Photomask Applications of Traceable Atomic Force Microscope Dimensional Metrology at NIST

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ABSTRACT

The National Institute of Standards and Technology (NIST) has a multifaceted program in atomic force microscope (AFM) dimensional metrology. Three major instruments are being used for traceable measurements. The first is a custom in-house metrology AFM, called the calibrated AFM (C-AFM), the second is the first generation of commercially available critical dimension AFM (CD-AFM), and the third is a current generation CD-AFM at SEMATECH–for which NIST has established the calibration and uncertainties. All of these instruments have useful applications in photomask metrology.

Linewidth reference metrology is an important application of CD-AFM. We have performed a preliminary comparison of linewidths measured by CD-AFM and by electrical resistance metrology on a binary mask. For the ten selected test structures with on-mask linewidths between 350 nm and 600 nm, most of the observed differences were less than 5 nm, and all of them were less than 10 nm. The offsets were often within the estimated uncertainties of the AFM measurements, without accounting for the effect of linewidth roughness or the uncertainties of electrical measurements. The most recent release of the NIST photomask standard–which is Standard Reference Material (SRM) 2059–was also supported by CD-AFM reference measurements. We review the recent advances in AFM linewidth metrology that will reduce the uncertainty of AFM measurements on this and future generations of the NIST photomask standard.

The NIST C-AFM has displacement metrology for all three axes traceable to the 633 nm wavelength of the iodine-stabilized He-Ne laser. One of the important applications of the C-AFM is step height metrology, which has some relevance to phase shift calibration. In the current generation of the system, the approximate level of relative standard uncertainty for step height measurements at the 100 nm scale is 0.1 %. We discuss the monitor history of a 290 nm step height, originally measured on the C-AFM with a 1.9 nm (k = 2) expanded uncertainty, and describe advances that bring the step height uncertainty of recent measurements to an estimated 0.6 nm (k = 2). Based on this work, we expect to be able to reduce the topographic component of phase uncertainty in alternating aperture phase shift masks (AAPSM) by a factor of three compared to current calibrations based on earlier generation step height references.

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

1. INTRODUCTION

The National Institute of Standards and Technology (NIST) has a multifaceted program in traceable atomic force microscope (AFM) dimensional metrology. There are three major components of the overall NIST effort: (1) a custom metrology AFM called the calibrated AFM (C-AFM)[1-3], (2) a first generation critical dimension AFM (CD-AFM), the Veeco SXM320[†], which has been calibrated using NIST standards and instruments, and (3) a CD-AFM based reference measurement system (RMS) at SEMATECH using the current generation CD-AFM–the Veeco Dimension X3D[†]. All three of these instruments have applications in photomask dimensional metrology. The CD-AFM based RMS is housed

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

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at SEMATECH and has been described elsewhere.[4-8] The C-AFM and the SXM320 are housed in the Advanced Measurement Laboratory (AML) at NIST and were used for most of the work described in this paper.

The NIST C-AFM is a custom AFM that was constructed by NIST to perform traceable dimensional metrology. It is based on conventional or one-dimensional AFM operation with conical tips. The C-AFM is intended primarily to calibrate physical standards for calibrating other AFMs and provides reference support to other NIST projects. The design, performance, and uncertainties of the system have been discussed elsewhere.[1-3] The C-AFM has metrology traceability via the 633 nm wavelength of an I_2-stabilized He-Ne laser (a recommended radiation for the realization of the meter in the visible) for all three axes, and this is accomplished using heterodyne laser interferometers.

In contrast to conventional AFM, CD-AFM uses flared tips and more sophisticated feedback and scan control to permit the imaging of structures with near vertical sidewalls.[9] The SXM320, which is the first generation of commercially available CD-AFM, was initially used at SEMATECH to implement an RMS.[7,8] We now have this instrument at NIST. Although it does not have intrinsic traceability, it can be calibrated using standards measured on other instruments–such as the C-AFM.

