Probabilistic Process Window: A new approach to focus-exposure analysis

Chris A. Mack and Jonathan Yannuzzi
Fractilia, LLC, Austin, TX, USA
Gian Lorusso, Mohamed Zidan, Danilo De Simone, Ataklti Weldeslassie,
Nadia Vandenbroeck, Philippe Foubert, Christophe Beral, and Anne-Laure Charley
imec, Kapeldreef, Leuven, Belgium

Abstract

Background: Focus-exposure process window measurement and analysis is an essential function in lithography, but the current geometric approach suffers from several significant deficiencies.
Aim: By clearly identifying the problems with the Geometric Process Window approach, a new process window measurement and analysis method will be proposed to address these problems.
Approach: The Probabilistic Process Window proposed here takes metrology uncertainty into account and rigorously calculates the expected fraction of in-spec features based on settings for best dose/focus and presumed random errors in dose and focus. Using the fraction of in-spec features thus calculated, a much more rigorous determination of the trade-off between exposure latitude and depth of focus can be performed.
Results: The Probabilistic Process Window approach is demonstrated on focus-exposure data generated from a standard extreme ultraviolet lithography process at three different pitches, showing the value of this method.
Conclusions: The new Probabilistic Process Window approach offers clear advantages in accuracy for both depth of focus determination and best dose/focus determination. Consequently, its use is preferred both for process development applications and high-volume manufacturing.

Keywords: focus-exposure matrix, FEM, process window, exposure latitude, depth of focus, DOF, EL vs. DOF

I. INTRODUCTION

The focus-exposure matrix (FEM) and its characterization has been an important part of lithography since the beginning of projection lithography in semiconductor manufacturing.[1] The measurement and analysis of this data gives rise to a focus-exposure process window – the region of exposure and focus parameter space that allows the process to produce features that meet specifications, such as for the critical dimension. Further analysis of the process window allows its size to be determined in a lithographically useful way, resulting in a measurement of the trade-off between exposure latitude and depth of focus, a determination of a single depth of focus value for the process, and the determination of best dose and best focus.

Focus-exposure process window metrology has important applications in both process development and high-volume manufacturing (HVM). In process development, the size of the process window is often used to judge one process as more capable than another. Measurement of the depth of focus is used to choose materials, resist process settings, mask treatments such as optical proximity corrections, and scanner source optimization. The process window, as a process capability, can also be compared to an assessment of dose and focus errors occurring in the process (the process requirement).[2,3] For these process development use-cases, accuracy and precision in process window determination is about making the best choices and developing an optimized process. In HVM, process window analysis is used extensively for best dose/focus determination and subsequent scanner monitoring and control. Errors in best dose/focus determination result in a loss of usable depth of focus and a subsequent increase in the probability that features will print out of spec. In the era of very small process windows at advanced nodes, even small errors in best dose/focus determination can have a notable impact on device yield and performance.

The conventional approach to FEM analysis, called the Geometric Process Window, has some significant limitations. As will be described in the next section, it does not take metrology uncertainty into account, it uses an arbitrary fitting function to deal with metrology errors, and the geometric interpretation of statistical dose and focus process errors leads to exaggerated sensitivity to small perturbations in the measured process window. Further, these problems have not been well characterized, and their impact on both accuracy and precision of the results are generally unknown.

This paper will describe and demonstrate a new approach to process window analysis that addresses the problems inherent to the Geometric Process Window. Called the Probabilistic Process Window (PPW), this approach is rigorously probabilistic by design, takes metrology uncertainty fully into account, does not use data fitting functions, and avoids overly sensitive geometric interpretations of process errors. The result, we expect, will be improvements in both accuracy and precision of process window measurement and analysis.

II. THE GEOMETRIC PROCESS WINDOW

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. The measurement is conveniently carried out on a stepper or step-and-scan lithography tool by printing rows and columns of fields on a wafer, stepping across exposure dose in one direction and focus in the other. Each field is then measured for all of the lithographic metrics of interest for all of the features of interest. One output as a function of two inputs can be plotted in various ways. Plotting CD versus focus for different doses is called a Bossung plot.[1] Figure 1a shows an example. Plotting CD versus dose for different focuses emphasizes the loss of exposure latitude when out of focus.

Another plotting approach is a contour plot: contours of constant CD as a function of dose and focus (Figure 1b). By selecting only two contours, those corresponding to the minimum and maximum acceptable values for CD (the “specs”), the result is called the Geometric Process Window (Figure 1c). 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. Thus, the process window provides a convenient and compact representation of the large amount of data found in the original Bossung plot.

The concept of the process window was first developed by Burn Lin using aerial image simulations to estimate CD versus exposure and defocus in what he called the E-D diagram.[4,5] Lin also demonstrated a valuable aspect of the contour-plotting approach: more than one output can be overlapped on the same contour plot. For example, if the focus-exposure behavior of two different patterns (for example, different pitches) were measured, the two process windows could be plotted on the same graph, and the region of overlap common to them both could be displayed. The common process window region represents the range of dose and focus that allows all measured feature types to meet their specifications. An example of this overlapping process window analysis will be given later in this paper.

