Comparison of modeling and experimental results in contrast enhancement lithography

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Introduction

Characterizing the effects of the many variables that are a part of photolithography is not an easy task. As more sophisticated patterning techniques, such as contrast enhancement lithography (CEL), are introduced the number of variables increases. Two tools are commonly used to deal with the complex task of understanding the interrelationships of these many variables: experimentation and computer simulation. While experimentation, and in particular statistically designed experiments, can give a great deal of insight into a particular system, it is often difficult to extrapolate trends outside of the experimental conditions (e.g., to other lithographic systems). Computer modeling, on the other hand, is rather poor at predicting exact outcomes of specific conditions, but is at its best when predicting trends which may exist over a broad or narrow range of conditions. There exists, however, an uncertainty as to how accurately the model reflects conditions of the real world.

Any process simulator has strengths and weaknesses. In optical lithography modeling the strong points include:

- the intensity distribution of the aerial image,
- the exposure (bleaching) of the photoresist film,
- the formation of standing waves, and
- the photoactive compound (PAC) gradients (called the latent image).

The weak areas are:

- a knowledge of the aberrations present in a projection system,
- accurately determined development parameters,
- the effects of processing conditions on the development parameters, and
- the development model itself.

In general, the process of exposure is better understood than development. Thus, experimental confirmation of simulated results is an important part of a comprehensive lithography modeling effort.

This paper compares the results of experimental work to computer simulations in contrast enhancement lithography. Effects to be studied include development latitude, feature size and proximity effects, exposure latitude, and focus latitude. In all studies, single layer resist and CEL are compared both experimentally and with the computer model PROLITH, v1.4 [1-3]. Also, an interesting anomaly has been observed experimentally. A mechanism to explain the phenomenon is proposed and computer simulations are used to confirm the predicted mechanism.

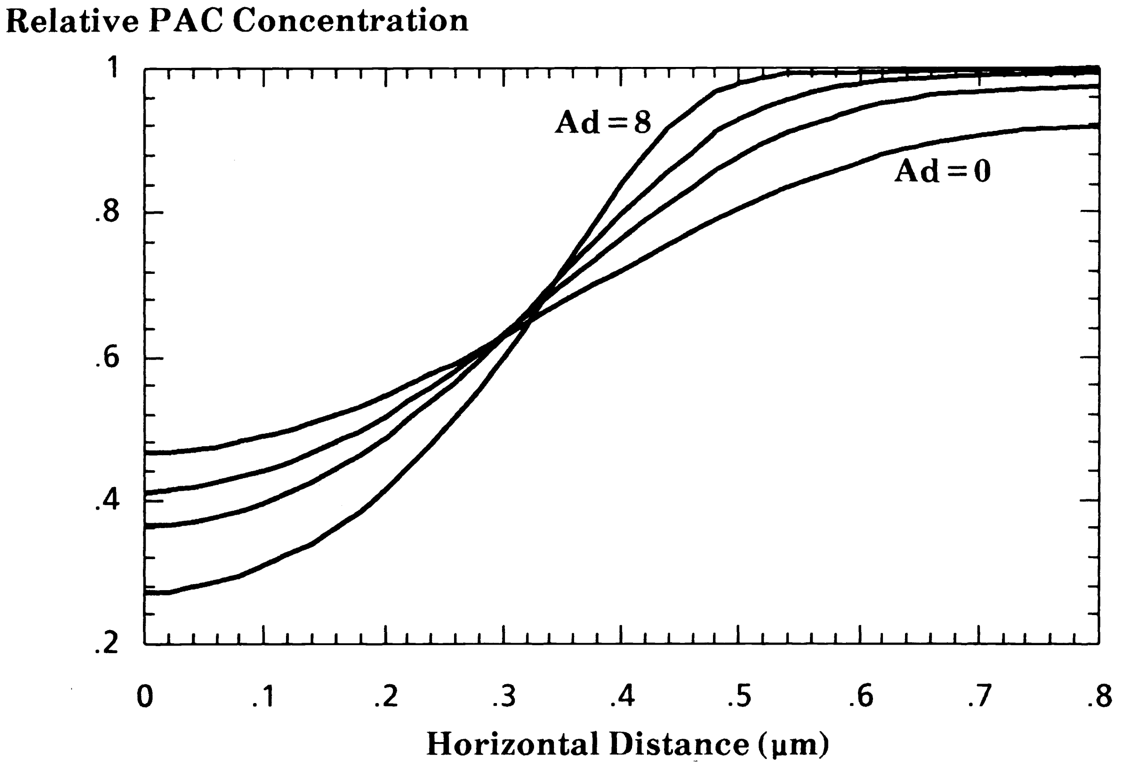


Figure 1: Latent image (PAC concentration) as a function of normalized CEL thickness (Ad = 0, 2, 4, and 8) as predicted by PROLITH.

Development Latitude

Although most lithography engineers tend to equate process latitude with exposure latitude, development latitude is also an important part of the total process latitude. A major source of linewidth errors is the inability to adequately control the development process. For example, resist "sensitivity" changes are almost always a result of a change in the resist development properties. Also, the importance of prebake is due to the extreme sensitivity of development to the prebake process conditions. A process with good development latitude will be resistant to these changes.

