Mapping the Edge Roughness of Test-Structure Features for Nanometer-Level CD Reference-Materials[¶]

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ABSTRACT

The near-term objective of the work reported here is to develop a protocol for rapidly mapping critical-dimension (CD) and edge roughness from high-resolution Scanning-Electron Microscopy (SEM) images of reference-material features patterned on Single-Crystal CD Reference Material (SCCDRM) chips. The longer term mission is to formulate a metric to enable automated characterization of as-fabricated reference-feature segments for rapid identification of fabrication-process enhancements and, ultimately, to select feature segments for further characterization as standard reference-materials. The selection of results presented here provides a new level of SCCDRM characterization showing that segments of some SCCDRM features appear to have very useful extended lengths of up to 200 nm of superior CD uniformity.

BACKGROUND

Fabrication processes and calibration procedures for making silicon-based prototype critical-dimension (CD) reference features available to industry have been under development in a multi-laboratory National Institute of Standards and Technology (NIST) project for several years.[1] The silicon technology is known as the Single-Crystal CD Reference Material (SCCDRM) implementation. The end application for these reference materials is metrology support for sub 100 nm gate-length IC fabrication. The project has so far delivered a selection of reference materials for evaluation to the International SEMATECH Manufacturing Initiative and other organizations.[2] The better SCCDRM calibrated reference features with sub-tenth-micrometer linewidths that have so far been delivered have expanded uncertainties as low as 1.25 nm.[‡] Navigation errors sustained during calibration team up with residual reference-feature CD non-uniformity to generate contributions of approximately 25 % of this amount. However, calibration with sub-single-nanometer uncertainty is understood to be highly desirable for end-user applications. The fact is that the significant uncertainty contribution above could be driven towards zero if a way could be found to fabricate reference features with CD roughness consistent with atomic-level feature-sidewall planarity along segment lengths as long as 0.25 µm, for example. Until very recently, the longest feature segments having this property extended for approximately 50 nm. However, further fabrication-process enhancement to generate greater lengths of quasi-atomic-sidewall-planarity is challenged by the possible existence of spatially random local regions of anomalous properties of the starting-material extending to over hundreds of nanometers. The approach that has been adopted here to minimize the adverse impact of these properties, and to produce 250 nm feature-segments having near-zero edge roughness, is to devise appropriate fabrication processing with the aid of a high-throughput data-acquisition protocol to identify regions of processing space that minimize, or zero, intra-feature CD and edge roughness. Simultaneously, the same data acquisition identifies the locations of segments on a feature having superior edge and CD roughness. The specific technical approach, namely automated dimensional analysis of high-resolution Scanning-Electron Microscopy (SEM) images, has been applied to a selection of SCCDRM features having CDs in the range 50 nm to 200 nm. The results provide an essential assessment of the current baseline SCCDRM fabrication process *vis-à-vis* CD-uniformity and edge roughness. This is a prerequisite to the next step of formulating a metric to enable automated identification and ranking of as-fabricated reference-feature segments to be used to support fabrication-process enhancements and, ultimately, to select features for further qualifying metrology for standard reference-material applications.[3]

One of many recent articles exemplifies how topical the issue of edge-roughness metrology has become.[4] However, there appear to be no prior reports on the unique and specific application that is the subject of this paper. Alternative methods include, for example,

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[‡] For a description of terminology see, for example, http://physics.nist.gov/cuu/Uncertainty/coverage.html .

performing the metrology on state-of-the-art production-level CD-SEM systems with built-in facilities for dimensional metrology. Unfortunately it is not practical to employ such systems for the preliminary laboratory research that is reported here because the approach that we have adopted is necessarily a chip-level implementation.

