Re-calibration of the NIST SRM 2059 Master Standard using Traceable Atomic Force Microscope Metrology

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ABSTRACT

The current photomask linewidth Standard Reference Material (SRM) supplied by the National Institute of Standards and Technology (NIST), SRM 2059, is the fifth generation of such standards for mask metrology. An in house optical microscope tool developed at NIST, called the NIST ultra-violet (UV) microscope, was used in transmission mode to calibrate the SRM 2059 photomasks. Due to the limitations of available optical models for determining the edge response in the UV microscope, the tool was used in a comparator mode.

One of the masks was selected as a master standard – and the features on this mask were calibrated using traceable critical dimension atomic force microscope (CD-AFM) dimensional metrology. The optical measurements were then used to determine the relative offsets between the widths on the master standard and individual masks for sale to customers. At the time of these measurements, however, the uncertainties in the CD-AFM reference metrology on the master standard were larger than can now be achieved because the NIST single crystal critical dimension reference material (SCCDRM) project had not been completed.

Using our CD-AFM at NIST, we have performed new measurements on the SRM 2059 master standard. The new AFM results are in agreement with the prior measurements and have expanded uncertainties approximately one fourth of those of the earlier results for sub-micrometer features. When the optical comparator data for customers masks are reanalyzed using these new AFM results, we expect to reduce the combined reported uncertainties for the linewidths on the actual SRMs by at least 40 % for the nominal 0.25 µm features.

Keywords: CD-AFM, metrology, CD, linewidth, photomask, standards, calibration, traceability, SRM, SRM 2059

1. INTRODUCTION

The National Institute of Standards and Technology (NIST) has had a robust program in photomask dimensional metrology since the late 70s when the late Diana Nyyssonen and coworkers developed the first chrome-on-glass (COG) Standard Reference Material (SRM) for linewidth metrology.[1] There have since been four more generations of the NIST photomask SRM[2], with the most recent being SRM2059.[3]

The general layout of SRM 2059 is illustrated in Figure 1. For width calibration, there are isolated line and space features ranging in width from 250 nm up to 32 µm. For pitch calibration, there is a "ruler" target approximately 250 µm in total length, with graduations as fine as 500 nm pitch in some portions of the pattern.

An in house tool developed at NIST, called the NIST ultra-violet (UV) microscope, is used in transmission mode to calibrate the SRM 2059 photomasks.[3] Due to the limitations of available optical models for determining the edge response in the UV microscope, this tool was used in a comparator mode. One of the masks was selected as a master standard – and the features on this mask were calibrated using traceable atomic force microscope dimensional metrology. The optical measurements were then used to determine the relative offsets between the widths on the master standard and individual masks for sale to customers.

Since 2001 NIST has cooperated with SEMATECH to implement a traceable critical dimension atomic force microscope (CD-AFM) reference measurement system (RMS) using the most current generation CD-AFM tool at SEMATECH.[4-8]

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The original measurements on the SRM 2059 master were made in 2004 as part of this collaboration. At the time of these measurements, however, the uncertainties in the CD-AFM reference metrology on the master standard were larger than can now be achieved – because the NIST single crystal critical dimension reference material (SCCDRM) project had not been completed.[9]