2. AFM DIMENSIONAL METROLOGY

2.1 Instrument Performance and Uncertainties

In general, the standard approach[10] to uncertainty budgets adopted by NIST[11] is to develop an estimated contribution for every known source of uncertainty in a given measurement and to include terms pertaining to both the instrument used and the particular specimen measured. Terms evaluated exclusively by statistical methods are known as type A evaluations. Other terms, known as type B evaluations, are evaluated using some combination of measured data, physical models, or assumptions about the probability distribution.

All 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.[11] The most common coverage factor used is $k = 2$, which would correspond to approximately 95 % confidence for a normal (Gaussian) distribution. We have previously developed uncertainty budgets for pitch, height, and width measurements using both the C-AFM and the CD-AFM, though these are being continuously refined.

In the current generation of the C-AFM system, the approximate limits on the relative standard uncertainty of pitch and step height measurements were 1.0×10^{-3} for pitches at the micrometer scale and 1.0×10^{-3} for step heights at the 100 nm scale. We expect further improvements in performance in the near future.

During prior work, while the SXM320 was at SEMATECH, uncertainty budgets were developed for pitch, height, and linewidth measurements using it.[7,8] Currently, the relative standard uncertainties are approximately 0.2 % for pitch measurements up to several micrometers and 0.4 % for sub-micrometer step height measurements.

Linewidth metrology is more challenging for the C-AFM because it uses conical tips and conventional one dimensional feedback. Despite such challenges, however, we have successfully performed top width measurements using the C-AFM as part of an inter-method comparison of linewidth metrology techniques.[12] An expanded uncertainty of 11 nm was ultimately attained for the C-AFM linewidth measurement. Although this uncertainty could probably be reduced in an updated experiment, the C-AFM is still only capable of measuring the feature width of near-vertical structures at the top. Since most real structures have some non-negligible top corner rounding, the usefulness of performing an accurate top width measurement with a conventional AFM will often be limited.

Consequently, we use CD-AFM for most of our work on linewidth metrology. The general template for an uncertainty budget of CD-AFM pitch and width measurements is shown in Table I. As a result of the NIST single crystal critical dimension reference material (SCCDRM) project, it is possible to calibrate CD-AFM tip width with a 1 nm standard uncertainty.[5, 13-15] and we are now using the SXM320 to support the next generation of the SCCDRM project and it is also expected that we will use this tool to support the next generation of the NIST photomask SRM.

2.2 Uncertainty Frontiers of CD-AFM Linewidth Metrology

For CD-AFM linewidth measurements, the tip-related terms are the most important sources of uncertainty. These are due to the uncertainty in the zeroth order tip width correction and to higher order tip effects. Since we have discussed the nature of these contributions in detail elsewhere[5,16], we give only an overview here.

The interaction of an AFM tip with the imaged surface is complex, but for many purposes a highly simplified and two-dimensional model is useful. In this basic model, the effect of the tip is represented as a simple additive offset which must be subtracted from the apparent width to obtain an accurate measurement. This offset is referred to as the zeroth order tip correction. Hence, the zeroth order uncertainty component represents the uncertainty in the value of this correction. As a result of the NIST SCCDRM project, it is possible to calibrate the zeroth order tip width with approximately a 1 nm standard uncertainty.[5,13]

Finer details of the tip-sample interaction, pertaining to things like flare radius, offset height, feature sidewall angle, feature corner radius, and the three-dimensional nature of both the tip and sample (*i.e.*, shape in the axes perpendicular to the scan direction) are thought of as being higher-order tip effects.[5,16] Because these effects have a strong dependence on the specific geometry of each tip and feature, it is difficult to make general statements about the resulting uncertainties, and it is necessary to make a specific assessment for every measurement. Until recently, this was of somewhat lesser concern in many measurements because these components were typically smaller than the uncertainty in the zeroth order correction. However, with reduction in uncertainty of the zeroth order term that resulted from the SCCDRM project, characterization and correction for these effects is now more important in CD-AFM width metrology.

