Full-Field Exposure Control Implications of the Mask Error Function

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ABSTRACT

This report considers a detailed method of rapid and accurate experimental calculation of the Mask Error Enhancement Function (MEF or MEEF) using localized CD variation across the exposure field. MEEF is defined as the non-constant bias of wafer-image replication to small changes in the reticle image. The extraction method of the MEEF response of a reticle to it's process environment is shown to contain a method of measuring the robustness of the OPC design structures on the reticle and their ability to compensate wafer-image replication across the scope of production-process perturbations.

This study demonstrates that a MEEF response can be characterized by a regressive comparison of reticle and wafer image sizes for any reticle OPC structure. Expanding the analysis to a focus-dose matrix that approximates normal production variations allows the MEEF response sensitivities to be deconvolved into their component contributions to critical feature variation across the wafer. IntraField dependencies such as sensitivity to the direction of the scan, and thus reticle-stage drive loading are investigated and their contributions are presented at the end of the report. Process induced perturbations such as focus and dose can also change the MEEF and their response is characterized and shown to be a significant contributing factor.

An algorithm is then used to extract the full-wafer systematic sensitivity of MEEF to slowly changing perturbations such as film thickness changes in the Anti-Reflective Coating (ARC) and Photoresist thickness. Correlation of the MEEF response to film thickness is discussed and shown to be significant for some films.

A budget summary of the systematic perturbation inherent in these MEEF factors is compared against the needs of sub-90 nm nodes with considerations toward the necessity of process-specific OPC design for critical layers.

KeyWords: MEEF, MEF, APC, Lithography, OPC validation, resist models, metrology, spatial model, Scatterometry

1. INTRODUCTION

The ITRS Roadmap for 2005 underwent a paradigm shift in the fundamental definition of progress in the industry by noting that DRAM technology no longer resides as the most significant driver of scaling. An article in MICRO magazine stated that "…the expectation now is that different device parameters will scale at different rates…"[1]. Driving this statement is the realization that critical feature design structures whose sizes approach the Rayleigh Limit are highly sensitive to the toolset and process specifics of each facility as well as the ultimate size of the structure in production. Features in this realm therefore replicate on the wafer at different rates than their neighbors if the reticle enhancements are not properly optimized.

Also stated in the roadmap is a process control feature uniformity goal reaching below 4 nm for upcoming technologies and, for the first time, a combination MPU gate length criteria that encompasses control elements in both lithography patterning and etch. If the industry is to achieve these goals it is critical that designs fully optimize the process and reticle toolset recognizing the interactions and sensitivities of each.

One key tool in driving device scaling and the Across Chip and Wafer Linewidth variation (ACLV, AWLV) down to 4 nm is a clear understanding of the Mask Error Enhancement Factor (MEF or MEEF). The MEEF formula is a very pliant metric used to describe the response of the wafer image with respect to variations in size of the reticle feature. More specifically, the MEEF metric describes the deviation from a constant reticle-wafer bias for the process as a rate of change of the wafer image in the resist driven by small changes in the corresponding reticle feature. The MEEF metric is sensitive to reticle structure as well as lens and process perturbations. It is therefore a very localized metric that can vary independently across the exposure-field and wafer as the local perturbations combine at each spatial point.

The MEF formula derivation has recently been expanded to a two-dimensional model that implements Singular Value Decomposition to quantify the impact of mask layout errors in Microlithography[2]. This implementation and other statistical derivations of the metric have a common theme in attempting to imbibe a single numeric value, the "MEEF", with a measure of the strength and stability of the pattern transfer function.

From a designer-simulation vantage, the concept of a specific single variable is most useful when trying to validate the range of a mask design to a generalized process requirement. Simulations that account for the reactive elements of the photoresist typically characterize the transition from the reticle-object to the final imaged profile in the photoresist. At best, the inclusion of the primary aberrations, described by the pupil map of the lens, are also included in the simulation.

However, consider that the lithographer receives this specific design in the codified format of a hard binary or enhanced reticle. Prior to first use, this hard-coded pattern must be validated for transfer under restrictions imposed by the device fabrication specification to determine if there is sufficient process range for yielding functional end product. In this spirit we address the needs of the sub-90 nm nodes by the empirical modeling of the additional perturbations introduced by the convolution of the reticle image with the electro-mechanical and optical components of the exposure tool for both Across Chip (ACLV) and Across Wafer Linewidth Variation (AWLV) from the reticle based artifact.

The method used to derive the local variation in MEEF will be discussed in detail in the next two sections along with some correlations to more classic methods of MEEF calculation.

A focus-exposure matrix experiment was setup and run over three “193” scanners. Data was measured using both CD-SEM and Scatterometry. MEEF variation is shown to be highly systematic and stable across the lens and at the same time highly sensitive to variations in focus and dose when non-optimum exposure or biasing is introduced.