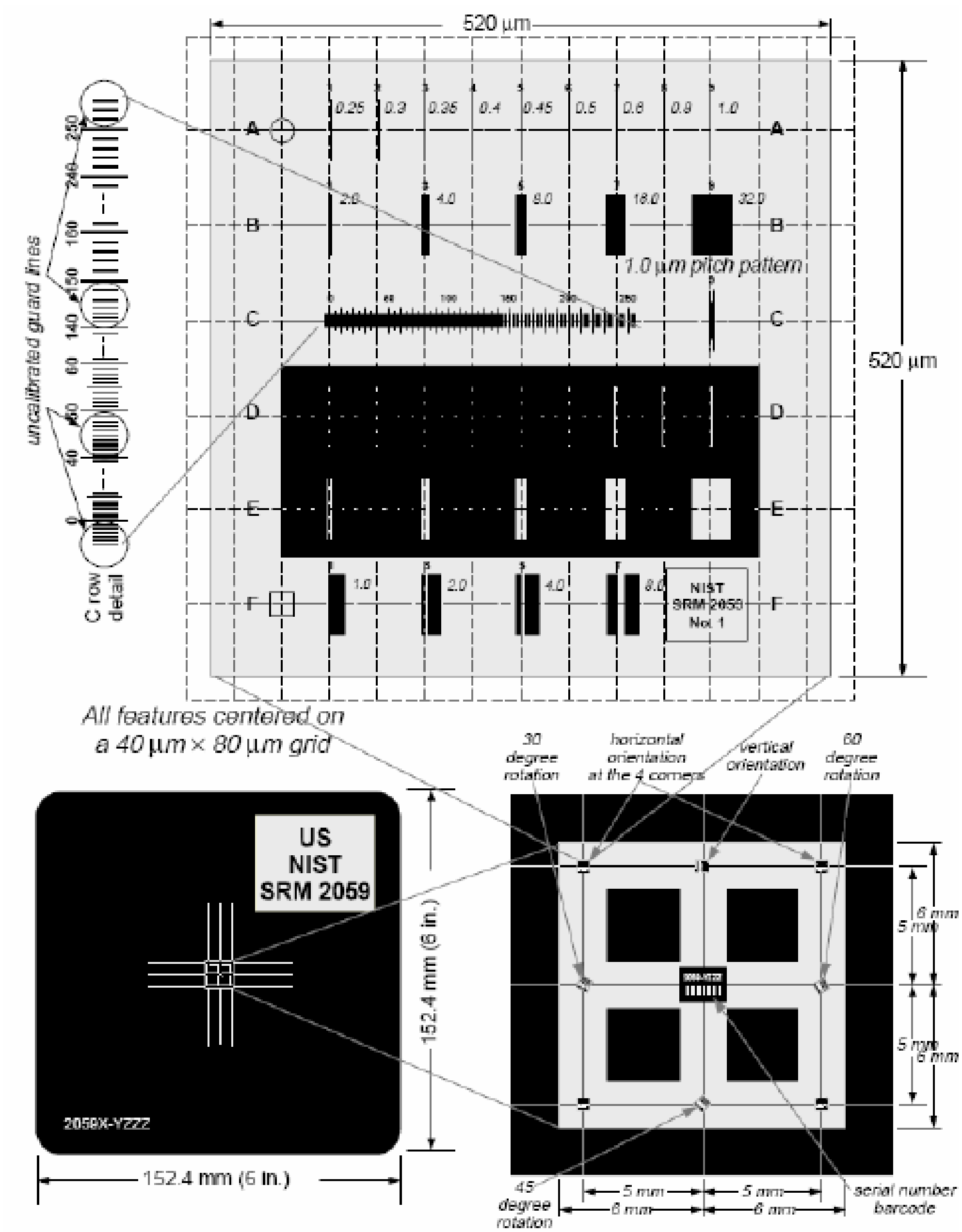

Figure 1. Schematic illustration of the layout of SRM 2059 – the current NIST binary photomask standard. The isolated line features are in rows A and B, and the isolated space features are in rows D and E. Both feature types range in width from 0.25 µm (the A1 and D1 features) up to 32 µm (the B9 and E9 features). (Note that due to AFM scale uncertainty, only features up to 8 µm width were measured in this work.)

Using our CD-AFM at NIST, we have performed new measurements on the SRM 2059 master standard. The new AFM results are in agreement with the prior measurements and have expanded uncertainties approximately one fourth of those of the earlier results for sub-micrometer features. When the optical comparator data for customers' masks are reanalyzed using these new AFM results, we expect to reduce the combined reported uncertainties for the linewidths on the actual SRMs by at least 40 % for the nominal 0.25 µm features.

2. AFM DIMENSIONAL METROLOGY AT NIST

NIST has a multifaceted program in traceable atomic force microscope (AFM) dimensional metrology.[10,11] There are three major components of the overall effort: (1) a custom metrology AFM called the calibrated AFM (C-AFM), (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 a second generation CD-AFM–the Veeco Dimension X3D[†]. All three of these instruments have applications in the NIST photomask standards program.

