Methodology for Utilizing CD Distributions for Optimization of Lithographic Processes

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ABSTRACT

As the critical dimension (CD) of optical lithography processes continues to decrease, the process latitude also decreases and CD control becomes more difficult. As this trend continues, lithography engineers will find that they require improved process optimization methods which take into account the random and systematic errors that are inherent in any manufacturing process. This paper shows the methodology of such an optimization method. Lithography simulation and analysis software, combined with experimental process error distributions, are used to perform optimizations of numerical aperture and partial coherence, as well as the selection of the best OPC pattern for a given mask.

I. Overview

The authors have previously published several papers on the theory and procedure for utilizing lithography simulation software and actual process errors to accurately predict the CD distribution of a lithographic process [1-3]. In addition to predicting CD distribution, when the user specifies a range of CD's that are tolerable for their process this analysis technique also results in a prediction of CD-limited yield. The CD yield is a single metric for the quality of a process, taking into account the existing process errors. While previous work has examined the theory and procedures for this analysis, this paper focuses on additional types of analyses that can be performed with this technique.

The first optimization example studies the influence of numerical aperture (NA) and partial coherence (σ) on linewidth control. Conventional methods of optimizing NA and σ find the best settings for NA and σ for a fixed set of process conditions. The resulting values of NA and σ are thus optimum settings for the nominal processing conditions, but are not necessarily the optimums for the range of processing conditions that exist in an actual manufacturing environment. By using the CD distribution to optimize NA and σ we can find the settings which provide the best process latitude taking into account the known systematic and random errors in a process. In this example, we optimize the NA and σ for a critical layer of a 0.4µm i-line process. PROLITH/2 [4] is used to create the process space while a new analysis package, ProCD, is introduced to determine the CD distribution and CD-limited yield from the process space and the process errors. ProCD [4] is then used to optimize the numerical aperture and partial coherence to give the largest CD-limited yield.

The second optimization example studies the effects of optical proximity correction (OPC) on the CD limited yield of a process. This example shows a methodology for selecting the best mask pattern for a given process based on resist critical shape error (CSE). The resist CSE is a metric for determining the quality of a 2-dimensional resist pattern [5], the 2-D equivalent of the critical dimension error. First, we use PROLITH/3D to determine the CSE for mask patterns with several different serif sizes. For each mask layout, we calculate the CSE values for a range of process conditions by varying exposure and focus. We then use ProCD to simulate the CSE distributions and resulting CSE yield, defined as the percentage of processing conditions that result in a CSE that is within specification. By comparing the CSE yield for different mask layouts, we quantitatively determine the mask that produces a resist pattern that best matches what is desired for a range of processing conditions typical in a real manufacturing process. The result is a systematic approach for determining the mask serif size that results in the most manufacturable process.

II. Study 1: Optimization of Numerical Aperture and Partial Coherence

The purpose of this study was to show the methodology of optimizing numerical aperture and partial coherence by using the CD distribution of the process as a metric. Other work has shown success in the area of optimizing NA and partial coherence through the use of CD distribution [5].

We chose to optimize an i-line process with a CD of 0.4 microns with two different pitches -- 1.0 micron and 1.2 micron. For reasons of time, we chose to optimize the process based on process errors of two parameters -- exposure and focus. However, this same methodology could be used to investigate CD distribution effects for almost any combination of process parameters.

As described in earlier papers [1-3], the first step in this investigation is to create a process space of linewidth (or critical dimension, CD) as a function of the parameters in which you are investigating. To create this process space, we used the Nested Multiple Run (NMR) function of PROLITH/2. The Nested Multiple Run is an algorithm that automatically calculates a given output metric for up to 20 different input parameters. For this example we used the four input parameters of NA, partial coherence, exposure and focus and the output parameter of Resist Feature Width. The inputs of exposure and focus allow us to investigate effects of dose and focus errors on the CD distribution of the process.