We then derive a method of characterizing OPC structures for performance using the standard error of the MEEF derivation algorithm. Process control and OPC design applications can benefit from the characterization of the optimum reticle and wafer feature sizes for the specific OPC structures and their interaction with the process environment.

Finally a MEEF-variation budget chart is presented summarizing the relative contributions of each factor.

2. LOCAL MEEF CALCULATION METHOD AND BACKGROUND

The classic concept of the MEF is defined as:

$$MEEF = m * \frac{\partial CD_{wafer}}{\partial CD_{Reticle}} = \frac{\partial W}{\partial R} \quad \ldots \mathbf{1}$$

where m is the reduction of the exposure tool, typically 4.0, and “CD” refers to a “Critical Dimension” or feature size. The MEEF metric is therefore ?CD_{wafer}, simplified to ?W, or features size change on the wafer given a scaled-change in feature size on the reticle = ?$CD_{Reticle}$. The MEEF metric is a dimensionless term that compares rate of change of the wafer feature dimension given a known change in the reticle’s final image dimension given by R = ?$CD_{Reticle}$/m .

Reticle feature size
Slit & Scan Aberrations/Perturbations
Local Dose and Focus
Film thickness variations for Resist and ARC

Table 1: Potential contributors to IntraField feature size variation

The potential contributors to IntraField feature variations are shown in table 1. Reticle feature size is constant for each site on the reticle given constant illumination. Each of the remaining contributors can perturb the fixed reticle feature size as it is imaged in the resist. Process and tool variations are included in the remaining contributors. For example, lens aberrations will be included primarily across the slit but also along the scan as the slit is traversed across the reticle. Perturbations can be the result of ray-bundle obscuration for the near-Rayleigh Limit feature sizes. Perturbations can also be introduced by the electro-mechanical components of the system such as non-planar reticle scan table travel and reticle bowing due to chucking and exposure heating. Films are an integral part of the exposure system and localized variations in thickness often introduce variations in image size in the local resist.

The key relationship in this discussion of IntraField feature sizes is that there is a fixed element in the nature of the reticle feature size and it’s associated final size “R”. This fixed element is then perturbed by remaining elements of the process whose convolution results in a variant final image size on the wafer characterized by the MEEF metric. In other words, we describe the MEEF metric as an equation presented by Jakuac et al. in the 2001 SPIE journal as[3]:

$$W = Wo + \frac{\partial W}{\partial R} * R = Wo + MEEF * R \quad \ldots \mathbf{2}$$

The final feature size on the wafer is described by the first order equation 2 as a wafer-offset that is added to a process-modified final-size reticle feature size. This process-modified factor is called the MEEF and it describes the process-accelerated contribution to image size. A MEEF value = 1 results in a direct translation of the reticle feature set, or signature, onto the wafer. A MEEF value not equal to 1 results in an amplified contribution of the reticle that scales with the local reticle-feature size. Note that this "wafer-offset" is related to but not equal to the bias from the final reticle size.

Figure 1 presents an application of equation 2 to a dataset of Bottom CD's taken across a focus dose matrix. The Bottom CD target value was 90 nm for a feature with a 1:1 duty cycle. As anticipated for dense structures, a MEEF = 1.9018 nm/nm is calculated from the slope of the graph with an offset of –99.426 nm. A total of 4078 data sites contributed to this graph.

Quite expectedly, with a focus/dose matrix of this size, there is significant variation about the best-fit curve. If the data is extracted into exposure-field localized components, as shown in figure 2, the variation in the local MEEF slope becomes apparent. The range of these variations are highly process dependent. Observe the variance of the MEEF calculation in the sign-reversal over sites located in the lower left quadrant of the exposure field in figure 2C.

This variation in feature response as a function of location on the field can be derived from lens aberrations or other process perturbations as contributed by the toolset and process. The next section sets up a simple experiment to understand the extent of MEEF variability and to deconvolve the individual contributors to the MEEF.

