Electron Beam Lithography Simulation for Mask Making, Part II; Comparison of The Lithographic Performance of PBS and EBR900-M1.

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Abstract

Development of a mask-making process, using a new resist, consists of a number of steps that take a great deal of time, effort and resources before a finished process can be qualified. It would be useful early in the development cycle to model the expected performance of a new resist material prior to determining its suitability. Extraction of modeling parameters and predicting their influence on lithographic performance can also guide the subsequent development work that needs to be done to complete a manufacturing process. This paper compares two different resists and models the expected lithographic performance as a function of its development rate parameters.

Resist dissolution rate measurements were done using two methods - an in situ development rate monitor (DRM) and the classical mechanical (Dektak) method. ProDRM was used to extract the development rate parameters from the data. ProBEAM/3D was used to simulate electron beam lithography using a 2-d model. This paper explores the relationship between dose, develop time, spot size and lithographic parameters such as critical dimension control and wall angle. Two resists, EBR900-M1 and PBS are examined and compared using MEBES 4500 and MEBES 4500S exposure parameters.

Keywords: MEBES, ProBEAM/3D, ProDRM, modeling, e-beam lithography, spot size

1.0 Introduction

The wafer fabrication industry has benefited from the availability of optical modeling tools. The ability to model lithography performance can have a significant impact on how experimental work is carried out and optimized. While some tools have existed for modeling electron beam lithography, platform and user interface limitations have limited their adoption for modeling of electron beam mask making. This paper details the use of a new modeling tool, ProBEAM/3D, and a development rate parameter extraction program, ProDRM, in a examination of lithography performance. Two competing resists (PBS and EBR900 M1) are modeled and compared, using typical MEBES exposure parameters. PBS has been thoroughly described in previous papers[1,2,3,4]. EBR-900 M1 has also been described in some detail[5,6,7,8].

Resist Exposure and Development

Resist exposure and development models have been borrowed from optical lithography simulation[9,10,11,12,13] and applied to e-beam lithography. The Dill exposure model is based on a first order chemical reaction of some radiation-sensitive species of relative concentration m.

$$\frac{dm}{dE} = -Cm \tag{1}$$

where E is the e-beam deposited exposure dose at some point in the resist (in J/cm^3) and C is the exposure rate constant (with units of 1/dose). The solution to this rate equation is a simple exponential.

$$m = e^{-CE} \tag{2}$$

The use of equations (1) and (2) differs from optical lithography simulation in that the e-beam case uses deposited energy per unit volume[11] and the optical lithography case uses energy per unit area. The difference is straightforward since the optical absorption coefficient of the resist relates energy per unit area to deposited energy per unit volume. Thus, the exposure rate constant C for electron beam exposure is roughly equivalent to the optical C divided by the resist optical absorption coefficient α. As an order of magnitude analysis, typical optical resists exhibit $C \sim 0.02$cm^2/mJ and $\alpha \sim 0.5\mu$m^{-1}. Thus, the e-beam equivalent value of C (for the same effective resist sensitivity) would be about 0.004cm^3/J.

The relative sensitizer concentration m (or the reaction product of concentration 1- m) then controls the development process. The Mack kinetic model[12] or the enhanced kinetic model[13] can then be applied. The standard Mack model takes the form (for a positive resist)

$$r = r_{\max}\frac{(a+1)(1-m)^n}{a+(1-m)^n} + r_{\min} \tag{3}$$

where $r_{\max}$ is the maximum development rate for completely exposed resist, $r_{\min}$ is the minimum development rate for completely unexposed resist, n is the dissolution selectivity (proportional to the resist contrast), and a is a simplifying constant given by

$$a = \frac{(n+1)}{(n-1)}\left(1 - m_{TH}\right)^n \tag{4}$$

where m_{th} is called the threshold value of m. For a negative resist, the terms 1-m in equations (3) and (4) are replaced by m.