In contrast to conventional or top-down AFM, CD-AFM uses flared tips and more sophisticated feedback and scan control to permit the imaging of structures with near vertical sidewalls.[12] The SXM320 was initially used at SEMATECH to implement an RMS.[7,8] Although no commercially available CD-AFM has intrinsic scale traceability, these tools can be calibrated using standards measured on other instruments–such as the NIST C-AFM–which do have intrinsic traceability to the SI (*Systeme International d'Unites,* or International System of Units).

The CD-AFM based RMS at SEMATECH is described elsewhere.[4-6] In 2004, this tool was used to perform the first set of reference AFM measurements on the SRM 2059 master sample. The SXM320 is housed in the Advanced Measurement Laboratory (AML) – a state-of-the-art, five-wing laboratory for leading edge research that was opened at NIST in late 2004. This tool was used to perform the new AFM reference measurements described in this paper.

2.1 Uncertainties in CD-AFM Linewidth Metrology

The general approach[13] to uncertainty budgets – as advocated by the International Organization for Standardization (ISO) and adopted by NIST[14] – 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.[13,14] The most common coverage factor used is $k = 2$, which would correspond to approximately 95 % confidence for a normal (Gaussian) distribution.

Although the uncertainties are being continuously refined, we have previously published the general uncertainty budget templates for measurements of pitch, height, and width using our CD-AFM at NIST.[7,8,10] Only the major sources of uncertainty in linewidth metrology will be discussed here.

For CD-AFM linewidth measurements below 1 µm, the tip-related terms are the most important sources of uncertainty, rather than the scale-related terms that become more important for larger widths. 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[15], we give only an overview here.

The interaction of an AFM tip with the imaged surface is complex, but for many purposes a simplified 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

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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.

apparent width to obtain an accurate measurement. We refer to this offset 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.[9] The features on the SCCDRM specimens are preferentially etched crystalline silicon with near-vertical sidewalls and are thus particularly suitable for CD-AFM tip calibration. The linewidths of the features were calibrated with respect to the silicon lattice using a combination of high resolution transmission electron microscopy (HRTEM).

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.[15] 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.

Given the 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. This is especially true for photomask features – which commonly exhibit more irregularity than etched polysilicon structures. A composite cross-sectional profile taken from the original CD-AFM data on SRM 2059 is shown in figure 2. This profile is the average of twenty linescans over a 2 µm sampling length along the slow scan axis. It illustrates some of the challenges in using CD-AFM reference measurements to support optical linewidth metrology.

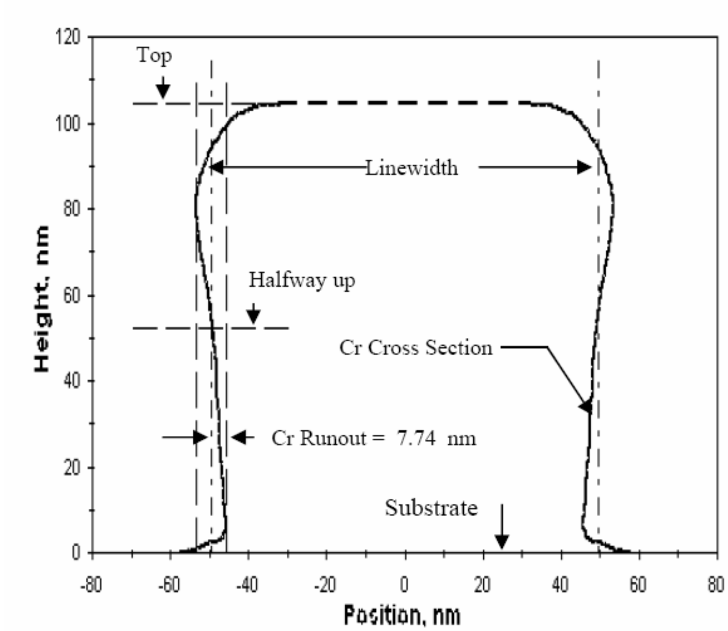

Figure 2. Composite CD-AFM cross-section of features on SRM2059. The irregular shape of some chrome-on-glass photomask features presents a greater challenge to CD-AFM metrology than typical poly-crystalline silicon structures. In particular, higher-order (e.g. shape) tip effects are a non-negligible source of uncertainty.

