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Electron Beam Lithography Simulation for Mask Making, Part III: Effect of Spot Size, Address Grid and Raster Writing Strategies on Lithography Performance with PBS and ZEP-7000

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Abstract

This paper examines, from a modeling perspective, the effects of spot size, data address and raster writing strategy on lithographic performance. Both PBS, the current U.S. standard for mask making, and ZEP 7000, a new, much higher contrast material, will be examined for their impact on lithographic quality. Simulation is used to demonstrate the differences between resists, writing strategies and their implementation.

Keywords: ProBEAM/3D, modeling, e-beam lithography, spot size, ZEP 7000, PBS

1.0 Introduction

There exists a large body of literature on optical lithography theory and operation. It is relatively easy to review and adapt literature values for resist dissolution rates, the effects of a stepper lens NA or sigma on expected lithographic performance, or other important parameters or processes. This growing body of knowledge has had an enormous influence on the optimization of optical lithography. While the e-beam theory of exposure has been extensive[1,2,3], joining of the theory of exposure with resist development has not progressed to the same state as for optical lithography. As a result, the effect of writing strategies used in e-beam lithography on lithographic performance is not as well understood.

Lithography modeling can provide a number of benefits. Trial and error is a trademark of lithographic optimization, with large numbers of experiments common to find the best mode of operation. A modeling program can be used to determine the tradeoffs between throughput, lithographic quality and the resulting acceptable performance. If a modeling program can be utilized to define the area of interest, a reduction in the number of experiments needed to complete a study can be achieved.

Previous papers have investigated ProBEAM/3D as a tool for modeling e-beam lithography performance for selected resist systems[4,5]. The properties of EBR 900 and PBS have been examined with ProBEAM/3D for their basic lithography properties[6]. In this study ZEP 7000, a promising e-beam material for advanced mask making[7], is investigated. PBS is included for comparison purposes. Both resists are positive in tone. This paper expands the scope of previous investigations and examines lithography characteristics under different writing conditions.

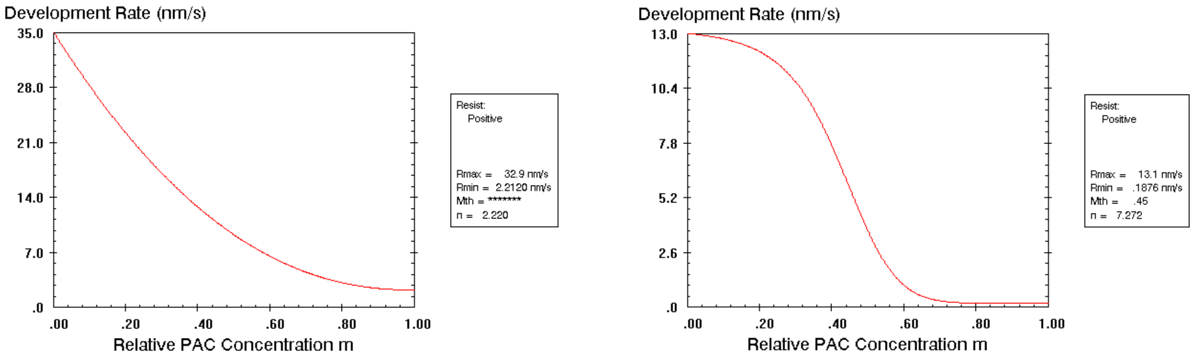
2.0 Initial Results

The ProBEAM3/D electron beam simulator (version 5.1k) was used for all work in this study. The Monte Carlo module was run with the following conditions; 10KeV electrons, 400 nm resist thickness, 100 nm chrome on quartz, and a resist density of 1.22 g/cm^3. The pixel generator module was run with spot sizes ranging from 100 to 300 nm (Full Width Half Maximum, FWHM). The development rate parameters were determined using open area exposures at 10 kV, the “poor man’s” develop rate method, and ProDRM. A series of exposures and development times suitable for PBS and ZEP resist were run using the simulator. The purpose of this study was to evaluate the lithographic response of the two resists and compare differences in their responses.

2.1 Dissolution Rate Parameters

Dissolution rate parameters were obtained by using the standard mechanical method of measuring film thickness and the "poor man's development rate monitor"[8]. Both PBS and ZEP 7000 resist at 400 nm thickness were obtained from a commercial mask supplier coated on 6 x 0.25" chrome and quartz masks. A series of open field or bulk exposures were made using a MEBES exposure tool, ranging from 3 to 12 $\mu C/cm^2$ for the ZEP 7000. A total of five plates were replicated with the same series of exposures. The five plates were then developed with a series of one of five develop times, ranging from 30 to 110 seconds. Each exposure was examined for remaining film thickness using a Dektak Model 2a. Film thickness was normalized by comparing to the original (before exposure) thickness. The data was smoothed by using a polynomial fit to the data. ProDRM, a program from FINLE Technologies, was used to extract the parameters from the smoothed data. The Mack model parameters[9,10] were used in subsequent modeling work.

Comparison of the dissolution characteristics for the two resists is instructive and can be seen in Figure 1. The PBS response (Figure 1a) is fairly linear over the exposure range (shown as the fraction of resist not yet converted into the soluble form). This is typical of low-contrast resists. On the other hand, ZEP 7000 (Figure 1b) exhibits a much higher contrast. The s-shaped curve noted in Figure 1b is closer to the ideal for an infinite contrast resist, i.e., a binary on or off response. The dissolution selectivity (n) is roughly proportional to the contrast and dictates the steepness of the s-shaped curve. The discrimination ratio, the ratio of maximum to minimum development rate, is another gauge of the resist's effectiveness. A larger discrimination ratio is an indirect measure of a higher contrast. The ratio for PBS is 15, versus 70 for ZEP 7000. Note that although both the discrimination ratio and the dissolution selectivity value for ZEP 7000 may be quite high by e-beam resist standards, they are quite low compared to optical resists.



