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## **Bossung Curves; an old technique with a new twist for sub90 nm nodes**

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## Bossung Curves; an old technique with a new twist for sub-90 nm nodes

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### ABSTRACT

The classic Bossung Curve analysis is the most commonly applied tool of the lithographer. The analysis maps a control surface for critical dimensions (CD's) as a function of the variables of focus and exposure (dose). Most commonly the technique is used to calculate the optimum focus and dose process point that yields the greatest depth-of-focus (DoF) over a tolerable range of exposure latitude.

Recent ITRS roadmaps have cited the need to control CD's to less than 4 nm Across-Chip-Linewidth-Variation (ACLV). A closely related requirement to ACLV is the need to properly evaluate the implementation of Optical Proximity Correction (OPC) in the final resist image on the wafer. Calculation of ACLV and the process points are typically addressed with the use of theoretical simulator evaluations of the actinic wavefront and the photoresist's interactions. Engineers frequently prefer the clean results of the simulation over the more cumbersome and less understood perturbations seen in the empirical metrology data resulting in a loss of valuable process control information.

Complexity increases when the analysis assumes a super-positioning of the responses of multiple feature-types in the search for an overlapping process window. Until recently, simulations rarely validated design response to the process and never incorporated the characteristics of the exposure tool and reticle.

Fortunately empirical Bossung curve calculations can supply valuable tool, process and reticle specific interaction information if the techniques are expanded through the use of spatial and temporal perturbation models of the actinic image wavefront.

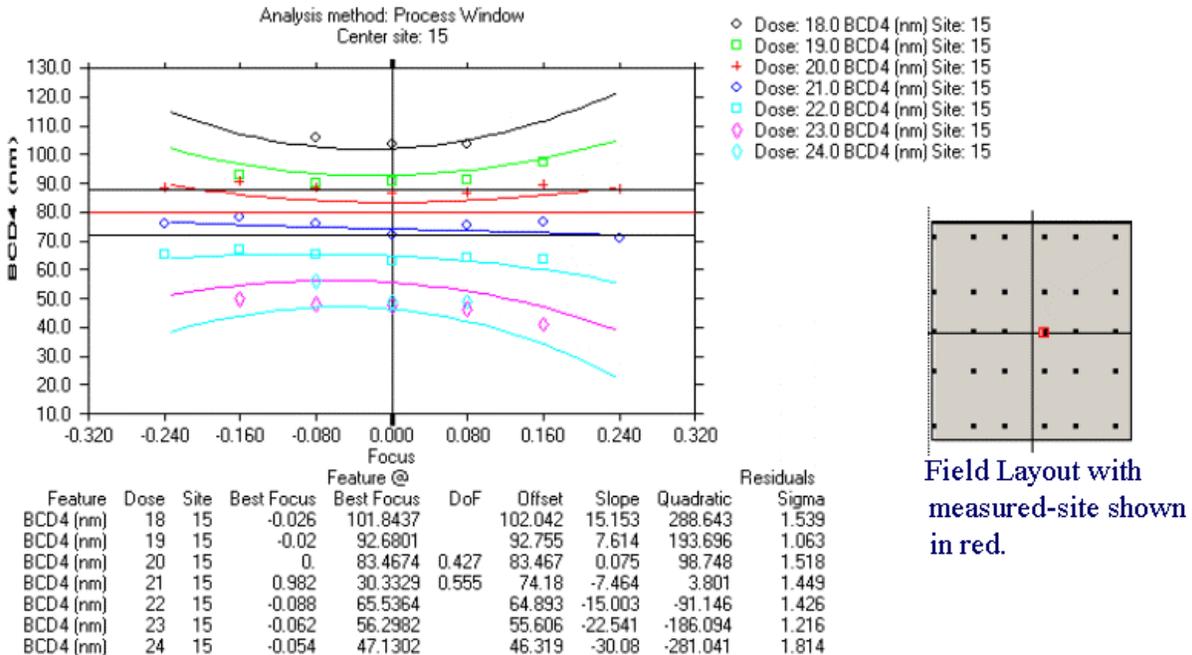
In this implementation the classic focus-exposure matrix is shown to be a powerful tool for the determination of optimum focus and focus uniformity across the full exposure field. Although not the tool of choice for pupil aberration analysis, the method is the best implementation for determining the behavior of device critical feature response when the constructs of OPC, forbidden-pitch and inherent reticle variability are involved. Improved process performance can be achieved with algorithms that provide a calculation of the optimum focus ridge whose resulting feature response-to-dose curves are more easily traced to simulation.

Response surface models are presented and applied to a calculation of the Best Focus surface for the exposure field. Unlike specialty reticles used in defocus error, the Bossung curve maps the response of the reticle specific feature or OPC design and can provide information on errors induced by the lens/optomechanical system of the exposure tool. The Bossung curve delivers several additional response surfaces needed for proper qualification of any exposure-tool and reticle set. These include the ability to contour-map the critical Feature-Best-Focus surface response across the exposure field of the reticle that accounts for feature and process design variations, the Depth-of-Focus uniformity surface for each critical feature across the full exposure, an Isofocal ridge analysis of the process and the associated process perturbation response and the effective dose-uniformity response needed to achieve target feature size uniformity across the exposure.

