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Response surface modeling of rim phase shift masks

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ABSTRACT

The use of statistically designed experiments provide an efficient method of investigating a lithographic process. Lithographic simulators have also been used as a tool in the investigation of these processes. This paper provides a general methodology for conducting designed experiments in which a computer simulator is the tool used as the data collection device.

The rim shifter is a phase shifting technique that was investigated. Response surfaces measuring depth of focus were generated from simulated data. The resolution and depth of focus capabilities of this phase shift technique were also measured by both experimental and simulated data.

1. SCREENING EXPERIMENTS USING FACTORIAL DESIGNS

The first stage of the methodology is to conduct a screening experiment by making use of full or fractional factorial designs. These designs were used to determine which factors significantly affect the response and to identify any two factor interactions. The method of data analysis will be the use of analysis of variance (ANOVA).

1.1 Designing the experiment

The rim shifted space[1-7] is one possible phase shift technique. This feature is obtained by adding a phase shifted rim to the edges of a standard space. The width of the rim has been shown to be most effective in the range of 0.1 to 0.3 microns. The rim provides an intensity null at the edge of the central opening, which significantly improves the aerial image contrast. The question of which stepper parameters and rim shift parameters provide optimum performance is of interest. The experiment described here evaluated stepper and reticle factors effecting the depth of focus for each combination. The stepper parameters chosen were numerical aperture (NA) and partial coherence. The reticle parameters chosen were transmission through the shifter, phase shift, and width of the rim shifter. The response used was the focus range or depth of focus that is attained by a +/- 10% variation in the maximum aerial image log slope. A fixed central opening of 0.65 microns was used. If the central opening is not a fixed size, the smaller contacts would appear to have a larger depth of focus due to smaller changes in aerial image slope with focus plane changes (i.e., the aerial image is already degraded at the optimal focal plane setting).

To obtain information about main effects and two factor interactions from, a full factorial design was chosen. This type of design will also provide the most information about the variance of the system compared to fractional-factorial designs. The variance is needed to provide an accurate measure of how strong the main factors and interactions are on the response. With the factors N.A., sigma, transmission, phase angle, and rim width, a design with $2^5=32$ runs or treatment combinations was produced. The lithographic simulator PROLITH/2 was used to conduct the experiment.

1.2 Analysis of the full factorial design

The results from the experiment were placed into RS/1 (a statistical software program) to conduct the analysis of variance (ANOVA). The ANOVA results allow a calculation of an F-ratio which is a measure of the significance of each factor and interaction on the response. A factor or interaction can then be deemed significant or not depending on the significance level chosen. It is generally accepted that a significance level of about 0.05 or less should show that a factor or interaction is significant. What a 0.05 significance level indicates is that a factor or interaction is significant 95% of the time. The significance level of each factor and interaction were found from the F-ratio. Based on this, it was found that the factors transmission and phase were not significantly effecting the depth of focus of the system and could therefore be removed from the model. The partial coherence was also found to be insignificant but was left in the model because it is involved in a two-factor interaction. The remaining factors after the screening experiment are NA, sigma and rim shifter width. Table 1. shows the factors and interactions and the corresponding significance level.

Term in Model	Significance Level	Term in model	Significance Level
NA	0.000	NA*Rim Width	0.000
Sigma	0.785	Sigma*Transmission	0.785
Transmission	0.785	Sigma*Phase Angle	0.785
Phase Angle	0.185	Sigma*Rim Width	0.00
Rim Width	0.000	Trans.*Phase Angle	0.785
NA*Sigma	0.070	Trans.*RimWidth	0.418
NA*Transmission	0.185	Phase Angle*Rim Width	0.418
NA*Phase Angle	0.185		

Table 1: Factors and interactions and their corresponding significance levels for the screening experiment. Significant terms are in bold.

2. RESPONSE SURFACE MODELING DESIGN

Response surface modeling is a method for visualizing the operating surfaces of a process. By obtaining these response surfaces, knowledge of the process is obtained not only at a fixed process point but throughout a whole range of factor settings. The experimental design chosen to best obtain response surfaces was the central composite design or CCD. This design is an extension of the full factorial design to several factor settings which now provides the ability to measure any non-linear behavior in the process. Table 2 shows the factors and the factor levels used to conduct the CCD experiment.