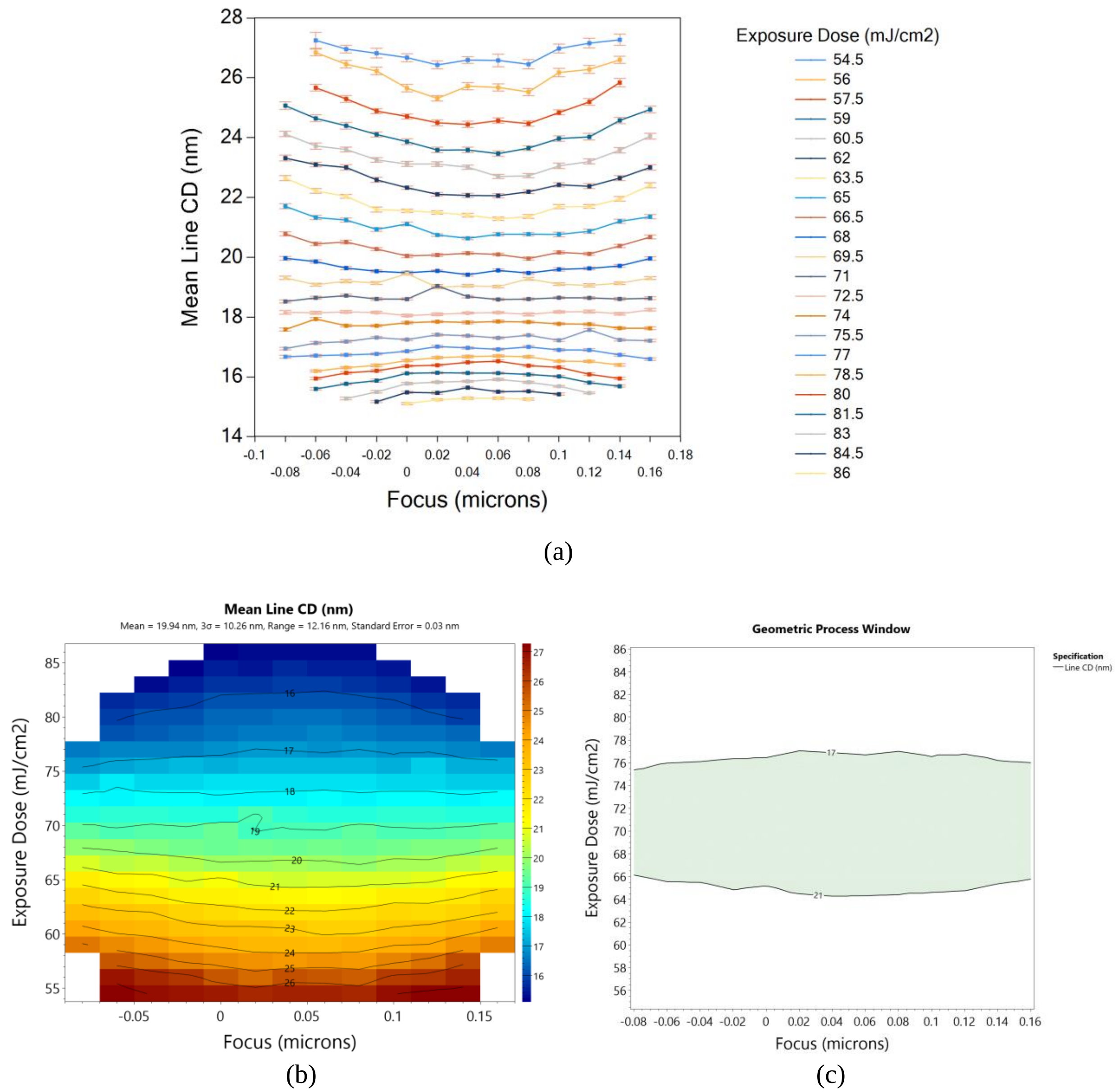


Figure 1. An example of the measurement and characterization of a focus-exposure matrix for a 32-nm pitch pattern printed with EUV lithography. a) Bossung plot of CD versus focus for different exposure doses, b) the same data plotted as a contour plot, and c) selecting two contours of CD based on the minimum and maximum CD specs to generate the Geometric Process Window. All measurements and analysis were performed using MetroLER v3.0.0 based on SEM images from a Hitachi CG6300.

While different features are usefully overlapped to determine a common process window, the same idea can apply to different characteristics of one feature type. Levinson and Arnold added resist sidewall angle and top resist loss as metrics, with specs for these metrics overlapped with the CD specs to create the process window.[6,7] Sidewall angle in particular tends to exclude the extremes of focus from the process window, even when the feature CD meets its specifications. Sidewall angle and resist loss are conveniently obtained when generating process windows through lithography simulation, but are difficult to measure experimentally (and generally impossible using top-down SEM images). However, other metrics are both valuable in characterizing the quality of a patterned feature and easier to measure using fab-friendly metrology. In particular, stochastic measurements such as unbiased line-edge roughness (LER) or linewidth roughness (LWR), line wiggling, local CD uniformity (LCDU), local pattern placement errors (LPPE), local edge placement errors (LEPE), and stochastic defectivity can be measured and overlapped with CD to provide a process window that better reflects the useful region of dose and focus. For example, Figure 2 has added unbiased LWR to the CD process window of Figure 1c, significantly changing the region of focus and exposure considered to produce in-spec features.