The parameters used in our simulations are shown in Table I. For the Nested Multiple Run, the beginning, ending and increment values were selected based on the known error range of the process being simulated. For instance, knowing the standard deviation of the exposure dose of our process, we chose a range of exposure that was greater than 6-sigma to ensure that our process space was sufficiently large for the ProCD analysis. The result of the PROLITH/2 simulations was a data file of several thousand CD's as a function of NA, partial coherence, exposure and focus. This data file was then used as an input to ProCD, the program that is used to analyze effects of process errors on CD distributions.

In ProCD, the user has the opportunity to specify the type of error for each parameter in the input file as well as a specification for the CD's. In this case we used the error types listed in Table II. A "Fixed Value" means that the program assumes that there are no process errors for this parameter. A"Gaussian" error is typical of random process errors and means that the error distribution for this parameter is assumed to be normal with a specified mean and standard deviation.

Modeling Parameter	Value - Study 1	Value - Study 2
Wavelength	365 nm	365 nm
Bandwidth	0 nm	0 nm
Numerical Aperture	Varied 0.45 to 0.65, steps of 0.02	0.57
Reduction Ratio	5.0	5.0
Image Flare	0.02	0.02
Aberrations	None	None
Pupil Filter	None	None
Partial Coherence	Varied 0.3 to 0.8 steps of 0.05	0.3
Linewidth	0.40 microns	2-D mask pattern
Pitch	(a) 1.0 microns; (b) 1.2 microns	N/A
Mask Bias	0 microns	N/A
Focal Position	Varied -1.0 to 0.6, steps of 0.2	Varied -1.0 to 0.6, steps of 0.2
PEB Diffusion Length	55 nm	40 nm
Layer #1	Polysilicon, 100 nm	none
Layer #2	Oxide, 100 nm	none
Substrate	Silicon	User Defined/Matched Substrate
Resist Thickness	0.91 microns	0.93 microns
Dill A	0.61 μm^{-1}	0.61 μm^{-1}
Dill B	0.089 μm^{-1}	0.089 μm^{-1}
Dill C	0.018 cm^2/mJ	0.018 cm^2/mJ
Refractive Index	1.70	1.70
Rmax	109.4 nm/s	109.4 nm/s
Rmin	0.123 nm/s	0.123 nm/s
Mth	0.11	0.11
n	8.78	8.78
Surface Inhibition	0.20	0.20
Inhibition depth	0.08 microns	0.08 microns
Exposure	Varied 110 to 180 mJ/cm^2, steps of 5	Varied by mask
Development time	60 seconds	60 seconds
Metrology	10% raw threshold	10% raw threshold
CSE Specification	N/A	CSE (80)

Table I. PROLITH/2 simulation parameters for the processes used in this paper.

Parameter	Error Type	Value
Numerical Aperture	Fixed Value	Varied in ProCD Multiple Run
Partial Coherence	Fixed Value	Varied in ProCD Multiple Run
Focus (μm)	User-Defined	Extended Gaussian: Standard Deviation = 0.3 Fixed Error = 1 standard deviation
Exposure (mJ/cm^2)	Gaussian	Mean: 145; Std. Dev: 10

Table II. Error types of parameters used in Study 1.

A "user-defined" error means that the user can create a data file that specifies any distribution. The error file used in ProCD is an ASCII text file that specifies the parameter value and the relative probability of each value. For this experiment, a distribution was used that had Gaussian tails and a flat portion near the mean as shown in Figure 1. This type of error distribution results from a combination of both systematic and random errors.

A CD specification is also used in ProCD. For this study, a CD specification of ±7% from nominal was used. This value was chosen based on the assumption that the total CD error budget is ±10% for this process. Since only errors in focus and exposure were investigated, we chose to allocate 70% of the error budget for these parameters. This methodology leaves another 30% in the error budget for other process errors not included in the study.

