The measurement uncertainty challenge of advanced patterning development

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ABSTRACT

The trend of reducing the feature size in ICs requires tightening control of critical dimension (CD) variability for optimal device performance. This drives a need to be able to accurately characterize the variability in order to have reliable metrics to drive improvement in development. Variation in CDs can come from various sectors such as mask, OPC, litho & Etch. Metrology is involved in all sectors and it is important to understand the accuracy limitations in metrology contributing to CD variability. Inaccuracy of the CD-SEM algorithm arising from profile variations is one example. Profile variation can result from process and design variation. Total Measurement Uncertainty (TMU) is a metric dependent on the precision of tool under test (CD-SEM here) and relative accuracy, and can track the accuracy of CD measurements in the presence of varying profiles. This study explores metrology limitations to capture the design and process contributions to the CD variation at the post litho step. In this paper lithography scanner focus-exposure matrix wafer was used to capture the process variation. CD and profile data is taken from varying focus fields. The sample plan described in this paper also covers the design variation by including nested features and isolated features of various sizes. Appropriate averaging methodology has been adopted in an attempt to decouple the process and design variation related uncertainty components of TMU. While the tool precision can be suppressed by sufficient averaging, the relative accuracy cannot. This relative accuracy is affected by the complex CD-SEM probe to sample interactions and sensitivity of CD-SEM algorithms to different feature profiles. One consequence of this is the average offsets between physical CDs (CD-AFM) and SEM CDs change significantly with the scanner focus. TMU worsens as the focus range is increased from nominal focus. This paper explores why this is so and also discusses the challenges for the CD-AFM to accurately measure complex and varying profiles. There is a discussion of the implications of this study for the production measurement uncertainty, OPC calibration measurement at process of record conditions (POR), and for process window OPC. Results for optimizing the CD-SEM algorithm to achieve superior accuracy across both design and process induced variation will also be presented.

Keywords: **Keywords:** CD-AFM, CD-SEM, OPC Model, Reference Metrology, Physical offset, TMU, RMS

1. INTRODUCTION

The trend of reducing the feature size in ICs and concurrently reducing the size variability requires tight control of CD variability essential for optimal device performance. Increasingly accurate CD metrology is needed to capture and enable tight control of CD variation as envisaged in the International Technology Roadmap for Semiconductors (ITRS) [1]. Figure 1 is a plot based on data from ITRS highlighting that continued shrinking of the gate CD in future also requires a tight control of gate CD uniformity and that requires even tighter control on the CD measurement uncertainty. This is clearly indicated by the aggressive need for sub-half and sub-quarter nanometer measurement uncertainty for dense and isolated 1D features respectively in the near term.

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Metrology, Inspection, and Process Control for Microlithography XXIII, edited by John A. Allgair, Christopher J. Raymond
Proc. of SPIE Vol. 7272, 727203 · © 2009 SPIE · CCC code: 0277-786X/09/$18 · doi: 10.1117/12.814170

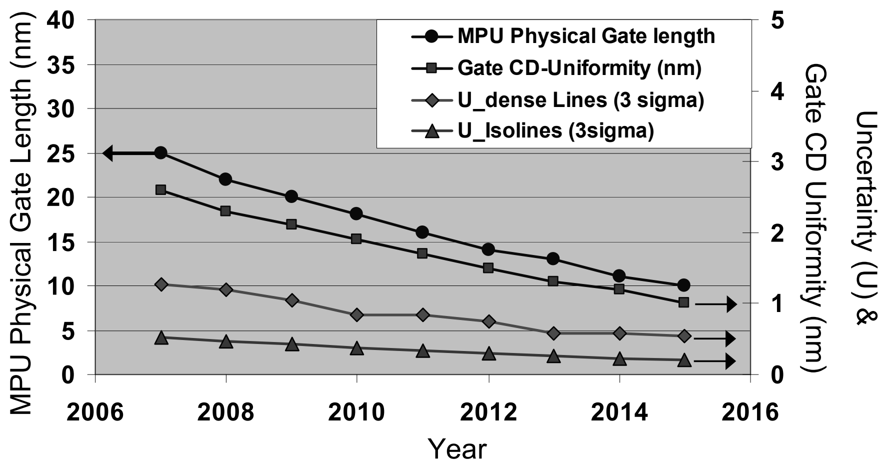

Figure 1: Aggressive uncertainty targets for gate CD control in ITRS.

These tight uncertainty specifications may be more pertinent to the manufacturing controls where the process tolerance and CD range of interest is narrow and optimized. However, achieving these specifications in manufacturing depends upon reducing the measurement uncertainties during development where more comprehensive design sizes and shapes are investigated. CD metrology is involved in all stages of IC fabrication including mask fabrication, development of optical proximity corrections (OPC), lithography, and etch processes. It is important to understand and attempt to reduce the measurement uncertainty related to different variables involved in these sectors.

Advanced patterning processes pose challenges for metrology. One key challenge is a result of the complex variations in resist profiles for high NA 193 nm lithography. Small scanner depth of focus, focus variations, feature size and proximity significantly contribute to sidewall profile variation. Quite often the profiles ranging from re-entrant to exposed-bottom with top edge rounding are observed, as shown in Figure 2. Metrology techniques have limited sensitivity to capture such profile changes and hence add to the uncertainty of measurements.

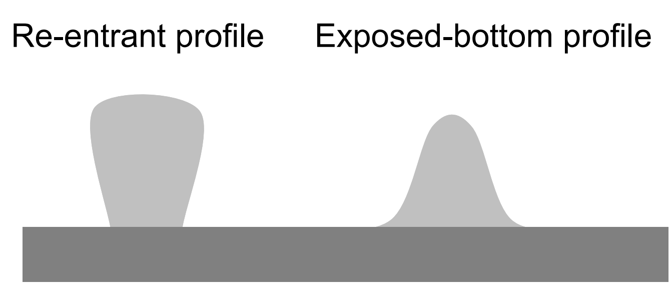

Figure 2: Profile variation poses challenge for metrology.

Optical Proximity Correction (OPC) is one important way advanced patterning is achieved and thus extends the printing range of optical lithography. The success of an empirical OPC model predicting print fidelity is highly dependent upon model fine tuning based upon accurate dimensional feedback. This model requires careful input from all the unique families of shapes and typically involves thousands of dimensional measurements of resist images. The OPC modelers need to be sure that all unique shapes are accurately printed in the wafer sufficient enough to produce a functioning integrated circuit. The OPC model needs to predict patterning for all regions of image space [2] represented in chip designs. This requires the simulation model to be calibrated using measurements from geometries spanning the same regions of image space. Predominately today this is done by using many simple shapes measurable by standard CD-SEM algorithms. A trend in the industry is to replace these many simple shape measurements with a smaller set of more complex contours obtained from the CD-SEM images [3]. Regardless of the model calibration method, it is the task of the metrologist to ensure that the modeler gets accurate measurements i.e. with minimum possible measurement uncertainty. There is a clear need of appropriate statistical metric and methodology for best estimate of the measurement uncertainty.