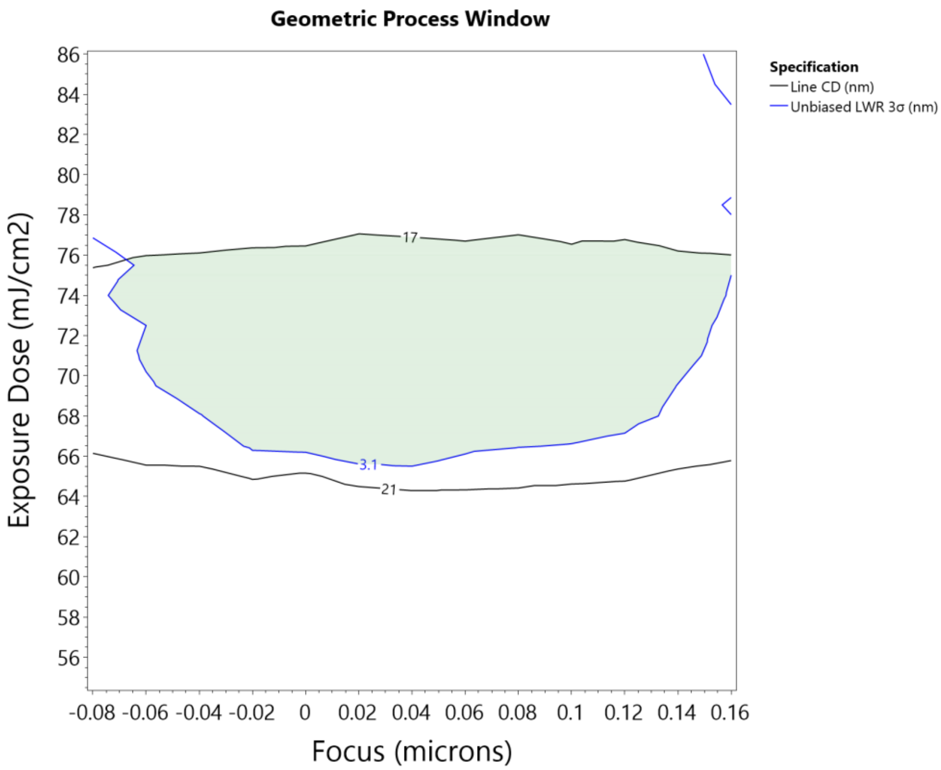


Figure 2. The Geometric Process Window of Figure 1c was modified by overlapping a spec for unbiased LWR measured from the same SEM images used to determine mean CD. All measurements and analysis were performed using MetroLER v3.0.0 based on SEM images from a Hitachi CG6300.

Once a process window has been determined, the next step is to measure the size of the process window. The Geometric Process Window is measured using a geometric approach: fitting the maximal rectangles or ellipses inside the process window.[8] A rectangle represents systematic errors in dose and focus, with the width of the rectangle equal to the systematic focus errors and the height equal to systematic dose errors. The ellipse is a surface of constant probability for independent dose and focus errors exhibiting Gaussian probability distributions. For an ellipse or rectangle of a specific width, the position and height of the shape is varied to find the maximal (tallest) shape that can fit inside the process window. That maximal shape expresses an exposure latitude (EL, range of exposure) – depth of focus (DOF, range of focus) condition, with the center of the shape indicating the position of best dose and best focus (see Figure 3a). By varying the width of the process-error-representing shape and finding the maximal height in each case, the trade-off between exposure latitude and depth of focus can be quantified. The result is the EL vs. DOF curve

(Figure 3b). Generally, the ellipse method is preferred since it better reflects the true sources of dose and focus errors expected in a lithography process. The exposure latitude versus depth of focus curve leads to an unambiguous definition of a single depth of focus value for a process. If the minimum acceptable exposure latitude is specified (for example, 10%, where the exposure range is expressed as a percentage of the best dose value), then DOF can be determined from the EL vs. DOF curve.[9]