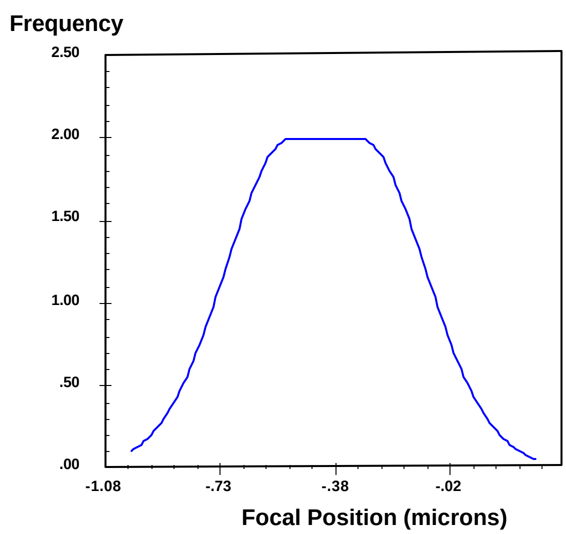


Figure 1. User-defined error distribution of focus showing a non-normal distribution which includes effects of both systematic (0.3 μm width) and random errors (std. dev = 0.3 nm).

To determine the optimum numerical aperture and partial coherence for this process, a ProCD Nested Multiple Run (NMR) was performed. For this NMR, we used input parameters of NA and partial coherence, and ProCD automatically created the output of CD Yield. The optimum NA and partial coherence are determined by the contour with the highest CD yield. Figure 2 shows the resulting output.

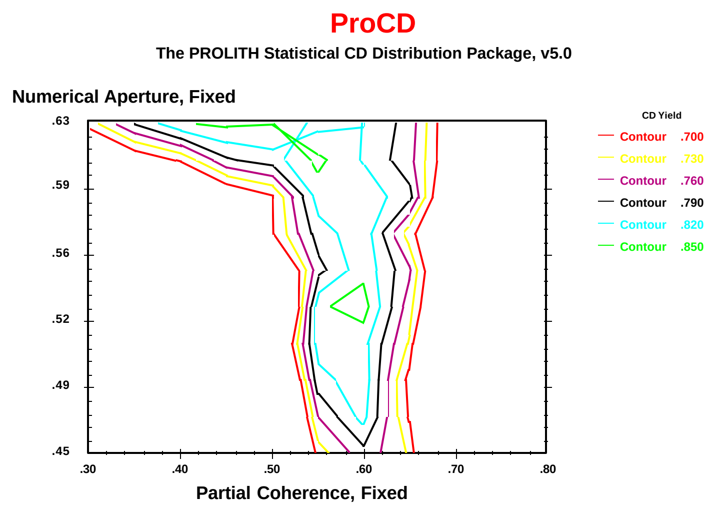


Figure 2. Nested Multiple Run output from ProCD showing CD yield as a function of numerical aperture and partial coherence for a 1.2 micron pitch. The optimum yield was at NA = 0.52 and partial coherence at 0.60.

The resulting optimum NA and partial coherence values were then used as inputs into ProCD and a new CD distribution was created which showed increased CD yield. Figure 3 compares the CD distribution and CD yield for a nominal case and for the case where NA and partial coherence were optimized using the CD distribution method for the case of 1.0 micron pitch. For this case, the CD yield rose from 76.5% to 84.1% after the optimization of NA and partial coherence.