(a) (b)

Figure 1. Dissolution rate functions as determined for (a) PBS, and (b) ZEP 7000 resists. Note that the two graphs use different scales for the vertical axes.

The dissolution rate parameters resulting from the best fit of the Mack model to the poor man's dissolution rate data are given in Table I for both resists.

Table I. Measured Dissolution Rate Parameters for PBS and ZEP 7000

Parameter	symbol	PBS	ZEP 7000
Maximum develop rate (nm/s)	(R_{max})	32.9	13.1
Minimum develop rate (nm/s)	(R_{min})	2.21	0.188
Threshold Concentration	(m_{th})	-1000	0.45
Dissolution Selectivity	(n)	2.22	7.27
Exposure rate constant (cm^3/J)	(C)	0.05	0.0096

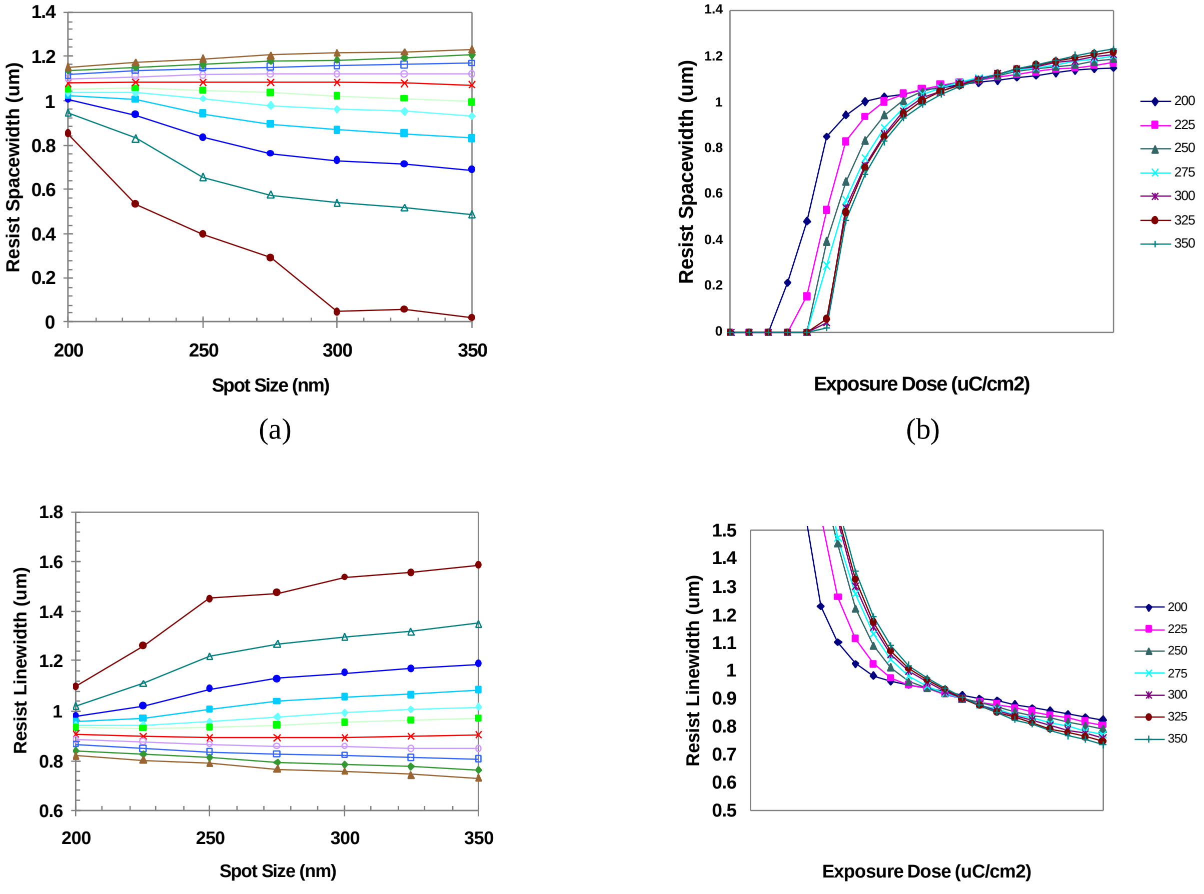
2.2 "Generic" Resist Response to E-Beam Spot Size

Before investigating the lithographic responses of specific resists, the generic response of a resist to variations in electron beam exposure spot size was investigated. By analogy to the world of optical lithography, printing a given feature size with increasing spot size is equivalent, over a certain range, to the optical printing of a given feature at greater amounts of defocus. Since this response is a strong function of exposure dose, the influence of spot size was sought over a range of exposure doses. The simulation results are shown in Figure 2. A generic resist of low contrast (similar to PBS) was used to print 1µm isolated lines and isolated spaces on a typical mask blank substrate. In all cases, the address grid was set equal to the spot size. An interesting phenomenon is observed. There is a certain dose at which variations in e-beam spot size have virtually no impact on the resulting feature width. This is seen as the flat curve in Figure 2a and 2c and as the crossover point in the curves of Figure 2b and 2d. In optical lithography this phenomenon is well known and is called the "isofocal" point. The exposure which produces this flattest curve is called the "isofocal dose" and the resulting feature width is called the "isofocal CD". Borrowing this same terminology and applying it to Figure 2, it is apparent the an "isofocal" effect is occurring here. In both feature types, it is significant to note that the isofocal CD occurs at linewidths that are ~100nm overexposed with respect to the target linewidth (100nm larger CD for the space and 100nm smaller CD for the line). Thus, we say that this process exhibits a 100nm isofocal bias. It should be notes that the smallest spot size produces the greatest exposure latitude.