PURPOSE

The mission of the work reported here has two parts. The first is to apply image-analysis software to extraction and analysis of multiple measurements of linewidth, linewidth roughness, and edge roughness of as-fabricated SCCDRM test-structure features from SEM images. The second part is to make an assessment of the status of the SCCDRM fabrication process for producing reference features with CD and edge roughness consistent with the longer term objective of fabricating Standard Reference Materials (SRMs) with sub-single-nanometer traceable uncertainty. The motivation for this study derives from the issue stated above: namely, that spatially random CD non-uniformity adversely impacts the level of uncertainty that is attributed to the certified CDs of deliverable reference features. The counter-measures to these problems that have so far been implemented include ranking and selecting features according to their linewidth uniformity and identifying the region of processing space that minimizes the observed non-uniformities. Since both are inspection-intensive operations, the specific longer-term target of the work reported here is providing a computer-based metric for fabrication-process enhancement and facilitating optimal selection of features to be delivered as SRMs for application in AFM (Atomic Force Microscopy), SEM, OCD (Optical CD), and/or SAXS (Small Angle X-Ray Scattering) environments. This report describes the analytical infrastructure that was developed and applied and presents a selection of the measurements that have so far been acquired. This sets the scene for future reports on the behavior of the dimensional parameter sets under various wafer-processing conditions.

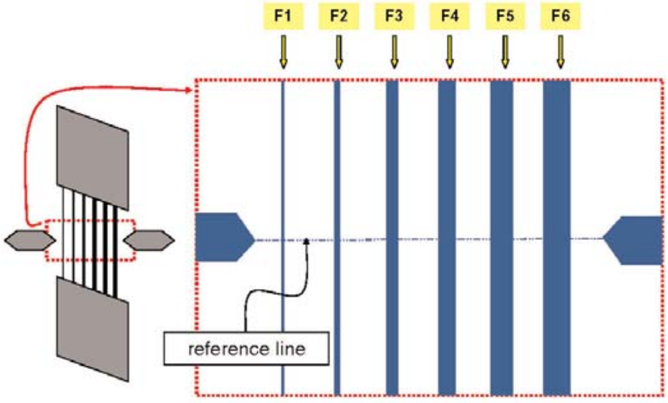

Figure 1. The labels F1 through F6 identify individual features of the test structure. F1 is the narrowest.

TEST-CHIP DESIGN AND FABRICATION

Test-Chip and Test-Structure Design

The test structure used in this project has multiple instances of a so-called "HRTEM (High-Resolution Transmission-Electron Microscopy) Target" that has six CD reference features. These six features were drawn with staggered linewidths so as to facilitate CD-extraction for multiple drawn-CD values. The basic geometry of an HRTEM target layout is shown in Figure 1. It was designed specifically to enable HRTEM imaging of the cross sections of all six features at a pre-determined location with a single sample-preparation. High-magnification top-down SEM images of all six features can be recorded in no more than two files. During lithography, the principal axes of the test structure are designed for alignment to <112> lattice vectors in the (110) surface of the SIMOX (Separation by Implantation with Oxygen) wafer to provide the pattern's features with planar (111) sidewalls.[5]

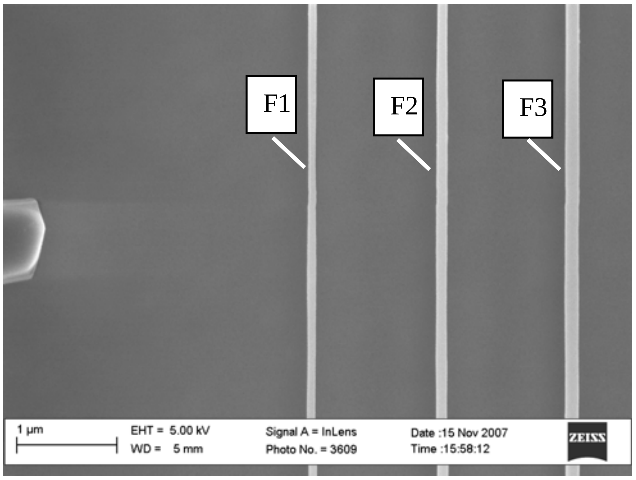

Figure 2. An SEM image of the left half of the central portion of the test structure shown in Figure 1.

Fabrication Process

The test chip pattern is replicated in the device layer of a (110) SIMOX wafer according to the SCCDRM fabrication process.[5] The nominal heights of all the reference features are 150 nm. The device layer is electrically isolated from the remaining thickness of the substrate by the 390 nm-thick buried oxide created by high-energy oxygen implantation.