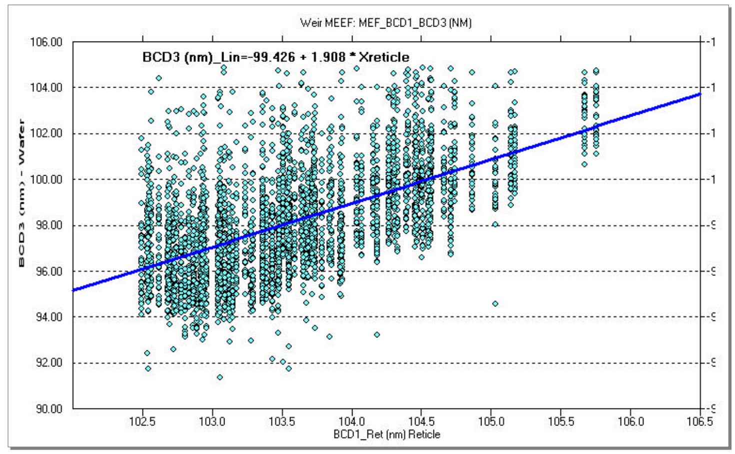
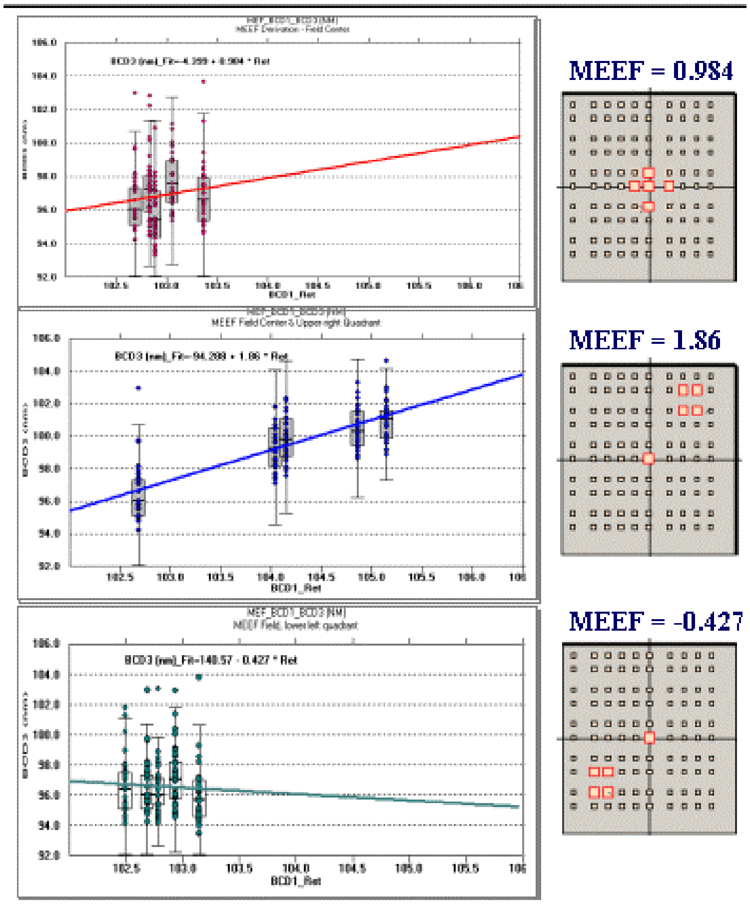


Figure 1: MEEF=1.9018 calculated from the measured Bottom CD (BCD) size in the resist and the Reticle feature size (BCD1_Ret) at final size.



Variation in MEEF local calculation across exposure field.
Figure 2a (top): MEEF calculated for five sites in the center of exposure field.
Figure 2b (Middle): Field center and four sites in upper right.
Figure 2c(Bottom): Field center and four sites in lower left.

3. EXPERIMENTAL SETUP

A Focus-Exposure Dose matrix (FEM) was exposed using variations that approximate those seen in production. Dose was allowed to vary by +/- 7% and Focus by +/- 0.15 um from best focus.

The experiment measured 96 nm target size features that were generated using a 100 nm design final size reticle feature on a 1:1 duty cycle; dense vertical lines. The reticle included OPC correction with assist features.

Several 193 nm scanners were used to expose 270nm of resist that included an 83 nm BARC (Anti-Reflective Coating). A 0.75 Numeric Aperture was used for the exposure along with a Ring Aperture of 0.71 sigma outer and 0.5 for the inner sigma.

Unlike previous studies, the direction of this paper is to examine the local variation in MEEF for a given feature rather than explore the general variation of the metric over many structure sizes and loading conditions.

For the reticle data, one CD-type was measured for a total of 121 sites of a 400 nm feature on an 800 nm pitch; full size. Measurements were taken using both an Hitachi CD-SEM and a Nanometrics ATLAS-M Scatterometer. These measurements and their high correlation were previously reported by the author to average a size of 96.6 nm for the feature width and to exhibit a range of 2.4 to 3.4 nm wafer-final-size on the reticle[4].

Wafer measurements were taken using a Nanometrics ATLAS scatterometer. The average field signature typical of the resulting reticle exposure is shown in figure 3 for the Best Focus derived image[5].

Wafer and reticle measurement analyses of the process window, modeled and raw data sets were performed using the commercial Weir PW software from TEA Systems. The actual MEEF values employed the facilities of a new software tool, Weir ProMEEF, to calculate the metric using the algorithms described in the next section. The resulting MEEF uniformity data is stored in spreadsheet workbooks and loaded into Weir PW for spatial and process window analyses.