2.3 Comparison of PBS and ZEP Response to Dose and Develop Time

A comparison of the two resist materials was carried out using ProBEAM/3D simulations. Monte Carlo simulations used 100,000 trajectories, 10KeV energy, 400 nm of resist and a chrome on glass substrate. Pixel generation runs used spot sizes of 100, and 300 nm (FWHM). Dissolution rate parameters were used as defined in Table I. For the first set of simulations, develop time was varied with a series of specific doses. One-micron clear and dark features were simulated using the Single Pass Printing (SPP) writing strategy. Doses for PBS were varied from 1.6 to 3.0 $\mu C/cm^2$. For ZEP 7000, the dose range was 7 to 9 $\mu C/cm^2$. For PBS the develop time were varied from 40 to 80 seconds. For ZEP 7000, the develop time range was varied from 200 to 400 seconds.

As Figures 3 and 4 indicate, the resist responses for the two materials are very different. ZEP 7000 exhibits much better development time latitude and better exposure latitude compared to PBS. The differences in the process latitude between the two materials can be attributed to the difference in resist contrast as expressed by the dissolution rate parameters.

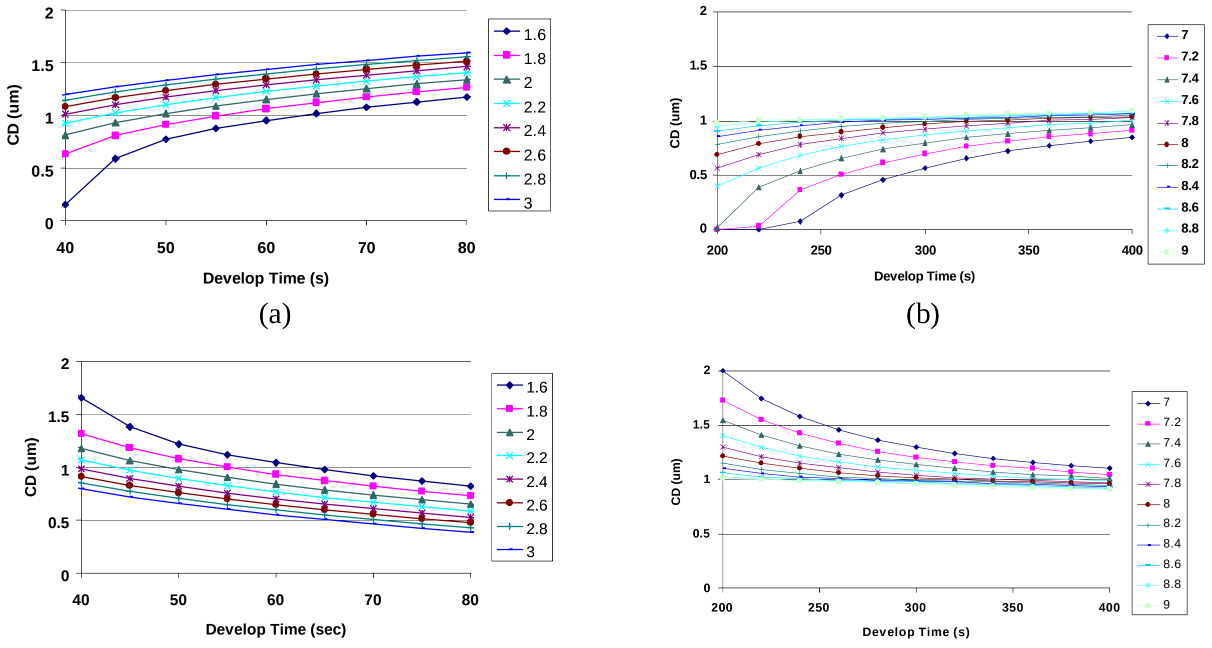


(a) (b)

(c) (d)

Figure 2. Simulated "Isofocal" behavior in e-beam lithography showing the effect of spot size and exposure dose on the resulting resist feature width: (a) spacewidth versus spot size for different exposure doses, (b) same data in (a) plotted as spacewidth versus dose for different spot sizes, (c) same as (a) but for a line feature, and (d) same data in (c) plotted as linewidth versus dose for different spot sizes.

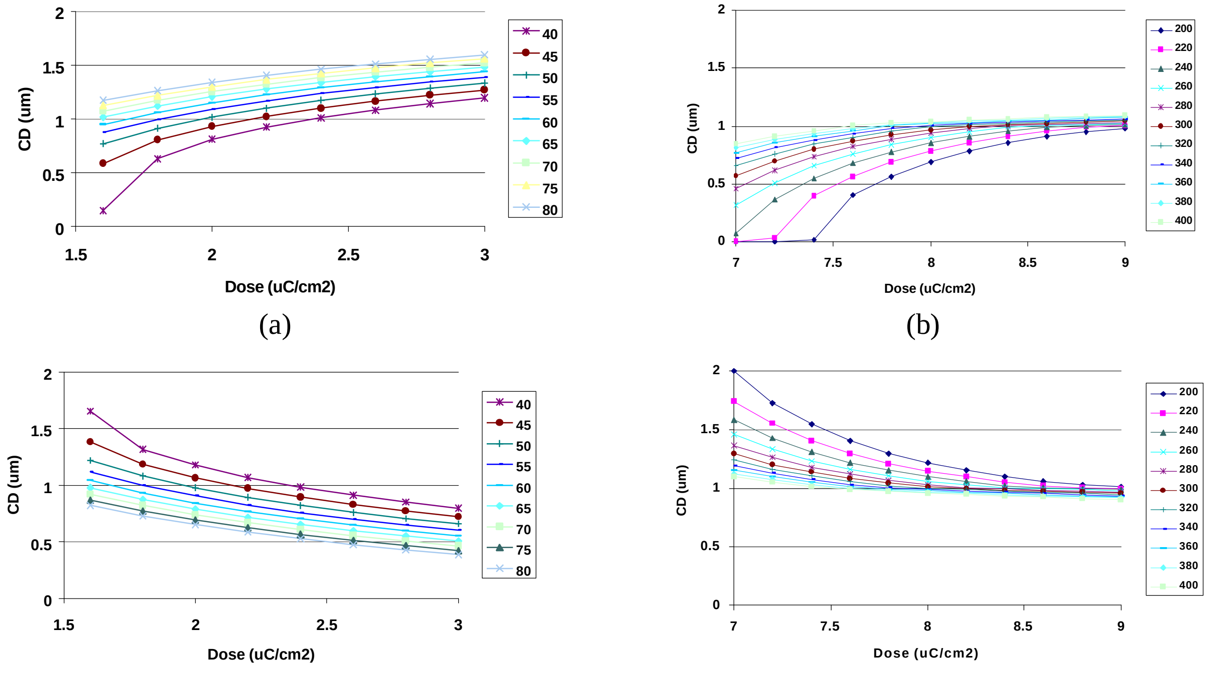
The simulations shown in Figures 3 and 4 were repeated with a 300nm spot size and shown in Figures 5 and 6. The impact of increasing spot size can be seen as a reduction in both development time latitude and exposure latitude.