In electron beam lithography modeling, a common model for development is the Neureuther model[14]:

$$r_E = r_{\min}\left(1 + \frac{E}{E_{th}}\right)^n \tag{5}$$

where E_{th} is called the threshold dose and represents the dose at which development begins to increase rapidly with further exposure. In general, a three parameter model is not sufficient to represent the variety of shapes that the dose response of dissolution rate can take. In the case of the Neureuther model, higher doses lead to ever-increasing development rates, rather than the more physical result of saturating at a maximum development rate.

Over most of the exposure range, the Neureuther model and the Mack model can be matched fairly closely to each other. Keeping $r_{\min}$ and n the same between the two models,

$$\begin{aligned} m_{TH} &\approx e^{-CE_{th}} \\ r_{\max} &\approx r_{\min}\, 2^{n+1} \end{aligned} \tag{6}$$

Chemically amplified resist can also be simulated using reaction-diffusion models developed for optical lithography[15,16]. In fact, some chemically amplified resists developed for deep-UV lithography are being extensively studied as candidates for the next generation of high resolution electron beam resists.

2.0 Procedure

Develop Rate Parameters

Development rate parameters were obtained with two methods. For EBR-900 M1, the parameters were obtained by using the standard mechanical method of measuring film thickness. This method is also called the "poor man's development rate monitor"[17]. Standard EBR-900 M1 resist at 400 nm thickness was obtained from a commercial mask supplier and coated on 6 x 0.25" chrome and quartz masks. A series of open field or bulk exposures were made using a MEBES 4500S exposure tool, ranging from 3 to 12 μC/cm^2. 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 DRM parameters[18,19] were used in subsequent modeling.

For PBS, the parameters were obtained by using SC Technologies Model INS800 development rate monitor. Because low reflective chrome adsorbs much of the detector signal, there was an insufficient signal to noise ratio to successfully use this tool with standard blanks. A work around was found by coating PBS on high (~50%) reflectivity chrome. A total of seven plates were written on MEBES, with a dose range of 0.7 to 4.0 μC/cm^2. Each plate had one dose and was developed to clear, with the SC DRM tool measuring thickness versus develop time in real-time. The data was smoothed by using a polynomial fit to the data. ProDRM was then used to extract the rate parameters. As with EBR-900, the Mack model was used.

ProBeam Modeling

A beta copy of ProBEAM/3D (v5.1h) was obtained from FINLE Technologies. A description of the modules and their operation has been previously described[20,21]. Briefly, a Monte Carlo simulation is run using 250,000 trajectories, 10 kV accelerating voltage, 400 nm resist thickness and a chrome (1000 nm) on quartz substrate. Features were digitized on a 100 nm address. The point spread function generated by the Monte Carlo module is convolved with the gaussian spot sizes used in the experiment to generate the pixel functions used in the simulations. The pixel functions are then convolved with the test patterns to generate 2-d aerial images. The aerial image is fit to a resist development model (Mack model). The development model gives x-z profiles or a two dimensional image of the resist profile. ProBEAM/3D is used to measure the CD size at a point close to the resist interface and to measure the wall angle of the developed resist.

For CD metrology, line widths were measured using the ProBEAM/3D threshold method and at a set point of 10%. For critical dimensions and wall angle the top and bottom 10% of the profile are ignored and a straight line is fit to the remaining 80% of the profile. The intersection of this line with the substrate gives the critical dimension and the slope of the line gives the angle. Both are automatically calculated with ProBEAM/3D.

For PBS, a wet etch of 100 nm undercut per side was assumed. Thus, all CD measurements used a bias of -200 nm. In other words, for a 1000 nm clear, exposed space, the nominal feature size in resist was assumed to be 800 nm. For a 1000 nm dark, unexposed line, a 200 nm bias gives a nominal size of 1200 nm. For EBR-900, dry etch was assumed and the bias for each feature was set at zero. This difference in bias was expected to be significant in the evaluation of the two resists and was chosen to reflect the conditions under which they are used. The response CD-nominal was chosen as a significant parameter.