For a development process with given properties, development latitude is determined by two factors: the gradient of PAC and the magnitude of the standing waves. A resist with a large PAC gradient near the mask edge will exhibit good development latitude. Shown in Figure 1 is the effect of CEL thickness on the latent image. As the normalized CEL thickness (defined as the bleachable absorbance, the absorption coefficient A times the CEL thickness d) goes from zero to Ad=8, the PAC gradient near the mask edge improves dramatically. (The exposure energy was adjusted to give the nominal linewidth for fixed development conditions). The improvement in the latent image is a result of an important, though often overlooked, property of CEL: the center of a space receives a higher exposure than normal since the CEL bleaches in the center first. This "over-exposure" of the center results in improved PAC gradients and thus, improved development latitude.

The higher exposure of the center can also reduce the effects of standing waves. As the resist becomes more exposed, the replication of the standing wave pattern begins to bleach out. This effect is shown in Figures 2a and 2b. These figures are gray-scale reproductions of the PAC concentration as a function of x and z. Darker colors mean higher concentrations of PAC. Figure 2a shows the case without CEL. The standing waves are evident as the horizontal light and dark regions. Figure 2b shows the equivalent case with CEL (again, the exposure was adjusted in each case to give the same linewidth). As can be seen, the standing waves have been somewhat "bleached out" by the higher exposure in the center of the space. As a result, development in the center is less hindered by the standing waves. Note from Figure 1 that the exposure near the mask edge is nominally the same regardless of CEL thickness.

Experimental results verify the above conclusions. Shown in Figure 3 is both the experimental and simulated variation of linewidth with development time, with and without CEL. The experimental and modeling conditions are given in Table I. Development time was chosen as being a representative parameter of the development process. Variations in development rate (caused by lot-to-lot photoresist differences, prebake, etc.) should have a similar effect on linewidth as variations in development time. Thus, development time latitude is a good measure of the overall development latitude. As can be seen in Figure 3, the CEL case shows greatly improved development latitude.

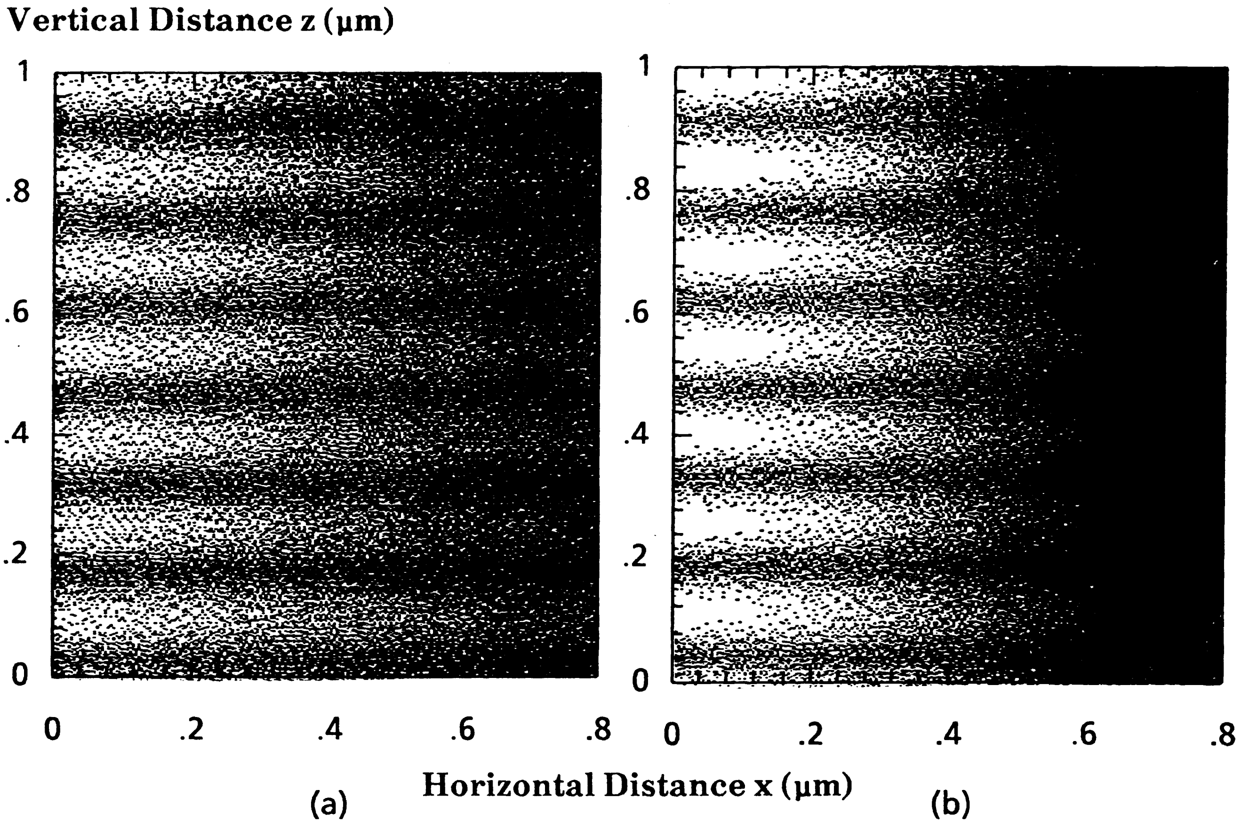


Figure 2: Gray-scale plot of resist PAC concentration a.) without CEL, and b.) with CEL. (Darker means more PAC, lower exposure.)