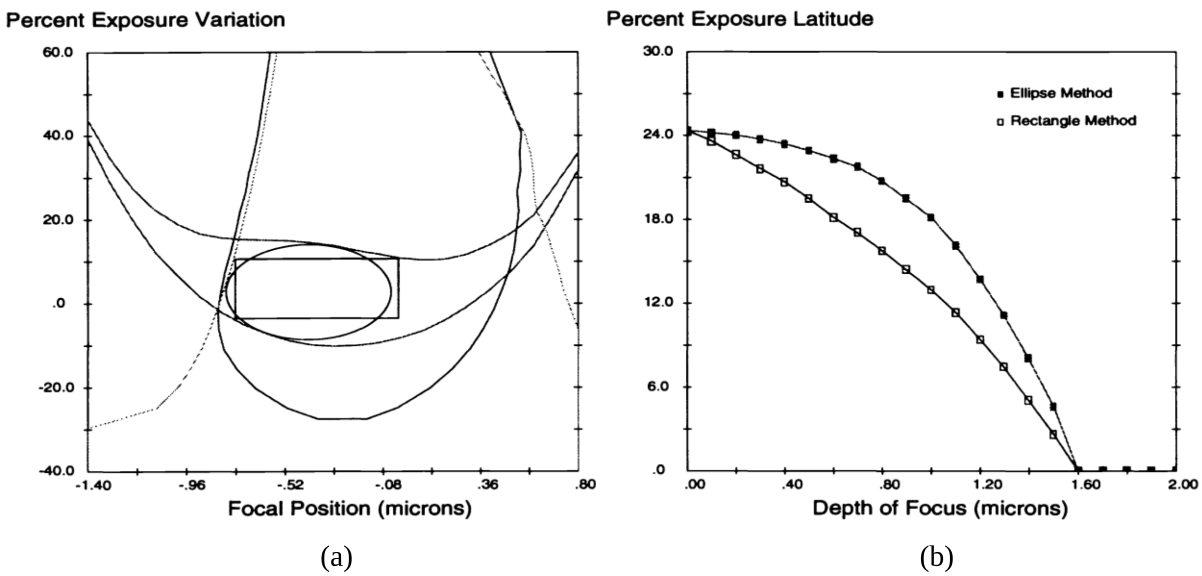
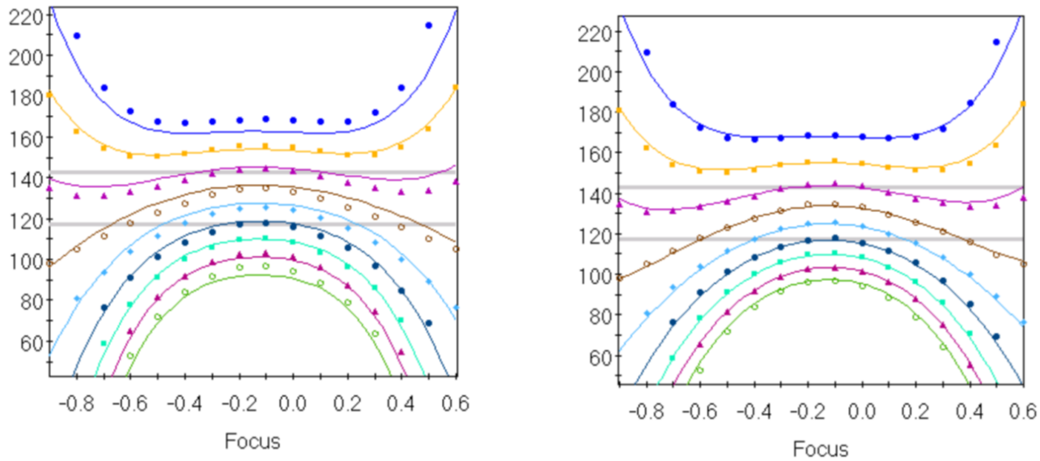


Figure 3. The measurement of process window size: a) the overlapping of CD, sidewall angle, and resist loss specs, with one maximal ellipse and one maximal rectangle shown, and b) varying the width of the maximal rectangle or ellipse leads to the EL versus DOF curves. Figures from Ref. 8.

The Geometric Process Window method has been in common use in the semiconductor industry for several decades, but it is not without its 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 bad 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.[10] However, there is no single fitting function that is universally the best, and different fitting functions produce different process windows.[11] Thus, the results of DOF and best dose/focus determination are influenced by the arbitrary choice of the fitting function to be used. Figure 4 shows an example of two common fitting functions being used upon simulated (and thus low-noise) data. Changes to the form and order of the polynomial fitting function can result in either underfitting (the actual shape of the Bossung curves are not well represented) or overfitting (the fit responds to measurement error rather than the true response), with subsequent impact on the resulting process window size and shape.



$$CD = \sum_{i=0}^{3}\sum_{j=0}^{4} a_{ij}\, E^i F^j \qquad\qquad CD = \sum_{m=0}^{M}\sum_{n=0}^{N} a_{nm}\left(1-\frac{E_s}{E}\right)^n F^m$$

Figure 4. Fitting of one set of Bossung curves to two different polynomial fitting functions. The form and order of the fitting function determines the quality of the fit (or overfit), and the resulting shape of the process window. Figures from Ref. 11.

The sensitivity of the process window edges to metrology error are exaggerated by the geometric approach to process window size measurement. As Figure 3a 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 the EL and DOF determination, as well as best dose/focus. Note that the use of a smoothing function (curve fitting of the data) will make the process window analysis *appear* well behaved (giving a smooth and realistic-looking EL vs DOF curve), but the uncertainty in this final result will remain unknown.