Experimental Design

A three variable, central composite design (CCD) was used to model the factor space for each resist. A design of experiments was chosen for its ability to interpolate inside the factor space and reduce the number of simulations. Values of dose were chosen so that a ±10 % range was chosen for both resists. For develop time, PBS used a range of ± 10 % while EBR-900, a more robust resist, used a range of ± 20 %. Spot size was varied ~± 40%. CD-nominal, wall angle, dose sensitivity, and develop sensitivity were chosen as the dependent variables for this simulation. Dose sensitivity (Δ CD/ % Δ dose) is defined as the change in CD that occurs when the dose is changed by 1%. It is a very sensitive parameter in modeling the resist performance from the tool design perspective. This figure of merit is related directly to the edge slope of both the aerial image and the developed profile. Develop sensitivity (Δ CD / % Δ develop time) is defined in a similar manner, the change in CD that occurs when the develop time is changed by 1%. Both dose and develop sensitivities are good measures of process robustness. Table 1 is a summary of the factor space covered for each resist. A total of 15 trials (i.e., simulations) were run for each resist.

In experiments run in setting up a process, EBR-900 was observed to exhibit a surface inhibition phenomenon. The mechanism for this is not well understood, but is thought to be related to (1) surface drying while in vacuum and (2) aging of the resist after exposure to air. The beginnings of a T-top formation can be noted in the EBR-900 simulated profiles and in 90^{o} experimental SEM profiles. This inhibition effect was modeled in ProBEAM/3D by including several inhibition terms in the develop model. This includes a relative surface rate of 0.01 and an inhibition depth of 50 nm. These conditions were chosen to replicate EBR-900 experimental SEM results.

Table 1. - Factor Space Examined.

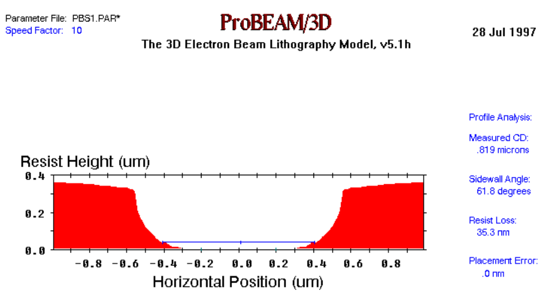
		PBS				EBR-900 M1		
Factor	**units**	**Low**	**Middle**	**High**		**Low**	**Middle**	**High**
Dose	$\mu C/cm^2$	2.0	2.2	2.4		7.2	8.0	8.8
Dev Time	sec	44.0	48.4	52.8		100	120	140
Spot Size	nm	100	160	240		100	160	240

3.0 Data

Simulations of 2-d wall profiles are displayed in figures 1-4. The development times have been adjusted to give ~ the nominal CD. These graphics show the effect of spot size on wall angle and CD. As expected, wall angles are more sloped (i.e. reduced angle from 90^{o}) when very large spots are used. The wall angle for EBR-900 is sharper than the PBS equivalent, particularly at the resist/chrome interface. The angle of the resist profile at the interface is a key parameter in influencing CD control.

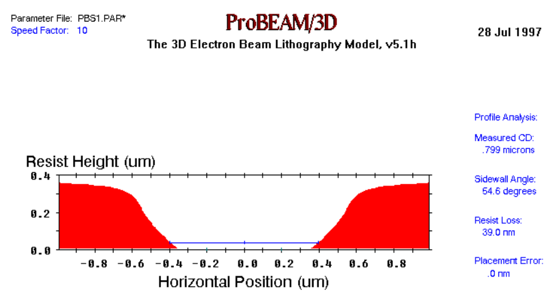
Figure 1. PBS Profiles - 1000 nm Clear Space