Beyond the shape-related higher-order tip effects, there are other potential small effects pertaining to the tip-sample interaction that could result in small biases. One example would be drift in the amplitude of the lateral dither–since the lateral oscillation essentially creates an apparent tip width that is larger than the purely geometrical value. The lateral vibration amplitude, however, is typically a few nanometers and is well stabilized. Observation of apparent width changes during repeated tip calibration runs allows an approximate limit of 0.5 nm to be set on the possible magnitude of such drift–and this is conservative.[17] During repeated measurements of the same structure, a long term trend of either wear or growth–such as when scanning photoresist– is typically seen in the tip width.

Advances in both CD-AFM scan algorithms and tip technology have resulted in a dramatic increase in tip lifetime[18]–to the extent that tip width change may be undetectable over the span of half a dozen images or more. When such relatively flat tip change is plotted, however, small fluctuations against the trend are sometimes observed–which could be the result of drift in the vibration amplitude. However, it is also possible–and at least as likely–that such fluctuations are the results of sub-nanometer particulates being picked up or dropped by the tip.

As a result of the SCCDRM project, the frontier of CD-AFM metrology now lies in understanding subtle effects of tip shape and control at the sub-nanometer level. Consequently, there are new efforts being made to understand such details. NIST and the Korea Research Institute for Science and Standards (KRISS) are currently collaborating on models of the CD-AFM tip-sample interaction–an effort that grew out of our collaboration on the use of carbon nanotube (CNT) tips with CD-AFM.[19]

3. PHOTOMASK APPLICATIONS

3.1 Linewidth Reference Metrology

In the manufacturing environment, the most pervasive tools for mask metrology are generally scanning electron microscopes (SEM) and, increasingly, scatterometer or scattering-optical critical dimension (S-OCD) tools.[20,21] CD-AFM and other profiling technologies typically function as reference metrology tools and sometimes play a larger role in process development.

However, electrical resistance methods–using both direct current (DC) and radio-frequency (RF) measurements–may have a role to play. Reference metrology from CD-AFM will help support further development of these methods–both at NIST and elsewhere.

NIST and the Scottish Microelectronics Center (SMC) at the University of Edinburgh are now collaborating on the development of DC electrical resistance methods for binary masks. SMC has experience in both the design of targets and in electrical resistance metrology.[22,23] NIST is providing CD-AFM reference metrology on selected targets for comparison with the electrical results and also with optical and SEM metrology in some cases. An AFM image of one of these test structures taken is shown in figure 1. Note that this is the raw image with no correction for the effects of the tip. Reentrance of about 5° is observed on this structure–which is not unusual for chrome-on-glass (COG) features. There is also noticeable line width roughness (LWR)–the standard deviation is approximately 6 nm over the measured area.

Since an electrical measurement involves both cross-sectional and along-the-feature averaging, a meaningful comparison between the electrical value and a single AFM image requires some knowledge about the magnitude of the LWR. Ultimately, this will mean taking multiple AFM images sampled along the length of the feature and developing a statistical understanding of the LWR. If the statistical properties of the width variation are sufficiently similar for different features on the same mask–as might be expected for some process sources of variation–it may be possible to assign uncertainties to electrical calibration values that could be usefully applied to AFM or even optical metrology.

In figure 2, we show the results of a preliminary comparison between linewidth–as measured by CD-AFM and by electrical resistance metrology–of selected test structures on a binary mask developed by SMC. The on-mask linewidths were between 350 nm and 600 nm. As the figure shows, the largest observed offset was less than 10 nm, and most were less than 5 nm. Additionally, several of the observed offsets are consistent with zero to within the preliminary AFM uncertainties shown. This is particularly encouraging when it is considered that these uncertainty estimates include only terms related to the AFM calibration and tip wear. No attempt has been made here to assess the uncertainty due to the LWR, and the uncertainty of the electrical measurement has also not been included.