(a) (b)

(c) (d)

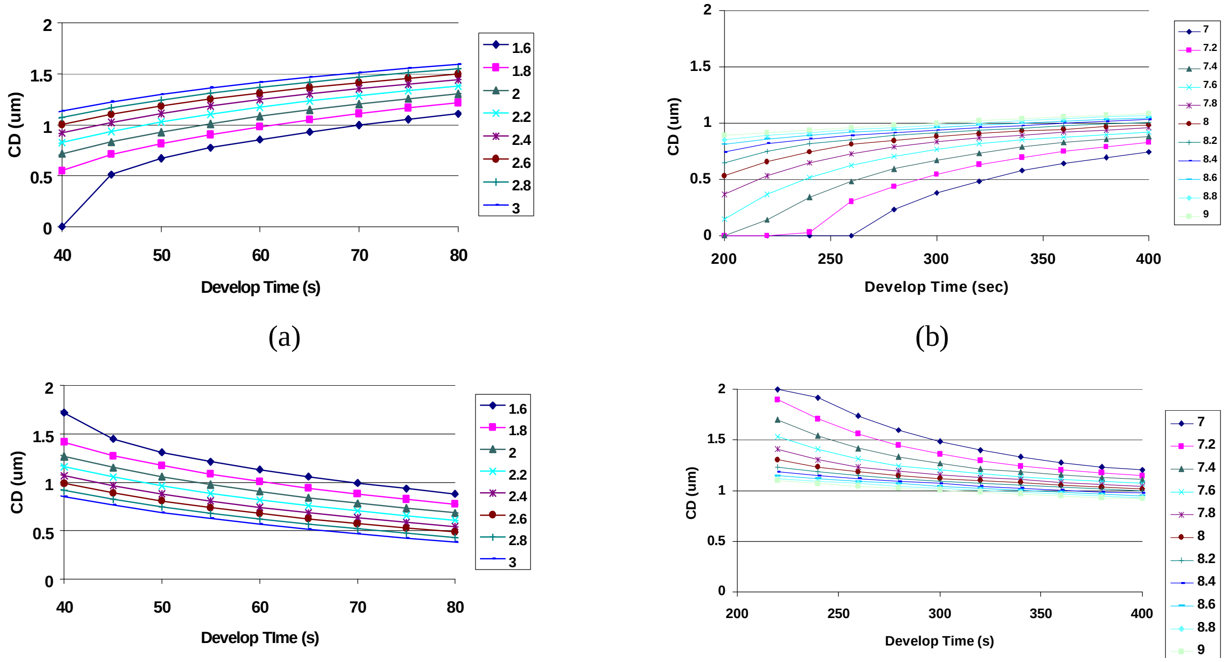
Figure 3. Variation of critical dimension (CD) as a function of development time for different exposure doses for (a) PBS, 1μm clear feature (space), (b) ZEP 7000, 1μm clear feature (space), (c) PBS, 1μm dark feature (line), (d) ZEP 7000, 1μm dark feature (line). Spot size was 100nm.



(a) (b)

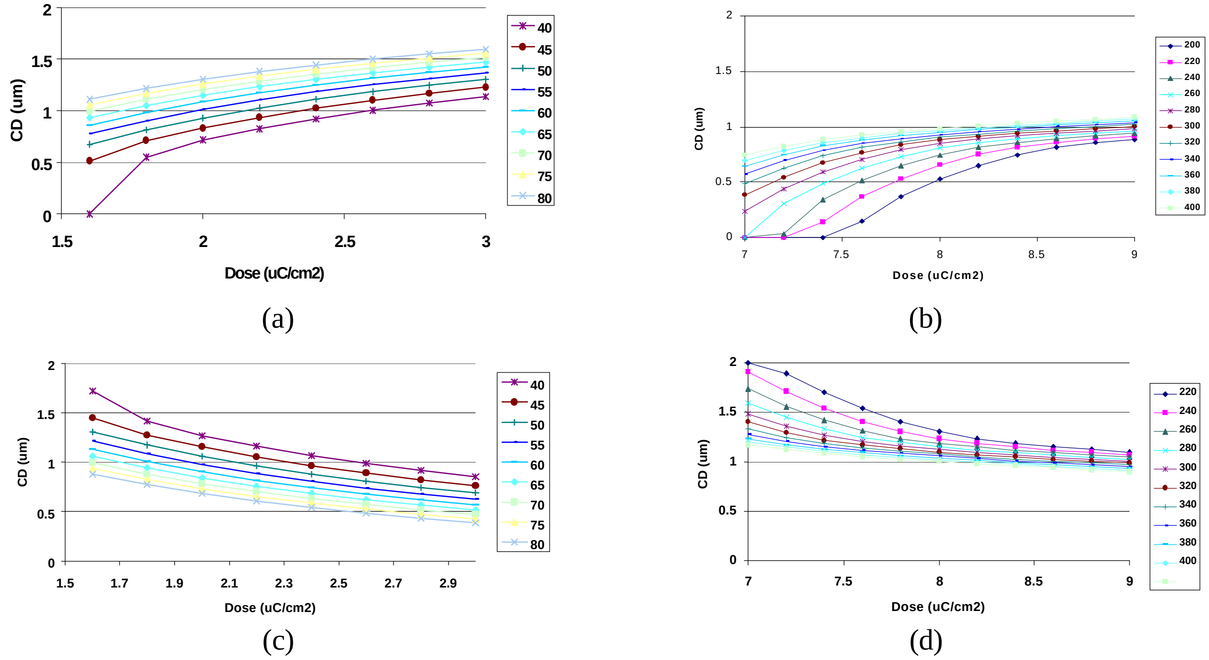
(c) (d)