Small Spot



Dose 2uC
Spot 100 nm
Dev Time 44.5 sec

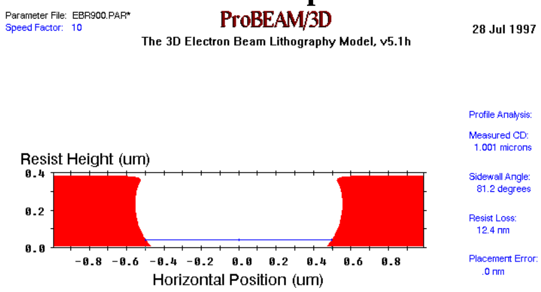
Large Spot



Dose 2uC
Spot 240 nm
Dev Time 48.0 sec

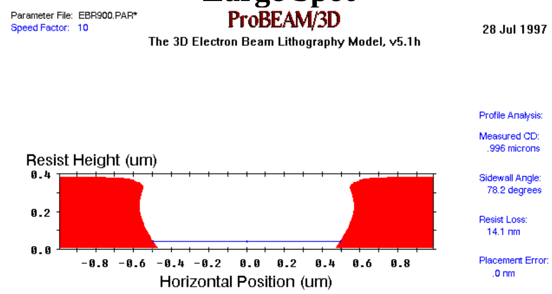
Figure 2. EBR-900 Profiles - 1000 nm Clear Space

Small Spot



Dose 8uC
Spot 100 nm
Dev Time 117 sec

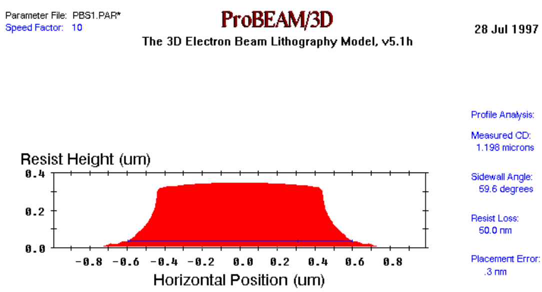
Large Spot



Dose 8uC
Spot 240 nm
Dev Time 126 sec

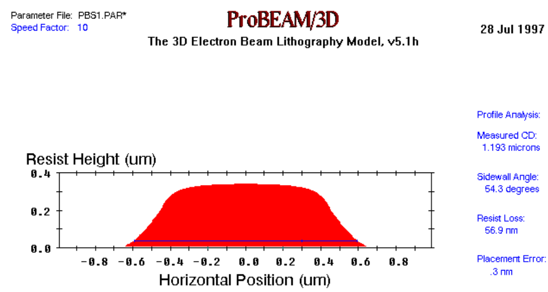
Figure 3. PBS Profiles - 1000 nm Dark Line

Small Spot



Dose 2uC
Spot 100 nm
Dev Time 42.5 sec

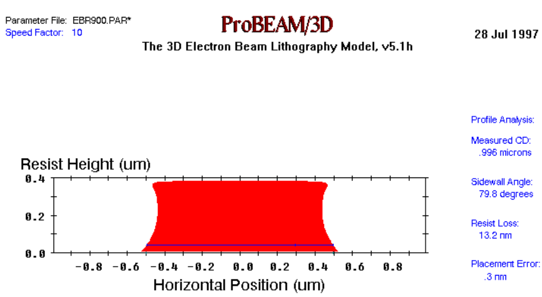
Large Spot



Dose 2uC
Spot 240 nm
Dev Time 46.5 sec

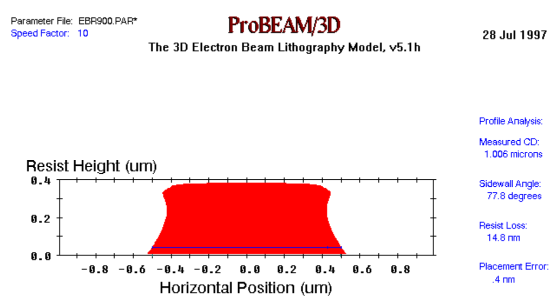
Figure 4. EBR-900 Profiles - 1000 nm Dark Line

Small Spot



Dose 8uC
Spot 100 nm
Dev Time 114 sec

Large Spot



Dose 8uC
Spot 240 nm
Dev Time 121 sec

Wall angle profiles displayed in figures 1-4 are typical for the factor space examined. In general, the profiles of EBR-900 show a steeper profile, particularly at the resist-chrome interface.