The Feature-Best-Focus response surface is critical to any systemic analysis because it is the optimum estimation of the reticle feature uniformity without the perturbations induced by exposure defocus. It is shown that when combined in the analysis these techniques provide improved and quick full-field and process-range feature control limit and tolerance calculation for new designs. The exposure limits thus calculated can then provide a realistic and stable process control set for use in the classic process window analysis.

Finally, by deconvolving the systemic reticle signature, the original data provides a feature-specific analysis of Dose-Uniformity. The dose-maps created in this step can be linked to local variations in MEEF and can be used for IntraField Dose Compensation in advanced exposure tools.

**KeyWords:** Bossung, Best Focus, Dose, APC, Dose Mapping, IsoFocal, Exposure, CD control, Lithography, OPC validation, spatial model, Scatterometry



**Figure 1: Set of Bossung curves for a Bottom Critical Dimension (BCD) vertical 80 nm target size for one site located in field-center. The analysis shown contains additional information on the Best Focus, feature size and DoF for each curve. (Weir PW software)**

## 1. INTRODUCTION

An Across Chip Linewidth Uniformity (ACLW) goal of 4.2 nm for critical feature half-pitches of 40 nm, as established in the 2005 ITRS Road Map is a daunting task for an industry now stretching the physical limits of optical lithographic science. A number of very sophisticated approaches are underway in this effort that involve the in-depth characterization of the Mask Error Enhancement Function (MEEF or MEF) and optimization of Optical Proximity Correction (OPC) mask enhancements<sup>1,2</sup>. However, complexity should be avoided whenever possible and at times it is beneficial to examine old, well-known techniques for more simplistic approaches to modern problems.

The Bossung Curve approach was first published in 1977 to setup and characterize Perkin Elmer projection printers<sup>3</sup>. This technique, a sample of which is shown in figure 1, forms the basis for the commonly used Process Window analysis for focus and dose setup of the photoresist process. In past times the technique was in common use for best focus analysis and was often also used for the determination of focal plane uniformity during the characterization of exposure tools<sup>4</sup>. The use of the technique for focal plane characterization soon fell into obscurity because of the increased accuracy obtained from the use of specialty structures such as those embodied in the Phase Shift Focus Monitor and Z-Spin constructs<sup>5,6</sup>.

The recent increase in the use of reticle enhancement techniques (RET) such as Optical Proximity Correction (OPC) structures and phase shifting features has been driven by the losses incurred in focus margin for small critical feature sizes. In the newest chip designs, adjacent features no longer respond equally to optical illumination because of their inherent size with respect to the actinic wavelengths used. Image formation is now a function of the feature's image and subtle interactions with perturbations from other structures in proximity on the mask. The actual image generated in the photoresist is therefore a convolution of the perturbations obtained from the mask-object, the RET structures and neighboring patterns. As a result, a clear-cut analysis of the wavefront uniformity and focal-plane flatness using specialty test patterns is not a sufficient analysis to determine the point and range of acceptable focus for production OPC structures.

By incorporating a return to the simpler techniques embodied in the Bossung curve analysis with the increased information on feature profiles, film stacks and ease of use obtained from the newer metrology techniques the engineer

can extract more information about image quality than was previously thought possible. In this manner, even the newest OPC designs can be easily evaluated for their true response in the process.

The following techniques will show how the full-field optimum focus plane can be evaluated for any RET enhancement. We'll then show how the lens-aberrated perturbed component of the feature can be removed from the data to yield the true exposure-dose response of the feature. This response surface also provides a method of calculating the depth-of-focus (DoF) and exposure latitude (EL) of the RET feature without the degrading influence of process window focus sensitivities. This is an important function for Anti-Reflective Coating (ARC) and photoresist evaluations because it provides an analysis of the process-critical metrics without the localized influence of the scanner focus errors originally incorporated into the test wafers.

With a clear understanding of the sources of feature size perturbation, the reticle can then be analyzed to determine the site-specific dose needed to obtain target size. A recent publication from ASML reported on the ability to adjust exposure-dose magnitude across the individual exposure field and wafer for dose-to-size feature control in production<sup>7</sup>. The authors however did not provide a simple and clear-cut method of determining the dose-mapping information needed for the procedure. Dose mapping can be easily determined from the Bossung plot and the algorithm for achieving this is discussed in the following sections.