1.1 Total measurement uncertainty

The general concept of measurement uncertainty and especially how it applies to the semiconductor industry has been discussed in several publications over the last twenty years. An international body of statisticians met in the early 1990's [4] to properly address the concepts of uncertainty. The International Technology Roadmap for Semiconductors (ITRS) revised in 2007 replaced the precision specification of earlier versions with the more general concept of uncertainty [5]. Last year at this conference, Bunday et al expanded on this discussion by exploring the contribution of sampling uncertainty [6]. In these recent publications, the combined uncertainty is partitioned into the following components:

$$U_{Combined}^2 = \sigma_S^2 + \sigma_P^2 + \sigma_M^2 + \sigma_{other}^2 \qquad \text{Equation 1}$$

According to Equation (1) combined uncertainty ($U_{Combined}$) contains the following components: σ_P (precision), σ_M (matching), σ_S (sampling) and σ_{other} (inaccuracy and other effects). The fourth term includes the uncertainty in the estimate of accuracy (absolute and relative accuracy or sensitivity). Depending upon the application some of these terms may not be relevant.

Total Measurement Uncertainty (TMU) [7], [8] is a statistical metric that could be described in relation to the above equation with all the terms except the matching term and the absolute accuracy part of the "other" term. This is particularly applicable to OPC metrology calibration, where a single workhorse metrology tool like a CD-SEM needs calibration with respect to a reference measurement system (RMS). Equation (1) could be rewritten for this application as

$$[TMU]^2 = [\sigma_P^2] + [\sigma_S^2 + \sigma_{other}^2] \qquad \text{Equation 2} \quad [9]$$

TMU is actually the variance addition of precision and relative accuracy of a tool under test. TMU analysis compares the data from a reference measurement system (RMS) and a tool-under-test (TuT). This analysis is based on Mandel's linear regression analysis where both dependent and independent variables are subject to errors. A linear relationship between the TuT and the RMS is characterized by a regression slope and intercept. TMU is then a measure of the scatter around the best fit line minus the contribution from the RMS measurement uncertainty. The systematic non-linear effects contributing to measurement uncertainty are captured in TMU. Relative accuracy is the ability of the tool under test to correctly measure the change of the primary feature property of interest (measurand) without being adversely affected by other secondary feature properties. For example, if primary feature property of interest is the bottom CD of lines corresponding to various design sizes, then for bottom CD corresponding to the same design size, variations in secondary feature properties such as height or side wall profile of the line can result in different measurements of the bottom CD measurements indicating poor relative accuracy towards the design size changes only and hence higher measurement uncertainty. It is therefore important to include the secondary feature properties in the estimation of uncertainty associated with relative accuracy. If the tool is not linearly tracking the changes in design size only while changes occur in profile, neighborhood and such other characteristics of the measured features then the TMU will be higher. TMU has dimensions of length and reduces to the precision of the TuT in the absence of any non-linearity between the RMS and the TuT.

Total Measurement Uncertainty (TMU) defined by IBM [10] is as much a methodology as it is a figure of merit for metrology tool assessment. That is, the methodology is critical in determining a good TMU estimate for the tool under test. This concept is a pivotal part of this paper. Following the methodology properly will determine the usefulness of the estimated number. The methodology comprises of systematic approach beginning with a definition of the application, choice of suitable workhorse metrology tool, choice of appropriate process stressed artifacts (PSA) induced with primary and secondary variables of relevance and optimizing the sampling, selection of suitable RMS, performing measurements on the RMS and TuT, exercising Mandel's linear regression analysis using least square fit, and then interpreting the output of regression analysis. The output of TMU methodology includes TMU which provides an estimate of relative accuracy of TuT, slope of the best fit line, and the average offset. Depending on the application other steps can also be included in the TMU methodology. For example in this study, special averaging strategy of data is involved to decouple or suppress the effect of one variable over another in order to extract the design-TMU or the process-TMU. Another example of an additional step in TMU methodology involved in this study is to use TMU methodology to optimize the CD-SEM measurement algorithm.

1.2 Capturing uncertainty related to design and lithography focus-induced CD variations

Historically, the primary control variables in OPC related CD-SEM calibration have been design size, shape and neighborhood, but this paper explores the consequences of the inclusion of process variables such as lithographic scanner focus. In the beginning, TMU methodology was developed for the manufacturing application which is primarily concerned about the process window for a single design feature and monitoring its variation due to any process changes. Later on, the OPC application adopted the TMU methodology, but used design variations as the primary control variable to test the metrology. The early days of OPC model construction required accurate CD-SEM measurements through various design shapes and a range of designed critical dimensions varying for each design shape only near optimum process conditions. This suite of test samples is chosen to evaluate the CD-SEM accuracy as it will be used for the larger population of feature shapes for OPC model construction. Today OPC development needs to cover the full patterning process window accurately. One purpose of this paper is to use the TMU methodology to explain how another very important variation, exposure focus, needs to be introduced into the suite of test samples to properly assess the CD-SEM's ability to accurately measure the features important for OPC model construction. This study will benefit both manufacturing and OPC applications. To make the TMU estimate meaningful it is important to capture most of the relevant variations that may adversely affect the measurement accuracy. It is convenient to acquire such a meaningful set of test samples by purposely inducing known important variations. This step of TMU methodology results in a set of Process Stressed Artifacts (PSA) [11]. The term Process Stressed Artifacts (PSA) has been historically used for structures induced with process variation [12]. This paper uses the term PSA in a more general context to refer to the test sites with intentional design and process variations. Various categories of induced variables can be conceptualized by considering a variation metric space. Figure 3 shows such a metric space in 3 dimensions for wafer level test artifacts. The cube shown in Figure 3 represents a selected sample from entire population of choices in this metric space. Each of the dimensions signifies a type of selection from the population of critical feature design sizes, secondary design feature shapes, sizes, and a process variable of the lithographic scanner such as its focus and dose. This paper shows that by expanding the PSA variations in this metric space the true challenges for accurate CD-SEM metrology for OPC model creation are revealed.

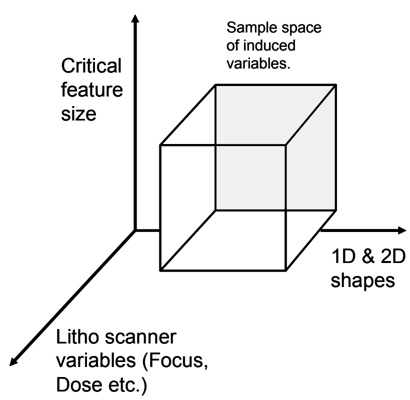

Figure 3: Sampling considerations in space covering size, shape and process variables for comprehensive metrology.