4.0 Results

Development Rate Parameters

Figures 5 and 6 are the development rate parameters for the two resists in this experiment. A comparison of their development rate coefficients is instructive. Both have similar behavior when the PAC (or the fraction of resist converted to its soluble form) is plotted against the development rate. R_{max} for EBR-900 is significantly less than that of PBS, a function largely of the differences in development time between the two processes. The higher n value for EBR-900 is significant and will lead to improved performance in this resist. This was confirmed by bulk contrast measurements, giving values of 2.1 and 1.7 for EBR-900 and PBS, respectively. In general, the two rate curves are very similar, suggesting that the two resists operate in a very similar fashion.

Figure 5. PBS Development Rate

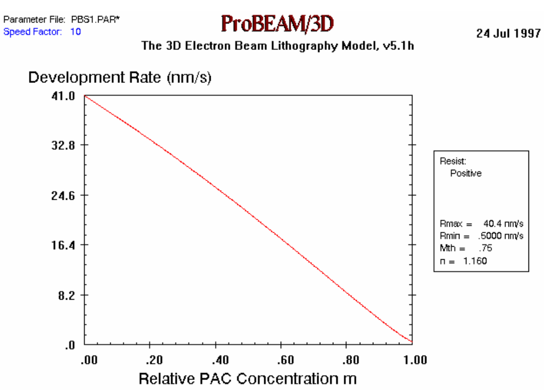
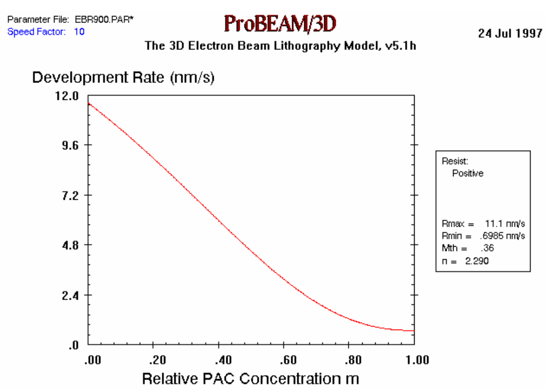


Figure 6. EBR-900 Development Rate

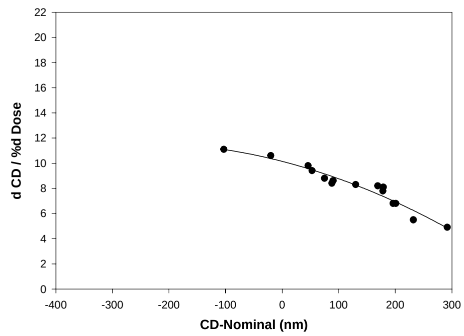


Effect of CD-Nominal on Lithographic Performance

Figures 7-10 are plots of CD-nominal versus dose sensitivity. The plots include all trials simulated, including the variations in dose, develop time and spot size. One surprising observation is that the dose sensitivity at nominal linewidths is approximately the same for both PBS and EBR-900 or ~ 10-12 nm/% Δ dose. They differ greatly in the slope of the curves. The effect of linewidth or CD-nominal is significant for its impact on lithography quality. The reduction in dose sensitivity that occurs with data biasing and additional dosing and/or development can be noted in these graphs. At nominal CD the dose sensitivity for the two resists are similar. This suggests that they will operate in a similar manner. When operating with data sizing however, EBR-900 demonstrates some advantages when dose and/or develop time is increased to compensate for data biasing.