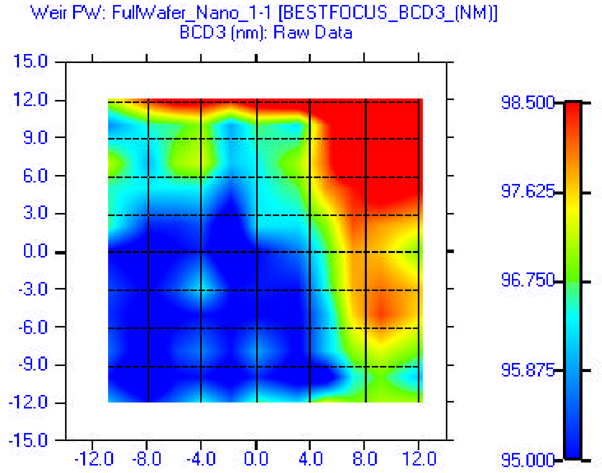


Figure 3: Bottom CD (BCD) average field from wafer scatterometer measurements.

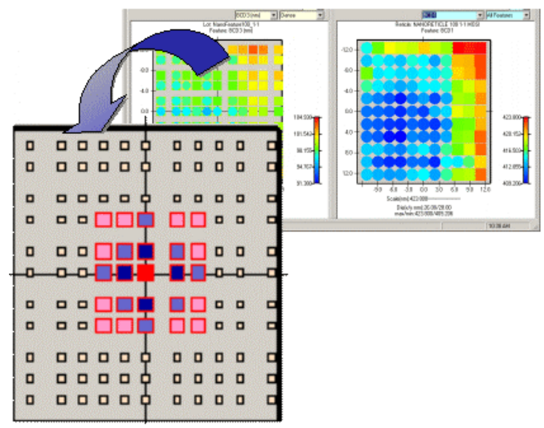


Figure 4: Wafer and reticle field datasets are analyzed using an Adaptive Floating Kernel for localized MEEF calculation.

4. LOCALIZED MEEF CALCULATION ALGORITHM

Prior to MEEF calculation, the reticle data is scaled to remove the exposure tool magnification. Reticle data is then aligned to the wafer dataset.

MEEF is assumed to be a slowly changing phenomenon across a single exposure field. Local variations are calculated using an adaptive floating kernel, schematically shown in figure 4, for reticle-feature size sampling. The gray-rectangular field to the left of figure 4 represents the 121 sites sampled on the reticle. The floating kernel schematic is shown in the red and blue highlighted sites in the center of the field.

During MEEF analysis, the kernel will center on every site of the field. At each site, the kernel varies in size and shape to optimize the accuracy of the MEEF derivation and to compensate for edge die effects. For illustration, the calculation focused on the site illustrated in figure 4 as the central bright-red square and is referred to as the reference site. The wafer and reticle feature size

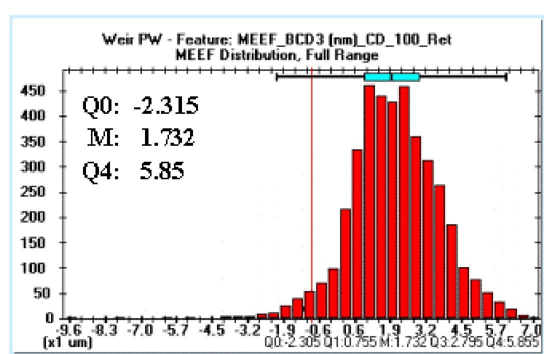


Figure 5: MEEF distribution across the wafer

values are then gathered with the reference's nearest-neighbors, in this case the dark-blue sites above and below it. A singular value decomposition (SVD) regression is used to calculate the MEEF value using the formula of equation 2. The data evaluation criteria of the SVD algorithm automatically removes poor metrology and, if needed, triggers an sequence that gathers additional data from the next-nearest neighbors designated by the light blue and light red sites.

The process is repeated for each of the 121 sites on the reticle. MEEF data along with the reticle, wafer and Reticle-to-Wafer-Bias values are stored in a spreadsheet workbook for later analysis.