Inter-method comparisons and cross-method calibrations do involve significant challenges. In addition to the inherent uncertainties of each measurement, care must be taken to understand the implicit measurand definitions of each method in order to compare equivalent quantities. Nevertheless, we believe that the electrical metrology of photomask features is sufficiently promising and potentially useful to warrant such experiments, and providing reference metrology for this development will continue to be an emphasis of the NIST CD-AFM program.

NIST is also collaborating with researchers at George Washington University (GWU) on the development of linewidth metrology based on the measurement of RF impedance of coplanar waveguides.[24] One advantage of such measurements over DC methods is that RF metrology can potentially be performed without mechanical contact between the probe and the mask. As with the DC electrical methods, we expect that CD-AFM reference metrology will play an important role in validating the performance of this method as it is developed.

3.2 SRM 2059: The NIST Photomask Standard

The NIST program in photomask metrology was launched in 70s under the leadership of Diana Nyyssonen, and the first installment in the series of photomask standard reference materials (SRM) was SRM 474, released in 1981.[25] Over the next two decades, this was followed by SRM 475, SRM 476, and SRM 473.[26] The most recent release of the NIST photomask standard is SRM 2059.[27]

Prior to SRM 2059, the linewidth calibration on the photomask standards was performed entirely using imaging optical metrology. For the release of SRM 2059, CD-AFM was used as a source of reference metrology to reduce the impact of uncertainty in the optical modeling. The AFM measurements were performed on a master standard and optical metrology was used as comparator for calibration of the SRMs for release. The next generation of the NIST photomask SRM is currently being designed, and it is also expected that we will use CD-AFM to support this standard as well.

As previously discussed, the achievable uncertainties in CD-AFM linewidth metrology have been improving significantly the last few years.[5,13-15] At the time of the reference measurements for SRM2059, the standard uncertainty due to CD-AFM tip width calibration was 5 nm ($k = 1$). This lower limit on uncertainty was subsequently reduced to approximately 1 nm ($k = 1$) as a result of the NIST SCCDRM project. Consequently, we are currently working on data reanalysis and new AFM reference measurements that will be used to refine the uncertainties on the current release of SRM 2059.[28]

A composite cross-sectional profile taken from the CD-AFM data on SRM 2059 is shown in figure 3. This profile is the average of twenty linescans over a 2 µm sampling length in the slow scan axis. It illustrates some of the challenges in using CD-AFM reference measurements to support optical linewidth metrology.

The chrome lines on SRM 2059 exhibit reentrant sidewalls and LWR–which is averaged in figure 3–both of which must be considered in modeling the response of an optical metrology tool to the features. Additionally, the contribution of the tip shape to the apparent sidewalls in figure 3 is not negligible–and has not been removed from the data. At the time of the original measurements, however, this was not a leading contribution to the uncertainty.

More recently, there has been considerable progress in the modeling and removal of tip-shape contributions from CD-AFM images. When we perform the reference measurements for the next generation of the photomask SRM, we expect to benefit from these advances in accounting for CD-AFM tip effects.

3.3 Phase Shift Calibration and AFM Step Height Metrology

There are a variety of important applications for AFM step height metrology in semiconductor manufacturing. In photomask metrology, one potentially significant application is the calibration of phase shift for alternating aperture phase shifting masks (AAPSM).

For these masks, the requisite optical path difference for phase shifting is accomplished with topographic steps etched into the quartz substrate. Consequently, one approach to the calibration of this phase shift is to perform a topographic step height measurement using a surface profiling tool such as AFM. Such an approach was previously implemented by Hughes, Goodman, *et al.*, and they demonstrated a relative phase uncertainty of approximately 1 % ($k = 1$).[29] This phase uncertainty was limited by the uncertainty of the height calibration used on their profiling tools. Consequently, if newer reference step height measurements were used for phase shift calibration, it should be possible to reduce relative phase uncertainty by up to a factor three.

