Evaluating the Probabilistic Process Window for use in high volume manufacturing

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ABSTRACT

Background: Process window metrology is used in manufacturing to determine best dose and focus for the scanner, but current metrology uses defect inspection to determine best focus and thus is expensive and time consuming.
Aim: Ideally, an alternate stochastics metric (such as linewidth roughness for line/space patterns) could be used as a substitute for defectivity measurements, saving time and money.
Approach: Here, the Probabilistic Process Window (PPW) is evaluated as an improved alternative to the plan of record approach, where only CD-SEM images are collected and evaluated.
Results: The PPW was found to provide results that matched to the plan of record approach, but with increased rigor and improved precision.
Conclusions: As a result, critical layers on future DRAM manufacturing nodes will use the PPW for best dose/focus scanner control.

Keywords: Focus-exposure matrix, FEM, process window, stochastics, Probabilistic Process Window, PPW

1. INTRODUCTION

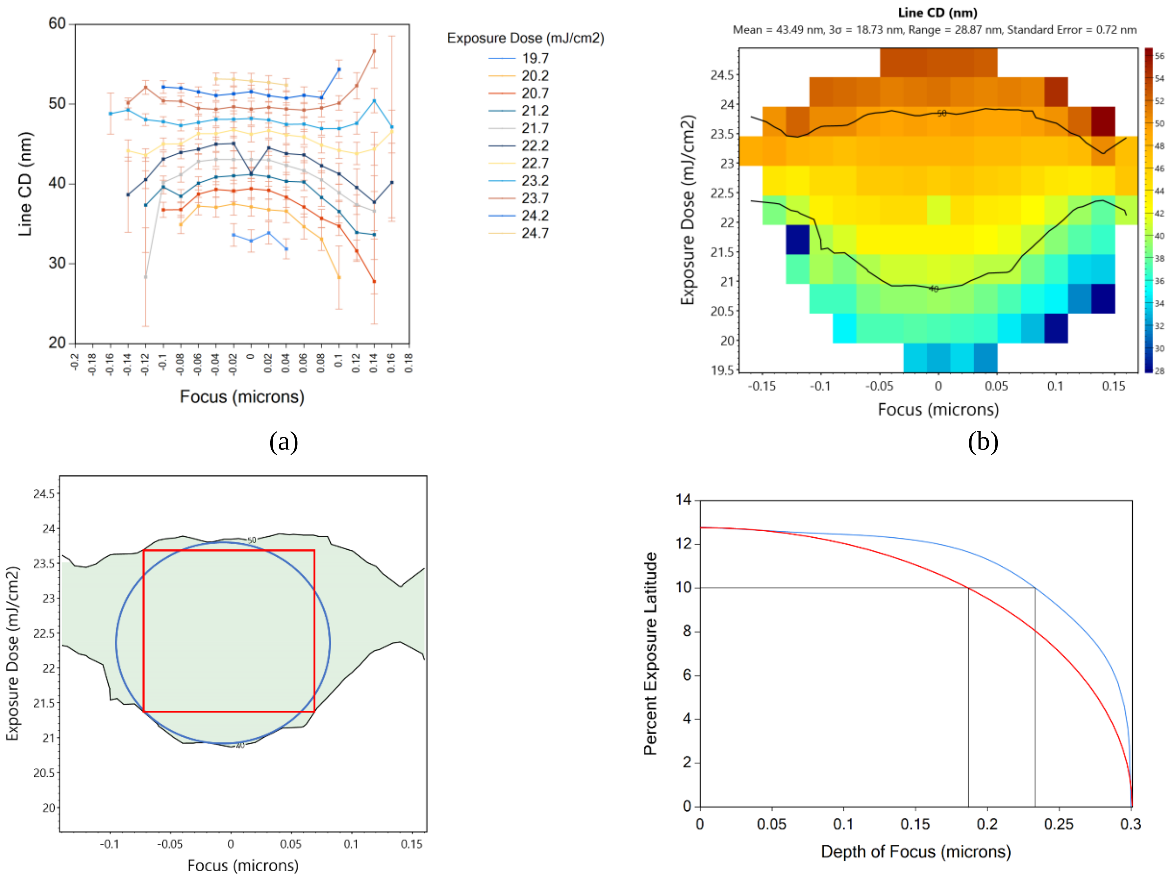
Focus-exposure process window analysis is a core tool in lithography, used to control scanners by setting best exposure dose and best focus, and to evaluate materials and optimize processes for largest depth of focus (DOF), among other uses to meet cost-effective production requirements. Process window metrology begins by printing a focus-exposure matrix (FEM) on a single wafer. A traditional process window uses contours of critical dimension (CD) at the CD specifications to define a region of dose and focus that keeps that CD in spec. But in the era of stochastics, stochastic variations such as the appearance of stochastic defects can limit the size of the process window. To include defectivity generally means using optical or e-beam defect inspection through focus (and sometimes through dose as well) and incorporating this defectivity information in addition to the CD process window. While defect inspection after develop (ADI) is sometimes possible, in many cases only the after-etch (AEI) data is useful for defining best focus due to better defect inspection sensitivity at AEI. This poses two major problems: the extra time and expense of using defect inspection, and the extra time and expense of using an AEI wafer. Thus, there is a strong desire to use ADI CD-SEM data to determine the process window without resorting to optical defect inspection or after-etch wafers.