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.[16] 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[17] –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, but the observed bias is routinely corrected for.

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 by investigators at NIST[18] and elsewhere to understand such details.

3. RECALIBRATION OF THE SRM 2059 MASTER STANDARD

3.1 SRM 2059: The NIST Photomask Standard

The NIST program in photomask metrology was launched in the 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.[1] Over the next two decades, this was followed by SRM 475, SRM 476, and SRM 473[2], and then most recently the release of the current NIST photomask standard: SRM 2059.[3]

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 sale to customers. 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 discussed above, the achievable uncertainties in CD-AFM linewidth metrology have improved significantly during the last few years.[9,15] At the time of the original reference measurements for SRM2059, the standard uncertainty due to CD-AFM tip width calibration was 10 nm (k = 2). This lower limit on uncertainty was subsequently reduced to approximately 1 nm (k = 1) as a result of the NIST SCCDRM project. Consequently, re-measurement of the SRM 2059 master standard using AFM should result in reduced uncertainties reported to customers of the standard.

The chrome lines on SRM 2059 exhibit reentrant sidewalls and line width roughness (LWR)–which is averaged over in figure 2–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 2 is not negligible–and has not been explicitly removed from the data. At the time of the original measurements, however, this was not the leading contribution to the AFM uncertainty.

For the line and space features less than 1 µm width, the final reported uncertainties were approximately 14 nm (k = 2). A breakdown chart showing the origin of the major uncertainty contributions for the smallest line and space features is shown in figure 3.

The AFM-only contribution results from the previously mentioned 5 nm (k = 1) uncertainty in the original tip calibration. Most of the optical uncertainty is included in the fit which is used to transfer the AFM reference values to those masks that were only measured in the UV microscope. The repeatability of the optical measurements contributes a small additional share. This relative breakdown means that new AFM reference measurements should result in at least a 40 % reduction in uncertainty – and possibly more if the characteristics of the AFM/optical fit are favorably impacted.

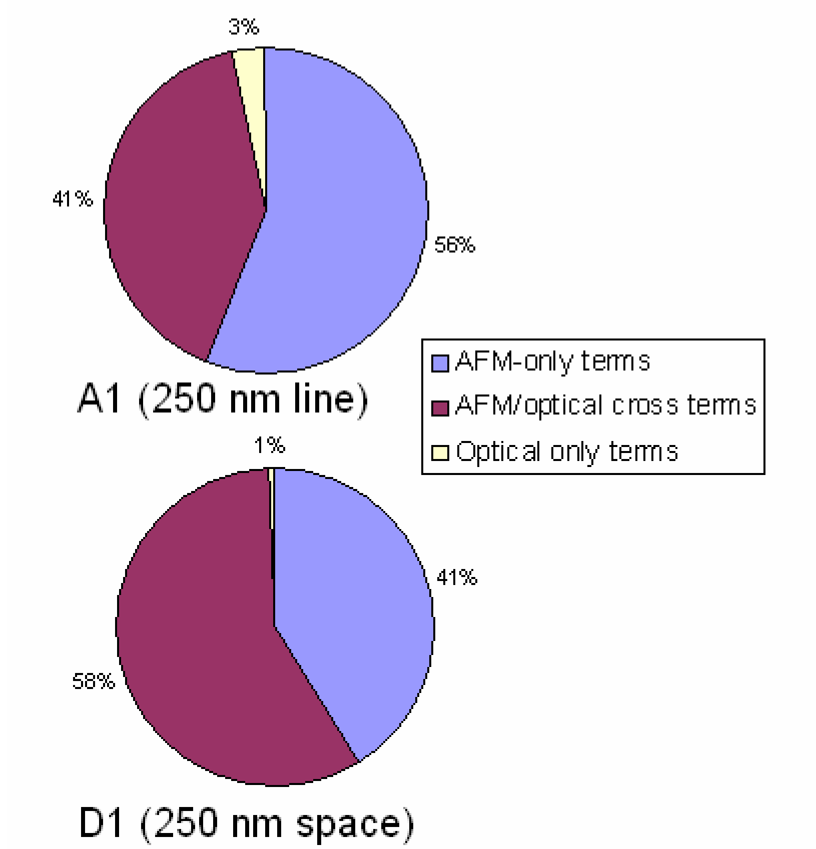

Figure 3. Origin of relative contributions to final combined variance for the 0.25 μm line and space targets which are A1 and D1, respectively. The combined expanded uncertainty in the linewidth of both features is approximately 14 nm (k = 2). Note that the optical-only share (type A) is a small fraction, but correlation of the optical and AFM results contributes roughly on par with the AFM-only share – which was due to tip calibration.