In figure 4, some recent monitor history of C-AFM step height measurements is shown. These measurements were taken on an approximately 290 nm step height sample-which was measured at the same time as our participation in an international comparison–known as NANO2–of step height metrology among the National Metrology Institutes (NMIs) of participating nations.[30] The individual data points shown in the figure are results taken using the current generation of the C-AFM, while the dashed lines represent values obtained at the time of the NANO2 comparison.

The choice of algorithm and measurand definition is an important consideration in step height metrology. In figure 4, there are results shown using two different algorithms to calculate step height. One of the algorithms is based on the method accepted by the International Organization for Standardization (ISO)[31] and the other is used for NIST step height calibrations with stylus profilers.[32]

The NIST algorithm involves linear fits with extrapolation to the step edges, while the ISO algorithm involves linear fits to the upper and lower surfaces with extrapolation to the step center. Relative biases between these two algorithms can result from both instrumental effects (e.g., scanner out-of-plane motion) and sample characteristics (e.g., curvature of the surface).

Although the NIST algorithm is more robust against profile curvature–from either the sample or the scanner, it also requires a sharper edge transition region than does the ISO algorithm. Since the apparent edge region in the image has a significant contribution from the tip geometry, this means that data taken with worn or slightly damaged tips cannot always be analyzed with the NIST algorithm–where as the ISO algorithm can be used with virtually all viable tips.

Consequently, there are more results in figure 4 for the ISO algorithm than for the NIST algorithm. However, for those data sets for which both algorithms could be used, the results are in excellent agreement. In fact the two algorithms agree more closely using the more recent data than they did at the time of the NANO2 comparison. We believe that this is due to the effect of the larger scanner out-of-plane motion in that generation of the C-AFM.

At the time of the NANO2 measurements, the expanded uncertainty in C-AFM step height measurements at the 290 nm level was estimated to be 1.9 nm (k = 2). The largest component of that uncertainty was the treatment of the non-linearity in the z-axis capacitance sensor. In the current generation of the instrument, we expect to push the relative standard uncertainty in step height measurements below 0.1 %.

The variation of the recent C-AFM results and the possible bias relative to the NANO2 era values is not fully understood. We are currently refining the interferometric calibration of the z-axis capacitance sensor and suspect that the uncertainty in this calibration is a major source of apparent drift in the measured step height. However, all of the recent values agree with the NANO2 era values well within the uncertainty of those values. The expanded uncertainty of the most recent values is currently estimated to be 0.6 nm (k = 2).

Unfortunately, the potential benefits of reduced step height uncertainty may be overshadowed by other contributions to phase shift uncertainty. A well known geometrical-optics contribution to the effective phase shift is related to the dependence of effective optical path length on numerical aperture.[29,33] This contribution, which is known in optical step height metrology as the "numerical aperture correction", alters the relationship between topographic step height and the resultant phase shift for normally-incident plane waves.

In the manufacturing environment, the most common method of measuring phase shift is based on shearing interferometry. Due in part to beam size constraints, these tools do not actually measure the phase shift on the primary patterns but on dedicated and larger targets. Since the numerical aperture correction does not depend upon the lateral dimensions of the target, there is no related bias between the phase shift on the dedicated target and the main pattern due to this effect.

However, as lithographers have continued to push pattern dimensions well below the illumination wavelength, the complex physical optics effects on phase shift have become significant and must be accounted for with target-specific optical modeling.[34-36] This means that the applicability of a phase shift based on a height measurement is largely limited to the pattern on which the measurement is made.

The next generation of the NIST photomask SRM is currently being designed, and we are still considering the possibility of including phase calibration targets of some type. However, due to the greater prevalence of half-tone or embedded attenuating phase shift masks (EAPSM) relative to AAPSM or hard-shifting masks, and the dependence of effective phase shift on target geometry, the general usefulness of a phase shift standard based on height measurements of steps etched into the quartz substrate is unclear. Our ongoing discussions and collaborations with SEMATECH and industry mask metrologists will be an important factor in making this decision.

