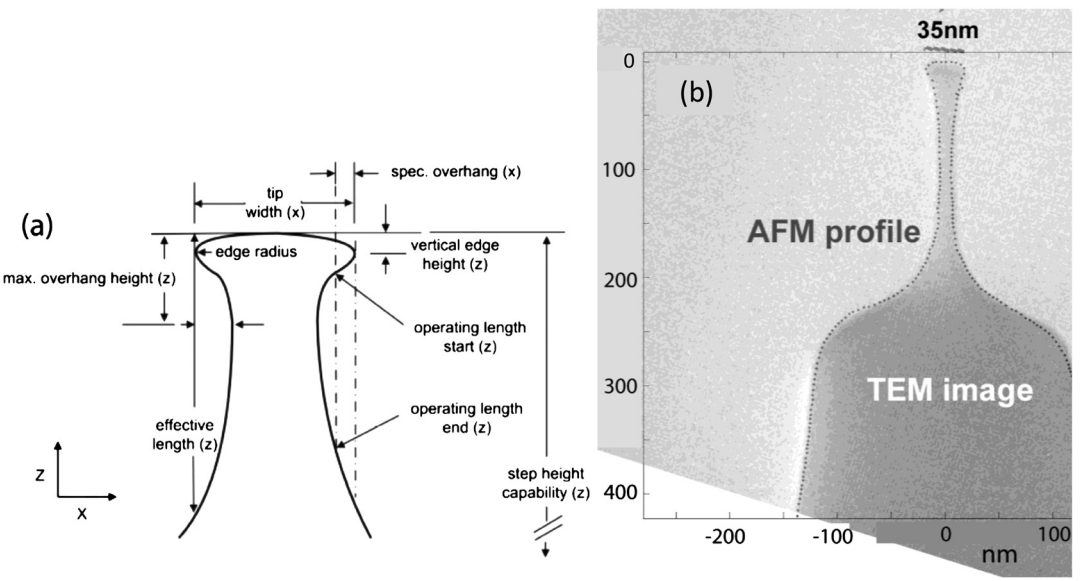

Fig. 11 (a) shows the important dimensions of a flared probe. (b) shows the superposition of the eroded probe image (red) scan of a characterizer and a TEM image of the same probe (Dahlen et al., Ref. 21).

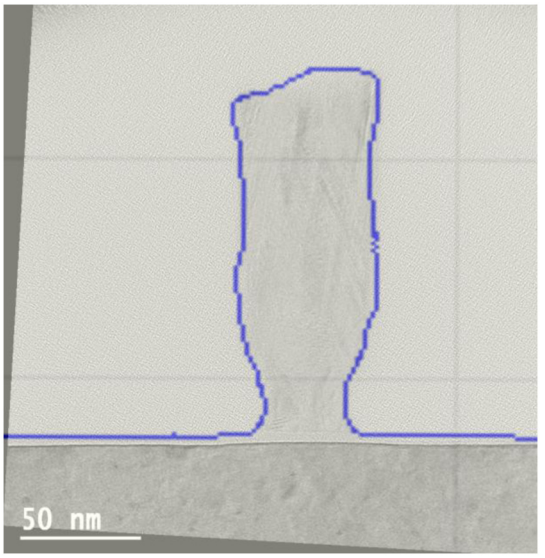

Fig. 12 Superposition of a reconstructed CDAFM scan and a TEM image of the same sample scanned by the CDAFM (Dahlen et al., Ref. 21).

shows remarkable agreement between a profile (in blue) from the corrected CDAFM image and the TEM cross-section. Further work in this area of CDAFM image reconstruction has been extended to three dimensions.[22] This new methodology uses a concept of dexels to extend the principle of image reconstruction to 3-D probe and specimen shapes.

These reconstruction methods mentioned here all assume a "hard-sphere" interaction model without additional tip-sample interaction forces and represent purely geometrical treatment of the interaction between the probe and specimen. As discussed in Secs. 4.1 and 4.2, the probe-sample interaction under actual measurement conditions may be somewhat more complex. That is, depending upon the probe and sample type, accurate image reconstruction will require accounting for the tip-sample interactions beyond geometrical effects.

5 The Future of Reference Metrology

There are potential solutions for CDAFM technology specifically, but it is also important to consider approaches to improving reference metrology generally and, ultimately, the accuracy of workhorse[3] metrology. A workhorse metrology tool is the measurement system used most commonly in a semiconductor or nanofabrication facility for process control. This term could also apply to the metrology typically used for some aspects of process development. In today's setting, the workhorse metrology tools are the CDSEM and the scatterometer or OCD.

5.1 *Is Hybrid Metrology a Viable Solution?*

The idea behind *hybrid* metrology is to improve the accuracy of a workhorse or a reference metrology tool by combining its measurements with those of another tool. This is not required, but the complementary metrology could be another measurement technology. A recent example of this is from Silver et al.,[23] who supplemented the OCD measurement with that of a CDAFM and significantly improve the OCD measurement uncertainty while still maintaining its high throughput. Table 3, which is taken from Silver's work, shows the benefit of using the CDAFM in concert with the OCD measurement. The table shows the average top, middle, and bottom linewidth measurements and standard deviations from the OCD metrology 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. This is a convincing example of the benefit of combining techniques to generate new forms of hybrid metrology.

Table 3 Results from Silver et al. (see Ref. 23) showing OCD accuracy improvement when assisted by CDAFM measurements.

	OCD fitting	AFM	OCD w/AFM
Top	120	119.2	121
Middle	112	117.3	115
Bottom	143	132.8	141
σ_{Top}	1.05	0.75	0.35
σ_{Middle}	1.58	0.75	0.60
σ_{Bottom}	0.78	0.75	0.42

6 Summary

This paper is predominately a review of prior work in the field of reference metrology and CDAFM for the purposes of highlighting a major problem confronting the semiconductor and nanotechnology industries and presenting potential solutions to this problem. There are other reference metrology technologies that need similar analyses on their current state and potential because no single technology will meet all the needs of industry.

There is an urgent need to address the limitations on metrology accuracy 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. Just as the lines between workhorse and reference metrologies are sometimes blurred, so are the lines between manufacturing and development metrology. 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 on to support this model build cycle. Conversely, the 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 the process bias variation of the workhorse metrology. We have shown each of the reference metrologies along with their strengths and weaknesses, but none are fully adequate in their present state. As such, this paper is a call to arms for suppliers and users alike to spend more resources on this poorly supported problem.

This paper pointed out the virtues and challenges of the CDAFM measurement technology for reference metrology. It has a good start with the potential to be much better. It was 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 were pointed out by reviewing the previous research and trying to encourage and focus future efforts. With this paper as a guide, there is significant promise for CDAFM if the technology deficiencies can be overcome, or at least mitigated, by novel and innovative work. This same effort needs to be encouraged for the other reference measurement technologies highlighted in this paper.

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