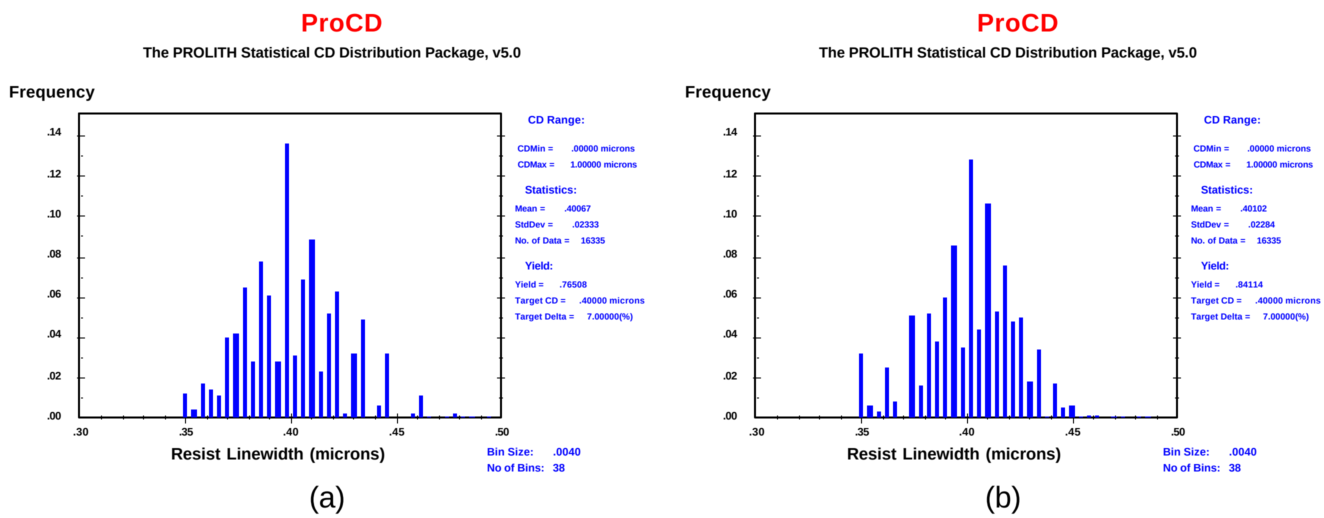
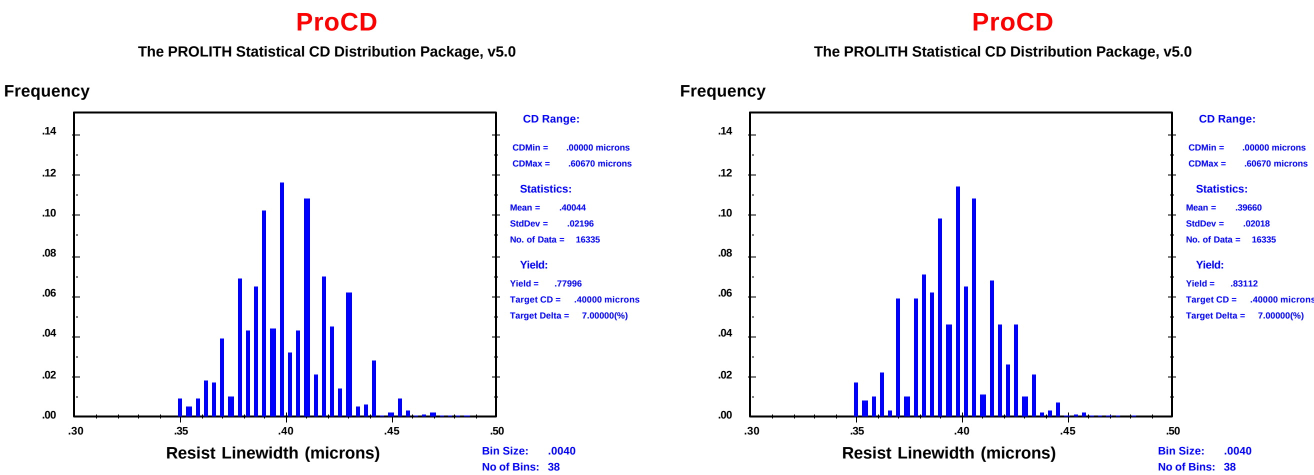


Figure 3. CD distribution and CD yield for 1.0 micron pitch (a) at nominal NA of 0.60 and partial coherence of 0.6 with 76.5% CD yield and (b) with optimized NA of 0.58 and partial coherence of 0.55 with 84.1% CD yield.

Figure 4 compares the CD distribution and CD yield for a nominal case and for the case where NA and partial coherence were optimized using the CD distribution method for the case of 1.2 micron pitch. For this case, the CD yield rose from 78.0% to 83.1% after the optimization of NA and partial coherence.