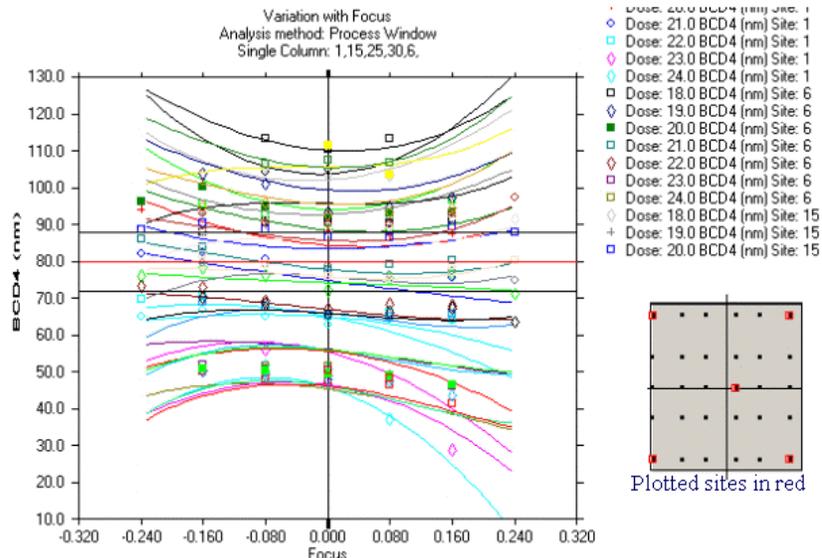
## 2. SETUP OF THE EXPERIMENT

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  $\mu\text{m}$  from best focus.

The experiment measured 80 nm target size features that were generated using a 100 nm (nominal) final size reticle feature on a 1:1 duty cycle; dense vertical lines. The reticle included OPC correction with assist features.

Exposure was made into 240 nm of resist that included a 78 nm BARC (Anti-Reflective Coating). A 0.75 Numeric Aperture was used for the exposure along with annular illumination. Wafer measurements were taken using a Nanometrics scatterometer that employed OCD metrology with normal incidence, rotating polarized light (Nano 9030).

Analyses of the process window, Bossung, modeled and raw data sets were performed using the commercial Weir PW software from TEA Systems.



**Figure 2: Bossung Feature v focus plot for five sites on an exposure field.**  
**This plot illustrates the variation in response to process stimuli when lens and exposure aberrations are present.**

### 3. STATEMENT OF THE PROBLEM AND ANALYSIS ALGORITHM

Bossung and process window analyses typically do not take into consideration the system perturbations seen by each site on the exposure field. At best a single site in the center of the field is selected in the hopes that lens aberrations will be minimal at this locations. With the ascension of scanner exposure tool lithography over that of the previous stepper technology the field center is not typically the optimal location for sampling. Consider the example shown in figure 2 and it's exhibition of process response for five sites in a 24 by 24 millimeter (mm) field. The data points are shown on the plot along with the surface calculated algorithm curve for each dose. For this example we used an algorithm common in the industry that takes the form of:

$$CD = \sum_{m=0}^M \sum_{n=0}^N a_{nm} \left(1 - \frac{E_s}{E}\right)^n F^m \quad \dots 1$$

where variables E and F represent the exposure-dose and focus of the analysis<sup>8,9</sup>. The coefficients  $a_{nm}$  maps the response of the process to the variables and it's cross terms. Several formats of this formula exist but none exactly describe the response behavior of the process because they do not include the optical aberrations and electro-mechanical perturbations introduced by the exposure toolset. Even a quick examination of figure 2 illustrates that some of the contours behave significantly different than others in focus, isofocal response and dose response.

Consider the Bossung schematic presented figure 3. The plot presents a response curve for each exposure-dose. Feature size changes significantly with focus unless the optimal dose for the feature and process is selected. The optimal dose is shown in figure 3 as curve "A" and is called the **IsoFocal Dose** because of the focus-independent response of the feature.

Often a process will be biased to another feature size and the acceptable process limits for feature size are specified as the Upper and Lower Control Limits, **UCL** and **LCL**. The distance between the IsoFocal feature size and the center of these limits is called the **IsoFocal Bias** of the process.

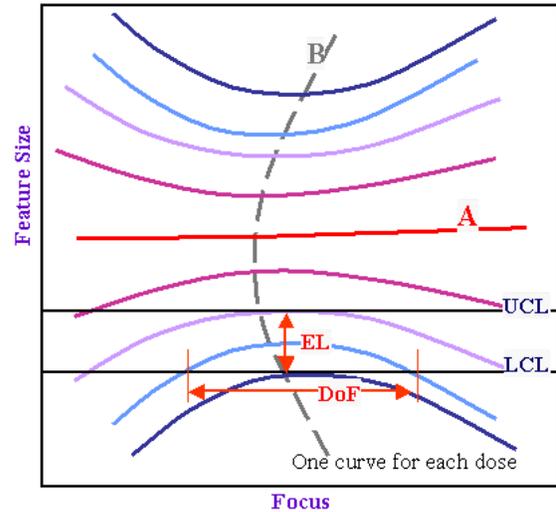
**Exposure Latitude (EL)** is defined as the range of dose values that reside within the UCL and LCL limits at best focus. The **Depth-of-Focus** can be defined for each dose as the range of focus over which that dose provides a feature size that can be contained within the UCL and LCL limits.

The optimal focus or **Best Focus (BF)** for each dose-curve is the maximum or minimum for the curve.