Feature Size and Proximity Effects

An important aspect of lithography is the ability to accurately reproduce the mask dimensions on the wafer. A typical mask will have features of many types and sizes. A plot of the printed linewidth versus the mask feature size will show any feature size effects that may be present in a lithographic process. Figure 4 compares the feature size effect for single layer resist and CEL processes using equal lines and spaces. At large (>1 μm) features, both processes faithfully reproduce the mask size. But as the linewidths go submicron, the printed line size becomes greater than that of the mask. As can be seen in Figure 4, the standard resist process shows worse feature size effects than the CEL process. In fact, the smallest line size, 0.7 μm, does not clear in the standard process, but is printed in the CEL process. PROLITH simulations confirm the improvement in feature size effect with the addition of CEL. The

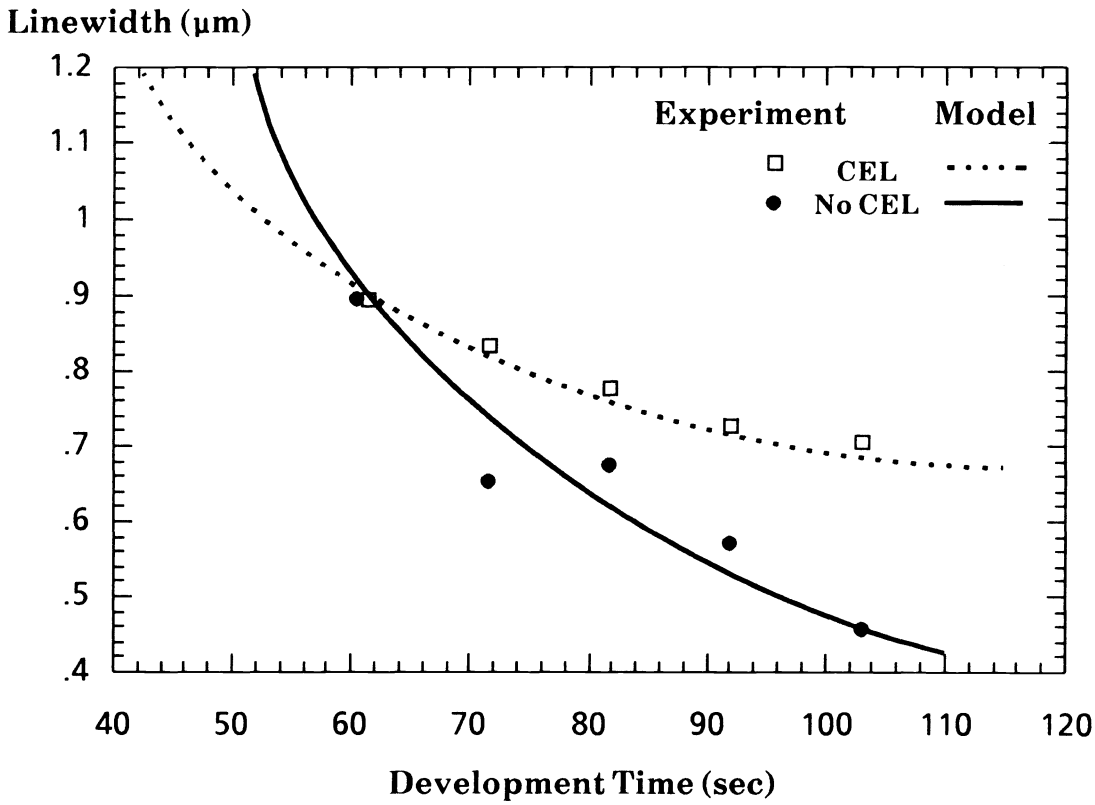


Figure 3: The effect of CEL on development latitude. Both experimental data and PROLITH results are presented for 0.9 μm lines (see Table I for conditions).