The artifact used in this work had both design variation and lithography process variation. We explore the consequences of averaging data sets in two ways prior to TMU analysis. By averaging the measurements (both CD-SEM and CD-AFM) over the design size variation we can then calculate a TMU sensitive to process variation which we call process-

TMU. Similarly, by averaging the measurements over the process variation, we estimate the design-TMU. This method of averaging is a key part of TMU methodology adopted in this paper.

1.3 Current reference metrology approach (CD-AFM as RMS, CD-SEM as TuT) and challenges

CD-SEM is the workhorse tool for fast and large amount of data collection needed for OPC modeling [13], process development and manufacturing. The accuracy of the CD-SEM is determined by way of a standard or a reference metrology system (RMS). Since no standards exist for the newest resists printed with the latest scanners, an in-house reference metrology is used. Most commonly a CD-AFM is used as the IBM reference metrology. CD-AFM is a much slower technique compared to the CD-SEM in data acquisition. Therefore, in order to calibrate the full range of design sizes and shapes considered in OPC model, a significantly smaller sample of the population of representative test sites is thoughtfully chosen as part of CD-AFM sample plan for reference metrology. This sample plan covers CD linearity, CD through pitch, 1D line and space, and 2D line and space. This sample plan without process variables can be represented by the plane in the sample space of Figure 3 defined by the 1D, 2D and critical feature axes.

Next consider the sequence of measurement steps. First, the CD-AFM data is collected in the nominal (best focus-dose) exposure field followed by CD-SEM data collection on the same measurand. This sequence overcomes a particular problem of the CD-SEM, namely the measurement damage. The situation for 193nm lithography resist system is particularly troublesome with a nonlinear slimming trend that is feature size dependent.[14] By conducting the CD-SEM calibration activity by choosing test sites representative of all the feature categories in the OPC sampling plan, the activity should correctly capture the embedded line slimming effect within the first CD-SEM measurement for all feature types. All the CD-SEM measurements are made after the CD-AFM measurements, so the estimated offset reflects future CD-SEM measurement situations where the CD-SEM measures once on a fresh target. It is important that the same location and extent of measurand is measured by CD-AFM and CD-SEM in order to minimize line roughness sampling error. Multiple repeats of measurements are undertaken in CD-AFM to take advantage of averaging to improve the estimate of the RMS measurement mean. This result comes from the variance of the average as the variance of multiple repeats divided by the total number of repeats, according to the central limit theorem. It is a good practice to take repeated CD-SEM measurements as well to determine the precision component of the TMU.

TMU analysis of the CD-SEM data as TuT and CD-AFM data as RMS is completed for 1D and 2D line and space data sets. TMU analysis provides best estimate of TMU with upper and lower bounds corresponding to the set confidence limits, F-test value indicating the non-linearity of data, and slope-intercept of the best fit line. TMU analysis also provides the average offset between CD-AFM and CD-SEM, called *physical offset,* because the CD-AFM measurement represents our best estimate of the true physical dimension. Physical offset is calculated for various feature types and then used to correct raw CD-SEM measurements for OPC model calibration. TMU value is used as part of the uncertainty associated with the physical offset as it also includes the relative accuracy and not only the TuT precision. In our normal calibration practice, the TMU and regression slopes are reviewed to determine whether a simple offset is adequate to describe the needed raw CD-SEM measurement correction. If the CD-AFM tip width is calibrated with a NIST (National Institute of Standards and Technology) traceable standard, then the physical offset can be NIST traceable estimate with an associated uncertainty. This yields an absolute accuracy estimate of the physical offset.

Calibration for process optimization and OPC model creation explores focus-dose space via focus-exposure matrix wafer (FEM) PSA. Employing the nominal field offsets only to correct the CD-SEM data from other fields exposed under different focus conditions may compromise the actual determination of the process window and the accuracy of OPC model. Such practice will risk subsequent patterning primarily because sidewall profiles are sensitive to patterning stack (resist and antireflective layers), processing temperatures, illumination conditions (focus), and pattern density. Overfocus can result in exposed bottom profile and underfocus can result in undercut profile. Taking into account the right offset based on the focus condition becomes more important as the CD-tolerances get tighter with the successive technology nodes and the process window gets narrower. Equally important is the testing of the CD-SEM's ability to accurately measure in the presence of these variations. While it is necessary to take into account the variable offsets due to scanner focus variation, obtaining and using variable physical offsets adds to the overhead of using CD-SEM measurements. It is necessary to find new CD-SEM measurement methods and algorithms that are less sensitive to profile variation producing constant physical offset and at the same time sensitive enough to capture profile variations to keep the measurement uncertainty low. Quite clearly it is a metrology challenge to meet such balance. Top-down CD-SEM algorithms are best suited for vertical sidewall profiles and have limitations in dealing with variation in sidewall profiles and hence compromise the accuracy of measurements. Challenges exist in both cases of deviation from vertical sidewall profiles (a) re-entrant profile and (b) exposed bottom profile. Other factors such as top edge rounding also contribute to the inaccuracy in measurement by top-down CD-SEM. CD measurements are derived by choosing appropriate topology points in the secondary electron intensity profile generated in SEM while scanning across the feature of interest. For the exposed bottom profiles the line edges are not sharp and possess certain edgewidth detected as wide bright bands along the line edges depending on the projected side wall. This effect can pose a problem in consistently picking the topology points in the CD-SEM profiles. Higher TMU in such cases invokes a need to choose robust (repeatable) topology points and correct the data using the edgewidth information. This methodology may be effective for exposed profiles but it cannot provide a similar solution for the re-entrant profile. Correcting the top-down CD-SEM data from the re-entrant profiles is not possible as the bottom CD is obscured in top-down CD-SEM. Bottom CD is critical in most instances and top down CD-SEM is essentially blind to bottom CD for re-entrant features. Potential solution in such case lies in the tilted-beam CD-SEM. This paper identifies such profile related measurement challenges and explores ways to improve the measurement.

CD-AFM is a nondestructive technique with the capability to physically scan the sidewalls providing direct measurement of 3D profile independent of material. Unlike the CD-SEM, this allows the CD-AFM to be calibrated by using reference artifacts. However, use of CD-AFM as a reference measurement system has its own limitations and it is important to understand these. The probe used in CD-AFM is flared at the bottom as illustrated in Figure 4. Particularly important tip properties are the tip width, lateral reach, edge height, and effective length. The geometric and dimensional constraints of the flared probes can limit the accurate measurements of a relevant CD in the case of aggressive profiles. CD-AFM measurements are relatively slow. CD-AFM is generally used for providing calibration at nominal printing conditions by choosing a sample plan that covers the design size and shape variations in the range of interest. It is important to understand the limitations of CD-AFM as a reference measurement system in future technology node and it specifically calls for CD-AFM probe development with smaller diameter, smaller edge height, while maintaining acceptable lateral reach and effective length.