Figure 7. PBS Dose Sensitivity - Clear Feature

Figure 8. EBR Dose Sensitivity - Clear Feature



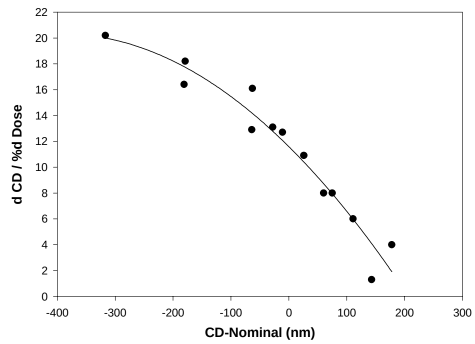
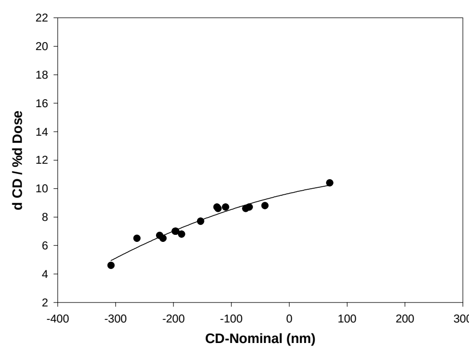
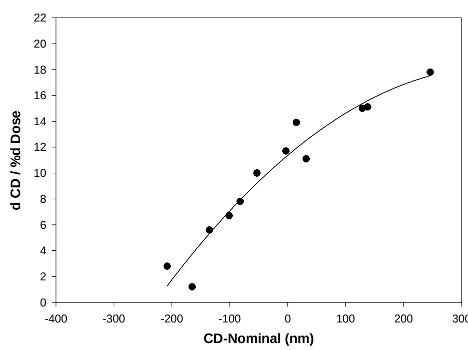


Figure 9. PBS Dose Sensitivity - Dark Feature

Figure 10. EBR Dose Sensitivity - Dark Feature





Modeling Results

All of the modeling data collected was fitted to a DOE matrix. Because of the volume of data collected, the results are summarized in figures 12-19 and have been displayed as contour plots of dose versus develop time for the four responses. For brevity, only clear spaces are considered here.

There is a difference between the plots for PBS and EBR-900. For develop time, PBS range was 8.8 seconds and 40 seconds for EBR-900. This should be noted when comparing resist responses. EBR-900 is a much more robust resist and it can cover a larger dynamic range of operating conditions.

CD-Nominal

Figures 12 and 13 are plots of the CD operating range, based on MEBES 4500S specifications of ± 35 nm, shown as the clear area on the chart. The same dose range ± 0.2 $\mu C/cm^2$ has been used for a fair comparison. The operating range of EBR-900 is clearly more robust with the effect of dose on nominal CD covering a wider range. EBR-900 is a more robust resist, compared to PBS. This modeling result agrees with our experience in hitting CD nominal with EBR-900. An iterative develop is not required with EBR-900.