The Best Focus points for the family of dose-curves for any process form a contiguous optimal ridge that is called the **Locus of Best Focus**. This locus represents a measure of the aberrations found in a lens and their convolution with the perturbations of the electro-mechanical supporting structures. Many microscope users encounter a common experience of this phenomenon that is a side effect of these aberrations. If the user centers on a feature in the field of a microscope and then ranges the focus of the microscope above and below this point, the object will move across the field of view as focus changes. The greater the aberrations of the microscope, the greater will be the amount of image-shift experienced. A straight-line, vertical locus represents an aberration free system.

Best Focus for each dose-curve is calculated by taking the first order derivative of equation 1 for the curve, setting it to zero and solving for focus<sup>10</sup>:

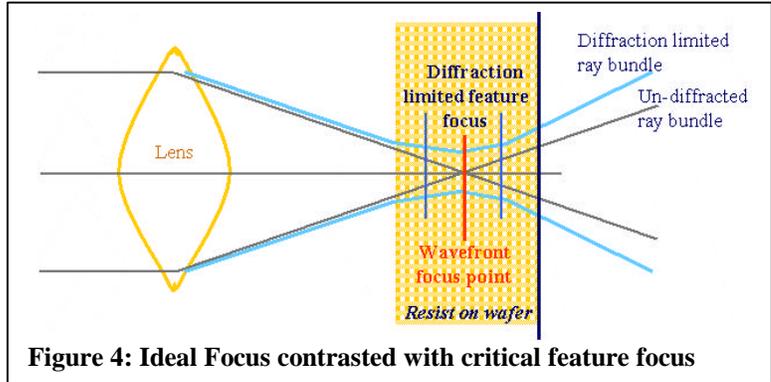
$$\frac{\partial CD}{\partial F} = \sum_{m=1}^M \sum_{n=0}^N m * a_{nm} \left(1 - \frac{E_s}{E}\right)^n F^{m-1} = 0 \quad \dots 2$$



**Figure 3: The Anatomy of a Bossung Plot. The response and shape of each dose-curve contains information on the process window and perturbations of the exposure process.**

This calculation is repeated for every dose and every measured site on the exposure field. Therefore the Best Focus for each site is calculated and, unlike the specialty focus features of the commercial test patterns, this focus represents the true response of the feature under test in that it includes all of the perturbations and responses of the RET enhanced photomask.

To explain the difference in reading optimal focus values, consider the behavior of focus for an ideal, un-diffracted coherent ray bundle as shown in figure 4. Coherent light will focus to a single point on the optical axis for the lens. Specialty focus measurement reticles measure focus much somewhat along these lines in an attempt to characterize the optimal wavefront response.



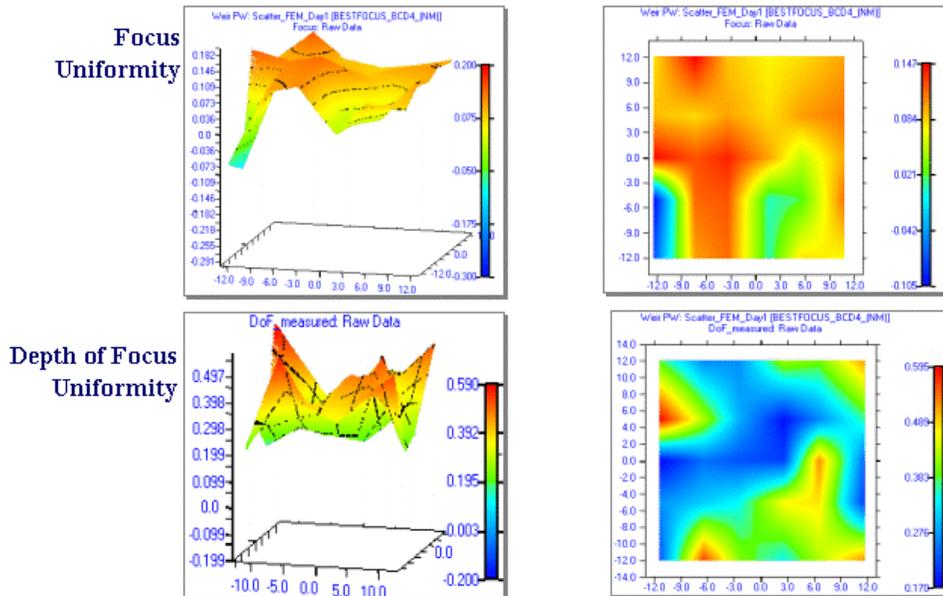
**Figure 4: Ideal Focus contrasted with critical feature focus**

As the optical system and the photomask move away from this ideal, the imaging no longer focuses at a single point. The ray bundle is now subject to diffraction and scattering and will not point-focus. The focused ray bundle for an object whose size approaches the Rayleigh Limit and contains sub-resolution perturbation features will focus into a region over which the ray-bundle point-spread is minimized, but not zero, to create the final image. This focus-range of this bundle is the depth-of-focus for the feature.

Focus-measurement specialty reticle’s each exhibit a simple wavefront response that will not be the same as that presented by the enhanced features of the production reticle. The Bossung method of focus calculation is therefore less precise than the specialty reticle but more accurate in replicating and measuring the focus experienced by the feature.