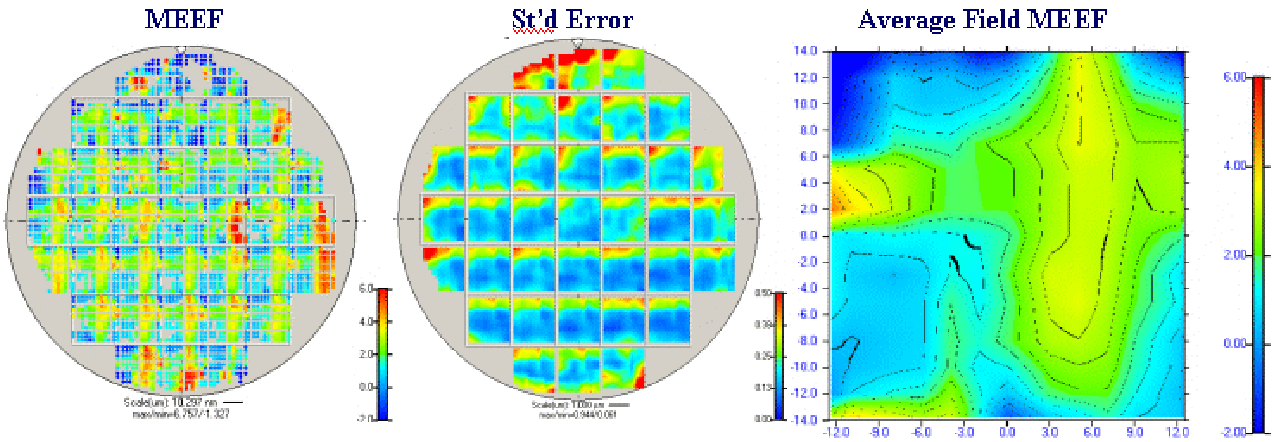


Figure 6A: (Left) MEEF spatial uniformity across the wafer for 4078 sites.
Figure 6B: (Center) Standard Error of MEEF calculations.
Figure 6C: (Right) Average MEEF Field for the DOWN-Scan direction fields of the scanner.

5. SPATIAL ANALYSIS OF MEEF

MEEF calculated in figure 1 with a value of 1.908 nm/nm for the simplistic full-wafer calculation is actually distributed in a slightly platykurtic population with a median of 1.732 nm/nm; a histogram of which can be found in figure 5. The deviation from binomial suggests the presence of systematic errors across the data. Notice that the MEEF quartiles vary from a negative value of –2.3 to +5.8 nm/nm across the full process. This extension across the MEEF=1.0 threshold implies that over their range there exists areas with a reversal of wafer bias replication of the reticle image.

The spatial distribution of MEEF across the wafer is shown in the vector plot of figure 6A. A well-defined signature for each field is visible along with some wafer-systematic sensitivity near the right and bottom edges.

The uncertainty of each of the 4078 calculations is displayed in the contour plot of figure 6B. Standard errors range up to 0.5 MEEF. The standard error of the MEEF calculation increases near the top of each field and at the wafer edges.

The average field's MEEF contour distribution, shown in figure 6C, was obtained here only for the DOWN scan-direction fields by first removing the wafer systematic MEEF variations and then averaging all the field values where the reticle stage scanned in the downward direction. The total range of MEEF is 8 nm/nm with a center at 1.73 nm/nm.

6. EFFECTIVE RETICLE, WAFER SIZE AND OFFSET

As an interesting aside, if we plot the Wafer Offset as a function of MEEF a well-behaved linear relationship

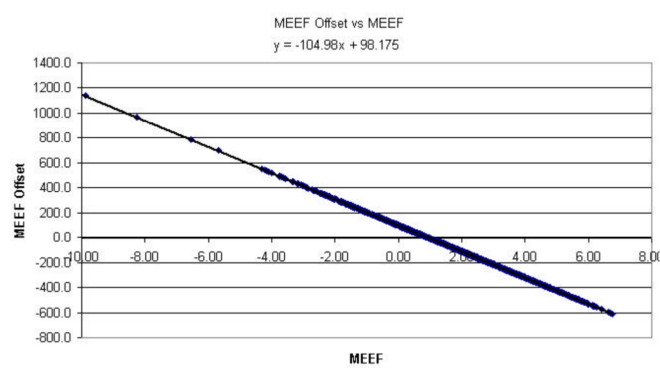


Figure 7: Wo (Wafer Offset) v MEEF
A total of 4078 data points with a fitted curve of
Wo = -104.98 * MEEF + 98.175

appears as shown in figure 7.

We can explain this relationship by transposing the variables in equation #2, to obtain equation #3:

$$Wo = W_{eff} - MEEF * R_{eff} \quad \ldots\ 3$$

In this format the Wo (wafer offset) term-derived coefficients are treated as dependent variables and the MEEF metrics are independent measurements of the coefficient terms Weff and Reff. The highly systematic behavior of the plot in figure 7 implies that there exists a constant R_{eff}, the "effective reticle size", for the feature and a corresponding Wafer Effective constant W_{eff} that describes a fixed and optimum MEEF response relationship for the reticle features as used in this production environment.

Fitting a linear curve to the data we obtain obtain a Weff = 98.18 nm and a Reff=104.98. These values equate to the median distribution point of the measured wafer BCD and reticle final-size populations. We can therefore derive a constant effective reticle and corresponding wafer feature-size for each site's OPC structure. This relationship clearly defines each feature's relationship for process induced MEEF and a natural bias that is the optimal difference between the reticle and wafer feature size. The composite of all measured sites for this data exhibits an a wafer offset = -6.805 nm for the given reticle and process when the MEEF = 1.