The problems with the Geometric Process Window approach have a common theme: metrology uncertainty is not taken into account when determining the process window, and the use of geometric shapes to represent statistical quantities (errors in dose and focus) is an approximation to the true statistical behavior that has high sensitivity to metrology error. Both of these shortcomings can be dealt with using a new approach to process window determination and analysis called the Probabilistic Process Window (PPW).

III. THE PROBABILISTIC PROCESS WINDOW

The Probabilistic Process Window (PPW) takes a fundamentally different approach towards determining the process window as well as measuring its size. The three PPW steps will be explained in some detail below.

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. For example, consider the measurement of CD at a specific dose and focus setting. That CD will likely be the mean value of multiple features measured on one SEM image, and possibly several SEM images. The outcome of the measurements is the mean CD and the standard error of the mean CD, SE(CD). Assuming a Gaussian sampling distribution for this mean CD (a very good assumption given the central limit theorem) with SE(CD) as its standard deviation, the probability that this measurement is in spec will be the integral of the Gaussian distribution function between the lower and upper CD specs. This is repeated for every dose and focus value in the data set, generating a probability of meeting spec as a function of dose and focus.

If the process window involves more than one spec, this process is repeated for each spec. For example, the unbiased LWR measured at each dose and focus setting has a mean and standard error that can be used to calculate the probability that the dose and focus value produces a feature that meets the unbiased LWR spec. The probability that a specific dose and focus setting produces a feature that meets all specs simultaneously is simply the product of each of the individual probabilities for each spec. An example PPW is shown Figure 5. 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. Note that the solid line contours (the Geometric Process Window) are displayed on the plot in Figure 5 as a visual aid only and are not used in the calculation of the PPW. It is interesting to note that the "fuzziness" of the process window edges varies depending on which spec is determining the probability transition. Metrology uncertainty for CD is smaller than for unbiased LWR, so that the top region of the process window edge, controlled by the CD spec, has a sharper transition from 0 to 1 probability than the left and right process window edges controlled by unbiased LWR specs.

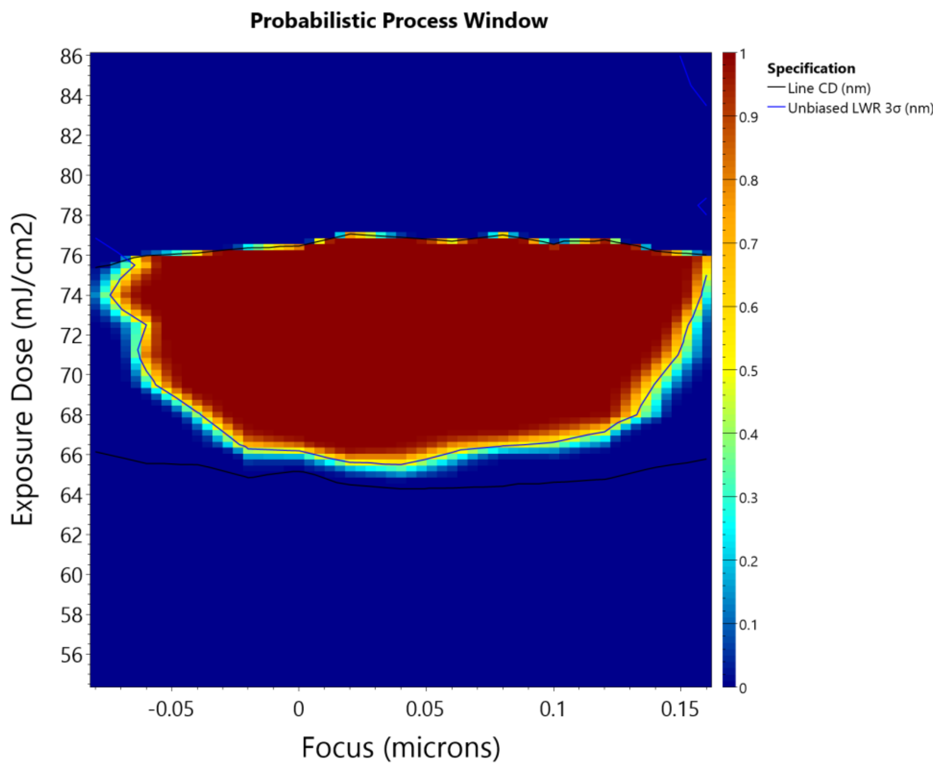


Figure 5. The Probabilistic Process Window (PPW) for the data set shown in Figures 1 and 2. Dark blue represents a near-zero probability that the dose and focus settings produce an in-spec feature. Dark red represents a near-one probability that the dose and focus settings produce an in-spec feature. Near the edge of the process window there is a gradual, fuzzy transition from 0 to 1 probability due to measurement uncertainty. Note that the solid line contours are displayed on the plot as a visual aid only and are not used in the calculation of the PPW.