Focus across the field is never fully flat and errors always exist. However, since the optimal focus is known for the feature-site, the critical dimension (CD) size that would be generated by the site at zero focus error can also be calculated. The optimal CD calculated at the IsoFocal dose and with zero focus error represents the wafer-response feature size that is closest to the constructed feature size on the reticle for the site for the given dose.

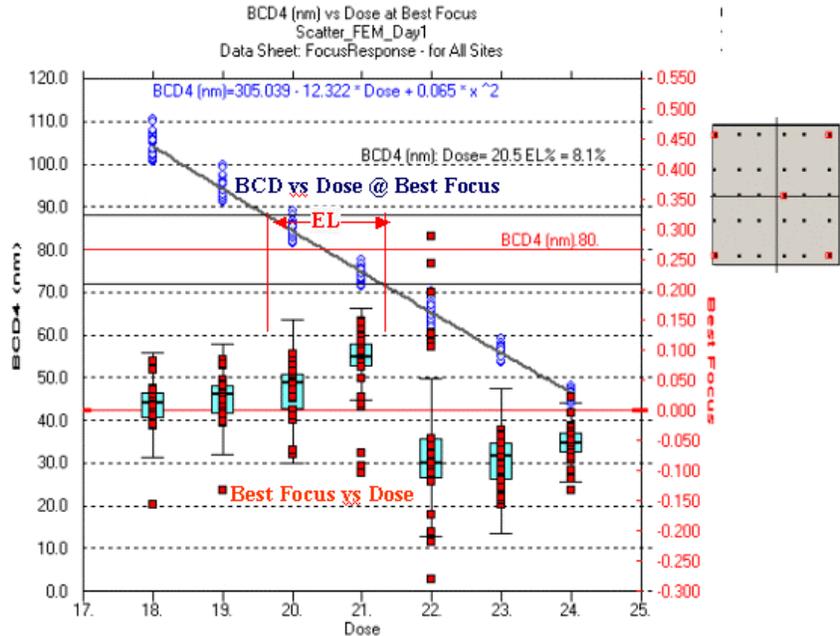
One critical characteristic of this method of calculation is that since the optimal focus of each site is influenced by it’s reticle-manufactured history and it’s exposure-aberrations from the wafer exposure, the Best Focus for each site will vary from that of it’s neighbors. If the reticle is damaged at this site or improperly constructed then the difference in



**Figure 5: Across-Field critical feature focus and depth-of-focus uniformity**

focus between the site and its neighbors will be large and reticle errors can be easily found. If the reticle is properly constructed, then the focus-error map across the field will replicate the focus uniformity experience by the reticle image. This is therefore a good first-step in reticle validation.

Film and resist calculations aren't interested in local lens focus related errors. Measuring the true focus errors of the field is critical if we want to determine the proper response of all of the reticle sites to dose. If we now calculate the feature-size of each site at the point of zero focus error for the site then the calculated response of the site to variations in dose will remove those perturbations induced by local wavefront focus errors and yield a true response curve for dose.



**Figure 6: Feature Size as a function of Dose @ Best Focus and Best Focus for each dose.**

A word of caution and an opportunity should be considered here in that the feature size, while independent of local focus perturbations, will still exhibit residual perturbations from other lens aberrations, reticle scan errors, reticle bowing due to chucking or thermal effects and even local dose variations of the exposure tool.

Local dose variations arise from illumination variation across the photomask. They are also influenced by the rate of scan of the reticle-stage. The dose experienced by the feature is the integrated time that it exists under the scanner-slit. During the exposure the velocity of the scan is held constant to avoid variations in dose. At the end of each scan, the reticle undergoes acceleration changes due to its reversal in scan direction. Ideally these residual accelerations are dumped to zero by the time the next exposure begins. However the scanner vendor is always aware of the throughput considerations and strives to maximize the scan speed. The end result, through improper setup or daily wear-and-tear on the system, is that the acceleration will sometimes be non-zero at the start or end of scan and dose variations will occur. This method provides a means of evaluating these perturbations.