(a) (b)

Figure 4. CD distribution and CD yield for 1.2 micron pitch (a) at nominal NA of 0.60 and partial coherence of 0.6 with 78.0% CD yield and (b) with optimized NA of 0.52 and partial coherence of 0.6 with 83.1% CD yield.

There are two main issues relating to the methodology used to determine optimum process settings. The first is the number of different process errors taken into account when optimizing the process, and the second is what metric is used to perform the optimization. Traditional methods of optimizing NA and partial coherence use two process errors, focus and exposure, to optimize either exposure latitude or depth of focus (DOF). These methodologies typically require a process specification for one of these metrics in order to optimize the other. Traditional optimization routines then find the NA and partial coherence that provides the "best" value. This methodology is limiting to the extent that two parameter optimizations do not take into account other process errors.

The second issue relating to the optimization methodology is the metric used to optimize the process. For a given process, if the process capability is larger than the requirements for the metric used in the optimization, there is a loss of process potential by not finding optimum process settings to allow a larger error budget for other process errors. Traditional methodologies use a metric of depth of focus to optimize the process which is not typically the ultimate determination of a "good" process. A good process will have a tight CD distribution with a large yield of CD's within specification. Traditional methods for optimizing NA and partial coherence will optimize for a metric that is not the final goal. The CD distribution method uses the metric that is of paramount importance to the engineer, and is therefore more likely to produce process settings that result in a good process.

III. Study 2: Optimization of Serif Size for a Lithographic Mask

The purpose of this second study was to show the methodology of optimizing the size of serifs for a mask by using lithography simulation software and critical shape error (CSE) yield as the metric. The size of serifs has a large impact on the shape of the resulting 3-dimensional resist image and can be accurately predicted by using 3-D lithography simulation software [6]. The quality of this resist image can be quantitatively determined using the Critical Shape Error (CSE), which compares the resulting resist image with a desired pattern [6].

PROLITH/3D version 5.1d was used to create the simulations of the process space for three different mask patterns, each with a different size serif. Figure 6 shows an example of a mask pattern used with no serifs.

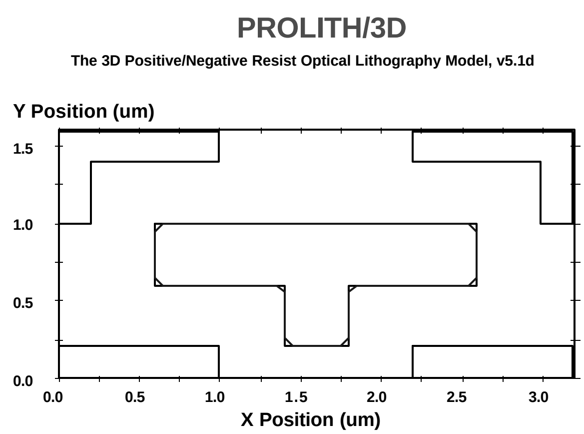


Figure 6. Mask pattern with no serifs used for Study 2 including desired pattern with cut corners.

A process space was generated in PROLITH/3D using a Nested Multiple Run (NMR) with input parameters of focus and exposure and the output of Critical Shape Error (CSE 80). Table I shows the modeling parameters used for these simulations and Table III shows the input error distributions. Notice that the exposure dose range was different for each mask because the nominal exposure changed for each. Figure 7 shows a typical 3-D resist pattern for these simulations as generated by PROLITH/3D.

Figure 8 shows the CSE contours through focus and exposure for a mask with no serifs and a mask with 150 nm serifs. The best focus for each was -0.46 µm and best exposure was 210 mJ/cm^2 for the mask with no serifs and 214 for the mask with 150 nm of serifs.

The NMR file was then used as the input file to ProCD. In ProCD, the user can specify the error distributions of each input as well as a process specification of the amount of tolerance of the output. For these simulations a CSE tolerance of 40 nm was chosen because the outputs with less than this amount of error printed resist patterns with acceptable dimensions and shapes.