4. SUMMARY AND FUTURE WORK

NIST has a robust and multifaceted program in traceable atomic force microscope (AFM) dimensional metrology. The major components of this program are the NIST C-AFM and a Veeco SXM320[†], both housed in laboratories at NIST, and a Dimension X3D[†] housed at SEMATECH and maintained as an RMS using NIST measurement expertise. Application of these tools to photomask metrology is an increasing emphasis of this program.

At NIST, CD-AFM metrology is being used to provide reference support to the photomask SRM program and is expected to play an important role in the next release. NIST and the Scottish Microelectronics Center at the University of Edinburgh are now collaborating on the development of DC electrical linewidth measurements. CD-AFM at NIST is being used as reference metrology for comparison with the electrical results on important test structures. NIST is also collaborating with George Washington University on the development of RF electrical metrology, and CD-AFM reference metrology will be used to support this effort.

Based upon the expected C-AFM performance in the relevant height range, it should be possible to reduce the topographic component of phase uncertainty by about a factor of three relative to the work done by Hughes, et al. Although the general applicability of phase standards is not clear, we are considering the possibility of phase targets on the next generation of the NIST photomask SRM.

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

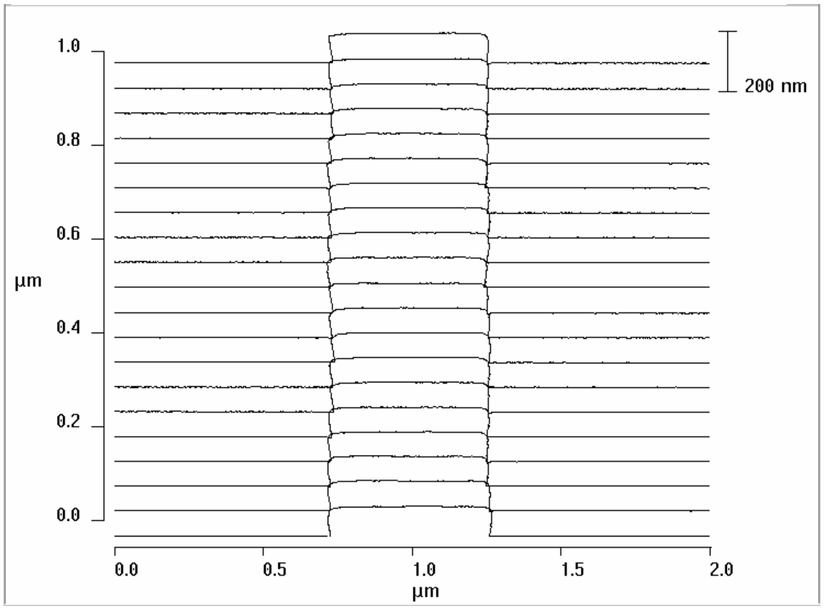

Figure 1. SXM image of a region of an electrical test structure on binary mask. The AFM result will be compared with electrical resistance measurements performed at the Scottish Microelectronics Center at the University of Edinburgh, where this test pattern was designed.