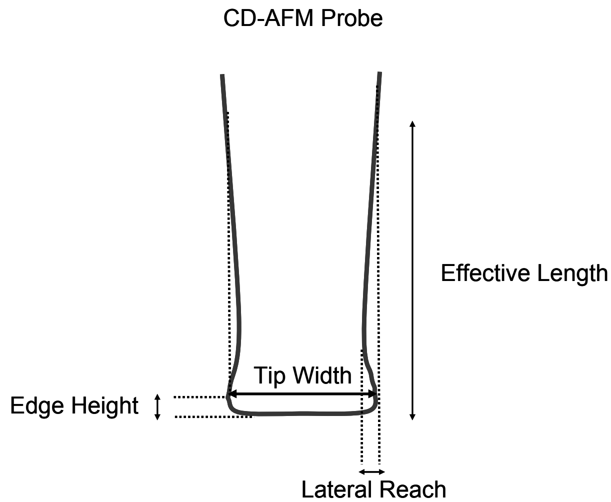

Figure 4: Schematic of CD-AFM probe showing key dimensional properties

2. EXPERIMENT AND DATA ANALYSIS

Gate linewidth is a critical dimension in the IC device and needs to be measured with the least possible uncertainty. Therefore, for the experiment a post-develop resist wafer with polysilicon gate stack underneath shot as focus-exposure matrix (FEM) is selected. The wafer represents a 193 nm high NA printing process and will be referred as "PC wafer" in this paper. The measurement sample plan for the experiment consists of ten different 1D features as processed stressed artifacts (PSAs) including five isolated lines and five nested lines. These features and corresponding design CDs and pitches are tabulated in Figure 5. The *design variable*s included in the PSAs are a range of line widths (70-100 nm) and neighborhood variation in nested lines (pitch ~ 170-100 nm) and completely isolated lines. Isolated and nested lines cover the extreme range of the neighborhood variation. The *Process variable* is induced in the PSAs by printing these chosen design features at nine different scanner focus values corresponding to nine different exposure fields with a constant dose of 19.1 mJ/cm^2. The scanner focus range is -200nm to 40 nm and focus step is 30 nm with the nominal focus of -80 nm lying in the center field. It is well known that scanner focus primarily affects the sidewall profile in resist compared to the dose. Dose mainly affects the CD. Therefore focus variation has been studied in this paper as part of process variable. Sidewall profile is also affected by the proximity of features which is captured by the isolated and nested lines in this sample plan. The data for ten features is collected along the center focus stripe column of the wafer as shown in Figure 7. CD-AFM data on the PC wafer is collected using flared probes with bottom width near 50 nm. The effective length of the probes is about 200 nm, lateral reach is about 4 nm and edge height is near 15 nm.

The design linewidth and pitch ranges chosen do not represent the most aggressive CD and pitch corresponding to the technology in development today which are relatively challenging to be measured with the available CD-AFM probes and are not considered necessary for the purpose of this experiment. The range of design linewidth and pitch chosen in this study is sufficient to allow a reasonable regression analysis and at the same time explores the metrology limitations due to the proximity effect in nested and isolated cases. It is acknowledged that while the chosen range of CD and pitch in this study is good enough to reveal the key challenges involved in metrology pertinent to the purview of this paper, there is definitely an argument for expanding the sample plan covering 1D and 2D shapes and sizes. CD-AFM data is collected with two repeats of measurements. At least two repeats of measurements are required to estimate the tool precision.

Subsequently, Top-down CD-SEM measurements have been taken on the same features at the same location, same feature length, and same exposure fields as were previously measured with CD-AFM. Our process-of-record (POR) SEM algorithm is used to derive the top, middle and bottom CDs during the recipe execution. When needed, analysis is also performed on an offline analysis station.

It is conceptually useful to think of the CD-SEM algorithm as determining specific locations on the signal intensity waveform and further, that these locations map to specific topology points on the measurand. This is certainly a gross simplification. For one thing, various types of smoothing techniques are essentially combining information over an extended region of the waveform. For another, the resolution limitation of the SEM results in another kind of filtering of the measurand topology. And thirdly, the limitations of the top/down CD-SEM to image undercut sidewalls further complicates the situation. Nevertheless, the language of topology point manipulation by algorithm parameter adjustment is still helpful and we will use it in this presentation.

Post acquisition offline data analysis of CD-AFM data is carried out using a linewidth analysis utility. Thresholds and bandwidth around the threshold for top, middle and bottom CD, left and right sidewall angles are specified in the linewidth analysis. The tip width is deducted from the raw measurements to provide actual CD measurements. The PC wafer revealed a limited variation in profile ranging from slightly undercut to large exposed bottom with rounded edges.

TMU analysis is carried out to evaluate the total measurement uncertainty of CD-SEM tool with respect to the CD-AFM in measuring the design induced CD changes as well as the scanner focus induced CD changes. TMU primarily associated with the design changes is called in this paper design-TMU while TMU primarily associated with scanner focus changes is called process-TMU. To understand the individual contributions of design-TMU and process-TMU to the total measurement uncertainty, it is necessary to deconvolve the two contributions. This paper explains a methodology of selected averaging the data to separate them. The basic concept behind this methodology is that when two variables affect a measurement, averaging the measurements over one variable suppresses its contribution to the measurement uncertainty which is then dominated by the uncertainty due to the other variable. This methodology is shown in Figure 5 which depicts the measurement of each feature site over nine different focus fields. The bottom row shows the averaging of all the design sizes in each focus field. This exercise suppresses the uncertainty contribution due to design size variation and highlights the uncertainty associated primarily with the scanner focus variation. Thus the TMU analysis with such averaged data yields primarily the process-TMU. Similarly, TMU analysis of the data obtained after averaging the measurements of each feature size corresponding to nine different focus fields provide predominantly the design-TMU. Such averages are depicted in rightmost column.