Table I
Experimental and modeling conditions for the study of development latitude

Experimental Parameters	Modeling Parameters
1.23 μm Shipley 1813 resist on silicon	R_{max} = 100 nm/s
60sec, 115°C hotplate prebake	R_{min} = 2 nm/s
Shipley MF321 developer in spray/puddle mode (60sec nominal development time)	m_{th} = 0.3
Optimetrix 8010D stepper NA=0.32, σ=0.7, λ=436nm	n = 3.0
0.9 μm equal lines and spaces	A_{cel} = 7.5 μm^{-1}
linewidth measured at bottom of resist using SEM	B_{cel} = 0.3 μm^{-1}
0.6 μm CEM-420	C_{cel} = 0.06 cm^2/mJ

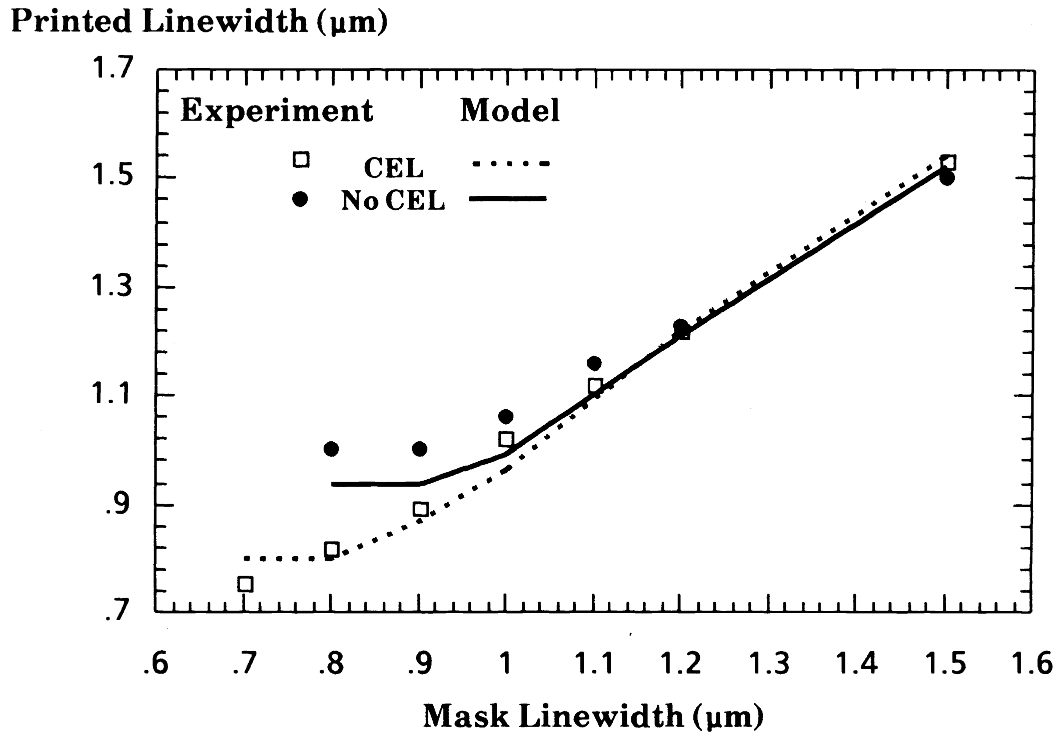


Figure 4: Feature size effect - the ability to reproduce the mask linewidth with and without CEL. Both experimental data and PROLITH results are presented.

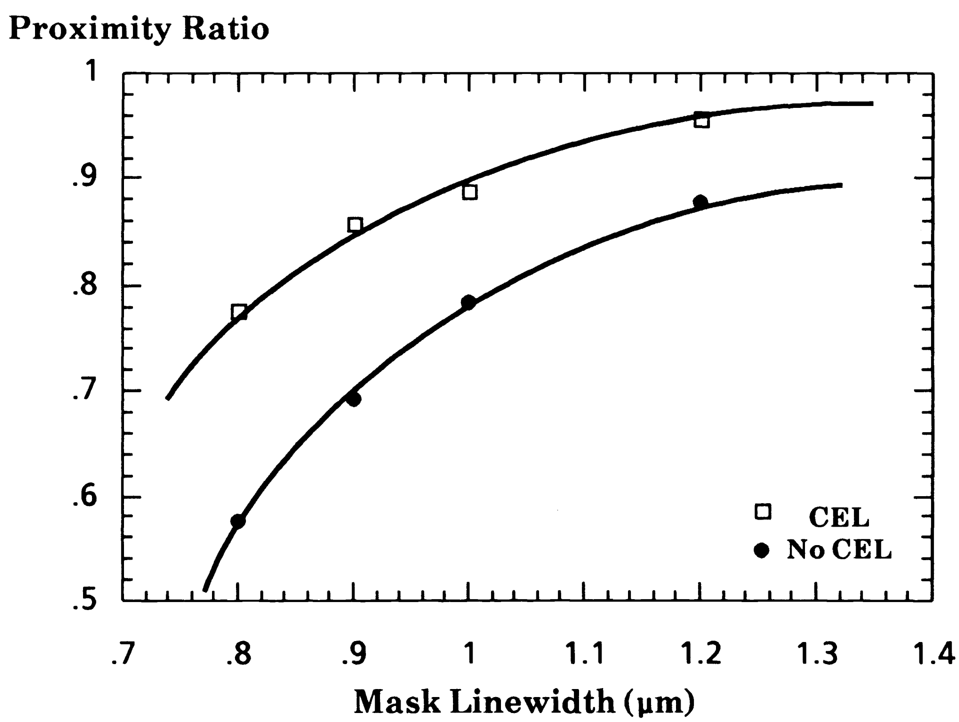


Figure 5: Proximity effect - the ratio of the linewidths of isolated to packed lines, with and without CEL. Values closer to one mean less proximity effect. (Solid lines represent curve-fits through the data).

reason for this improvement is again the higher exposure at the center of the space. As the feature size decreases, the peak intensity of the aerial image of the space decreases. This reduces the development rate in the space and results in a larger linewidth (smaller spacewidth). Since the use of CEL increases the exposure in the center of the space, the reduced peak intensity of the aerial image is less important.