This Wo = Wafer Offset is not the same as the Wafer-Reticle Bias except under the special condition when MEEF = 1.0. Reticle-Wafer Bias = MEEF-1. Therefore the –6.805 nm bias is a fixed, design inherent replication bias for the reticle in this process.

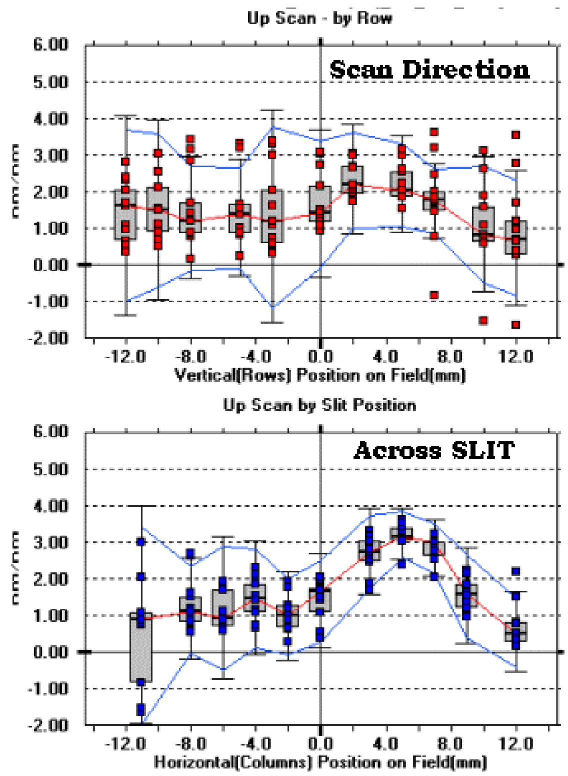


Figure 8A: MEEF variation along reticle SCAN
Figure 8B: MEEF variation across the Lens Slit

7. SCAN, SLIT AND FILM CONTRIBUTIONS

The two plots of figure 8 detail the calculated MEEF variation across the reticle scan, figure 8A, and along the lens slit , figure 8B). MEEF is uniform within calculation precision across all focus and dose values as the reticle stage is scanned during the exposure. The total variation due to scanning is 1.5 to 3 nm/nm. This implies that the mechanical scanning of the reticle adds small amounts to the MEEF factor.

The MEEF variation across the lens slit presents a strong and repetitive signature. This signature is tied to the lens aberrations and illumination and ranges approximately 4 nm/nm.

The graphs in figure 8 represent the UP-SCAN direction fields of the wafer. There is very little difference between UP and Down reticle-scan response so scan direction adds no discernable variation to the system MEEF.

An examination of figures 6 and 8 suggests that, as expected, lens aberrations are a significant factor in the MEEF calculation. The increase in calculation uncertainty at the top of each field in figure 6B suggest a reticle problem with the OPC or assist feature design since the uncertainty is not uniform across the entire process spectrum. Conversely, if the uncertainty were an artifact of the MEEF algorithm, then the uncertainty would also have increased at the bottom or sides of the field.

A bit more information can be gained if the results from three separate scanners, using the same reticle and FEM, are examined. The average MEEF contours are shown in figure 9.

All three scanners in figure 9 were 193 based. Fields on the left and center are from new tools manufactured by vendor

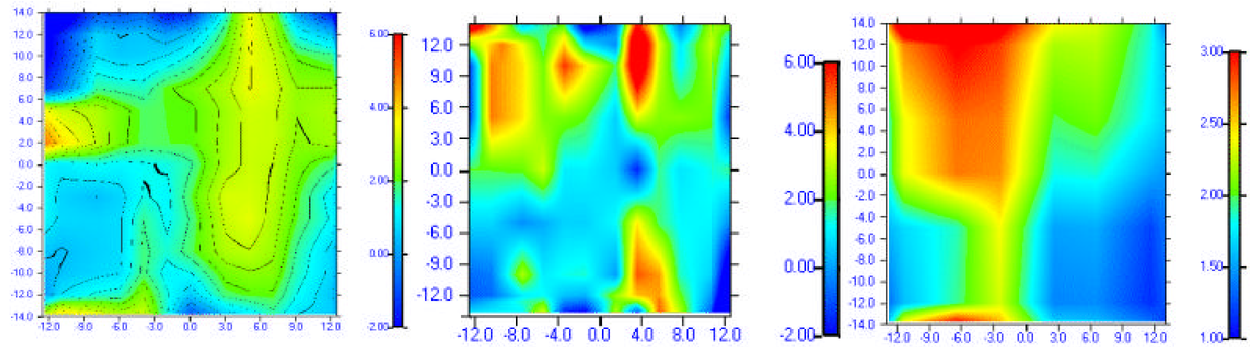


Figure 9: MEEF signatures from three separate scanners
Left: Current 193 scanner of vendor "A"
Center: New 193 scanner of vendor "A"
Right: In-production 193 scanner of vendor "B"

"A". These two fields exhibit both similarities and differences in their signatures. Both fields have a high, vertical ridge running at approximately the +6 mm column. In addition, both fields exhibit a high, horizontal ridge at about the 6 to 8 mm row location on the field. The plots for the first two scanners scale from MEEF values of –2.0 to +6.0 nm/nm.