	Focus Field ▸	1	2	3	4	5	6	7	8	9	Averaging over Focus Fields
Feature ▾	Line/pitch (nm)										
A Isoline 1	70	A1	A2	A3	A4	A5	A6	A7	A8	A9	AVG (A1...A8)
B Isoline 2	80	B1	B2	B3	B4	B5	B6	B7	B8	B9	AVG (B1...B8)
C Isoline 3	90	C1	C2	C3	C4	C5	C6	C7	C8	C9	AVG (C1...C8)
D Isoline 4	95	D1	D2	D3	D4	D5	D6	D7	D8	D9	AVG (D1...D8)
E Isoline 5	100	E1	E2	E3	E4	E5	E6	E7	E8	E9	AVG (E1...E8)
F Nestedline 1	90/180	F1	F2	F3	F4	F5	F6	F7	F8	F9	AVG (F1...F8)
G Nestedline 2	95/171	G1	G2	G3	G4	G5	G6	G7	G8	G9	AVG (G1...G8)
H Nestedline 3	95/190	H1	H2	H3	H4	H5	H6	H7	H8	H9	AVG (H1...H8)
I Nestedline 4	80/176	I1	I2	I3	I4	I5	I6	I7	I8	I9	AVG (I1...I8)
J Nestedline 5	90/198	J1	J2	J3	J4	J5	J6	J7	J8	J9	AVG (J1...J8)
	Averaging over Design	AVG (A1...J1)	AVG (A2...J2)	AVG (A3...J3)	AVG (A4...J4)	AVG (A5...J5)	AVG (A6...J6)	AVG (A7...J7)	AVG (A8...J8)	AVG (A9...J9)	

Figure 5: Sample plan and schematic of averaging methodology for extraction of process- and design TMU from the data

3. RESULTS AND DISCUSSION

3.1 Design-TMU and process-TMU

Following the TMU methodology with two ways of averaging as described in the previous sections the best estimates of design-TMU and process-TMU have been calculated separately for isolated lines (IL), nested lines (NL), and combined isolated and nested lines. The corresponding TMU values are plotted in Figure 6. The upper and lower confidence limits of the best estimates of TMU are also calculated and used as error bars in the plot.

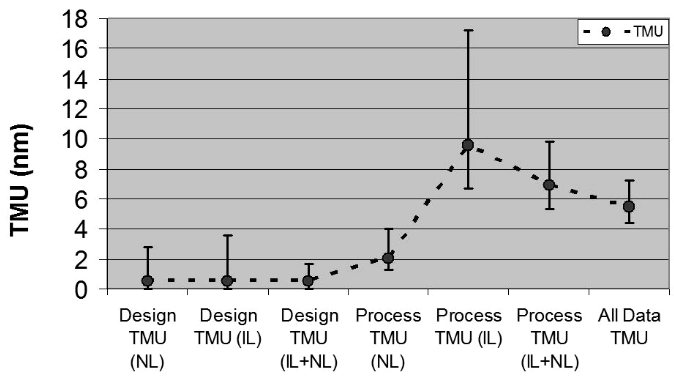

Figure 6: Design-TMU and process-TMU

The design-TMU for nested lines and isolated lines calculated separately and combined are significantly smaller than the corresponding process-TMU for nested lines and isolated lines. The design-TMU is essentially the CD-SEM precision. This implies that for the range of design size studied here the CD-SEM algorithm tracks the design-size changes very accurately and precision of CD-SEM is a fair estimate of measurement uncertainty. The process-TMU for nested-lines is also significantly smaller than the process-TMU for isolated lines. Not only the process-TMU for isolated lines is large but the upper and lower limits of confidence for the process-TMU are quite significant. This implies the CD-SEM is not accurately tracking the process induced variation in the isolated lines and nested lines, more so for isolated lines. In this case precision of CD-SEM is a gross underestimate of the measurement uncertainty. Process-TMU of the combined isolated line and nested line data is between their individual process-TMUs. From these observations it is evident that the CD-SEM is accurately tracking the design induced variation but fails to accurately track the process or more specifically scanner focus induced changes. TMU obtained from the raw data corresponding to combined isolated lines, nested lines, design and process variations, as shown by "all data TMU" in the plot is also a large value. However, “all data TMU” does not reveal the details of design and process related contributions to the measurement uncertainty. Following the TMU methodology thus is quite effective in determining an estimate for the measurement uncertainty.

Figure 7 shows the nearly linear increment in process-TMU for isolated lines and nested lines as the data from both sides of the center nominal field is successively added in the TMU analysis. Process-TMU is close to 1 nm for both isolated and nested lines in the nominal field. Process-TMU for isolated lines increases significantly compared to the nested lines as the scanner focus range increases around the nominal focus. This indicates that focus induced variation in the features increases with focus and CD-SEM analysis is increasingly unable to accurately track this variation. These observations point towards limitation of CD-SEM POR algorithm in tracking the process induced changes in the bottom CD. Large process-TMU is a concern and needs to be addressed.

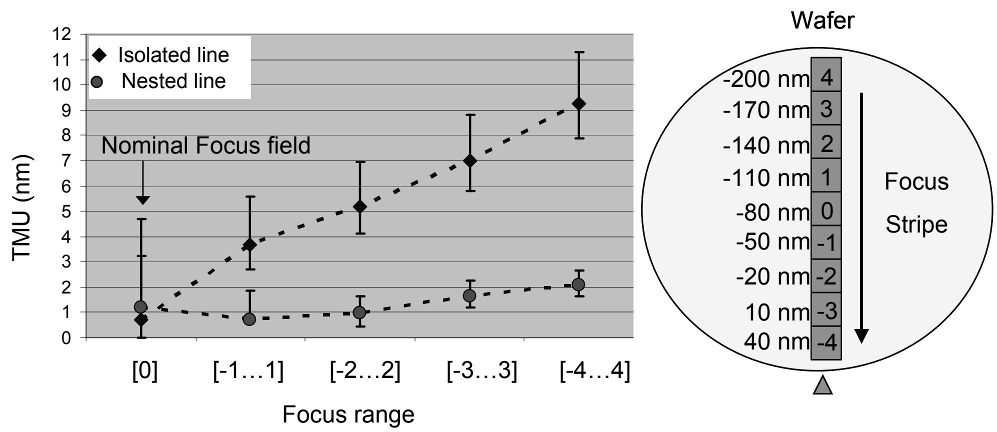

Figure 7: Process-TMU variation for isolated lines and nested lines with defocus range. Diamonds are IL values; circles, NL values. [0] represents the center and nominal field as shown in the focus stripe. [-1…1] implies the TMU analysis of data from center field, one field above and one field below the center field. Similarly other x-axis representations imply successive addition of data from next fields.

Examining the sidewall angle and profile from the CD-AFM data reveals the primary cause for large process-TMU for isolated lines and small process-TMU for nested lines. As shown in Figure 8 the sidewall angle variation for isolated lines is much larger compared to the nested lines. This is expected as the scanner focus variations largely affect the profile and more so for the isolated features. The profile ranges from exposed bottom for positive scanner focus to slightly re-entrant for negative scanner focus. The PC wafer does not offer aggressively re-entrant profiles as the sidewall angle reaches maximum value of 92 degrees. Top edge rounding is also evident from profiles corresponding to more positive scanner focus for isolated lines alongwith exposed bottom profiles.