Recently, the Probabilistic Process Window (PPW) was introduced to rigorously include stochastics effects into process window determination.[1] From the same SEM images used to measure CD, measurements of unbiased linewidth or line-edge roughness (LWR/LER) for lines and spaces or unbiased local CD uniformity (LCDU) or local pattern placement error (LPPE) for contact holes or pillars can be incorporated into the process window in a rigorous way. If these stochastic metrics are well correlated with stochastic defectivity, then defectivity measurements through focus and/or dose can be avoided. The reduction of costs and improvement in cycle time using this approach can be significant.

This paper will compare the traditional approach of ADI CD plus AEI defectivity for best dose/focus determination to a fully automated CD-SEM-only PPW calculation approach for a critical level of a Nanya DRAM production process. A single line/space layer with multiple features across the device will be used. The costs, benefits, and problems with each approach will be described and compared. The goal of eliminating the expensive defect inspection step will be evaluated, with the final result that the PPW is capable of providing improved best dose/focus determination as compared to the traditional process window approach.

2. APPROACHES FOR PROCESS WINDOW METROLOGY

The focus-exposure matrix involves the measurement and characterization of one or more lithographic results (such as critical dimension, CD) as a function of exposure dose and focus, usually by stepping through dose and focus in even increments. By plotting contours of those metrics at the specifications for them (e.g., plotting the minimum and maximum CD spec contours) the result is called the geometric process window. The term “geometric” comes from the geometric representation of the process window as a polygonal region in dose-focus space. Values of focus and exposure that land inside the process window produce CDs that are in spec, but values outside the process window produce out-of-spec CDs. The basic steps in forming and analyzing the geometric process window are shown in Figure 1.



(a) (b)

(c) (d)

Figure 1. Example of the measurement and characterization of a focus-exposure matrix. a) Bossung plot of CD versus focus for different exposure doses, b) the same data plotted as a contour plot with two contours of CD based on the minimum and maximum CD specs to generate the geometric process window, c) finding the maximum rectangle or ellipse that fits inside the geometric process window, and d) a plot of all maximal rectangle/ellipse height versus width (EL vs. DOF) at an EL spec of 10%, the DOF for both the rectangle or ellipse method is shown.

The geometric process window method has been in common use in the semiconductor industry for several decades[2,3] and follows these basic steps.

1. Fit the data (such as CD versus dose and focus) to a function (such as a polynomial) in order to smooth the data and reduce the impact of noisy data (optional).
2. Create contour plot of the data or data fit versus dose and focus for each spec of interest (Figure 1b).

3. Find overlapping geometric region of all specs – this is called the geometric process window (Figure 1c).
4. Fit maximal rectangles (representing systematic errors) or ellipses (representing random errors) inside the process window (Figure 1c) to generate the exposure latitude vs. depth of focus (EL vs. DOF) curve (Figure 1d).
5. By selecting a minimum acceptable exposure latitude, the EL vs. DOF curve yields one value for depth of focus. Further, that DOF corresponds to one ellipse or rectangle, the center of which corresponds to best dose and focus (Figure 1d).

Sometimes step 1 is omitted, and sometimes steps 4 and 5 are approximated with visual inspection and estimation of best dose and focus. In such a case, best dose/focus can be estimated at best to within about plus or minus one step size in the focus-exposure matrix.