Step 2. Determine Fraction of Features Meeting Spec. In this step, the impact of dose and focus errors across the wafer (or slit, or field, or wafers, depending on the application) 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 across the wafer, 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 6 shows an example Fraction of In-Spec Features calculation using the PPW of Figure 5 and the 6σ focus error set to 0.15 μm and the 6σ exposure error set to 10 mJ/cm^2. The setting that produces the maximum fraction of in-spec features is considered the best dose and focus (signified by the white X seen in the middle of the plot). Such a Fraction of In-Spec Features can be produced for any values for the 6σ errors in focus and exposure. Note that the use of a 2-D Gaussian probability distribution for dose and focus replaces its geometric equivalent of an ellipse falling inside the process window. Also note the gradual fall-off of the fraction of in-spec features expected on the wafer as the scanner settings for dose and focus deviate from the best dose/focus values indicated by the white X in the plot. This variation of in-spec features through dose and focus is quite smooth, in contrast to the jaggedness of the geometric process window contours, since the entire PPW is being used in its generation.

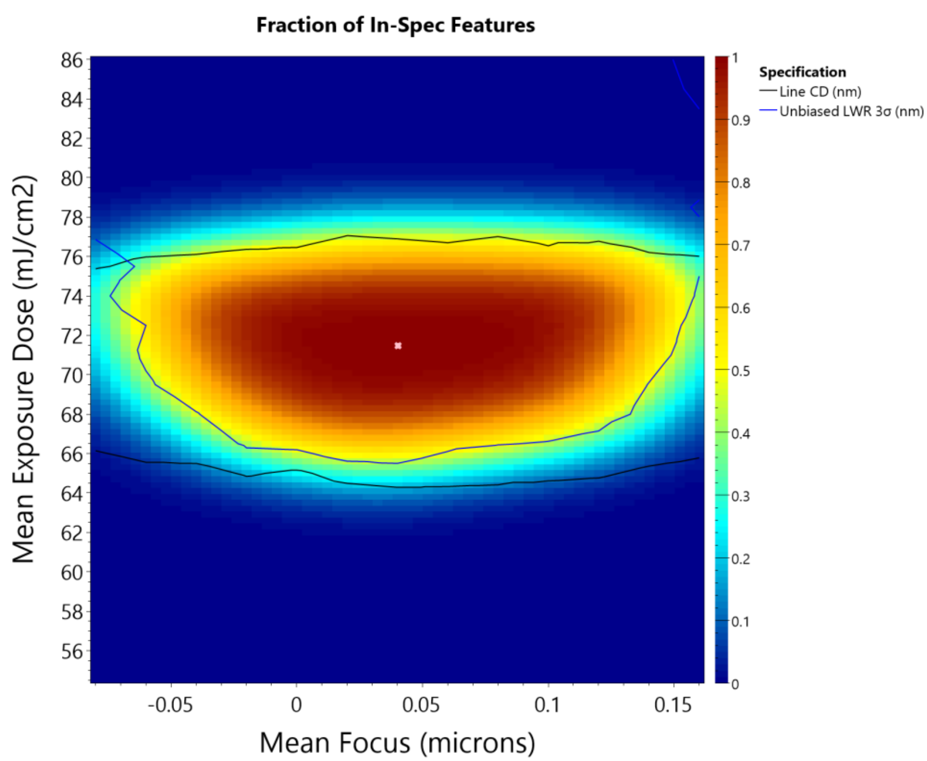


Figure 6. The Probabilistic Process Window (PPW) is combined with set process errors in dose and focus to calculate the fraction of features that are predicted to meet all feature specifications for each mean dose and focus setting. In this case, the 6σ focus error was set to 0.15 μm and the 6σ exposure error was set to 10 mJ/cm^2. The mean dose/focus setting that produces the maximum fraction of in-spec features is considered the best dose and focus (signified by the white X seen in the middle of the plot). Note that the solid line contours are displayed on the plot as a visual aid only and are not used in the calculation.

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 is incremented from zero upwards. 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 compared to the target of 0.9973. If above the target, the 6σ process error in dose is increased and if below, the 6σ process error in dose is decreased. 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 7.