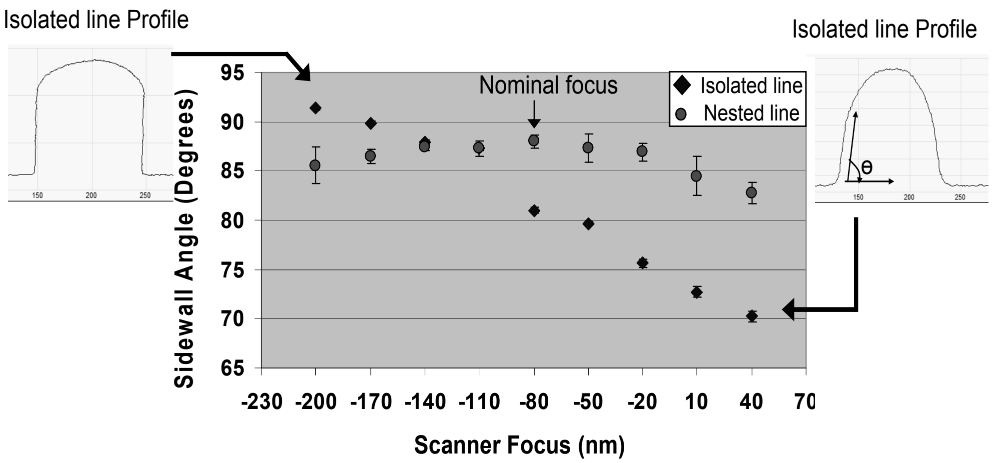

Figure 8: Side wall angle (ө) variation for isolated line and nested lines for different scanner focus fields. Average isolated line profiles are also shown for the extreme scanner focus fields. The profiles are shown prior to tip width deconvolution.

It should be noticed that the sidewall angle changes by up to about 18 degrees from normal for exposed bottom profile but change for re-entrant profile is quite small, approximately 2 degrees. A question that can be asked here is whether the CD-AFM probe has enough lateral reach to be able to scan the re-entrant profile. The type of AFM probe used in this study has a typical lateral reach of 4-10 nm. A lateral reach of 4 nm of the AFM probe will be limited in reaching more than 4 nm of recess in the re-entrant profile as shown on the left side probe in Figure 9. This points towards a limitation of the reference measurement system and can be resolved with probes with larger lateral reach. AFM probes with smaller tip width (<70 nm) and larger lateral reach (>15 nm) are not available and pose a limitation for measuring nested dense features with re-entrant or undercut profile. AFM probes with larger tip width (250 nm) with larger overhang (> 25 nm) are commercially available and shown on the right side of Figure 9. Such wider probes can be used to measure the isolated features easily but are not suitable for measuring the tight space. For the PC wafer under investigation, use of AFM probe with lateral reach of more than 20 nm and edge height of 18 nm also revealed that the smaller change in sidewall angle from normal is due to process itself and the measurements were not limited by the probe's lateral reach.

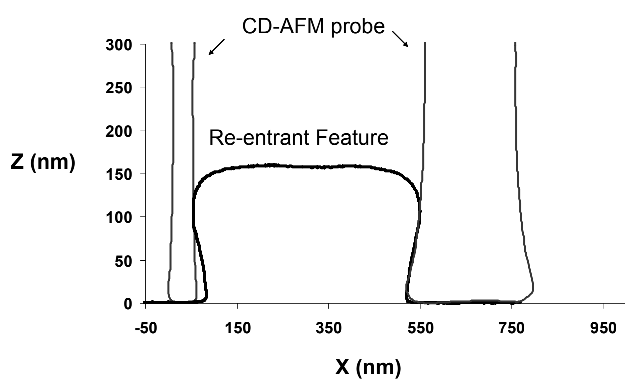

Figure 9: CD-AM probe limitation due to smaller lateral reach for reentrant feature bottom CD measurement

At this point it will be appropriate to point out that for pushing the use of CD-AFM as RMS, robust flared probes with smaller tip width, smaller edge height and larger lateral reach need to be developed. To achieve all these attributes is a challenge.

3.2 Average offset variation with lithography scanner focus

It is noticed that the average physical offset (SEM-AFM) depends on exposure focus and proximity of features, as plotted in Figure 10. The average offset range is approximately 2 nm for the nested lines but 10 nm for the isolated lines for focus variation from -200 nm to 40 nm. The average offset for isolated lines depends strongly on focus compared to the nested lines. This suggests there is either a need to correct the through-focus SEM data with variable physical offsets specific to feature type and exposure focus or to modify the SEM algorithm such that it can detect the process induced profile variation in features and consistently choose the topology points for measurements so that a single physical offset is achieved independent of process variation such as variable focus.

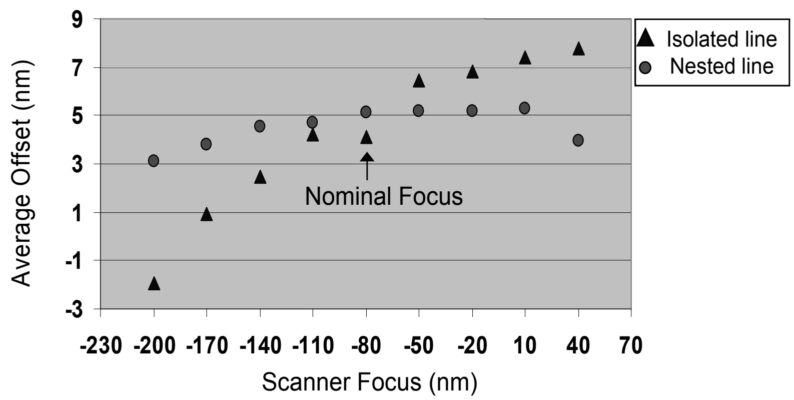

Figure 10: Average offset (SEM-AFM) versus scanner-focus. The plotted average offset corresponds to the bottom CD. The uncertainty estimates are same for isolated and nested average offsets

Focus dependent physical offsets impact the OPC model calibration and process development. Conventional model based OPC model is calibrated based on nominal focus and nominal exposure dose to provide optimal patterning at these nominal conditions exposing the printing fidelity to risk in presence of process variations.[15] Use of physical offsets derived from the nominal focus field to correct CD-SEM data obtained from non-nominal focus fields will add inaccuracy in the OPC model calibration as well as in determining the process window. Process window is shrinking with the successive technology nodes and it becomes important to identify process window more accurately. The same applies to OPC model calibration. The CD uniformity budget is tightening with the technology nodes and accurate OPC model calibration is needed to correct for focus variation or general process variation to realize better CD printing uniformity.