An SEM image of the left half of the as-fabricated central portion of the test structure that has been shown in Figure 1 is reproduced in Figure 2. One near term objective of the work reported here is to configure the Spectel Research "*MEASURE*" program to extract CD, CD-roughness, left-edge roughness, and right-edge roughness parameters from multiple contiguous locations on all three features, of which those shown in Figure 2 are an example, in less than several seconds.[§] Whereas the as-distributed Spectel "*MEASURE*" program has a facility for automatically extracting the parameter values at one particular location on multiple images, the same is not true for multiple locations along a single feature on a single image, which is an essential component of the SCCDRM feature-ranking/selection task. Therefore the interim approach that was adopted here was to drive *MEASURE's* CD/roughness-extraction algorithm with a macro facility.

The CD-Uncertainty Issue

The complexities of the SCCDRM reference-feature calibration procedure have been described in detail elsewhere.[5] This synopsis explains why the issue of devising a convenient metric for fabrication-process enhancement is so important for further reduction of uncertainty.

The SCCDRM reference-feature program at NIST originated with AFM measurements of the linewidths of a selection of features that were subject, among others, to an error attributable to the unknown width of the AFM tip that was employed. A sub-selection of the measured features was then set aside for use internally for the future calibration of other AFM tips. The remaining features were then subjected to traceable HRTEM linewidth metrology. The AFM and HRTEM measurements were then reconciled to provide an estimate of the *AFM Offset* correction applicable to the features that were unavoidably destroyed during HRTEM imaging as well as those that were set aside. The set-aside features are thus able to serve as references for measuring the offsets applicable to replacement tips in future calibration of other reference materials.

The calibration of a newly fabricated reference material, with traceability to the HRTEM measurements described above, involves providing for uncertainty contributions from four sources.[5] The expanded uncertainty applicable to an AFM measurement of its CD is computed by combining the four contributions by "root-sum-squares" and multiplying the result, which is known as the "*combined standard uncertainty,*" by k=2 to generate the total 2-sigma uncertainty value. Among the four sources of the combined standard uncertainty that are referenced above, the one identified as *CD Non-Uniformity/Navigation* typically contributes approximately 0.2 nm or more to the total 2-sigma uncertainty. Currently, the better SCCDRM calibrated reference features have expanded uncertainties in excess of 1.25 nm. Thus the *CD Non-Uniformity/Navigation* contribution of 0.2 nm or more is not trivial in the ultimate quest to reduce the expanded uncertainty to below end-user-stated requirements of 1 nm. The fact is that this contribution could be driven to near zero if a way could be found to fabricate reference features with quasi-zero CD roughness along reference-feature lengths approaching 0.25 µm. Further reduction of uncertainty may also accrue through a second contributor to the expanded uncertainty, namely one labeled the "*Estimated AFM offset.*" Further details are provided in Reference 5.

The end-user of a SCCDRM reference material may also benefit from zero CD roughness while he or she navigates to the calibrated location of the reference feature. Residual roughness compounds the effect of spatially "missing" the calibrated location during, for example, a tip-width calibration.

The core reason that this work was undertaken is to reduce the zero CD-/edge-roughness condition to practice as far as possible, thereby reducing the calibrated-feature uncertainty. An essential prerequisite of the management of optimizing the fabrication process to provide at least local regions of features with zero edge roughness is having an extensive high-throughput data-acquisition protocol, an example of which is to be exemplified here, to assist in identifying optimum process conditions.

TECHNICAL APPROACH

SEM Imaging

The individual feature-referencing designation that is used extensively in this document follows a format that has been used in prior articles on SCCDRM technology. The basic components of the designation uniquely identify each of typically 500 features that are replicated on each chip according to its :<Chip Number>, <Target-Array Number>, <Target Number>, and <Feature Number>. For example, A10-T3-5p3-F4 is a reference feature on chip A10, in the T3 HRTEM target array, specifically the 5p3 target, where it is the fourth feature. Examples of wafer and target-array maps are shown in Reference 5.