A lithographic process must also reproduce the mask regardless of feature type, e.g., packed versus isolated lines. A change in linewidth due to the presence of nearby features is called the proximity effect. The most common example of the proximity effect in optical lithography is the difference in linewidth between an isolated line and a line in the center of a line/space array. This difference can be quantified as

$$proximity\ ratio = \frac{size\ of\ isolated\ line}{size\ of\ packed\ line} \quad . \tag{1}$$

Proximity effects are a strong function of feature size. In general, smaller features exhibit larger proximity effects. Figure 5 shows the proximity ratio as a function of mask feature size for resist with and without CEL. Simulated results are not shown because PROLITH does not adequately predict this effect. The cause of this discrepancy is unknown, but under investigation. As can be seen, the CEL case shows less proximity effect (a proximity ratio of 1 means no proximity effect). This effect is also shown in Figure 6a and b, where 0.8 µm lines have been imaged with and without CEL.

Exposure Latitude

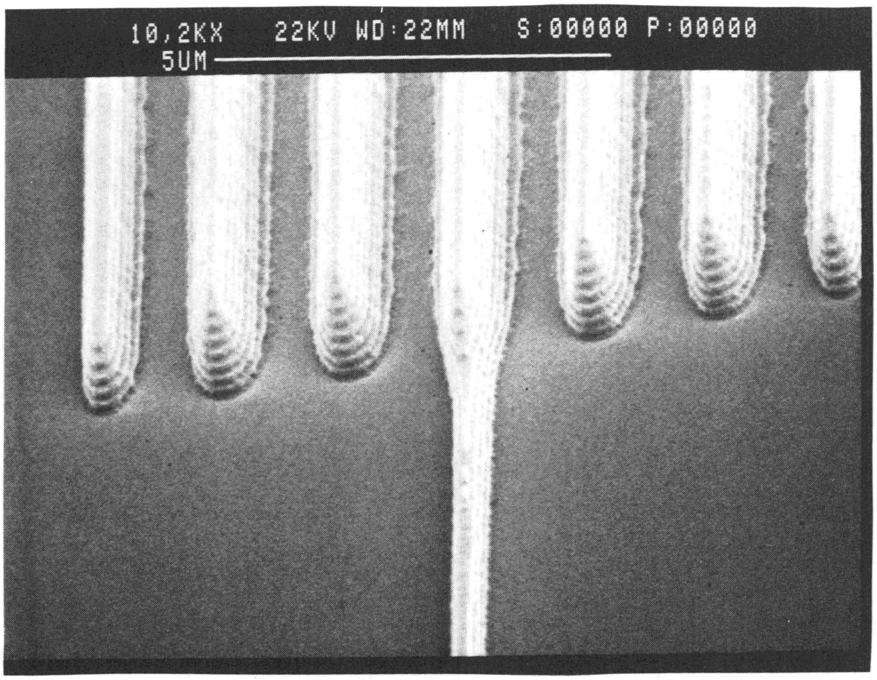
The effect of CEL on exposure latitude is determined by measuring the change in linewidth with exposure energy. Figure 7 shows that the experimental data does not indicate any improvement in exposure latitude with the use of CEL. The modeling results, however, indicate otherwise. Williams, et al., [4] have reported that exposure latitude was improved when 1 µm of CEM-420 was used, but that no improvement was seen for 0.5 µm of CEM-420 (0.6 µm was used in this study). Clearly, more work, both experimental and modeling, must be done in order to adequately resolve this issue.