3.3 Addressing high process-TMU by expanded use of CD-SEM data and improvements in SEM algorithm

With higher NA printing, the depth of focus is reduced to the extent that it leads to significant profile variation ranging from re-entrant to exposed-bottom. The profile variation and inability of metrology tools to accurately track these changes is key factor resulting in larger TMUs. Therefore, it is necessary to look into ways to reduce the high TMU especially the process-TMU. The practice of using the CD-AFM to determine physical offsets for different scanner-focus conditions and then correcting the corresponding CD-SEM data adds to the measurement overhead. Therefore, a preferable approach would be to expand the use of CD-SEM information by taking into account the edgewidth or improving the SEM algorithm to handle the variations in profile by better optimizing the topology points for measurements by minimizing the TMU. This approach still addresses only half of the challenge i.e. only the case where the sidewall profile is vertical or exposed. The other half of the challenge corresponds to the re-entrant profiles. Traditional top-down CD-SEM is just not capable of capturing the bottom CD in re-entrant profiles. This paper explores the options for addressing the challenge posed by exposed bottom profiles and talks about options to handle the challenge of re-entrant profiles.

3.3.1 Edgewidth compensation

A simple approach is to correct the CD-SEM data by taking into account the edgewidth information derived from the CD-SEM image analysis. In the case of PC wafer the sidewall profile ranges from nearly vertical to a large exposed bottom. The top-down CD-SEM image of a vertical sidewall profile has sharp edges while the image of an exposed bottom sidewall profile has wide edges observed as a bright band along the each line edge in Figure 11.

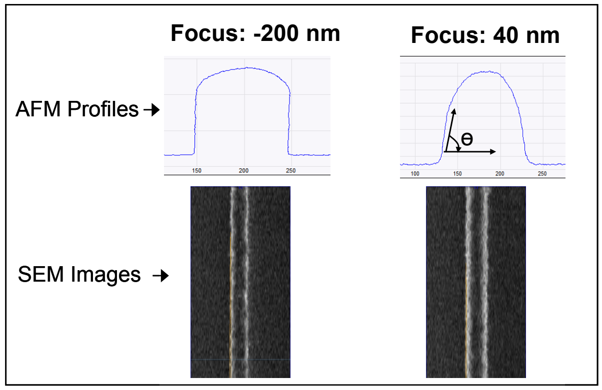

Figure 11: CD-AFM profile (top) and corresponding CD-SEM images (bottom) of an isolated line corresponding to different scanner focus conditions showing different edgewidths as narrow and wide bright bands at the line edges.

The edgewidth consists of information about the profile, specifically, the exposed bottom profile in top-down CD-SEM. Edgewidth is naturally defined as the distance between the top and bottom topology points. It can be calculated from normal CD-SEM reports as the bottom CD minus the top CD divided by two. Figure 12 shows that the edgewidth derived from CD-SEM top and bottom CD measurements is well correlated with the offset between the CD-AFM and CD-SEM data and to first approximation can be described by the least square linear fit with the standard error of 1.4 nm. The linear dependence obtained from the best fit line is formulated as equation 3:

$$\textbf{(AFM - SEM) = 1.6 x Edgewidth – 22.1} \qquad \text{Equation 3}$$

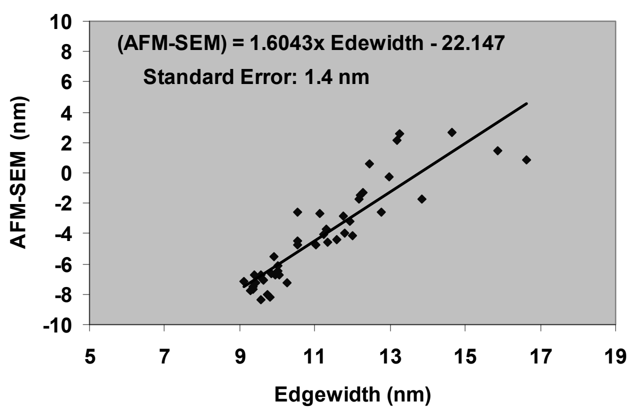

Figure 12: Correlation of CD-AFM and CD-SEM offset with the edgewidth from CD-SEM measurement

The corrected value of CD-SEM measurements should ideally be equal to the CD-AFM measurement and is represented as SEM_c. Therefore substituting SEM_c for AFM in the above equation provides the corrected CD-SEM measurement values as formulated in equation 4:

$$\mathbf{SEM_c = SEM + 1.6 \times Edgewidth - 22.1} \qquad \text{Equation 4}$$

Figure 14 shows the improvement in the TMU before and after CD-SEM data correction using edgewidth concept. The TMU is reduced less than half from 9.5 to 3.9 nm. This is a significant improvement and validates the proof of concept. Use of edgewidth for SEM data correction and resulting improvement in TMU is pointing in the right direction. Edgewidth depends on the choice of top and bottom topology points. The edgewidth correction in SEM data is one way to mitigate high TMU challenge due to exposed bottom profile variation. A more direct and robust solution would involve improving the CD-SEM algorithm itself by having the bottom topology point align with that determined by the RMS. In the following section we show how to do this by using TMU analysis.

3.3.2 Optimizing CD-SEM algorithms

CD-SEM tool offers two types of algorithms which we call algorithm1 and algorithm2 in this presentation. The original waveform images were remeasured using an offline workstation while sweeping a key parameter for each algorithm. TMU analysis was performed for each set of CD-SEM measurements. TMU estimates, average offset, and regression slope for the isolated lines are shown in Figure 13. The POR measurement algorithm corresponds to algorithm2 with a parameter setting of 100%. Sweeping the baseline from 90% to 10% in algorithm1 reduces the TMU from 9.0 nm to 5.6 nm. Slope of the best fit line improves but not significantly and the systematic average offset increases from 0.7 to 12.8 nm. Ten percent baseline implies that the topology points are pushed further down the waveform away from the centerline. On the other hand, sweeping the threshold in algorithm2 from 100% to 10% decreases the TMU from 9.2 nm to 3.7 nm. Slope of the best fit line in regression analysis improves significantly but the systematic average offset also increases significantly from 4.0 to 26.0 nm. Algorithm2 is less sensitive to the changes in profile or the sidewall slope. It is interesting to note a kink in the slope near 20-30% threshold region. In that region the TMU also becomes flat. A clear understanding is needed for this effect. It is possible that the algorithm2 reaches some sort of limitations. Significant amount of details of these algorithms are hidden as if in a black box and few key parameters are available to the user to tweak. The observed kink in slope suggests a need to peek in these details to understand if the algorithm2 is reaching some sort of limitation. Algorithm2 provides significant improvement in the TMU but at the cost of large average offset. Large average offset between CD-SEM and CD-AFM in this case may appear to be discomforting but it may still be acceptable as the TMU is significantly reduced.