In spite of the common presence of these ridges, there is a significant difference in the overall contour heights and peaks. This suggests a sensitivity of MEEF to the individual perturbations, optical and mechanical, of the exposure system.

The older and harder used scanner of vendor "B" that is displayed on the right hand side of figure 8 differs significantly from the previous two plots. The majority of the MEEF variation ranges in the 1 to 3 nm/nm range. The field has a ridge-row, reminiscent of the previous two scanners, running across the top half of the scan. It also has a high edge value in the lower left side of the field similar to that seen in the scanner "A" field on the left side.

The conclusion drawn from these results is that there is a base-OPC reticle design MEEF contribution that can be seen along the top half of the reticle and is contributing a 4 nm/nm range to the metric. There may also be some OPC error in the features along the column located at about +6 mm but their contribution is more difficult to assess. The remaining contributors to the MEEF are the system's response to process variations of the FEM and will be examined in the next

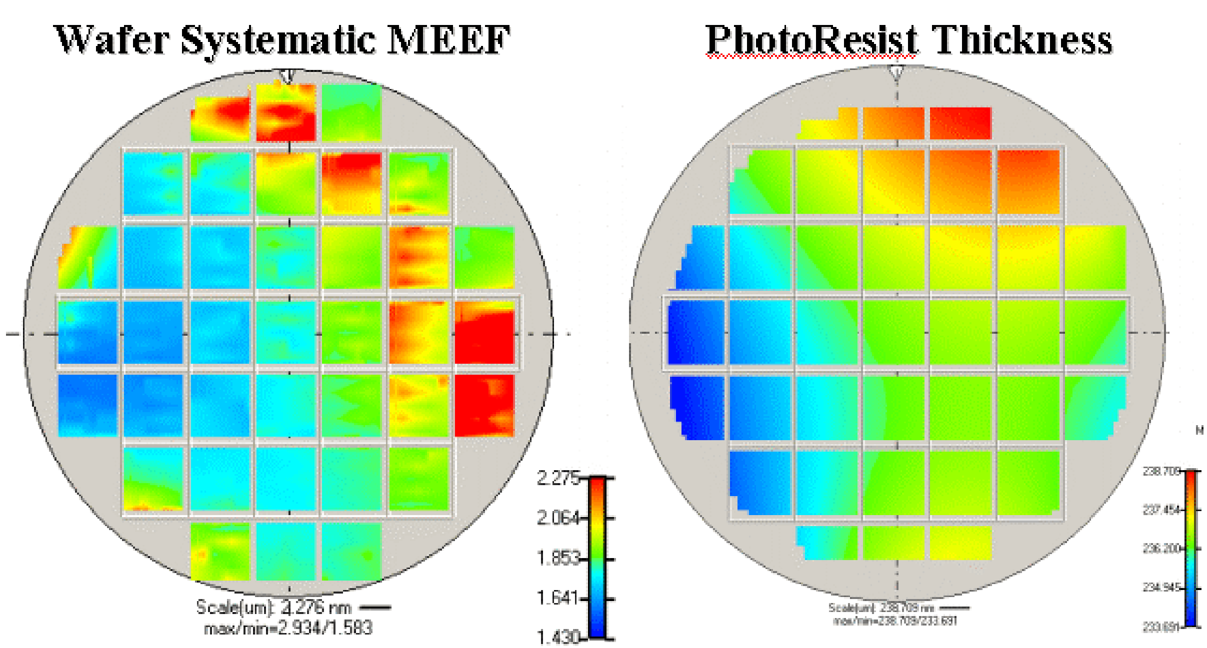


Figure 10: MEEF response to resist thickness.

section.

The derived MEEF data is next analyzed for wafer-systemic variations using the Weir spatial model, as reported in the 2004 SPIE conference.[6] This model provides a view of the wafer systematic response of the variables for MEEF and Resist Thickness as measured by the scatterometer. MEEF wafer systematic variation and the corresponding resist thickness contour are shown in figure 10. While not exact, correlation was better than 80% for this data set. Similar correlations were seen on the other two systems tested. Shown here, the variation in photoresist thickness results in a 0.84 nm/nm range of range about the mean. Quite surprisingly this correlation was not seen for the BARC thickness as measured on two of the three scanners.