The Spectel Research "MEASURE" Program

The program *MEASURE* was developed with SEMATECH funding in the 1990s and is an offline metrology analysis tool designed for scanning electron microscope images. Besides providing a menu of conventional line-edge algorithms, with which to perform measurements, its capabilities were extended to include inverse scattering techniques based on Monte Carlo simulation. *MEASURE* can handle a wide variety of file

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[§] Certain commercial equipment, instruments, or materials are identified in this document in order to specify adequate measurement procedures. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

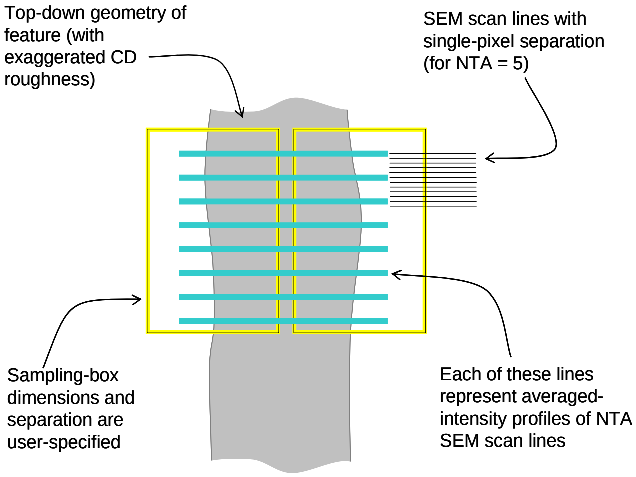


Figure 3. The intensity profiles of NTA rows (beam scans) are averaged before a user-selected line-edge finding algorithm is applied

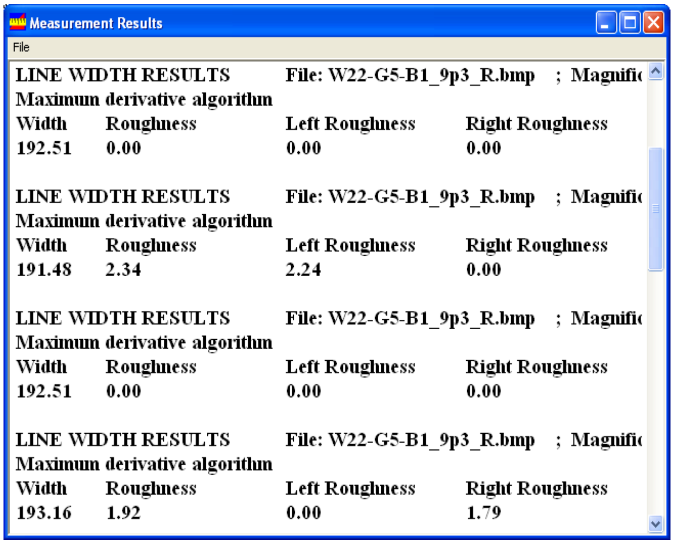
formats, can perform automated measurements of folders containing many files, and includes some algorithm alignment capability. Its features can be further automated by using PC macro-writing tools such as *autoIT*, *autoHotKey*, or *MacroMaker*. A limited version of *MEASURE* is available free of charge from the Spectel Research FTP site.

When performing CD, CD-roughness, and line-edge roughness calculations, *MEASURE* uses a parameter called "The Number-of-Rows to Average" (NTA). The default for this parameter is 5 rows, each "row" being generated by a single scan of the beam, as depicted in Figure 3. The intensity profiles of this number of scans are averaged, and then a user-selected line-edge finding algorithm is applied to the averaged-intensity data. During measurement, each of a pair of sampling boxes with user-defined dimensions is located over the feature edges. The feature edges are found by a user-selected algorithm applied to the averaged profiles within the sampling boxes. The separation of the left and right edges is then calculated for each averaged set of rows. The CD for each sampling-box placement is then calculated as the average left-to-right separation. Similarly, for each placement, CD roughness is the standard uncertainty of the extracted CD value. The right- or left-edge roughness for the prevailing sampling box location is similarly calculated but by referencing the neighboring sampling-box boundaries.