Focus Latitude

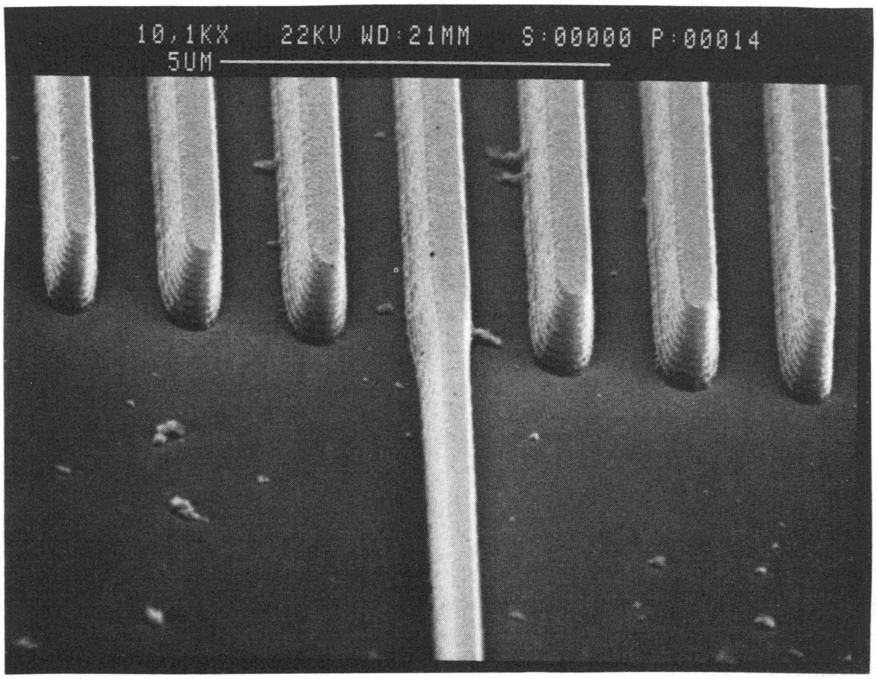
Focus is another critical parameter in optical lithography. Poor focus conditions have two effects: a change in linewidth and reduction of the resist sidewall angle. Since one of the main benefits of CEL is an improvement in resist sidewall angle, it seems likely that the use of CEL would make the resist sidewall less sensitive to focus changes. Figure 8 shows simulations of the effect of focus on the sidewall angle for various thicknesses of CEL. Obviously, the use of CEL reduces the degradation of the resist sidewall due to defocus. Thus, for a process which is sidewall limited CEL can greatly improve focus latitude.

The effect of CEL on linewidth changes with defocus is less obvious. Figures 9a and b show linewidth versus focus for 0.8, 0.9, 1.0, and 1.2 µm lines with and without CEL. Both the experimental data and the simulations show some improvement in focus latitude with CEL. (Note: PROLITH v1.4 with the enhanced focus model was used for these simulations [3]). From the perspective of modeling, the focal position has been defined as zero at the top of the resist (or CEL). Thus, a focal position of -0.5 µm means that the aerial image is being focus 0.5 µm into the resist/CEL.

It should be noted that exposure latitude is a strong function of focus and focus latitude is a strong function of exposure. The best way to characterize the effects of focus and exposure is to measure linewidth over a large matrix of exposure and focus values and determine process windows of linewidth control. This work is currently in progress.



(a)



(b)

Figure 6: SEM micrographs depicting the proximity effect of 0.8 μm lines, a.) without CEL, and b.) with CEL.

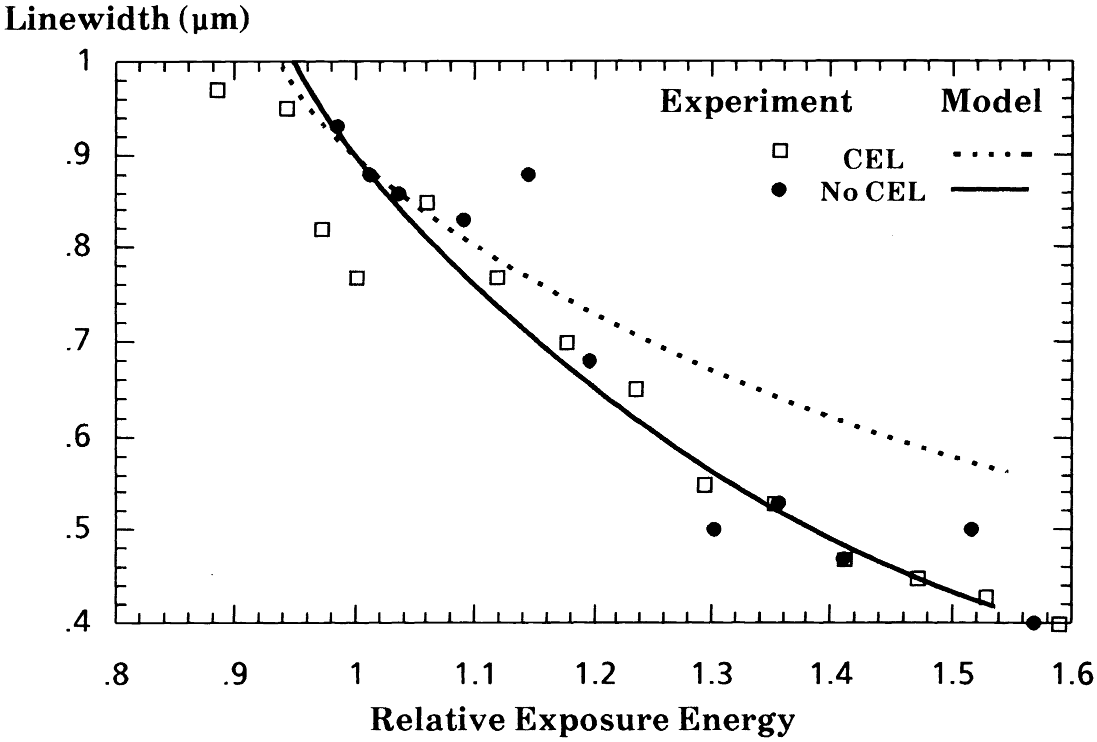


Figure 7: The effect of CEL on exposure latitude (0.9 μm line/space). Both experimental data and PROLITH results are presented.