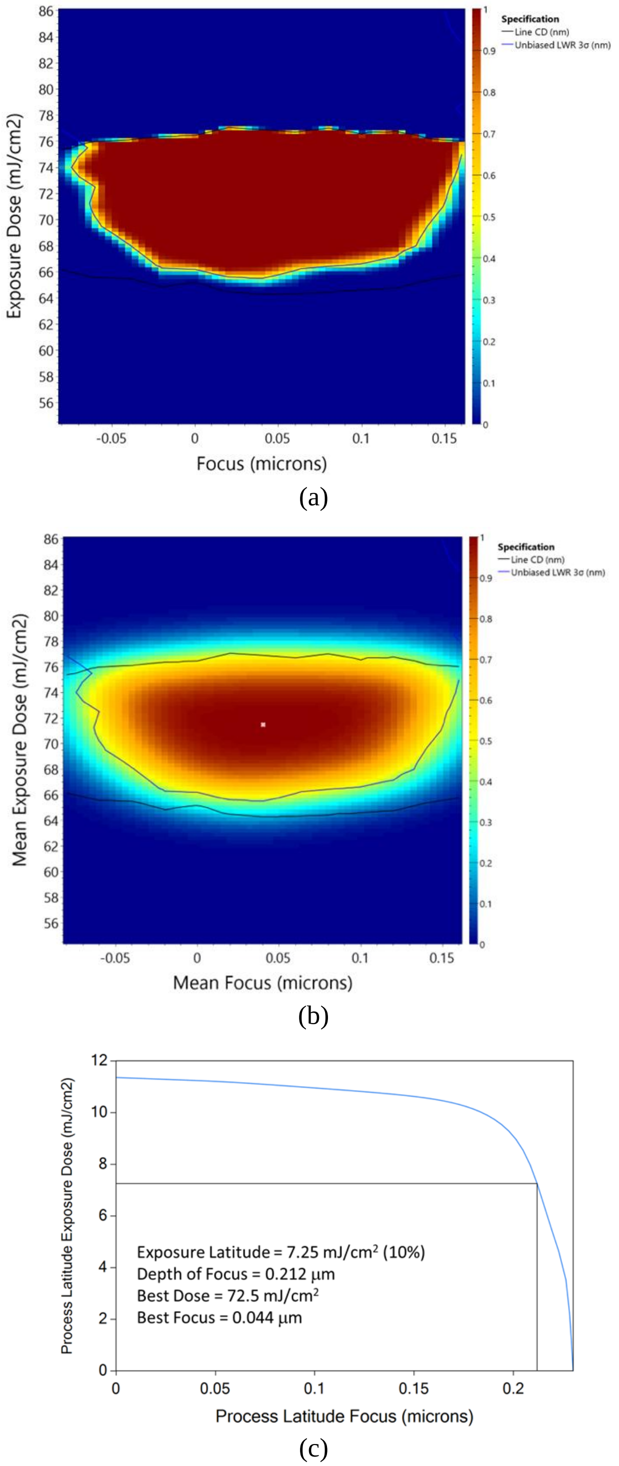
Using only CD for process window metrology is limited since often lithographic processes are optimized so that critical feature dimensions have minimum sensitivity to focus. A common supplement to CD data is defectivity data, collected either through focus or as a function of dose and focus. A maximum criterion for defectivity can be used to limit the acceptable range of focus, and often the center of the acceptable focus range is used to define best focus. This approach is expensive and time-consuming, however. If defectivity measurements are made after etch (sometimes required to achieve the desired defect sensitivity), then the result is also a scrapped wafer.

The geometric process window method has problems and difficulties. The first difficulty is metrology error. The contours of the metric specs (such as CD) that make up the process window are interpreted, in the geometric process window approach, as a sharp edge between in spec and out of spec, a strictly binary proposition that does not take metrology error into account. In fact, one error-prone data point near the process window edge could significantly distort the process window shape and affect the determination of DOF and best dose/focus. To deal with the problem, it is common to first "smooth" the focus-exposure data by fitting CD to a function such as a polynomial. Then, contours of the polynomial fit are plotted as the process window. However, there is no single fitting function that is universally the best, and different fitting functions produce different process windows. Thus, the results of DOF and best dose/focus determination are influenced by the arbitrary choice of the fitting function to be used (or choosing no fitting function). Further, the sensitivity of the process window edges to metrology error are exaggerated by the geometric approach to process window size measurement. As Figure 1c shows, the maximal ellipse or rectangle will, in general, touch the process window contours at only three points. Thus, the measurement of that EL-DOF data point is a function of only three process window points rather than the entire size and shape of the process window. Obviously, any uncertainty in the determination of those three process window points will translate directly into uncertainty in the EL and DOF determination, as well as best dose/focus.