Measurement-Extraction Procedure

For each of the reference features F1 thru F6 on each target, CD and roughness measurements were extracted from thirteen contiguous placements pairs of 300 nm long sampling boxes along the length of the imaged feature by the Spectel *MEASURE* program. This baseline protocol provided near-total coverage of their 3900 nm imaged lengths. For each feature, *MEASURE* thus provided 13 sets of 1 CD, 1 CD-roughness, and 2 edge roughness values. From this point on in this manuscript, these four quantities are referred to as the "dimensional parameter set" (DPS). The baseline NTA parameter was set at 5 rows per sampling-box.

The *MEASURE* program tabulates the extracted values of the dimensional parameter set in a "Report," an example of which is shown in Figure 4. In this case, it can be seen that the so-called "Maximum Derivative Algorithm" for DPS extraction was applied. It identifies the locations of the points where the derivative of pixel intensity vs. cross-section location is a maximum. It is one of several that *MEASURE* makes available to the user. For each sampling-box placement, the report lists the name of the image file, lists the local values of the dimensional parameter set, and identifies the actual algorithm that was selected to generate the latter. The summary page for each target lists the CDs of segments that report zero average CD roughness for all six features on a particular target.



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LINE WIDTH RESULTS       File: W22-G5-B1_9p3_R.bmp   ; Magnific
Maximum derivative algorithm
Width      Roughness     Left Roughness        Right Roughness
192.51     0.00          0.00                  0.00

LINE WIDTH RESULTS       File: W22-G5-B1_9p3_R.bmp   ; Magnific
Maximum derivative algorithm
Width      Roughness     Left Roughness        Right Roughness
191.48     2.34          2.24                  0.00

LINE WIDTH RESULTS       File: W22-G5-B1_9p3_R.bmp   ; Magnific
Maximum derivative algorithm
Width      Roughness     Left Roughness        Right Roughness
192.51     0.00          0.00                  0.00

LINE WIDTH RESULTS       File: W22-G5-B1_9p3_R.bmp   ; Magnific
Maximum derivative algorithm
Width      Roughness     Left Roughness        Right Roughness
193.16     1.92          0.00                  1.79
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Figure 4. The Spectel *MEASURE* program tabulates the extracted values of the dimensional parameter set in a "Report." This Report is for four placements of the sampling boxes.

An open-source program called *MacroMaker* was used to drive *MEASURE* so as to compile a Report listing of 39 dimensional parameter sets acquired from each image of three features.[**]

Examples of Variation of CD and Edge Roughness

An example of a part of a worksheet listing of dimensional parameter set values for a six-feature HRTEM target is shown in Table 1. The yellow high

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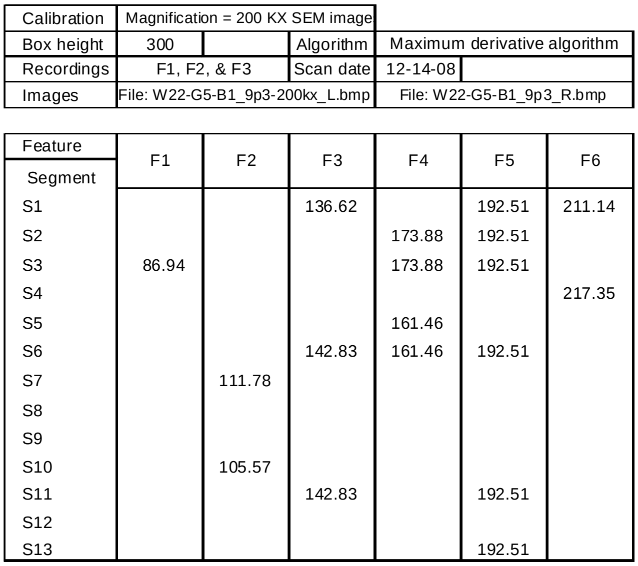
[**] http://www.sharewareplaza.com/MacroMaker-download_3600.html



Calibration	Magnification = 200 KX SEM image				
Box height	300		Algorithm	Maximum derivative algorithm	
Recordings	F1, F2, & F3		Scan date	12-14-08	
Images	File: W22-G5-B1_9p3-200kx_L.bmp			File: W22-G5-B1_9p3_R.bmp	