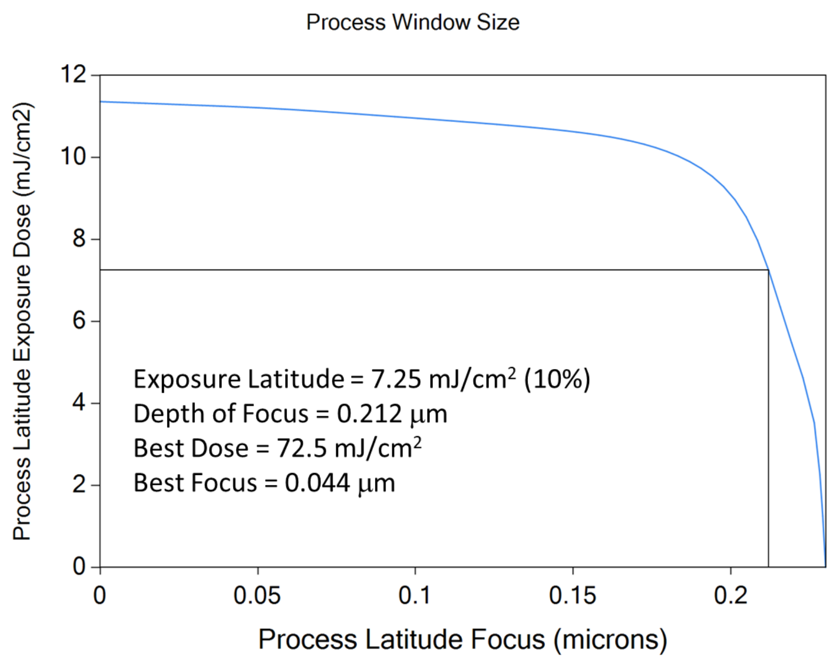


Figure 7. The exposure latitude versus depth of focus curve generated for the PPW of Figure 5. The inset rectangle is for an exposure latitude setting of 10%, with the resulting DOF = 212 nm.

As this brief description of the Probabilistic Process Window 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. One can think of the Geometric Process Window in probability terms: inside the process window, the probability of meeting specs is 1, while outside the process window the probability of meeting specs is 0. Thus, the Probabilistic Process Window approaches the Geometric Process Window as the metrology uncertainty approaches 0. 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 (which is the surface of constant probability for a multivariate normal distribution and thus represents just one slice of the full probability distribution). 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 Probabilistic Process Window. 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.

IV. AN APPLICATION OF THE PROBABILISTIC PROCESS WINDOW

The example data set used in the previous section was a 32 nm pitch pattern printed in resist using imec's standard process (0.33 NA Extreme Ultraviolet Lithography scanner with a source optimized for 32-nm pitch, 30-nm thick chemically amplified resist on an organic underlayer). SEM images were generated with a Hitachi 6300 CD-SEM (2048x2048 pixels/image, 0.8nm x 0.8nm pixel size, 500V, 16 frames). A total of 277 images (one image per dose/focus condition) were then analyzed using MetroLER v3.0.0. From the same wafer two other pitches were also measured: 54 nm and 80 nm (both approximately 1:1 duty cycle).

The geometric process windows for the 54-nm and 80-nm pitch data are shown in Figure 8. For these pitches the unbiased LWR spec had to be relaxed as compared to the 32-nm pitch case. Higher LWR is a consequence of a lower image log-slope since the illuminator was not optimized for these larger pitches. Overlapping the process windows for all three pitches is easily accomplished with the Probabilistic Process Window by simply multiplying the probabilities of each individual PPW. The resulting overlapped PPW and EL vs DOF curve measured from it are shown in Figure 9. As can be seen, the final shape of the PPW is influenced by several different specs on different data sets. It is important to note that accurate assessment of the PPW and the resulting EL vs. DOF curve requires data covering a sufficient range of both dose and focus so that the process window probability reaches near 0 (or at least below 0.5) along the extremes of dose and focus.

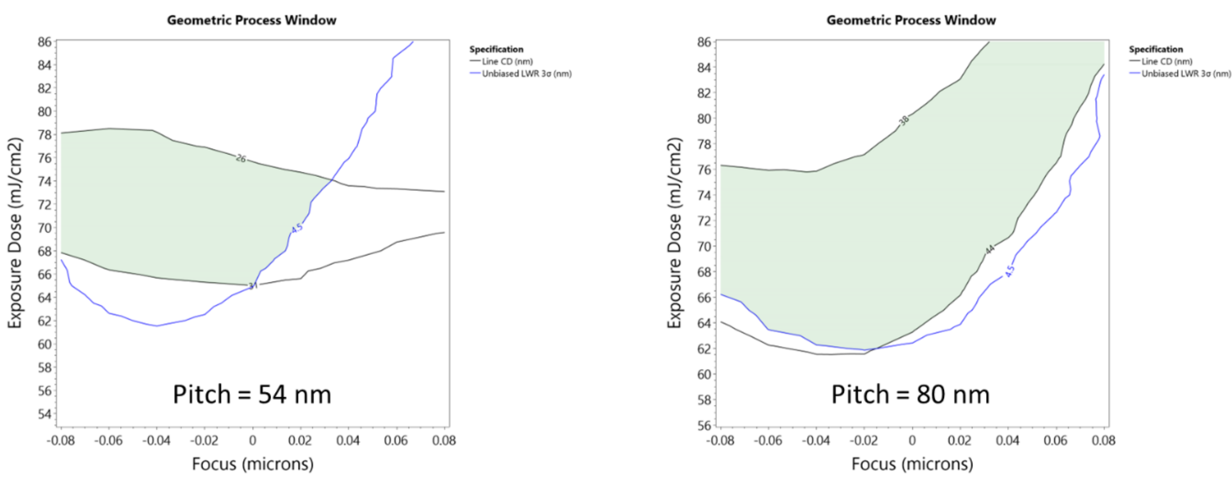


Figure 8. Geometric process windows for the cases of pitch = 54 nm and pitch = 80 nm. Compared to the 32-nm pitch data shown in Figure 2, best focus is shifting negative and a relaxed unbiased LWR has been used.