#### 4. FOCUS RESPONSE ANALYSIS

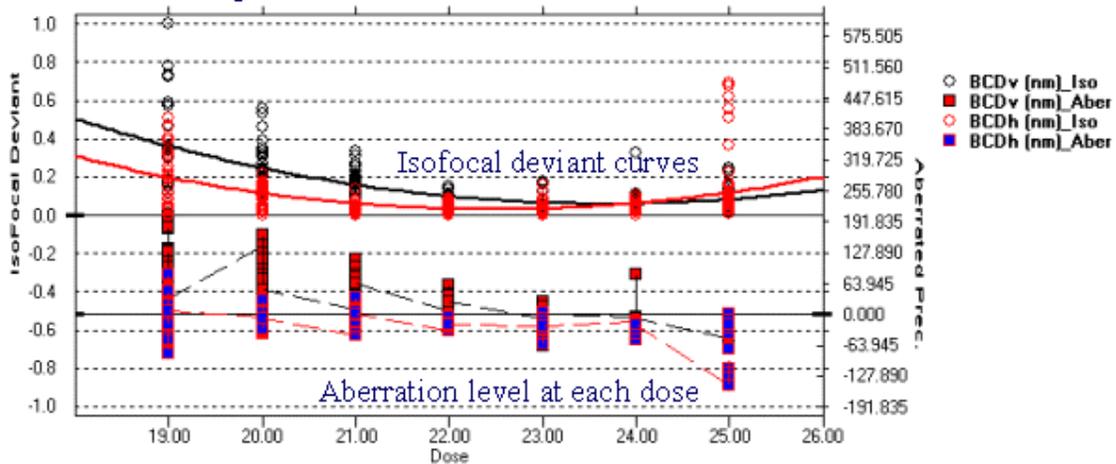
Best Focus and DoF were calculated for each site using the methods described in the previous section. The data was then collected and is presented in figure 5 as contour plots for the process and exposure tool. Upon examination of the plots we can see a significant drop in the site-best-focus for the lower left corner of the field. This could arise from lens or from feature OPC construction error. The corresponding DoF plots in the lower half of the figure also exhibits a loss of process window for the lower left corner corresponding to the point of poor focus in the upper contour.

Continuing with the analysis results of figure 6 we find plotted the response of the Bottom CD feature (BCD4) as a function of dose when considered at the optimum focus for each site (focus errors have been removed). Five sites per field were taken for this plot.

The BCD v. Dose curve for this data now exhibits a very uniform and linear response for each individual site. The linearity is gained when the focus perturbations to the feature size are removed. If we now fit a curve to all sites of the dataset, we see that the resist response for BCD4 is:

$$BCD4 = 305.39 - (12.322 * Dose) + (0.065 * Dose^2) \dots 3$$

Even though each site-curve exhibits linearity, a small, non-zero 2<sup>nd</sup> order coefficient value of 0.065 nm/(mj/cm2)<sup>2</sup> remains in the total-data fitted blue curve of figure 6. The spread of the five points at each dose is the difference in reticle



**Figure 7: Isofocal and aberration level response for a comparison of Bottom CD Horizontal (BCDh) and Vertical (BCDv) feature sets.**

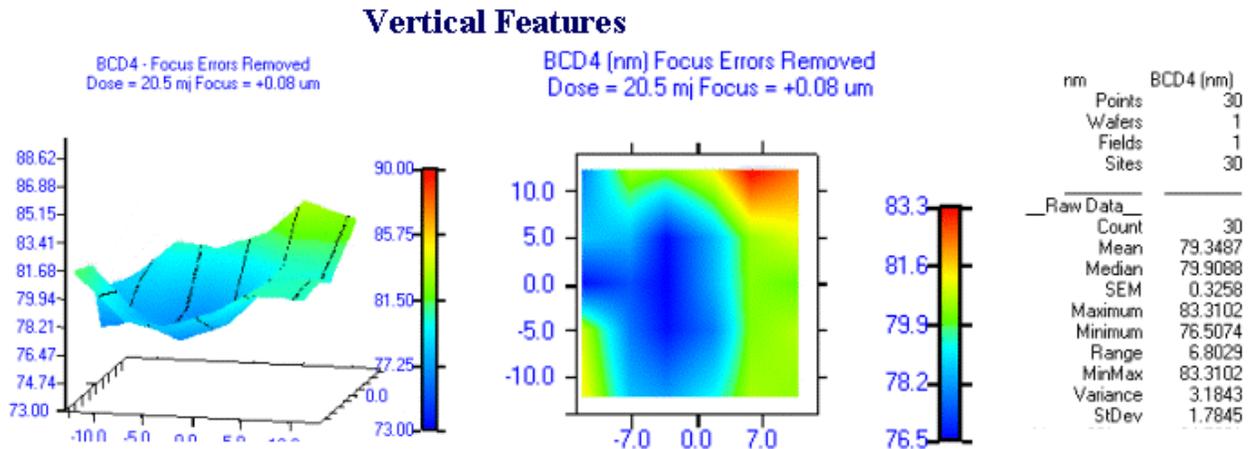
feature size and response to the process perturbations for the given dose. This spread, and the differing response of the five sites, results in a small 2<sup>nd</sup> order value for the response. The nonlinearity is the residual, nonlinear errors contributed by the non-focus perturbations of the image that include the RET design enhancements and the MEEF of the system.

The lower, red curve of figure 6 plots the spread of Best Focus calculated at each site and dose. These points graph against the right-hand Y-axis. An aberration-free system would exhibit a flat Best Focus response across all dose values. The single point residing below each dose box-plot is the lower-left corner of the field signifies a problem with the OPC design of this site.

The discontinuity of the Best Focus plot between 21 and 22 mj/cm<sup>2</sup> occurs at the isofocal dose.

### 5. DOSE RESPONSE ANALYSIS

The upper curve of Figure 7 represents a very accurate method of calculating the Isofocal Dose for the tool. The higher-orders of the focus-dose response measure the distance from the isofocal point. The higher order coefficients approach zero as the exposure-dose approaches the Isofocal Dose. The minimum of the top-curve in figure 7 therefore represents the Isofocal Dose for each curve-feature. Since two curves are plotted here, one for both horizontal and the other vertical



**Figure 8: Optimum BCD, Vertical feature response with focus perturbations removed.**

features, we can see the difference in IsoFocal behavior for each feature type.