3.2 New CD-AFM Reference Measurements on SRM 2059

Using our CD-AFM at NIST, we have completed a new set of reference measurements of the line and space features ranging from 0.25 μm to 8 μm on the SRM 2059 master mask. These results are shown in figures 4 and 5. For comparison, the original measurements are shown along with the new results. An intermediate partial run – labeled as 'a' in figure 4–on the line features is shown in figure 4, but lower uncertainties were subsequently achieved in a final complete run – labeled in both figures 4 and 5 as run 'c'. There is good agreement between the two runs and with the 2004 data.

Although the scale-related uncertainties become dominant at the larger widths, the tip-related terms are most significant for widths below 1 μm. It can be seen that the expanded uncertainties have been reduced by approximately a factor of four at these small feature widths.

Tip wear was not completely negligible, but typically contributed an uncertainty less than 0.5 nm (k = 2). The master tip width calibration–derived from the SCCDRM project–contributed 0.6 nm (k = 2). The higher order tip effect of apparent width bias due to the tip offset height and sidewall slope contributed approximately 2 nm (k = 2) to the final quadrature sum and was the single most important effect.

This situation is also an important factor in our analysis strategy. The middle width (i.e. feature width at 50 % of the height) was chosen as the measurand to anchor the optical values in the comparator fit. In part, this choice is driven by the fact that the effect of the tip shape on the apparent middle width is more readily managed than for the top and bottom widths.

In part, this is because we are currently using 'single-measurand' methods of correcting for the effect of tip shape instead of a rigorous morphological erosion of an estimated tip shape to correct an image. Such methods are becoming available, but this is still an area of active research.[18]

For many practical purposes, however, a rigorous morphological erosion of the tip shape from the image is not necessary. As we and others have previously pointed out, a conceptual decomposition of the tip effects into the zeroth order tip width correction and higher order effects provides a useful framework for approaching the subject in regard to specific measurements. [5,9,15] This is because the most significant effect of the tip geometry is to simply make the apparent width larger by an approximately constant bias and to induce small variable biases on specific measurands that result from the detailed dilation of feature shape with the tip shape.