The Probabilistic Process Window (PPW) takes a fundamentally different approach towards determining the process window as well as measuring its size.[1] The three PPW steps are:

Step 1: Determine the Probabilistic Process Window. Unlike the geometric process window, where each dose and focus value either produces a feature that is in spec or not, the PPW calculates the probability that a specific dose and focus value produces an in-spec feature based on the uncertainty of the measurement values. This is repeated for every dose and focus value in the data set, generating a probability of meeting all specs as a function of dose and focus. An example PPW is shown in Figure 2a. Far away from the edge of the process window the behavior of the PPW is identical to the geometric process window, with zero probability of meeting specs outside the window and a probability of one inside the window. Near the edge of the process window there is a gradual, fuzzy transition from 0 to 1 probability due to measurement uncertainty.

Step 2. Determine Fraction of Features Meeting Spec. In this step, the impact of dose and focus errors is assessed. If the dose and focus settings of the scanner are set to specific values, dose and focus variations across the slit, across the field, or across the wafer will result in a range of actual dose and focus values seen by any specific feature. Treating the actual dose and focus experienced by any given feature on the wafer as a 2-D multivariate Gaussian probability distribution with mean dose and focus equal to the scanner setting and standard deviations set by the expected variation for the process, we can combine the PPW with this distribution of process errors to calculate the expected fraction of features on the wafer that meet all specifications. Figure 2b shows an example Fraction of In-Spec Features calculation using the PPW of Figure 2a.



(a)

(b)

(c)

Figure 2. The Probabilistic Process Window (PPW) approach. (a) An example of the PPW. Dark blue represents a near-zero probability that the dose and focus settings produce an in-spec feature, while dark red represents a near-one probability. Near the edge of the process window there is a gradual, fuzzy transition from 0 to 1 probability due to measurement uncertainty. (b) the PPW is combined with set process errors in dose and focus to calculate the fraction of features that are predicted to meet all feature specifications for each mean dose and focus setting. (c) The exposure latitude versus depth of focus curve generated for the PPW of part (a). The inset horizontal and vertical lines show that an exposure latitude setting of 10% corresponds to DOF = 212 nm. Figure adapted from Ref. 1.

Step 3. Generate the EL vs. DOF curve. Using the fraction of in-spec features calculation outlined in step 2, the final step involves the systematic variation in the 6σ process errors in dose and focus to find the values that produce exactly 99.73% of features meeting specs at best dose and focus. The choice of 99.73% of features meeting specs is arbitrary, but based on the standard ±3σ criterion for meeting specs traditionally used in the industry. First, the 6σ process error in focus (that is, the depth of focus) is incremented from zero upwards (forming the x-axis in Figure 2c). At a specific focus error setting (that is, at a specific DOF), the 6σ process error in dose is increased, best dose and focus determined, and the resulting fraction of in-spec features at best dose/focus is calculated (equivalent to the output of step 2, as seen in Figure 2b). Iterations continue until the fraction of in-spec features has converged to 0.9973. At this point, the 6σ process error in dose is the exposure latitude and we have determined one point on the EL vs DOF curve. This process is repeated for different DOF values until the full EL vs. DOF curve is generated, as shown in Figure 2c. Each point on this curve also corresponds to a best dose and focus value.

As this brief description of the PPW approach has shown, all of the limitations of the Geometric process window have been addressed. Metrology uncertainty is taken into account from the beginning, and as a result the process window edges are fuzzy, not sharp. Because metrology uncertainty is inherent to the calculation of the PPW, no arbitrary fitting functions or other smoothing of the data are required. Further, the process errors in dose and focus are represented by a multivariate normal distribution rather than an ellipse. The calculation of the fraction of in-spec features makes use of the entire multivariate normal probability distribution and the entire set of probabilities in the PPW. As the EL vs DOF curve is generated, there is never an issue of just a few points on the process window contour determining the outcome. The result is a much more statistically rigorous determination of EL vs DOF and of best dose and focus.