The 1<sup>st</sup> order slope of the feature v. Dose curve represents the aberration trend of the lens. The range of slopes exhibited by each site not only represents the aberration levels at that dose but also can be used to determine the optimum range of dose for process operations. Notice the single out-lying point at the 24 mj/cm2 dose representing the lower left vertical feature response for BCDv. This is the same site that exhibited poor DoF, Focus and dose behavior in our previous graphs. Since the site does not also contain a corresponding outlier for the BCDh feature, the problem is most likely with the reticle OPC and not the lens.

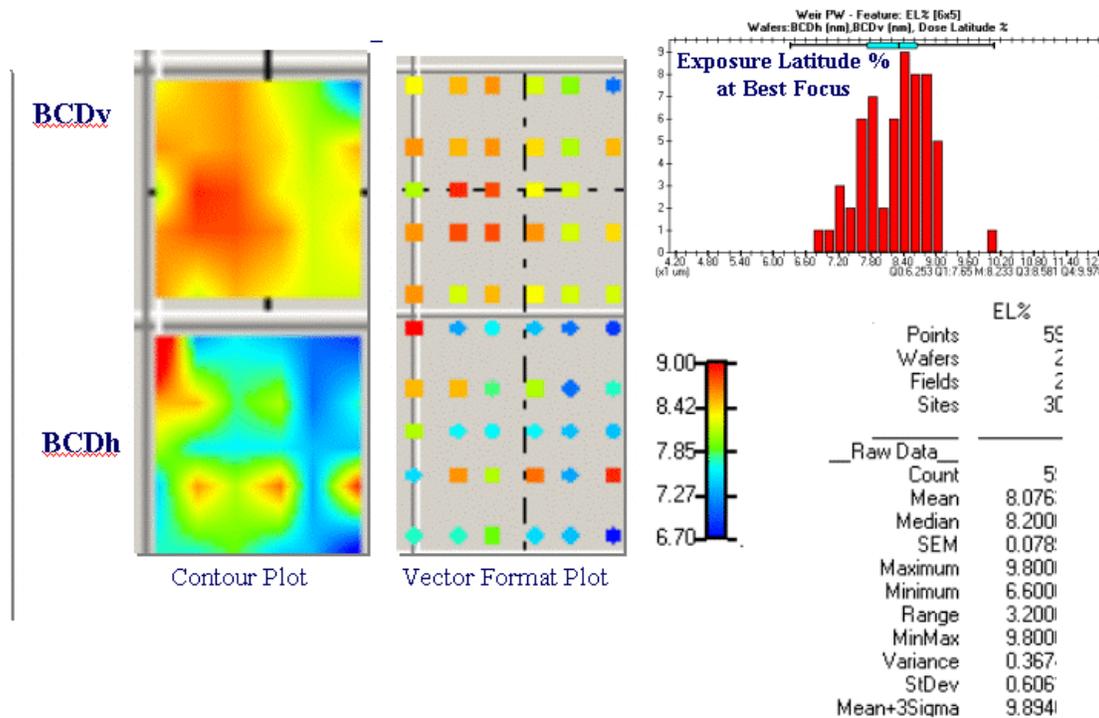
Now having a clear understanding of the optimum focus and dose response for the vertical features, we go back and describe the optimum, focus-free response of the BCD feature across the exposure field in figure 8. One again, this is at the IsoFocal dose for the system and does not include perturbations due to focus. This feature size distribution is the closest evaluation we can achieve for replication of the distribution of feature sizes for each site on the reticle. The feature sizes plotted here also contain tool-specific perturbations such as reticle bow, dose non-uniformity and some optical aberration effects as well as the errors induced by reticle manufacture.

The BCD vertical and horizontal features exhibit a process window exposure latitude plotted as a percentage of the optimum dose in figure 9. For visualization purposes, figure 9 takes the opportunity to illustrate the individual site response by plotting a one-dimensional (1-D), color-scaled vector plot of the data next to the corresponding contour plot for each feature.

These plots represent the optimum response of the Vertical and Horizontal features in tolerable dose latitude for an 80 nm target size. The vertical features exhibit improved response relative to their horizontal brethren. The average EL%=8.76% for the system with a range of 3.2%

With a well-defined mapping of the focus independent feature-size response of the reticle for both horizontal and vertical features, we can now calculate the effective dose uniformity of the tool. Having the dose uniformity, we can next create a dose-map describing the corrections needed to obtain 80 nm feature sizes across the field with a minimum of ACLW.