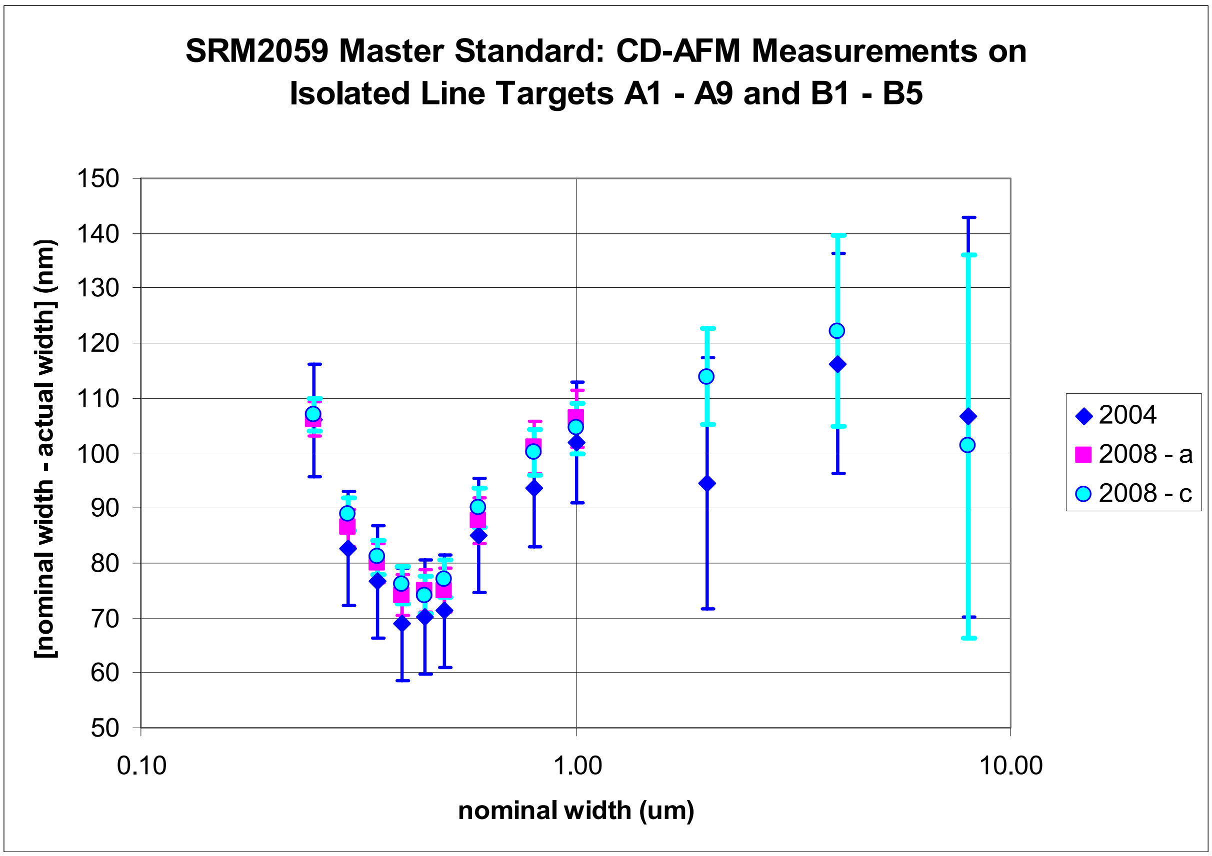

Figure 4. New and original CD-AFM reference measurement on the isolated line targets of SRM 2059 – ranging from 0.25 µm width (A1 feature) up to 8 µm (B5 feature). The error bars represent expanded ($k = 2$) uncertainties, which have been reduced by approximately x4 for the smallest features.

For example, the finite radius of the CD tip flare results in an offset height between the actual and apparent imaging points along a sidewall. In the case of features with non-vertical sidewalls, the apparent width is thus biased by approximately

$$\Delta W = 2 \times \Delta h \times \tan(\theta_{SWA} - 90°) \quad (1)$$

where ΔW is the apparent width bias, Δh is the offset height of the tip flare, and θ_{SWA} is the angle of the feature sidewall. Erosion of the tip shape from the entire image is not necessary in order to approximately make this correction. However, the accuracy of such a simplified approach is dependent upon the extent to which the feature profile conforms to an idealized geometry. In this case, the important assumption is that the sidewall is well described by a single sidewall angle.

For the features on SRM 2059, figure 2 clearly the reveals that this model is relatively robust for widths near the half-height, but is not appropriate for widths near the top and bottom where a more complex model is necessary to relate the apparent and corrected values of the measurand. Consequently, it seems most appropriate to use the AFM middle width as a reference anchor for the optical comparator scheme.

In future efforts, the next step in improving our reference measurements on the SRM 2059 master will be to implement rigorous morphological tip 'deconvolution' to account for the effects of tip shape. We are currently collaborating with Villarrubia and Qian[18] to explore that possibility.