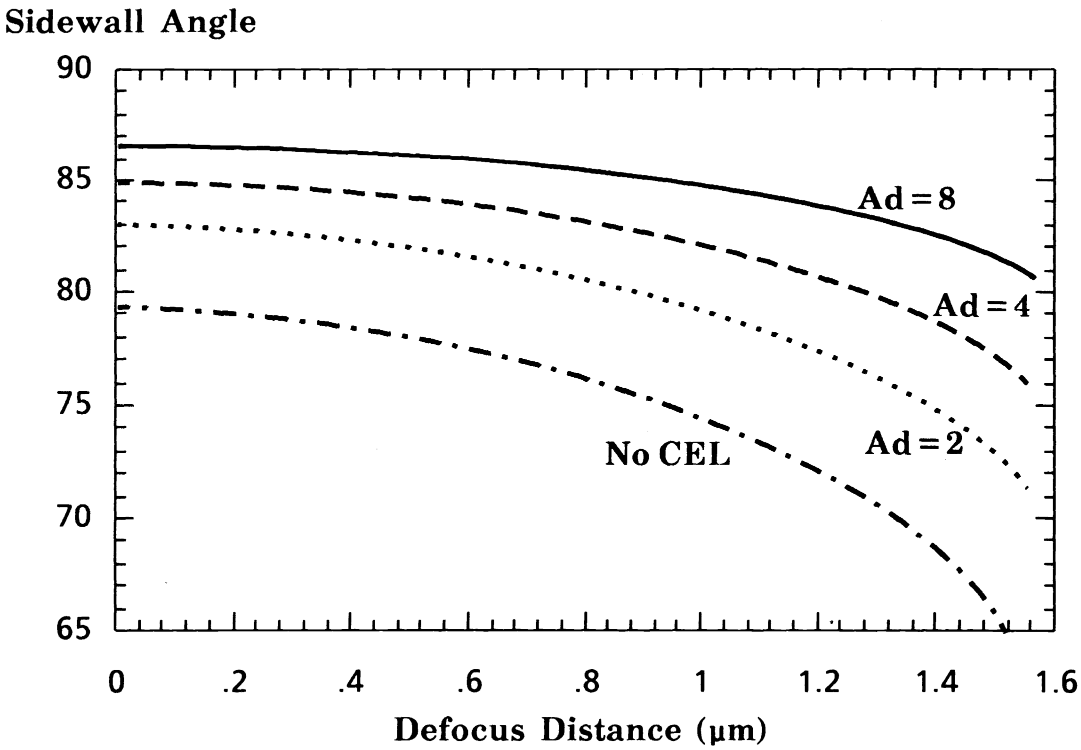


Figure 8: The improvement in resist sidewall angle (0.8 μm line/space) with CEL also improves focus latitude (from the point of view of sidewall angle).