The PPW in Figure 2 also shows the value of using stochastics measurements in defining the process window in addition to CD. Often stochastics metrics such unbiased line-edge roughness (LER) or linewidth roughness (LWR) for lines and spaces, or local CD uniformity (LCDU) for contact holes are more sensitive (and differently sensitive) to focus than CD. Placing a spec on LWR, for example, often limits the extremes of focus in the process window and makes best focus determination more accurate and realistic. For large data sets, defectivity (bridges and breaks for line/space, or missing and merged contact holes) as measured from the CD-SEM images can also be used as a stochastics metric. Figure 3 shows how the addition of an LWR spec to process window analysis results in a 30% reduction in the measured DOF.

3. COMPARING EXISTING PROCESS WINDOW METHOD TO THE PPW

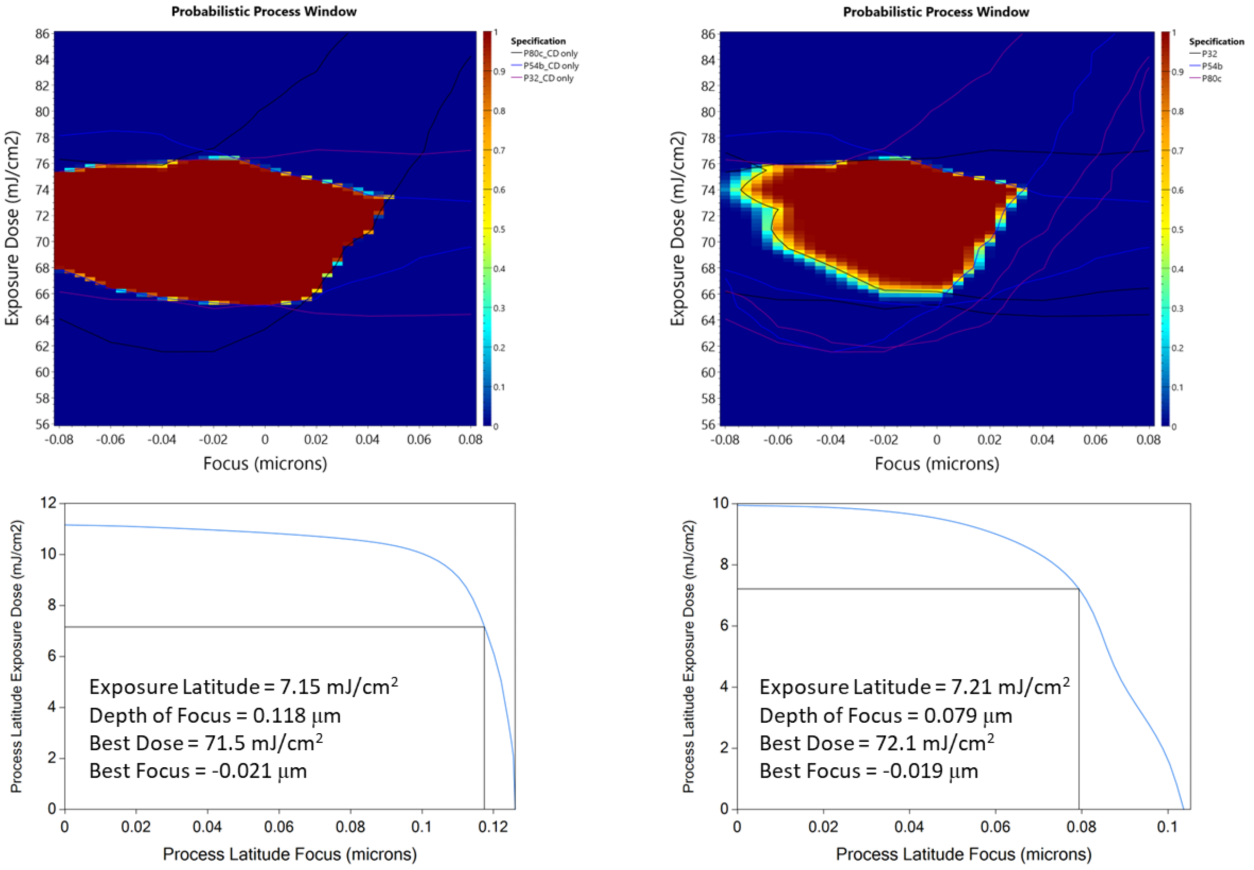
High-volume manufacturing (HVM) for memory production at Nanya involves the need for process window metrology at several critical levels. The current plan of record (POR) method involves the printing and measuring of a focus-exposure matrix after develop, then carrying out the subsequent etch step followed by the same measurements again. CD is measured for several scribe line test structures through dose and focus. Additionally, optical defect inspect is carried out on the FEM wafer both before and after etch. An example data set is shown in Figure 4.