Figure 12. PBS CD-Nominal Operating Range

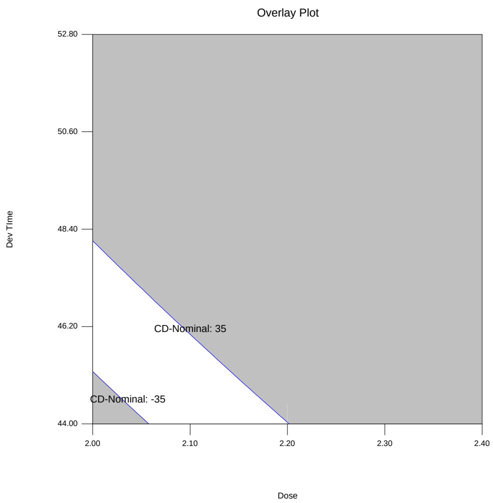


Figure 13. EBR CD-Nominal Operating Range

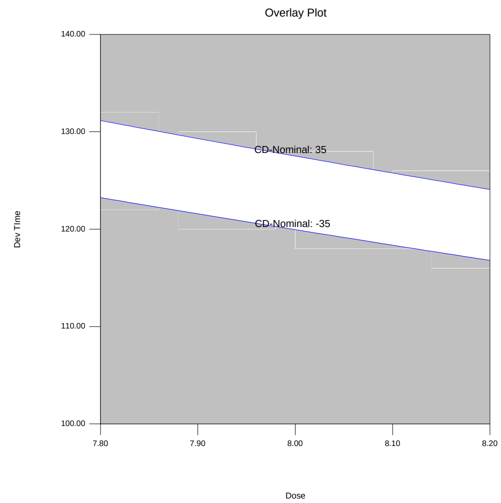


Figure 14. PBS - Wall Angle

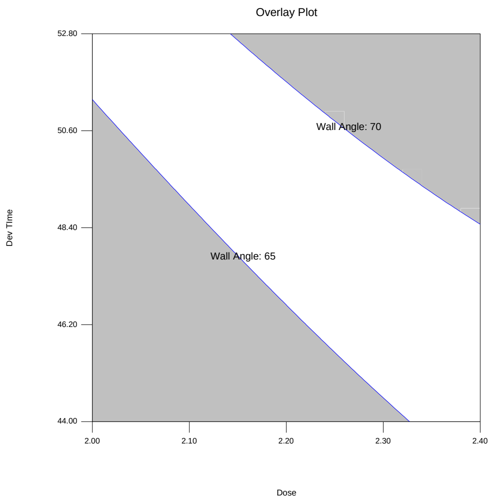
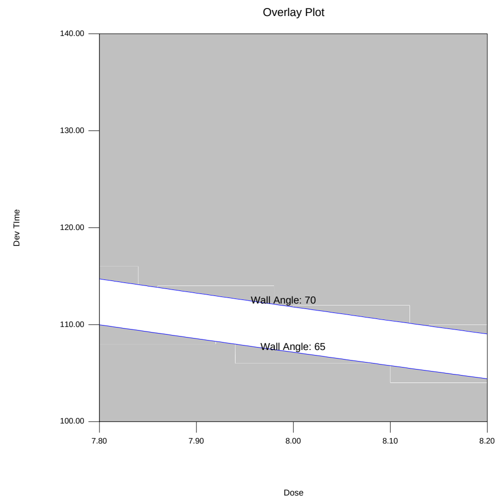


Figure 15. EBR - Wall Angle



Wall Angle

Figures 14 and 15 compare the two resists and their response to wall angle. An operating range of 65 to 70^{o} was chosen for comparison. Generally, wall angles for EBR-900 were steeper than

PBS. The figures show the relative insensitivity of EBR-900 to dose and process changes. Much higher wall angles can be expected at higher develop times with EBR-900. EBR-900 in general has an angle closer to vertical. Increasing the dose and or develop time increases the wall angle, consistent with a reduction in the residual foot.

Dose Sensitivity

Figure 16 and 17 compare the two resists and their response to dose sensitivity. A range of 8-10 nm/% Δ dose was chosen for comparison. EBR-900 exhibits a greater dynamic range in response with a change in dose. For develop time the results of the two resists were comparable.