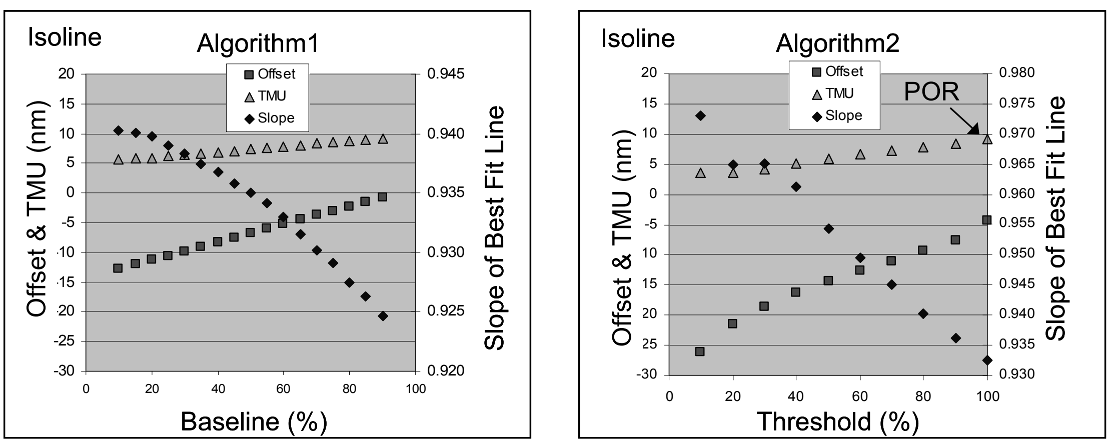

Figure 13: CD-SEM algorithms showing average offset, TMU, and slope of the best fit line inregression analysis as a function of baseline threshold sweep

Figure 14 summarizes the TMU improvement and corresponding average offset for isolated lines as a result of edgewidth-based CD-SEM data correction and CD-SEM algorithm optimization.

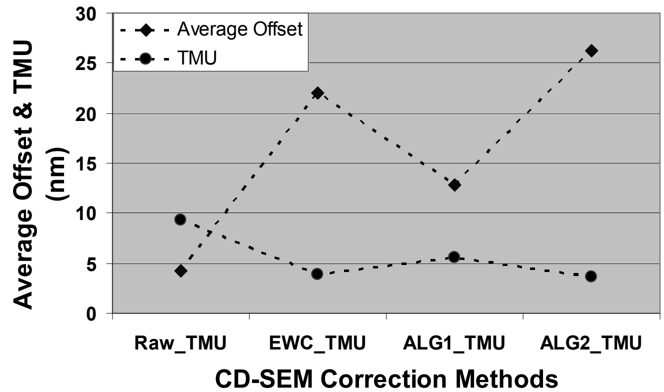

Figure 14: TMU improvement for isolated lines as a result of edgewidth based CD-SEM data correction and CD-SEM algorithm optimization.

Based on the study above it is clear that smaller TMU can be achieved by optimizing the CD-SEM algorithms. One concern is related to the universality of this solution. Is this improvement specific to this application and feature type or is it applicable to all or at least more than one application? This needs to be further evaluated. It should also be pointed out that these improvements are valid for sidewall profiles that range from vertical to exposed bottom. The other extreme of profile variation i.e. re-entrant still poses a challenge for top-down CD-SEM measurements. Top-down CD-SEM is just not capable to detect the re-entrant profiles. Tilt beam CD-SEM is seen as a potential solution to such challenging measurements.

4. SUMMARY AND CONCLUSIONS

Patterning advancement and metrology limitations continue to pose challenge in reducing the measurement uncertainty down to the required values. TMU analysis presents a methodology to evaluate the measurement uncertainty of a TuT such as CD-SEM, taking into account its precision and relative accuracy. TMU methodology, when followed properly, is quite effective in capturing the measurement uncertainty of the CD-SEM to the variables under investigation namely design and scanner focus in this study. Design variable and corresponding design-TMU has been historically calculated for OPC calibration but this paper explores and presents the need to expand the variable space from design to litho-scanner variables such as focus. Scanner-focus has been studied as an additional process variable and the corresponding TMU is called process-TMU. Significantly high process-TMU is found for isolated lines due to the variation of physical offset with respect to the scanner focus. Scanner focus variation gives rise to the profile variation and POR CD-SEM algorithm is not robust enough to provide accurate measurements independent of profile variation. Scanner-focus dependent physical offsets result from limitations of CD-SEM measurement algorithm to capture the profile changes due to focus variation. As a consequence, the CD-SEM data obtained from different focus exposed fields either needs to be corrected with the corresponding physical offsets or the CD-SEM algorithm needs to be optimized to locate the topology points for measurements consistent with the RMS as the profile varies. Otherwise, OPC model calibration and process window determination in process development will be inaccurate. Determination of physical offsets using the CD-AFM as RMS for different scanner focus conditions other than nominal scanner focus becomes a resource exhaustive exercise during the fast development cycles. It will be preferable to optimize the CD-SEM algorithms to reduce the TMU and obtain a fixed physical offset applicable universally for different scanner focus conditions as well as design variation. This study also reveals the limitations of CD-AFM tool as RMS and points towards the urgency of probe development with even tighter specifications especially smaller tip width with large lateral reach and small edge height. A key challenge with top-down CD-SEM is that CD-SEM measurement algorithm can be modified to reduce the TMU in case of vertical and exposed bottom profiles but are fundamentally limited to detect the bottom CD topology points in re-entrant profiles as these are shadowed in image acquisition. To address this limitations tilted-beam CD-SEM should be explored. This paper exposes and recognizes the limitations of both the reference and workhorse metrologies and prompts to seek out various workhorse and reference metrology options currently evolving or being newly added. Among the reference metrology options, charged particle beam based milling, imaging and measuring option seems promising. Different options of charged particle beam that are compatible with the resist metrology also need to be explored. Transmission electron microscopy (TEM) has been a candidate for reference metrology but sample preparation and throughput limitations are in way. However, TEM assisted with faster sample preparation using the charge particle beam techniques remains a viable candidate for reference metrology. Among the workhorse metrology techniques angled beam CD-SEM, model based CD-SEM such as using Monte Carlo simulations and scatterometry could be potential candidates. Apparently a single technique may be limited in providing reference or workhorse metrology at all scales. Each technique acts as a filter of information and combined use of various techniques can also act as a viable solution for reference as well as workhorse metrology. Such option of hybrid metrology needs to be explored for reference as well as workhorse metrology.

5. ACKNOWLEDGEMENTS

We would like to acknowledge the IBM management support of this work by Ahmad Katnani, Scott Bukofsky, and George Gomba.

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