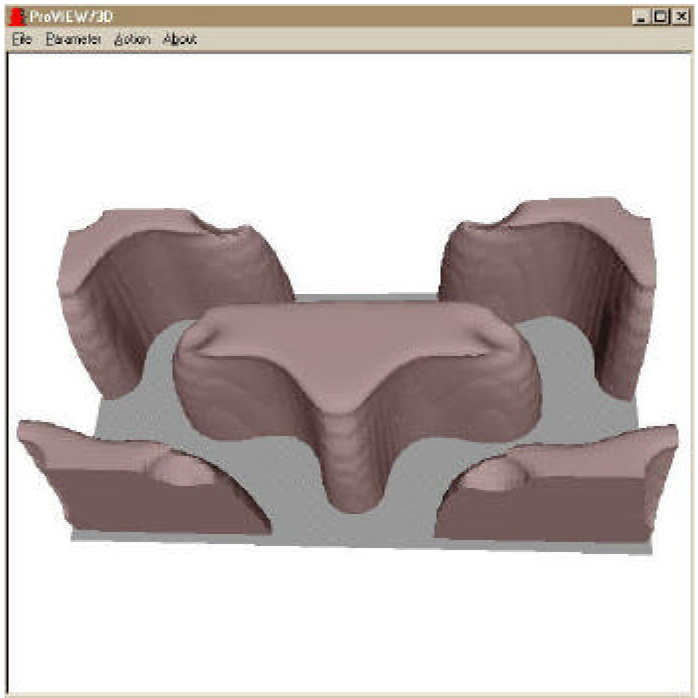


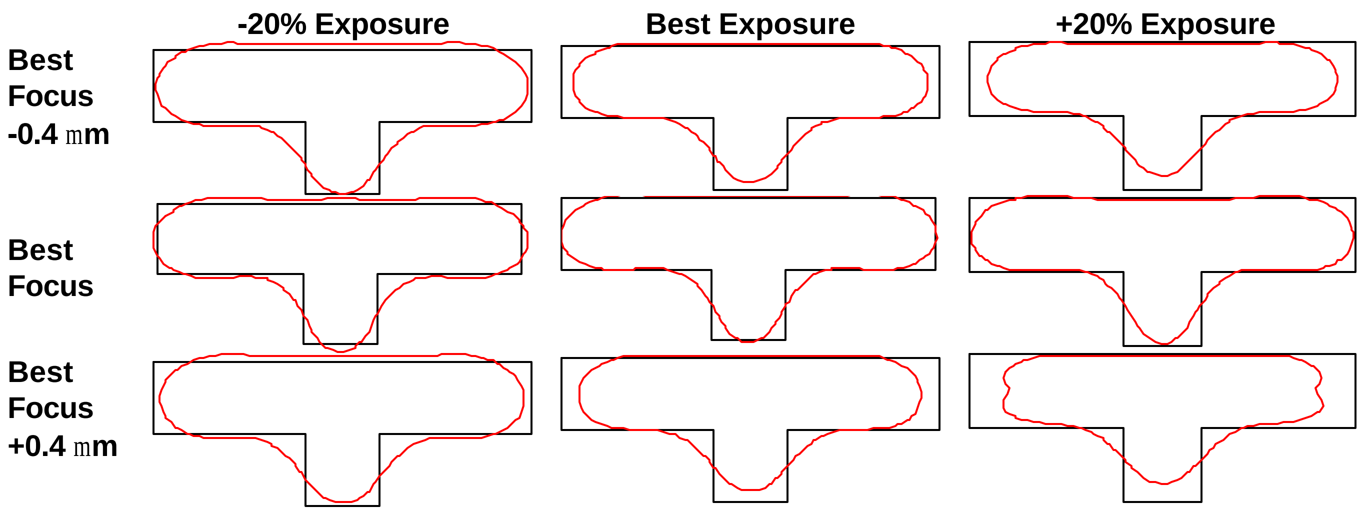
Figure 7. Example 3-dimensional resist simulation produced by PROLITH/3D.