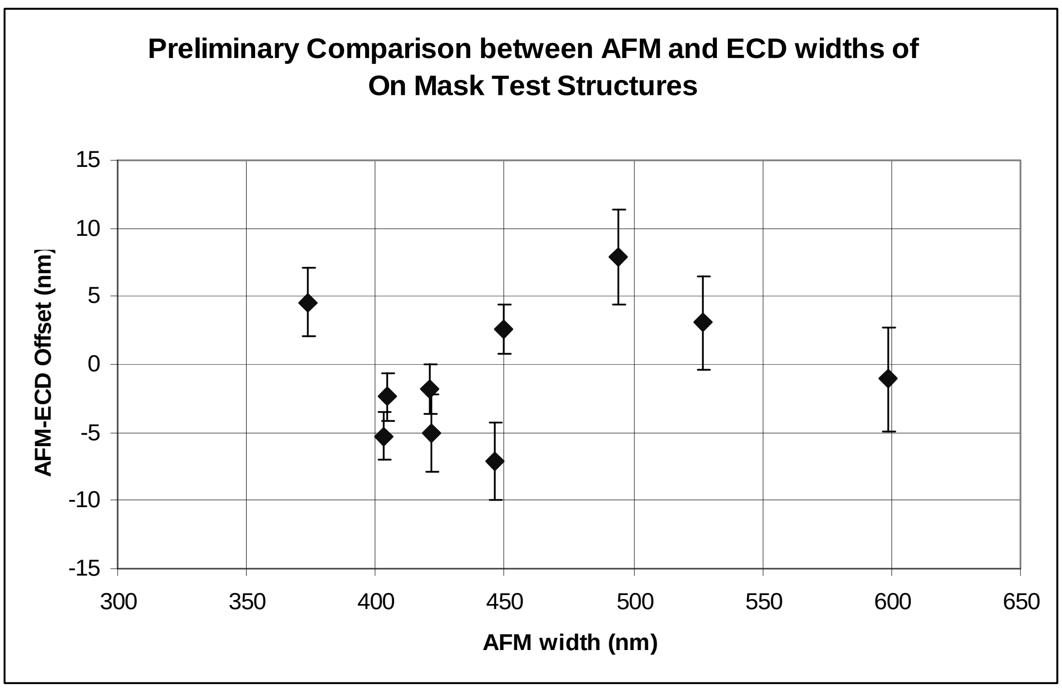

Figure 2. Preliminary comparison of linewidth as measured by CD-AFM and electrical resistance. The AFM values are an average of top, middle, and bottom width – in an attempt to approximate the 'average' seen by the electrical method. Note: The expanded uncertainties (k = 2) shown represent only the portion of the uncertainty due to AFM calibration and tip wear. A more comprehensive uncertainty analysis is underway.

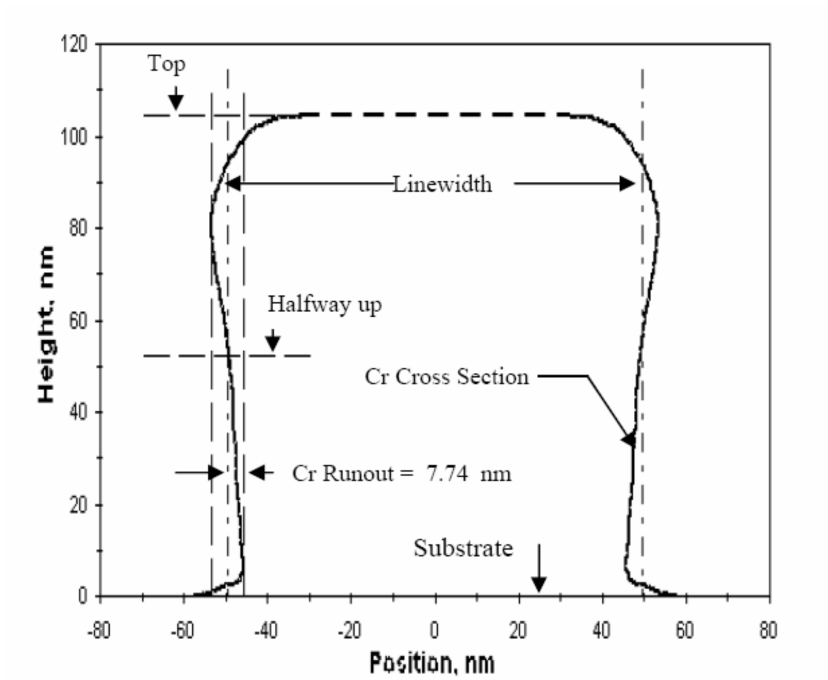

Figure 3. Composite CD-AFM cross-section of features on SRM2059. The irregular shape of some chrome-on-glass photomask features presents a greater challenge to CD-AFM metrology than most polysilicon structures. In particular, higher-order (e.g. shape) tip effects can be a non-negligible source of uncertainty. In this profile, note that much of the apparent corner rounding at the top is due to the shape of the tip flare.