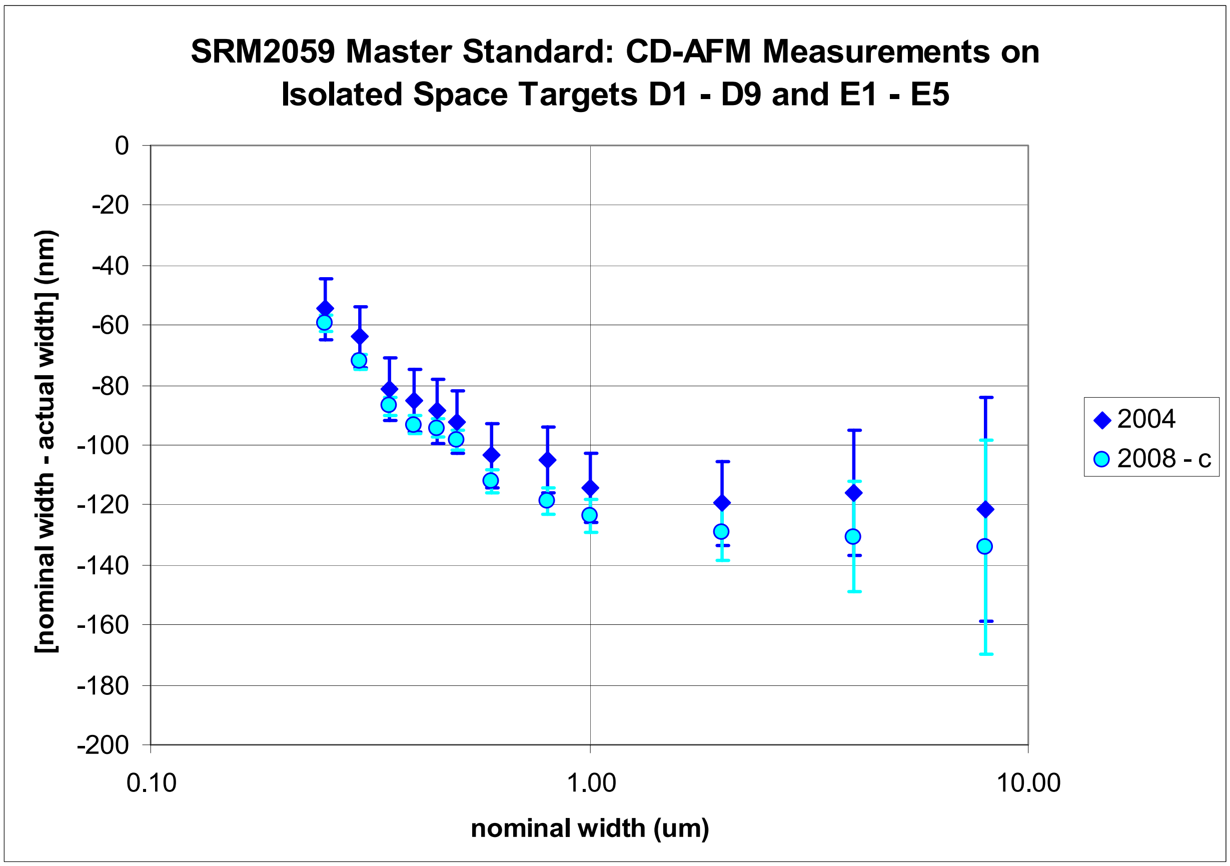

Figure 5. New and original CD-AFM reference measurement on the isolated space targets of SRM 2059 – ranging from 0.25 µm width (D1 feature) up to 8 µm (E5 feature). The error bars represent expanded (k = 2) uncertainties, which have been reduced by approximately x4 for the smallest features.

In figure 6 the uncertainties for the A1 and D1 features based on the original calibration are compared with two bounding estimates–one 'optimistic' and one 'pessimistic'–of the final uncertainties once the new AFM data have been incorporated into the analysis.

The new combined expanded uncertainties should be no larger than the 'pessimistic' estimate – because this assumes that all optical uncertainties remain unchanged and that only the contributions exclusively related to the AFM are reduced. However, since it is possible that the uncertainties related to the optical/AFM fit will also be improved with the use of the newer AFM data, this is potentially a pessimistic model.

On the other hand, using the new AFM reference data, the final combined expanded uncertainties cannot possibly be lower than the 'optimistic' estimate – because this assumes that the optical/AFM fit term is reduced to zero and only the optical repeatability and AFM uncertainties contribute.

If we can reach the optimistic level, the relevance of SRM 2059 to our leading-edge customers will be considerably enhanced. However, it may be necessary to perform both improved optical and AFM measurements to fully achieve this goal. This is already on the drawing board as part of a planned international comparison of linewidth measurements on photomasks.[19]

4. SUMMARY AND FUTURE WORK

NIST has robust and multifaceted programs in both optical photomask metrology and traceable atomic force microscope (AFM) dimensional metrology. The current NIST binary photomask standard, SRM 2059, represents the fifth generation of this NIST standard since it was launched in 1981 with the release of SRM 474.