Figure 4. The same data from Figure 3, plotted as a variation of critical dimension (CD) as a function of exposure dose for different development times for (a) PBS, 1μm clear feature (space), (b) ZEP 7000, 1μm clear feature (space), (c) PBS, 1μm dark feature (line), (d) ZEP 7000, 1μm dark feature (line). Spot size was 100nm.



(a) (b) (c) (d)

Figure 5. Variation of critical dimension (CD) as a function of development time for different exposure doses for (a) PBS, 1µm clear feature (space), (b) ZEP 7000, 1µm clear feature (space), (c) PBS, 1µm dark feature (line), (d) ZEP 7000, 1µm dark feature (line). Spot size was 300nm.

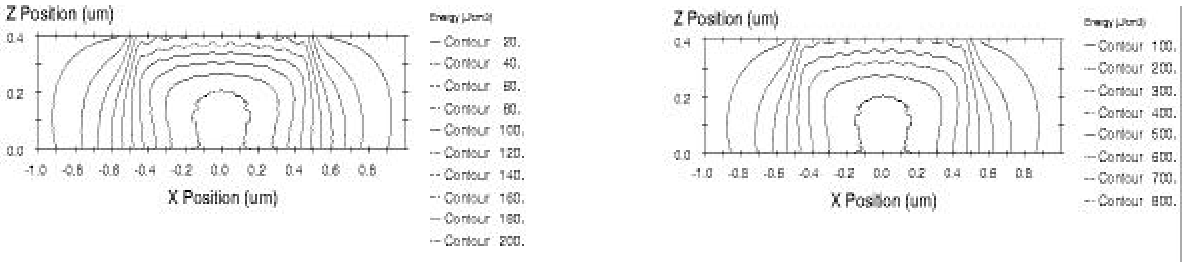


(a) (b) (c) (d)

Figure 6. The same data from Figure 5, plotted as a variation of critical dimension (CD) as a function of exposure dose for different development times for (a) PBS, 1µm clear feature (space), (b) ZEP 7000, 1µm clear feature (space), (c) PBS, 1µm dark feature (line), (d) ZEP 7000, 1µm dark feature (line). Spot size was 300nm.

2.4 Comparison of Aerial and Latent Images

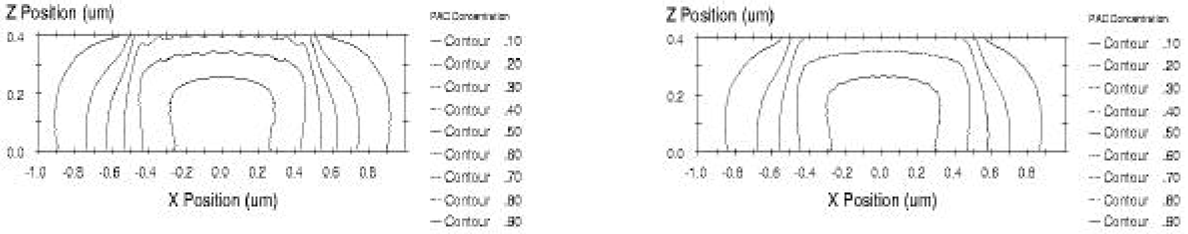
While it is clear that the resist development rate is responsible for most of the differences between the lithographic response of PBS and ZEP 7000, other factors were also investigated for their contribution to lithographic performance. Figure 7 shows plots of the “aerial” image (contours of constant deposited energy) for the two resist materials, simulated at 10 kV and a 400 nm resist thickness and with a 100 nm spot size. Both images are of clear, 1µm features, modeled using SPP. As the plots show, the aerial images of the two features are nearly identical, indicating that there is little in the exposure of the two materials that are different. The performance differences of the two materials are due to other factors.



(a) (b)

Figure 7. Aerial image simulations (contours of constant energy deposited in the resist) for (a) PBS exposed at 2µC/cm^2, and (b) ZEP 7000 exposed at 8µC/cm^2 show no difference outside of a scale factor.

Figure 8 shows latent image plots (relative concentration of the unexposed resist) for the two materials. While the contours are not exactly the same, the two profiles are very similar, except for a scaler factor that is nearly proportional to the dose delivered. From Table I, the exposure rate constant (C) is 0.05 cm^3/J for PBS and 0.0096 cm^3/J for ZEP 7000. As with the aerial images compared in the earlier figure, little difference in latent images is noted for the two materials.