The POR analysis process involves a manual inspection of the CD data versus dose and focus for multiple features coupled with defect counts versus dose and focus. Each dose and focus value in the FEM is labeled as either acceptable or not based on meeting the CD specs for each feature and a defect count spec. Best focus is the center of the acceptable focus range, and best dose is based on interpolation of CD versus dose to the target CD using the best focus condition. Data is collected both before and after etch.

This POR process window metrology has several disadvantages. First, the process is time consuming with a long turn-around time. It is also expensive, involving optical defect inspections and eventually a scrapped product wafer. Finally, the process is manual, involving some amount of engineering judgment and less-than-ideal precision. For these reasons, a replacement process window metrology is desired. The goals of a new process window metrology are:

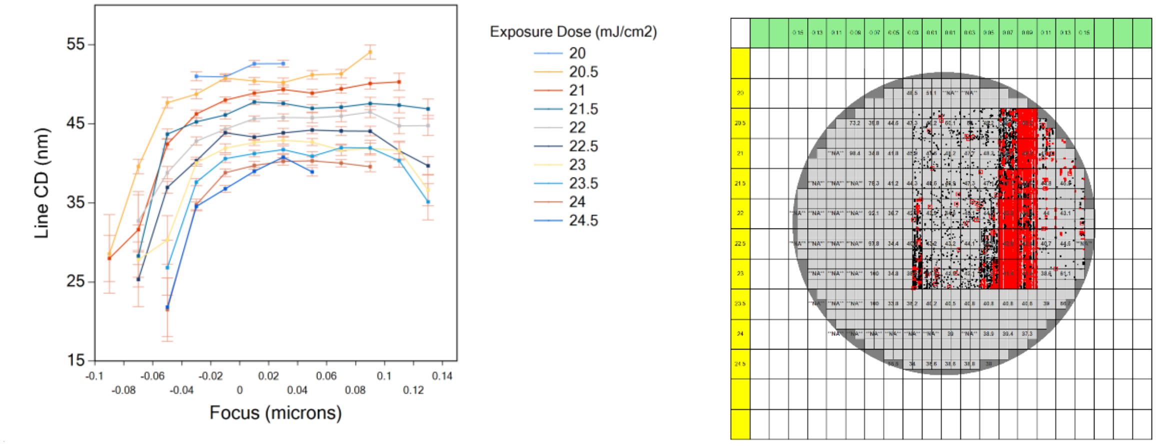
1. Replace manual data evaluation with automated analysis and remove engineering judgement to produce more consistent and higher precision results
2. Eliminate the need to etch the FEM wafer to save money, with no need to scrap a product wafer
3. Reduce cycle time
4. Determine best dose and focus simultaneously from only CD-SEM images, thus eliminating the optical defect inspection step

MetroLER’s PPW (Fractilia) was evaluated as the replacement process window metrology.



(a) (b)

Figure 3. Process window results from the overlapping of three different features (lines and spaces of different pitches). (a) using only CD specs, and (b) addition of an unbiased LWR spec. Data from Ref. 1.



(a) (b)

Figure 4. The POR process window analysis involves the measurement of (a) CD versus dose and focus, and (b) defectivity versus dose and focus. Shown here are typical results at one critical level after develop.

The first step in the evaluation was to calibrate MetroLER CD measurement to the POR measurement from the CD-SEM. Figure 5 shows one calibration set through dose and focus for one feature, where the MetroLER CD Calibration Threshold parameter was adjusted to get the best match. One data point was found to be a poor measurement of CD by the POR CD-SEM metrology. Other features showed similar calibration results and one CD Calibration Threshold was chosen for all MetroLER measurements.