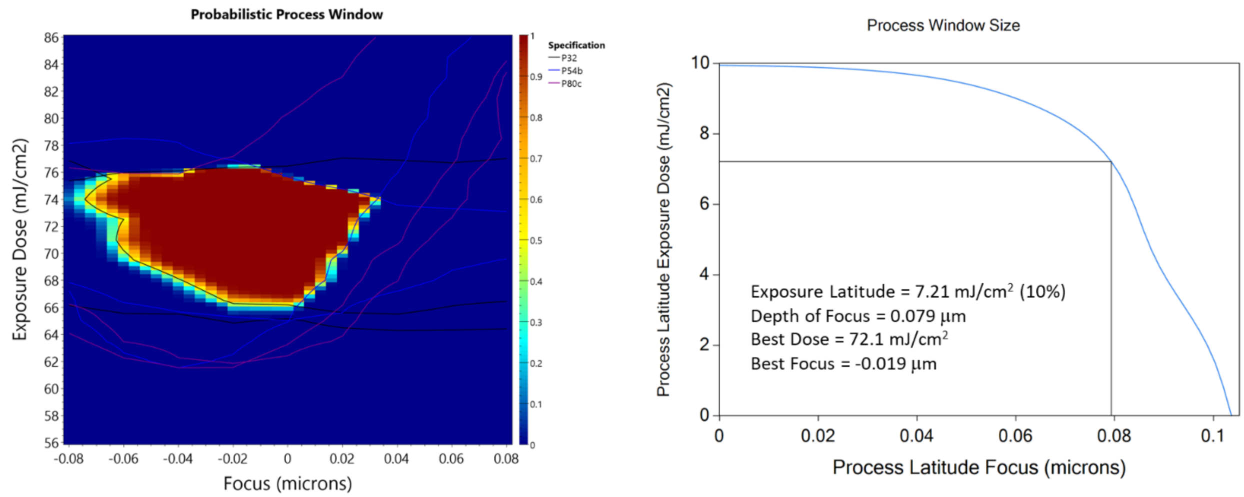


Figure 9. Overlapping PPW for the 32-nm, 54-nm, and 80-nm pitches, along with the measurement of the EL vs DOF curve. Contours of the individual specs used for each pitch data set are shown on the PPW for reference and are not used in the calculation of the PPW.

V. CONCLUSIONS

The focus-exposure process window and its analysis to measure depth of focus and best exposure/best focus is an essential part of the practice of lithography. The Geometric Process Window has been the standard approach to process window analysis for over 20 years and is still the dominant approach used today. However, there are several important limitations to the Geometric Process Window approach that are completely overcome by the new approach proposed here, the Probabilistic Process Window (PPW). The difference between the new and old approaches are summarized below.

Metrology Uncertainty. The geometric approach does not take metrology uncertainty into account and so produces sharp edges to the resulting binary process window. Further, these edges are sufficiently sensitive to metrology variations that curve-fitting functions are often used to smooth the data before using it to generate the process window contours. Not only do these curve-fitting functions modify the data, they do so in a way that differs depending on the somewhat arbitrary choice of form and order of the fitting function(s) used. If many different lithographic specs are to be used to generate the process window (unbiased LWR, line wiggling, local CDU, local pattern placement error, defectivity, etc.), how are the fitting functions to be chosen for each one? The PPW avoids all of these issues by rigorously taking metrology uncertainty into account from the beginning.

Geometric vs. Rigorous Representation of Process Errors. The geometric approach represents one slice of a 2-D multivariate Gaussian probability distribution as an ellipse, and then geometrically fits that ellipse inside the (perfectly sharp) contours of the process window. As a result, the size of the maximal ellipse that can fit inside the process window is generally determined by only three points. This results in a high (but not quantified) sensitivity to the data near those three points and a resulting high (but not quantified) uncertainty in the output results. In contrast, the PPW approach uses the full 2-D multivariate Gaussian probability distribution combined with the full PPW to calculate the fraction of in-spec features expected on the wafer for any values for best dose/focus and for any process errors in dose and focus. The result is a far more rigorous and a far more realistic assessment of the impact of dose and focus errors on the wafer features. It also completely avoids the “few points touching” problem inherent in the geometric approach.

The new Probabilistic Process Window approach offers clear advantages in accuracy for both depth of focus determination and best dose/focus determination. Consequently, its use is preferred both for process development applications (comparing process window sizes) and HVM applications (determining best dose/focus for scanner monitor and control). The concept is also applicable to general process window analysis, not just focus-exposure process windows. For example, a study of etch time and power using after-etch metrology metrics could be analyzed in the same way.

Further development work is ongoing. The rigorous nature of the PPW analysis should enable realistic assessment of the error bars on the EL vs. DOF curve and the best dose/focus associated with each point on that curve. For HVM, error bars on the best dose/focus outputs of the PPW analysis would not only aid in the use of these values for process control, but could be used to improve the data collection procedure to meet the requirements of HVM process control.

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