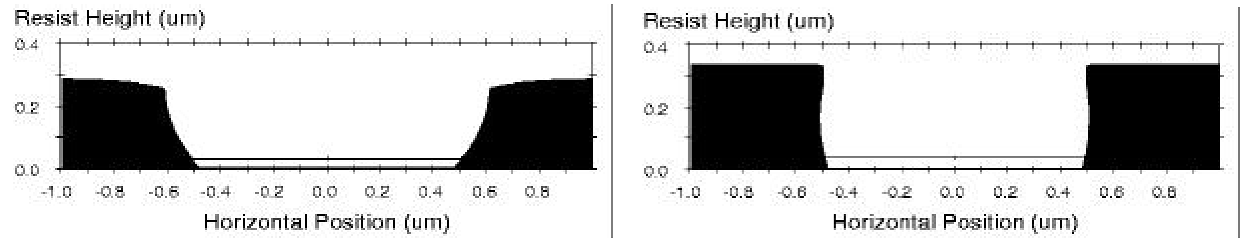


(a) (b)

Figure 8. Latent image simulations (contours of constant extent of exposure reaction) for (a) PBS exposed at 2µC/cm^2, and (b) ZEP 7000 exposed at 8µC/cm^2 show no practical difference outside of a scale factor.

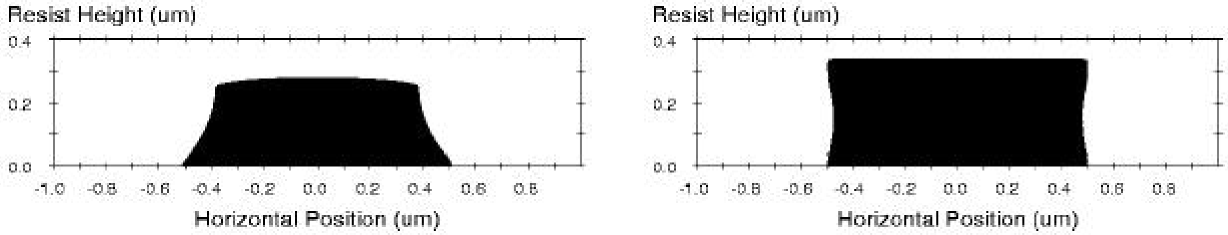
2.5 Comparison of Resist Images

Next, the latent images in Figure 8 were developed, using the development parameters in Table I. PBS was developed for 50 seconds and ZEP 7000 was developed for 310 seconds, reflecting typical values used for these two materials. Figures 9 and 10 show the developed profiles for the two materials for clear and dark features.



(a) (b)

Figure 9. Developed resist profile simulations for (a) PBS (CD = 1018nm, sidewall angle = 54°), and (b) ZEP 7000 (CD = 981nm, sidewall angle = 85°) for a nominal 1μm space.

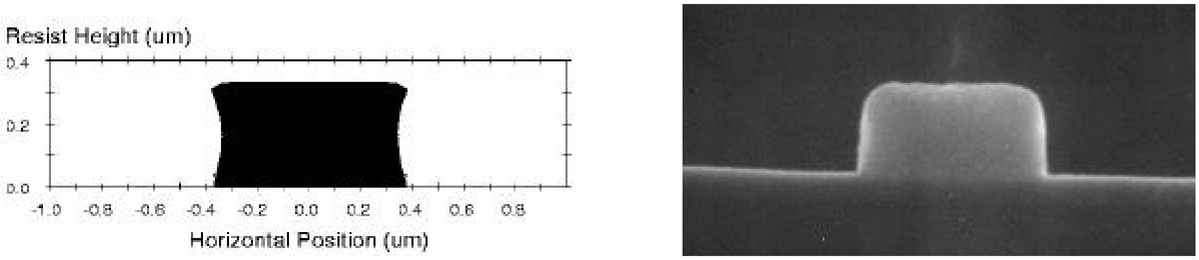


(a) (b)

Figure 10. Developed resist profile simulations for (a) PBS (CD = 978nm, sidewall angle = 53°), and (b) ZEP 7000 (CD = 1004nm, sidewall angle = 84°) for a nominal 1μm line.

Results show a significant difference in profiles between the two materials. PBS has a rather shallow resist slope while the ZEP 7000 profile is near verticle. Resist erosion rate for PBS is substantial and is in excess of 25% while the ZEP 7000 dark ersoion rate is closer to 15%. This comparison of resist profiles might be considered misleading, since PBS uses a wet chrome etch while the ZEP material can use a dry (plasma) chrome etch. Under such conditions, the PBS would be need to be under-dosed and/or underdeveloped to meet about an 800nm clear CD or a 1200nm dark CD, making the PBS profile even worse.

Figure 11 shows plots of a simulated profile and an experimental cross section of a ZEP profile at the same conditions, using a multipass gray (MPG) writing strategy. As the pictures show, there is agreement with the general size and shape of the wall profile. The exception to this is the very top of the profile that has a different shape. This can be attributed either to (1) resist erosion of the top of the resist that occurs during the taking of the SEM picture (the resist is electron sensitive, after all) and/or (2) deficiencies in the poor man's DRM method of measuring the variation of the resist development rate parameters through the thickness of the resist. Further work on measuring the develop rate parameters on an in-situ basis would help determine if there is any significant depth dependence to the dissolution rate.



(a) (b)

Figure 11. Comparison of (a) simulation, and (b) experiment for ZEP 7000.

3.0 Preliminary Optimization of Lithographic Responses

The power of simulating lithographic performance is that a large number of experiments can be performed in a short period of time. Another tool for reducing the time required to screen resists and estimate performance is design of experiments (DOE). In order to compare the two resists, a central composite design of experiments[11] was performed using simulation. Dose, develop time, address and spot size were the four independent variables examined. A total of 25 runs were made with each resist. Since this is a simulated result, no center point replicates were made. As with previous studies[6], wall angle, CD, and ΔCD/Δ%dose were examined. Table II is a list of the parameters and the ranges tested.