The dose uniformity for each feature’s response field ranges only 0.9 mj/cm2 as shown in figure 10. The mean dose for



**Figure 9: Exposure Latitude Percentage (EL%) uniformity across the reticle for Vertical and Horizontal features. The contour plot on the left is repeated as a 1-D vector plot to its right. The histogram is a composite of both vertical and horizontal feature sites.**

vertical features is 22.4 mj/cm<sup>2</sup> while the horizontal features would require an average dose of 21.5 mj/cm<sup>2</sup>. These statistics plus the signature plots for each feature suggest that a single dose-mapping correction scheme for advance dose control on an exposure tool would be a valuable asset for anyone attempting to reduce their ACLV for this device.

The signature representing a raised ridgeline across the top of the reticle and a vertical high-dose ridge at approximately the +6 mm reticle site-column suggest OPC errors in the construction of the reticle. A concurrent report on the Mask Error Enhancement Function (MEEF) response of this reticle in these areas shows the feature locations to be higher in MEEF response in these areas but we leave this to and refer the reader to the findings of the publication referenced below<sup>11</sup>.

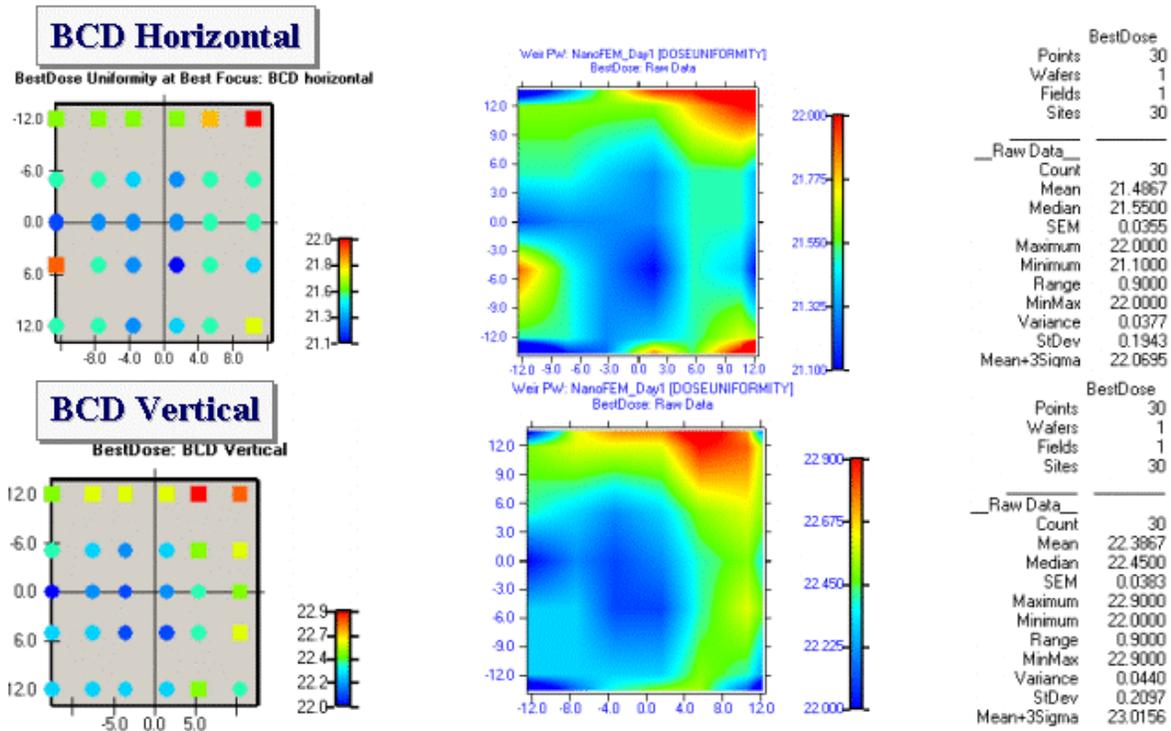


Figure 10: Dose Uniformity at Best Focus for 80 nm Features

## 6. SUMMARY AND CONCLUSIONS

We have shown in this paper that a drive in the industry to reduce across chip linewidth variation down to 4 nm or better for 40 nm half-pitch designs coupled with the non-classic response of RET product designs provides new possibilities for the analysis of focus using techniques originally published in 1977 and known as the Bossung Curves. Analysis of Best Focus for any exposure tool using these methods can improve control in the process because the method successfully takes into account the non-classic response of OPC enhance reticles.

Recognizing that this method of lens focus uniformity calculation has process setup and control advantages over the specialty test reticles such as the Phase-Shift Focus Monitor, Z-spin structures and End-of-Line constructs, we can expand on the information gained directly from the process reticle to characterize the IsoFocal Dose response for every site and the effective dose uniformity across the exposure.

Process control applications stand to gain from this approach because the true response of the product reticle can be directly measured. These benefits can be extended for new exposure tools capable of IntraField dose mapping correction because the design specific optimization of ACLV can now be directly calculated and mapped into the exposure tool's IntraField dose correction. The technique provides added benefit for new reticle designs since features covering the entire reticle can be quickly and easily evaluated for realistic process window control limits without having to run a

multitude of process window analyses.

New reticle qualification and in-process validation of existing patterns can benefit from this analysis technique since the RET structures can be easily and reliably evaluated for depth-of-focus, exposure latitude, individual and comparative feature site performance.

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