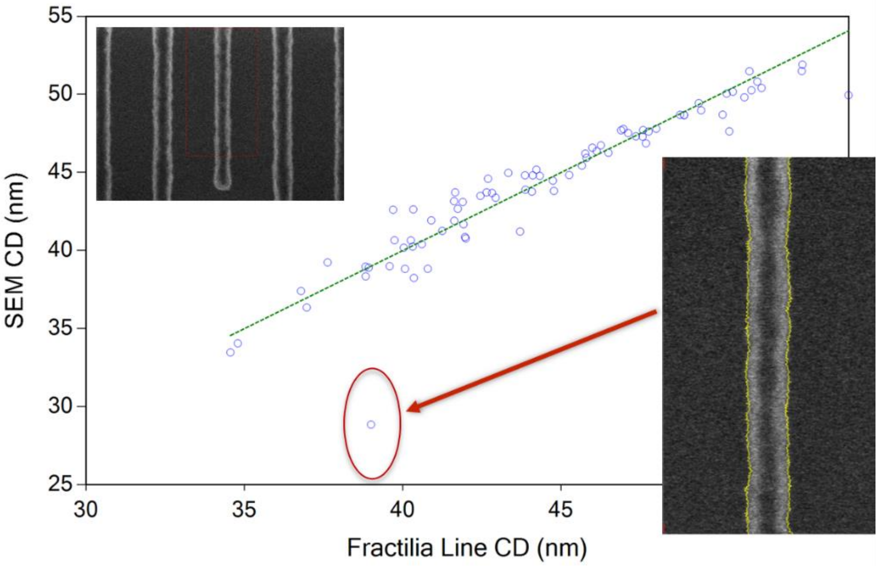
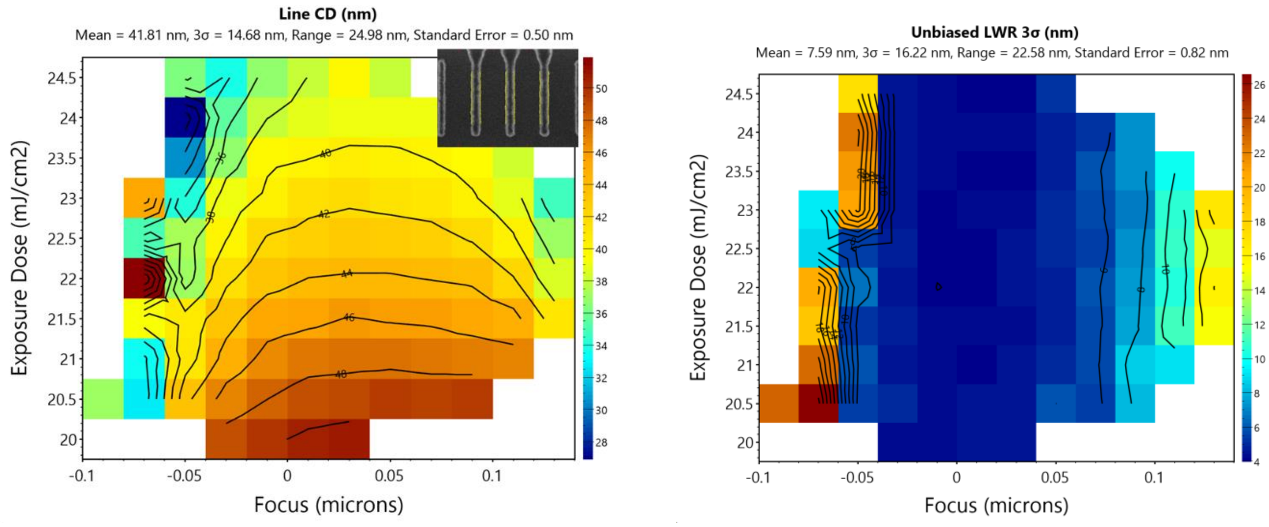


Figure 5. CD calibration for one feature type (inset SEM image). MetroLER's CD Calibration Threshold was adjusted to get the best match to the CD-SEM measurement values. One data point did not fit the linear trend but was discovered to be a bad measurement from the CD-SEM (MetroLER's detected edges for this image are shown to the right).

The next step in the application of the PPW is to decide on the process window metrics. Obviously, CD was used for each feature. LWR was chosen as the best metric to correlate with and ultimately replace the defectivity data. Figure 6 shows an example data set for a 3-bar pattern. The unbiased LWR shows an interesting asymmetry with respect to focus direction. At positive focus, unbiased LWR slowly increases as positive focus increases, but at negative focus there is a very sharp increase in LWR (exhibited as a crowding of the LWR contours). Also note that these unbiased LWR contours are quite vertical, indicating a parameter with a strong focus dependence but very little dose dependence.