8. MEEF RESPONSE TO FOCUS AND DOSE

An examination of the MEEF response to focus is shown for one site on the field in figure 11.

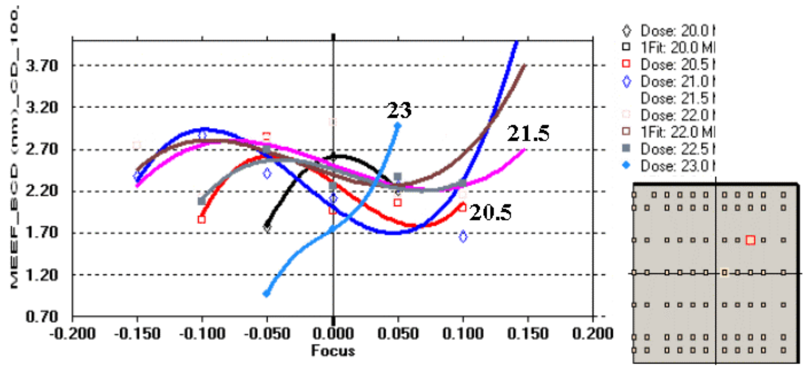


Figure 11: MEEF Response to Focus for one site, shown as highlighted site in the inset on the right.

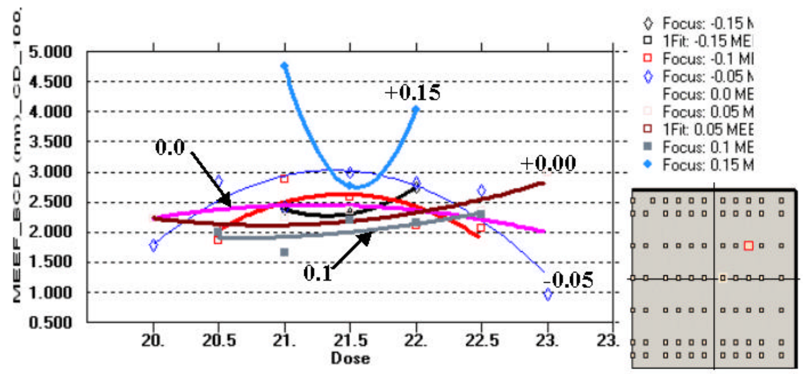


Figure 12: MEEF Response to Dose for one site.

Recognize that while the dose values shown in this section are accurate as to range, their actual values may vary from those shown.

MEEF is shown to vary asymmetrically about best focus with a total range of less than 0.5 nm/nm for the optimum dose. Based on these criteria, optimum dose for this setup is 21.5 mj/cm2 and this corresponds to the IsoFocal dose.

As the process moves away from the optimum dose, as shown in figure 12, the sensitivity of the MEEF to defocus increases rapidly. Within a 1 mj deviation from optimum dose we can see a corresponding +/-1 nm/nm change in MEEF sensitivity. At 23 mj/cm2 the system is uncontrollable for production.

MEEF response is relatively independent of dose for values very close to optimum focus, as shown on the "+0.00" defocus curve of figure 12. Deviation from optimum focus results in quickly increasing sensitivity to dose. Results are asymmetric about the optimum focus. Focus sensitivity is thus shown to contribute approximately a 1 nm/nm variation at optimum dose and can vary as much as 1.5 nm/nm with a dose change as small as +/0 0.5 mj/cm2.

This behavior illustrates that the accuracy and precision of autofocus and auto-leveling algorithms need to be increased substantially during production situations as Isofocal Bias is increased through the use of dose-offsetting if a 4 nm ACLW goal is to be achieved.

9. SUMMARY AND CONCLUSIONS

Table 2, shown below, summarizes the approximate contributions of each element to the MEEF budget.

MEEF Contributor	Influence	Total Effective Range +8 nm/nm
Slit Signature	Strong	4 nm/nm
Scan Signature	Strong	1.5 nm/nm to 3 nm/nm
Scan Direction	None	0 nm/nm
OPC	Strong	1.0 to 2.5 nm/nm
ARC	None	0 nm/nm
Photoresist Thickness	Mild	1 nm/nm
Focus	Mild	1 nm/nm
Dose	Strong	3 nm/nm

Table 2: Budget summary of MEEF range contribution

If the root-sum-squares of the 3rd column are added, using the maximum range values, the table confirms a component total range of 8 nm/nm for the MEEF variation originally determined. Component convolutions are therefore estimated within reasonable bounds.

The Lens Slit champions as the greatest contributor to MEEF followed closely by the Scan signature and the variation due to OPC corrections on the reticle. Although reportedly low in magnitude the Focus and Dose contributions can be significant if the IsoFocal Bias of the feature is pushed.

10. ACKNOWLEDGEMENTS

We want to thank the engineers and management at Nanometrics for their help in providing some of the data and initial encouragement for this study.

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