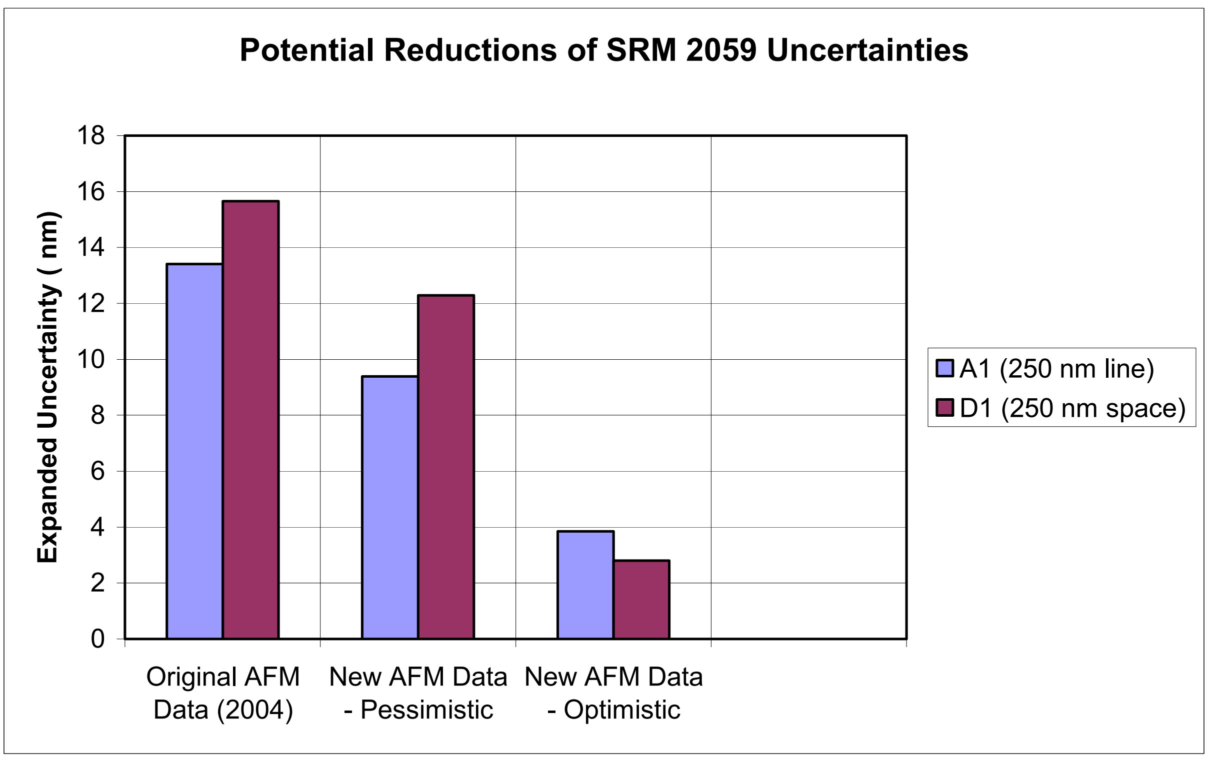

Figure 6. Original SRM 2059 uncertainties compared with optimistic and pessimistic estimates of final uncertainties based on the new AFM reference data.

The NIST AFM dimensional metrology program includes a strong component in CD-AFM linewidth metrology – which encompasses both wafer and photomask applications. We originally used CD-AFM reference metrology to calibrate the SRM 2059 master standard in 2004, and we have now completed a remeasurement resulting in the AFM uncertainties being reduced by approximately a factor of four on the 0.25 µm line and space features.

This reduction in AFM uncertainties on the master standard will, in turn, lead to a reduction of between 40 % and 75 % in final uncertainties of the optically-determined linewidths on the SRMs for sale to NIST customers. If we can reach the optimistic level, the relevance of SRM 2059 to our leading-edge customers will be considerably enhanced. However, it may be necessary to perform both improved optical and AFM measurements to fully achieve this goal. This is already on the drawing board as part of a planned international comparison of linewidth measurements on photomasks.[19]

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