Factors	Factor Levels
N.A.	0.40 to 0.54
Partial Coherence	0.30 to 0.52
Rim Shifter Width	0.10 to 0.20

Table 2. Factors and factor levels for the CCD design.

2.1 Analysis of the response surface modeling design

The analysis of the design is similar to that of the full factorial design in that the F-ratio is used to determine if a factor is significant or not. The method of least squares is used to efficiently conduct the ANOVA and determine the coefficients on the resulting empirical model. The difference here is that all of the interaction and squared terms must be

tested to check their significance. The method to do this is called reverse elimination which removes the insignificant terms from the model one by one and then recalculates the ANOVA for the remaining terms. The advantage of this method is that as more insignificant terms are removed, the precision of the error term or variance of the system becomes greater. The remaining empirical model is in the form of a polynomial containing the main factors, interactions, and squared terms that are significantly affecting the response. Table 3. shows the coefficients on the resulting polynomial along with the significance level of each of the terms in the model. The influence of each of the terms can be measured by its significance level. The lower the significance level, the more influence that term has on the response.

Term in Model	Coefficient on Polynomial	Significance Level
Constant	1.42	
NA	-0.625	0.000
Sigma	+0.01	0.473
Rim Width	+0.09	0.000
NA ²	+0.175	0.000
NA*Rim Width	-0.081	0.000
Sigma*Rim Width	-0.044	0.013
Rim Width ²	+0.05	0.058

Table 3. Terms remaining in response surface model with their respective coefficients and significance levels.

The polynomial built from the coefficients in the above table is what is then used to construct response surfaces. Figures 1-3 show the possible response surfaces that can be obtained from this polynomial.

Figure 1 is a contour plot with the surface of the plot being the depth of focus values. The plot shows that NA is the more dominant influence on DOF but increasing sigma does show a slight increase in DOF. This confirms that NA is the driving force on the DOF of a system. The effect that sigma has on the depth of focus should be questioned here because of the high significance level of this factor. Figure 2. shows how DOF is significantly increased as the rim shifter width is increased. This is due to the rim shifter's improvements of the aerial image through the central opening. As the rim shifter size is increased, its effect on the aerial image through the central opening is much stronger. Figure 3 also confirms the advantage of a larger rim shifter by showing the DOF increase as the width is increased. Sigma is a significant contributor below a rim shifter width of 0.15 microns. In this range, the increasing sigma does again show a slight increase in the depth of focus. With a rim shifter of 0.20um, the sigma increases actually cause a slight decrease in the DOF.

From these response surfaces, the DOF of the system in use can be predicted but the actual system should be chosen from a desired resolution standpoint. The next section looks into the resolution possible when using rim shifted spaces.

Figure 1: Sigma vs. NA for a fixed Rim Shifter of 0.15 microns

Figure 2: Rim Width vs. NA for a fixed sigma of 0.41

Figure 3: Rim Width vs. Sigma for a fixed NA of 0.47

3. Experimental Results

The advantage of using phase shifting is not only an improved depth of focus but also increased resolution. The above experimental procedure could be used again to obtain response surfaces for the resolution obtained when varying the NA, sigma and rim shifter width. Due to limited stepper setups, the resolution capabilities for two different steppers was looked at instead. The rim shifter width in these cases was allowed to vary. Three different central opening sizes were also looked at.

The first stepper evaluation is one with a 0.40 N.A. and a partial coherence of 0.54. Figure 4. shows the space width vs. RIM shifter width with a focus setting of 0.0um(top surface of photoresist coating). For optimum resolution, a shifter width of 0.20 microns is optimum for a central opening size of 0.60 to 0.70 microns. The central opening size should be at least 0.65 microns due to depth of focus issues. The 0.60um size on this stepper configuration has demonstrated a lower depth of focus compared to the larger sized openings. This type of technique could be used to extend the lifetime of a stepper into future generation devices. By adding a 0.20um rim shifter, sub-half micron features can be obtained with current production equipment.

Figure 4. Photoresist space size vs rim shifter dimension using an ASM 2500/40 (NA=0.40 with a partial coherence value of 0.54).