Feature Segment	F1	F2	F3	F4	F5	F6
S1			136.62		192.51	211.14
S2				173.88	192.51	
S3	86.94			173.88	192.51	
S4						217.35
S5				161.46		
S6			142.83	161.46	192.51	
S7		111.78				
S8						
S9						
S10		105.57				
S11			142.83		192.51	
S12						
S13					192.51	

Figure 5. The summary page for each target reports the CDs, in nanometers, of segments that report zero average CD roughness for all six features on a particular target.

lighted cells indicate those segments for which the average CD roughness for a particular segment was reported as zero. Their distribution along the length of a particular feature is of central interest in the subject application because they identify segments that have greater potential usefulness as reference features and/or flag processing conditions that promote, or discourage, the patterning of segments having uniform CDs.

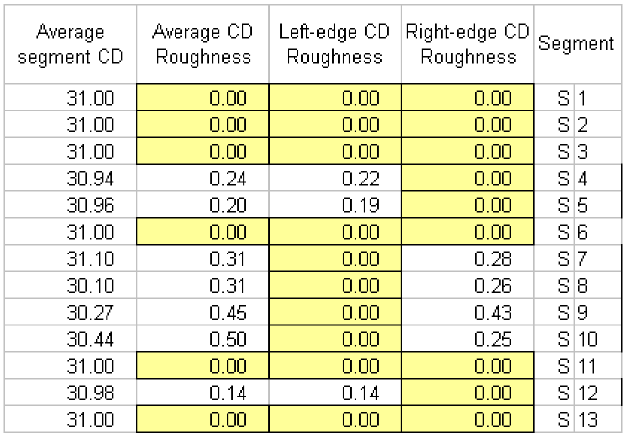
In addition, a summary page lists the highlighted CD data for all six features on a particular target. This allows a broader overview of the CD distribution across an entire target. An example of the summary page for the same target is shown in Figure 5, this time with the pixel counts in nanometers, as delivered by the *MEASURE* report.

Examples of Variation of CD with Location: During the initial phase of this work, data sets such as that shown in Table 1 were extracted from almost 100 features on three different chips. The few examples shown here have been selected by the authors on the basis of some preliminary observations; e.g., the curve in Figure 6 shows a degree of full-length uniformity, other than for a sharp drop in CD around the 2100 nm mark. The left-most section that is comprised of segments S1 thru S7 appears to have a CD-uniformity of better than 1 nm over 2.0 µm. On the face of it, this region would be a candidate for inspection for a reference-material application.

Another observation, which has been made on several CD profiles, is also exemplified by Table 1 and Figure 6. Namely, contiguous segment-sets having zero CD roughness often have among the highest CDs along the feature lengths. What is somewhat surprising is that generally, but not always, the segments of a particular feature having zero CD roughness also have the *same* segment-average CDs. Both of these points are exemplified by the data in Table 1 and Figure 6.

Example of Edge-Roughness Results: In this and the following sections, the examples are drawn largely from images collected from target G5-B1-9p3 because it usefully illustrates some of the points from which provisional observations may be made on the status and characteristics of SCCDRM fabrication.

Table 1. Example of a part of a feature-page listing of Dimensional-Parameter-Set values generated from a Report such as that shown in Figure 4. The feature is W22-G5-B1-9p3-F5, and the units are pixels, each pixel calibrated as 6.21 nm.



Average segment CD	Average CD Roughness	Left-edge CD Roughness	Right-edge CD Roughness	Segment
31.00	0.00	0.00	0.00	S 1
31.00	0.00	0.00	0.00	S 2
31.00	0.00	0.00	0.00	S 3
30.94	0.24	0.22	0.00	S 4
30.96	0.20	0.19	0.00	S 5
31.00	0.00	0.00	0.00	S 6
31.10	0.31	0.00	0.28	S 7
30.10	0.31	0.00	0.26	S 8
30.27	0.45	0.00	0.43	S 9
30.44	0.50	0.00	0.25	S 10
31.00	0.00	0.00	0.00	S 11
30.98	0.14	0.14	0.00	S 12
31.00	0.00	0.00	0.00	S 13