The final step in applying the PPW is to set a specification on unbiased LWR. As the example in Figure 3 shows, Adding an LWR spec can have a significant impact on the determination of the process window and the DOF plus best dose/focus. But as the example in Figure 6 shows, choosing the value of the LWR spec can also impact best focus when the LWR response is asymmetric with respect to focus. This is shown more explicitly in Figure 7 where the data from Figure 6 is converted into PPWs with two different LWR specs. Best focus shifts by 0.014 μm as the LWR spec changes from 6 to 10 nm.



(a) (b)

Figure 6. Metrology results for a 3-bar pattern (inset) showing contours of (a) CD and (b) unbiased LWR.

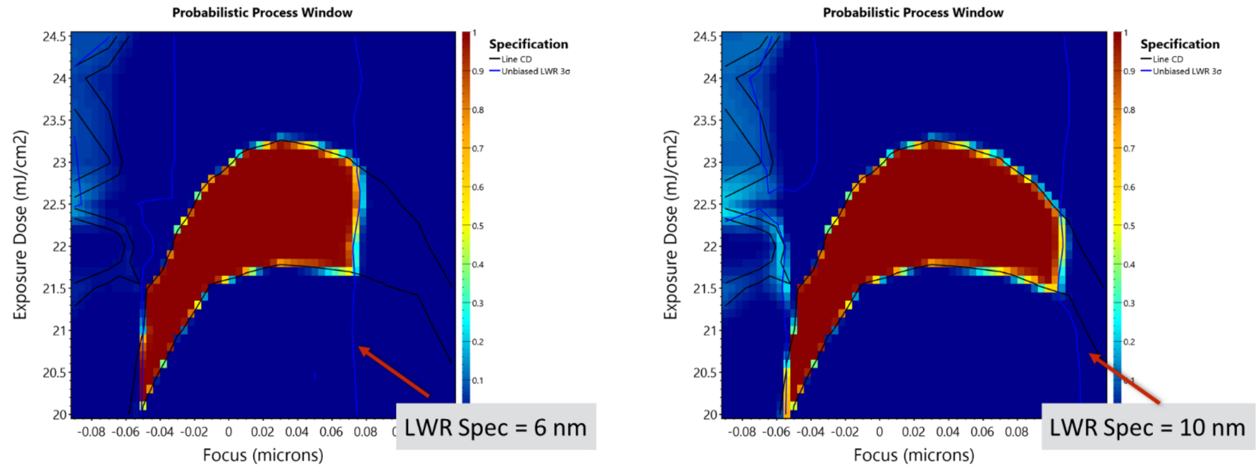


Figure 7. The data from Figure 6 expressed as Probabilistic Process Windows with two different unbiased LWR specs.

While it is possible to apply different unbiased LWR specs to each feature of interest, in this case all six test features used in the process window analysis were lines of different but similar sizes and pitches and exhibited similar LWR behavior. Thus, one LWR spec was chosen for all features. The LWR spec was varied to provide the best match to the POR process window methodology (where defectivity was used to limit the range of acceptable focus). An LWR spec of 5.5 nm was found to provide the best match.

As mentioned earlier, one advantage of the PPW is the explicit incorporation of metrology uncertainty into the calculations. When doing so, it can become apparent that a POR sampling plan may not be sufficient to provide the needed best dose/focus precision. For example, a target with one feature per SEM image and one image per dose/focus value will likely have metrology uncertainty (especially for the LWR) that is too large to be useful. This lack of precision is present in the POR process window approach, even if it is not explicit, but can be better managed in the PPW approach.

4. CONCLUSIONS

Traditional process window analysis approaches can suffer from several limitations, including high cost, long turnaround time, and lack of precision and accuracy. For example, in the era of stochastics it has become common to supplement traditional CD process windows with defectivity through focus data. In many cases, to achieve sufficient defectivity sensitivity either e-beam inspection after development must be used, or optical inspection after etch. Both methods are expensive and time consuming, and are often manual and involve engineering judgement. An alternate approach is to use more easily obtained stochastics metrics, such as LWR or LCDU, as a substitute for defect measurements.

In this paper the Probabilistic Process Window approach was applied to a critical line/space level of a DRAM manufacturing process. By choosing LWR as a stochastics spec that correlates with defectivity and matching the LWR spec used to provide results consistent with the Plan of Record process window method, improved determination of best dose/focus was obtained while reducing cost and turnaround time for the results. As a result of this study, Nanya is pursuing the use of the PPW for all critical levels of future DRAM manufacturing nodes.

5. ACKNOWLEDGEMENTS

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