The second stepper used had a 0.48 N.A. with a partial coherence of 0.64. Figure 5. shows the results of this experiment. Due to the increased resolution of this stepper, the rim shifters started to print for widths of greater than 0.30um. The optimum shifter width was again 0.20um. This is the shifter width at which a minimum space width is obtained.

figure 5. Photoresist space size vs rim shifter dimension using an ASM 5000/50 (NA=0.48 with a partial coherence value of 0.64).

3.1 Simulation versus experimental results- resolution capabilities

The ability to match a simulator to experimental data was next investigated. Outlined below in figures 6-8 are Silvaco's SOLID 3.1 optical lithography simulator (Simulation of Optical Lithography in three Dimensions) and experimental data for 0.65 micron central opening spaces with varying RIM phase shifters. The simulator was calibrated for the particular photoresist process used here.

figure 6. SOLID 3.1 simulated and experimental data photoresist space size vs rim shifter dimension using a lens with NA=0.40 and a partial coherence value of 0.54.

These results for three different lens and illumination combinations show excellent agreement between simulation and experimental results. One result not shown by these plots was that making the illumination more coherent reduces the effectiveness of larger rim shifters and they begin to print.

figure 7. SOLID 3.1 simulated and experimental data for photoresist space size vs rim shifter dimension using a lens with NA=0.48 with a partial coherence value of 0.40.

figure 8. SOLID 3.1 simulated and experimental data for photoresist space size vs rim shifter dimension using a lens with NA=0.48 with a partial coherence value of 0.64.

3.2 Simulation versus experimental results- depth of focus capabilities

The effect of partial coherence and numerical aperture on the depth of focus was evaluated using experimental and simulated data. The experimental data was generated using an ASM model 5000/50 waferstepper equipped with a NA = 0.48 lens and variable partial coherence. Simulations were performed using Silvaco's SOLID 3.1 optical simulator. The RIM shifted feature with a central opening of 0.65 microns with a 0.2 micron RIM shifter width was used for all evaluations here. These dimensions were chosen because they produce a minimum space width without bridging or printing the RIM shifter, which was determined from a previous evaluation.

Figures 9-10 show the experimental and simulated data for a varying partial coherence. The main result here was the increase in depth of focus as the partial coherence decreased. This general trend was in agreement when comparing the experimental to simulated data.

Figure 9. The effect of partial coherence on RIM shifted space depth of focus. Experimental data generated using an ASM 5000/50 (NA=0.48) and OCG 897i photoresist.

Figure 10. SOLID 3.1 simulation of the effect of partial coherence on RIM shifted space depth of focus.

Figures 10 and 11 show the effect of varying NA on the depth of focus. Decreasing the NA caused the RIM shifted space dimension to decrease and the DOF to increase. The aerial image contrast improvement resulting from the increased numerical aperture causes the phase shift interference null spread to be resolved better. This image contrast improvement contributes to the increase in space width and DOF. This means that RIM shifted space or contact dimension will need to be tuned to a given numerical aperture.

Figure 11. The effect of numerical aperture on RIM shifted space depth of focus. Experimental data generated using an ASM model 5000/50 (NA=0.48) and 2500/40 (NA = 0.40) wafersteppers with OCG 897i photoresist.

Figure 12. SOLID 3.1 simulation of the effect of numerical aperture on RIM shifted space depth of focus.

Conclusion:

Response surfaces that visualize the depth of focus for the factors NA, partial coherence, and rim shifter width have been obtained. The effect of the three factors on the depth of focus of the system can easily be seen.

The resolution capabilities of rim phase shifted spaces have been demonstrated on two different steppers. The minimum resolution with a 0.65 micron central opening was obtained with a rim shifter width of 0.20 microns. Sub half-micron features can be constructed with this sized phase shifter.

Experimental data was compared to simulated data for a fixed central opening size. Different lens and illumination combinations were used and all showed excellent agreement between experimental and simulation.

Depth of focus studies were done to determine the effect of partial coherence and NA. Decreasing the partial coherence caused the rim shifted space DOF to increase slightly. This was confirmed by experimental and simulated data. This is due to the increased phase shifting effect as one makes the illumination more coherent. The contrast and hence DOF increase from this phase shift interference effect. Decreasing the NA caused the RIM shifted space dimension to decrease, which is a result of the interference null width decreasing with NA. The width of this null is given by: $LW = 0.25\lambda/NA$. Increasing the NA reduces the "choking" effect of this opaque null increasing the clear space width.

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