In the fabrication of features with sub 50 nm linewidths, our experience has been that isolated features, even when replicated by optical ultra-violet lithography, can have their linewidths driven down to this range by prolonging the etching with which they are patterned. The limiting factor, as far as the reference-material application is

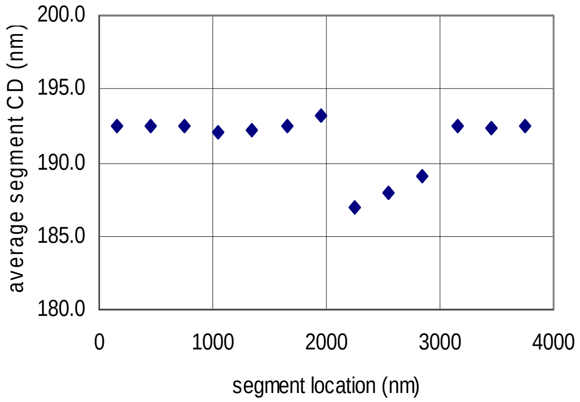


Figure 6. CD averaged over 300 nm vs. segment location on the feature. The zero location is the extreme top of the image and the 4000 nm location is at the bottom, consistent with the orientation shown in Figure 1 and Figure 3.

concerned, is replicating features with superior CD uniformity. Experience in the inspection and rating as-produced features with the SEM-MEASURE approach reports results for CD-variation patterns quite similar to those generated by the AFM approach. It happens that the former is much more rapid and, therefore, can be applied much more extensively. Of course, it is not traceability-capable while ranking features for superior uniformity, as is the AFM approach, which is uniquely responsive to the traceability issue.

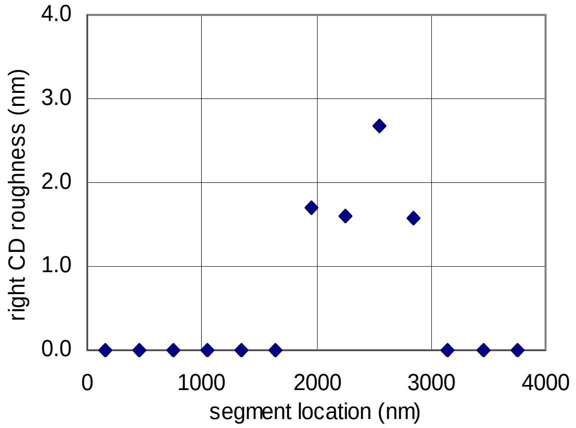


Figure 7. Non-zero right-edge roughness occurs almost exactly along the length of the feature where the local CD degradation shown previously in Figure 5 occurs. (Feature is W22-G5-B1-9p3-F5).

The right-edge roughness profile shown in Figure 7 also derives from Table 2 and illustrates that anomalous right-edge roughness occurs almost exactly along the length of the feature where the local CD degradation that has been shown previously in Figure 6 occurs. Whereas we later propose a physical model for how this could happen, such behavior has not yet been widely cataloged.

So far in this paper, all the reported measurements were conducted with the *MEASURE's* "Maximum Derivative" (MDA) algorithm for linewidth extraction. We also examined the repeatability the G5-B1-9p3-F5 feature measurements with *MEASURE's* alternative "Maximum Second Derivative" (MSD) algorithm. The repeatability *per se* was somewhat improved, and both the linewidth and roughness values closely tracked those generated by the MDA algorithm. If there was a repeatability issue, our preliminary observations indicate that the application of MSD might be preferable.

SUMMARY

The results that have been presented here show that segments of some SCCDRM features appear to have very useful extended lengths of up to 200 nm of superior CD uniformity. In general, however, these segments have no predictable spatial distribution. A major unintended benefit of the results that have been generated is that we may have acquired some useful insight for understanding the etching process that is used to pattern the features. We have observed that (a) the most uniform feature segments tend to have the highest local CDs along a feature length and (b) such CDs tend to have the same values. As a result, a model for the generation of the non-uniformity of the CD, which in principle might be expected to be quasi-atomically uniform, is that the starting material may have nanometer-scale regions, which, for an as-yet unknown reason, destroy local etch anisotropy and accelerate silicon dissolution.

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