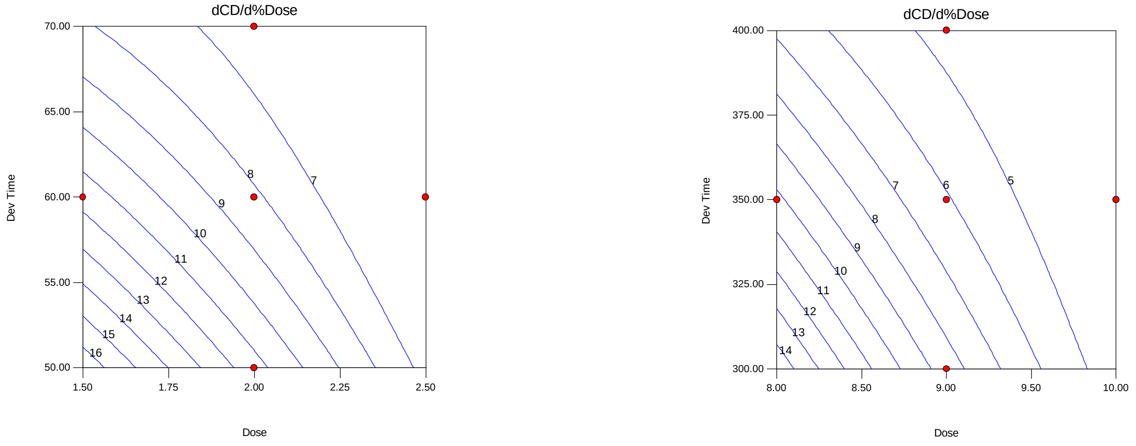
Table II. Variables and values used for the design of experiments.

Variables	**PBS**	**ZEP 7000**
Dose ($\mu C/cm^2$)	2 ± 0.5 (± 25%)	9 ± 1 (± 11%)
Develop Time (sec)	60 ± 10 (± 17%)	350 ± 50 (± 14%)
Address (nm)	125 ± 75 (± 60%)	125 ± 75 (± 60%)
Spot Size (nm)	200 ± 100 (± 50%)	200 ± 100 (± 50%)

The data collected was analyzed using a DOE package (Design Expert version 5 from Stat-Ease) and a multiple linear regression was performed (quadratic form) with the three dependent variables. The equations were used to generate contour plots so that comparisons between the two materials could be facilitated. One power of using DOE is the ability to quickly estimate process latitude under different operating conditions. Only a small subset of the results are shown here for brevity. Midpoints for spot size (200 nm) and address (125 nm) were held constant for the dose/development time plots shown.

3.1 Comparisons of DCD/D%dose

Figures 12 shows contour plots of ΔCD/Δ%dose as a function of dose and develop time. A head to head comparison of the two materials shows a moderate advantage for ZEP 7000. However, if the bias requirements of the two resists are considered, the ΔCD/Δ%dose results for ZEP 7000 have a distinct advantage. This will be examined closely in section 3.3.

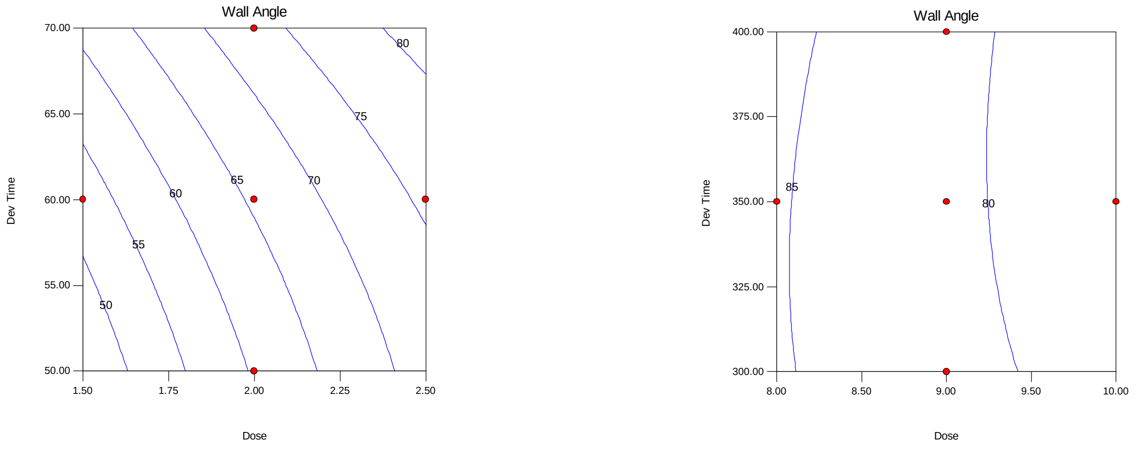


(a) (b)

Figure 12. Comparison of ΔCD/Δ%dose contours versus dose and development time for (a) PBS, and (b) ZEP 7000.

3.2 Comparisons of Wall Angle

The difference between the two materials and their representative wall angles is noticable. Figure 13 shows contour plots of wall angle at the midpoint for spot size and address. The PBS range, over the conditions tested, was 50-80°. A similar plot for ZEP 7000 shows a range of 80-85°. Poor wall angles are typical of lower contrast resists. The small range of wall angle for ZEP 7000 is a good indicator of good process latitude. With ZEP 7000 the effect of dose and develop time on the wall angle is minimal.



(a) (b)

Figure 13. Comparison of resist sidewall angle contours versus dose and development time for (a) PBS, and (b) ZEP 7000.