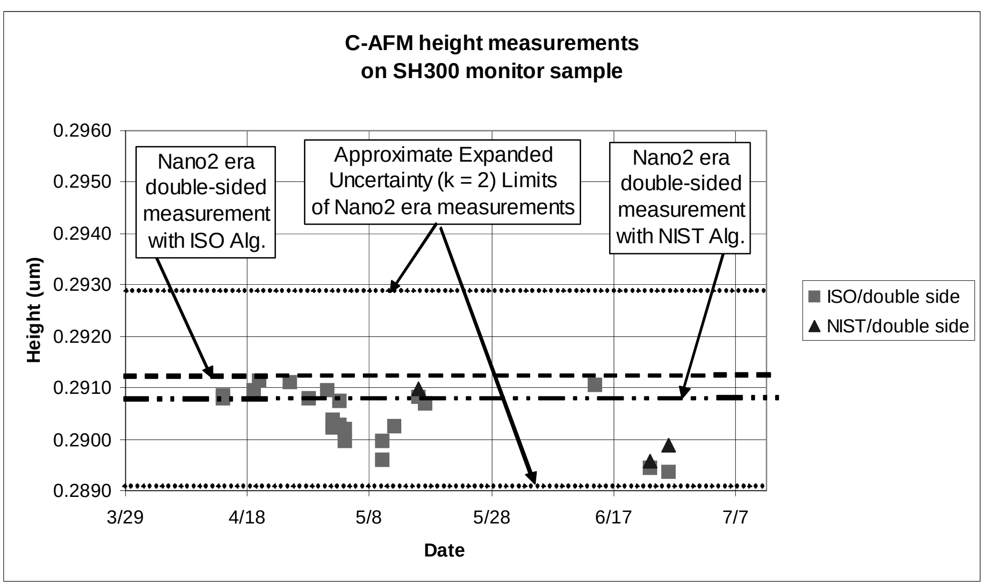

Figure 4. Example of measurement history on a step height standard using the NIST C-AFM. Recent results, obtained with the current generation of the instrument, are shown using two different algorithms for step height, along with historical reference values and prior uncertainties, shown as dashed and dash-double-dotted lines, dating back to a major international comparison in 2002. Currently, the expanded uncertainty at this height range is estimated at 0.6 nm (k = 2).

Table I. Uncertainty Budget for SXM320 Pitch and Width Measurements (k = 1)

Component		Standard Uncertainty
Type A		
(repeatability, reproducibility, sample non-uniformity, etc.)		Observed SD[a] or SDOM[a]
Type B		
Algorithm (edge/peak detection)/measurand definition		*
Tip contributions applying to width only:		
Tip width correction (zeroth order)	*Using SCCDRM:*	0.8 nm
Tip-related (higher order–e.g., offset height, overhang, corner rounding, tip wear)		‡
Scale Calibration (linear term)		$1.0 \times 10^{-3} W$ *or* P†
Scale Non-linearity		$2.0 \times 10^{-3} W$ *or* P†
Differential Abbe errors (offset between calibration plane and wafer or mask plane)		‡
Non-position-dependent motion errors (e.g., mechanical, tip holder piezo hysteresis)		‡
Cosine Errors (in-sample-plane)		$0.15 \times 10^{-5} W$ *or* P†
Cosine Errors (out-of-sample-plane)		$0.15 \times 10^{-3} W$ *or* P†

Combined standard uncertainty, u_c (*width*) = $[(SD)^2 + (0.8\ \text{nm})^2 + (2.2 \times 10^{-3} W)^2]^{1/2}$

u_c (*pitch*) = $[(SD)^2 + (2.2 \times 10^{-3} P)^2]^{1/2}$

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

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

‡ Indicates that contribution is negligible in many circumstances, but has not been fully evaluated for all cases or is sample dependent and should be evaluated for every measurement.

† Indicates that the uncertainty is proportional to the measured value of linewidth W or pitch P.

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