Figure 16. PBS - Dose Sensitivity

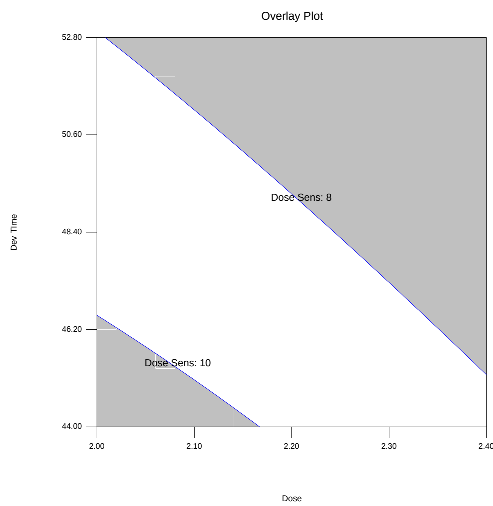
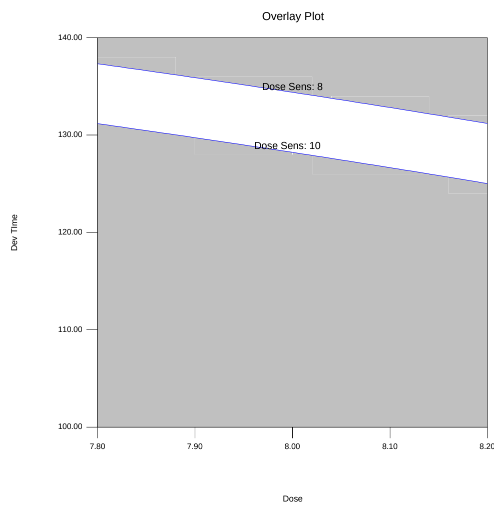


Figure 17. EBR - Dose Sensitivity



Develop Sensitivity

Figures 18 and 19 are contour plots of develop sensitivity. A range of 6-8nm /% Δ develop time was chosen for comparison. As with dose sensitivity, develop sensitivity of EBR-900 is superior to that of PBS.

Based on the operating range responses and the steeper sidewall angles of EBR-900, its lithographic properties are superior to PBS.

Figure 18. PBS - Develop Sensitivity

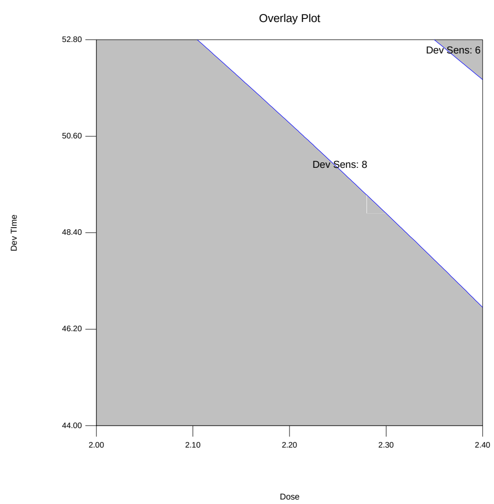
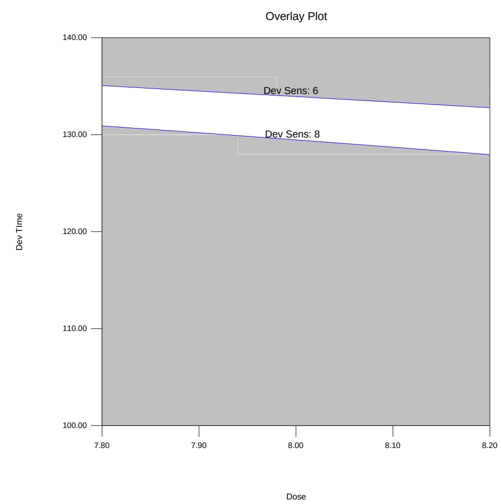


Figure 19. EBR - Develop Sensitivity



5.0 Conclusions

Based on DRM measurements and ProBEAM/3D simulations, we can conclude that EBR-900 M1 is a robust resist and is superior to PBS in its lithographic response. The sensitivity of EBR-900 to dose changes and response to spot size have advantages over PBS. Develop rate parameters, a function of resist contrast, are similar for both resists with EBR-900 exhibiting slightly better performance.

When response to dose changes are evaluated (Δ CD / % Δ dose), both resists at nominal CD are similar. When overdeveloped, the lithographic response of EBR-900 improves at a greater rate than PBS. This suggests that a biased process with EBR-900 is superior to PBS. EBR-900 is clearly superior to PBS for all four responses tested.

An inhibition layer on EBR-900 has been observed. Development inhibition can have noticeable impact on CD control and uniformity. Ability to control this phenomenon will be a key in its successful integration of EBR-900 into the mask shop.

6.0 References

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