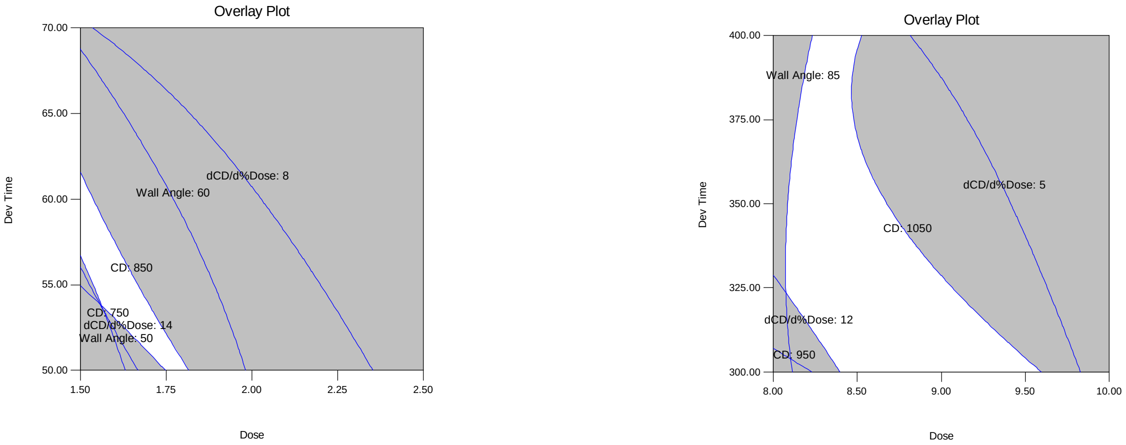
3.3 Simultaneous Optimization of Lithographic Responses

An advantage of using contour plots to visualize results is that more than one output can be plotted on the same contour graph. This allows the simultaneous optimization of more than one parameter in what is called the "process window" approach. Figure 14 shows plots of dose versus develop time, examining CD, ΔCD/Δ%dose and wall angle contours on the same graph. For these plots, spot size was kept constant at the 200nm mid-point, and address was constant at the 125nm midpoint. Table III is a list of the conditions used in the optimization, assuming a wet etch process for PBS and a dry etch process for ZEP 7000. The clear area of each graph indicates the region of dose and development time that simultaneously satisfies the conditions listed in Table III, and is called the process window.

Note that the process window for the PBS is quite small compared to that available for ZEP 7000. This is a very good indicator of process robustness – the larger the area, the more process latitude that is available.

Table II. List of Optimization Parameters

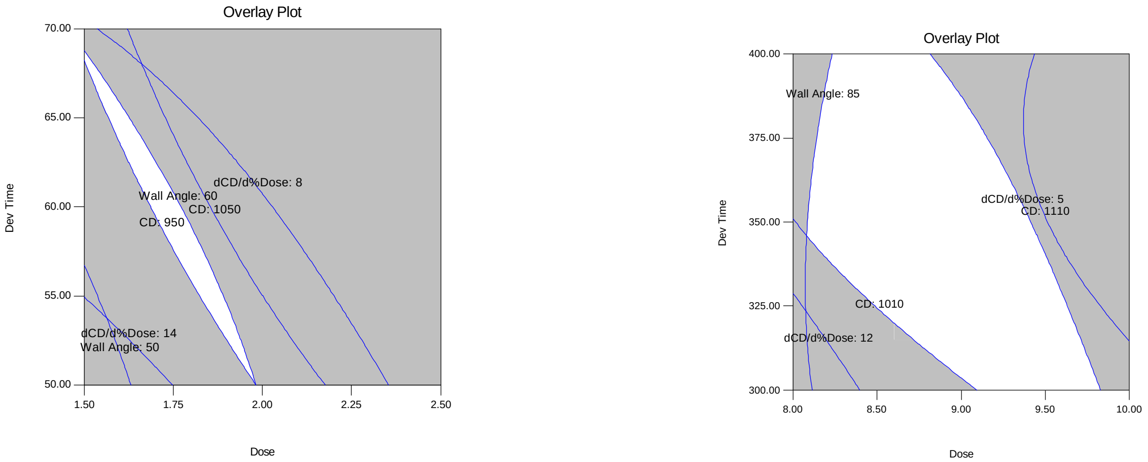
Variables	**PBS-Normal**	**ZEP-Normal**	**PBS-Biased**	**ZEP-Biased**
CD Range (nm)	750 - 850	950 - 1050	950 - 1050	1010 - 1110
ΔCD / %ΔCD (nm/%)	8 - 14	5 - 12	8 - 14	5 - 12
Wall profile (degrees)	50 - 60	70 - 85	50 - 60	70 - 85



(a) (b)

Figure 14. Comparison of overlapping contours (i.e., the process window) versus dose and development time for (a) PBS, and (b) ZEP 7000 using the standard (unbiased) process.

Figure 15 is similar to Figure 14, except that a change in the target CD is allowed. Rather than re-run the simulations with a data bias, the target CD range was allowed to increase. In Figure 15a, the allowable factor space has changed its position in the window. However, there is little difference in the process robustness for this material (PBS). With ZEP 7000 as shown in Figure 15b, the change in the process bias has opened up the operating window considerably. These four plots show the differences in the two resists and their accompanying processes. The process latitude, the wall angle, and ΔCD/%Δdose all show the advantages of ZEP 7000 as compared to PBS.



(a) (b)

Figure 15. Comparison of overlapping contours (i.e., the process window) versus dose and development time for (a) PBS, and (b) ZEP 7000 using the biased process.

4.0 Conclusions

Simulation of the electron beam lithography process was used to explore the differences between two resists used for mask making. Using simulation, it became clear that the differences between these two resists lie in their dissolution characteristics. Measurement of dissolution rates for an e-beam resist should prove to be a powerful screening tool for resist performance, since the development rate function is the major resist characteristic that defines the process window. ZEP 7000 has significantly greater process latitude, when compared to PBS, due in large part to the more favorable resist dissolution characteristics. However, the ability of ZEP to be dry etched permits its operation at closer to the optimum bias for this resist.

All resists perform better at or near their “isofocal” exposure. This point is defined as the dose in which changes to the spot size result in little or no change to the linewidth. In all cases studied, the optimum dose and develop latitude occur at points where the features exceed the desired linewidth (i.e., at an isofocal bias). Use of a data bias could greatly improve the available process window by moving the operating point closer to the isofocal point.

Acknowledgments

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