Parameter	Error Type	Value
Focus (μm)	Gaussian	Mean -0.4; Std. Dev. 0.2
Exposure (mJ/cm^2)	Gaussian	Mask 1: Mean: 210; Std. Dev. 10 Mask 2: Mean: 214; Std. Dev. 10 Mask 3: Mean: 214; Std. Dev. 10

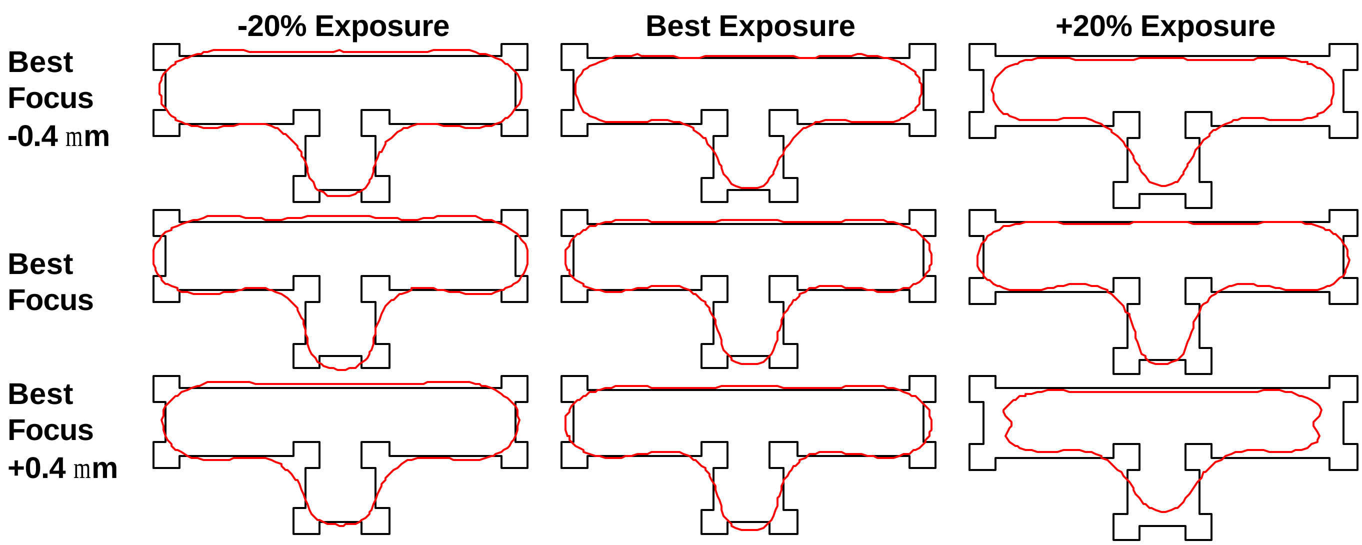
Table III. Error types of parameters used in Study 2.

The Nested Multiple Run in ProCD was then used to determine which mask created the best CD yield through focus and exposure. Figure 9 shows the graphs of CD yield as a function of focus and exposure for the three masks.

The CD yield for the mask with no serifs is 47%, with 100 nm serifs is 71% and with 150 nm serifs is 95%. Notice that the CD distributions are tighter for the larger serif sizes and that the mask with 150 nm serif size has the best CD yield through focus and exposure. Also, the best focus and exposure settings are not the nominal settings. Further investigations were run on other mask patterns with varying serif sizes ranging from 100 to 180 nm. The result of this study was that the optimum process latitude was obtained at 150 nm serif size.

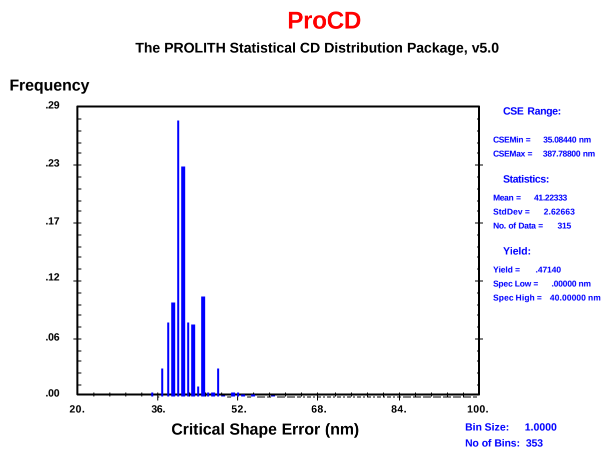


(a)

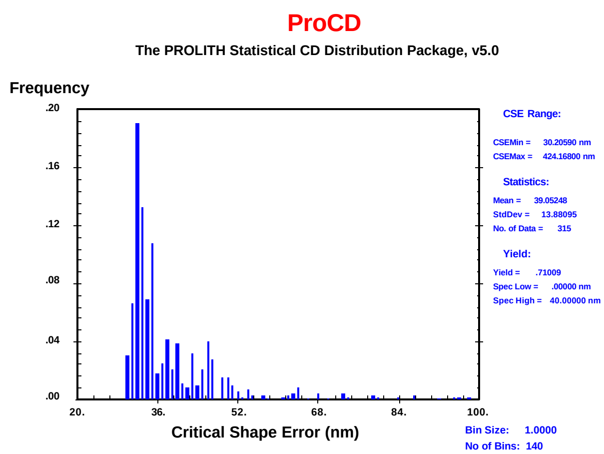


(b)

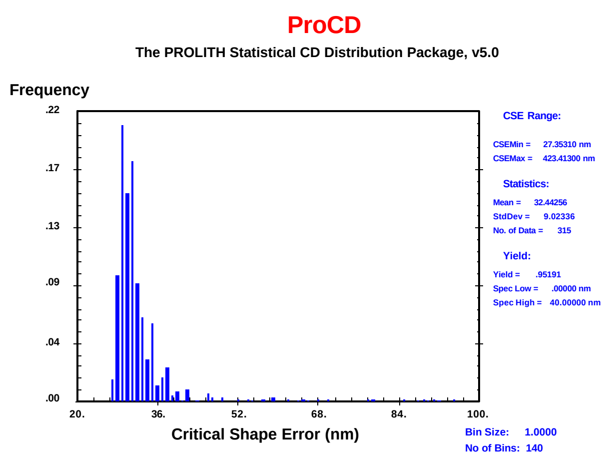
Figure 8. Resist shape contours through focus and exposure for mask with (a) no serifs and (b) 150 nm serifs.



(a)



(b)



(c)

Figure 9. CD distributions for masks with a) no serifs (47% yield), b) 100 nm serifs (71% yield) and c) 150 nm serifs (95% yield).

As discussed earlier, the CSE uses a contour method to determine the quality of a resist image. This criteria is very sensitive to changes in the top-down shape of the resist contour, but does not take into account other aspects of the resist image such as sidewall angle, minimum cross-sectional CD, and resist loss. The risk in using CSE alone as the metric of the quality of a process is that the resulting resist image may not meet the other specifications for the process. One solution would be to combine several process criteria into an optimum set so that the process can be optimized based on meeting many different specifications.

IV. Conclusions

The results of these investigations show that the methodology for using lithography simulation software with CD distribution analysis results in a quantitative method for determining the optimum process settings taking into account process errors inherent in a manufacturing environment. These optimum settings can be substantially different than the optimums determined by using other methodologies.

There are many opportunities for future work. This same methodology can be used to investigate more complex scenarios and take into account additional process errors. Future work can take into account important error sources such as resist thickness variation, film stack thickness variation, variation in index of refraction of a layer, mask CD variation, lens aberration variations or several others. While a useful metric in and of itself, the CSE can also be combined with other metrics of quality such as resist sidewall angle and resist loss. Such a combined metric could create a more complete methodology for determine the quality of a 3-dimensional resist pattern.

References

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