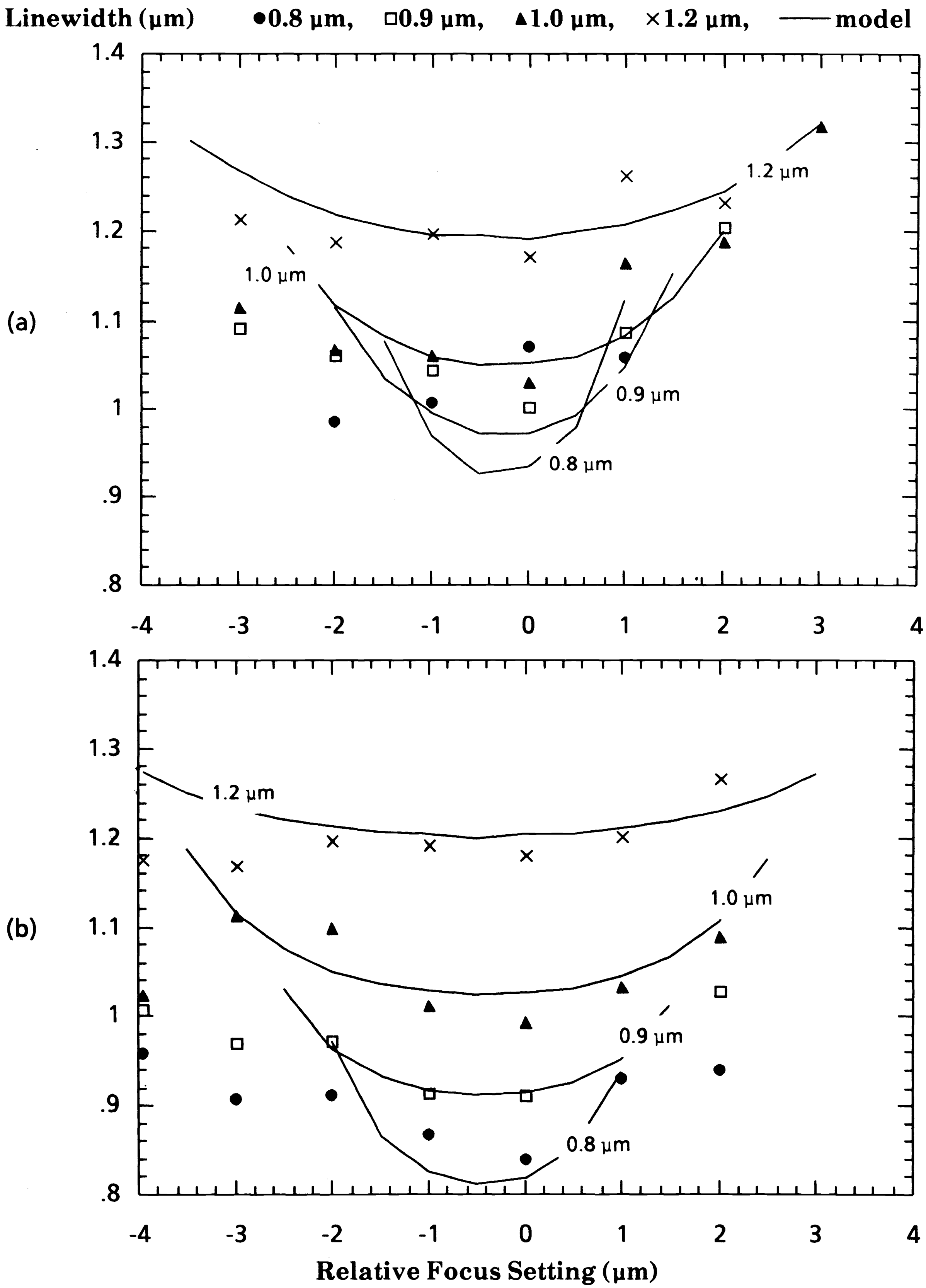


Figure 9: Focus effect - variation of linewidth with defocus: a.) without CEL, and b.) with CEL.

Diffraction Effects

Controlling the shape of a resist profile can be as important as maintaining control of its dimension. Figure 10 depicts several common resist profiles. The normal profile, obtained by a typical single layer positive resist process, has sloped sidewalls due to absorption and the nature of the development process [5]. The negative profile can be obtained using a negative resist (or image reversal of a positive resist) where absorption may overcome development properties and make the sidewall negatively sloped. The hourglass profile is obtained when forces compete to make the profile positive and negative. Usually, vertical resist profiles are the most desirable for purposes of pattern transfer and dimensional control. However, negative profiles are sometimes purposely created for metal lift-off. In a normal process, negative profiles can cause problems during etching and critical dimension measurement. Also, high aspect ratio features tend to topple over if the profile is too negative.

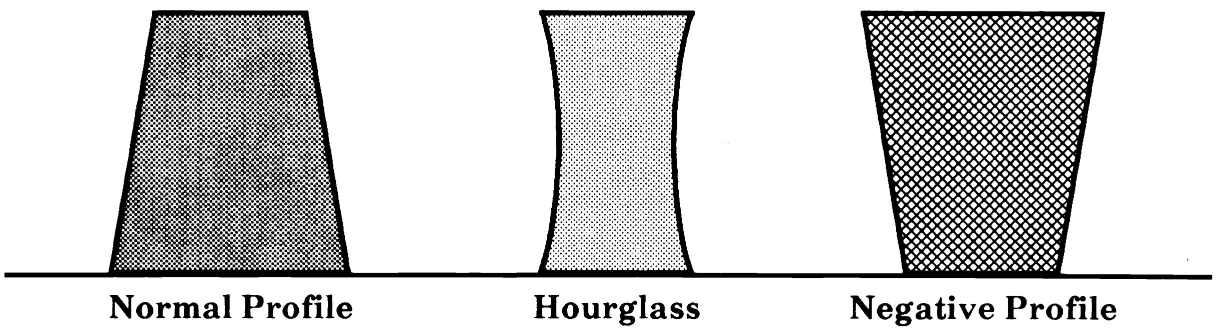


Figure 10: Typical photoresist profile types.

Under certain conditions, the use of CEL will contribute to the creation of hourglass or negative profiles. These anomalies in profile shape are not always experienced, but are a result of the interaction of the exposure tool, photoresist system and CEL used. We propose that the mechanism for the creation of these effects is diffraction. When a separate bleachable layer is placed on top of photoresist and is exposed to an aerial image, the bleached areas of the CEL act as apertures which diffract light. Typically one thinks of diffraction as occurring with a perfectly opaque mask with transparent apertures. However, diffraction also occurs with CEL, which acts as a diffuse mask.

To verify this mechanism, a modeling study was initiated to quantify the diffraction by the CEL and to determine if this phenomenon could be responsible for the creation of negative profiles. A modified Kirchoff's diffraction approach, previously introduced to model contact printing [1], was again modified to model diffraction by a diffuse mask [6]. The "mask" transmittance is determined using the standard model for CEL [7]. Because the transmittance varies with exposure time, these calculations must be repeated over a series of small time increments. Simultaneously, exposure of the photoresist is calculated. Development is carried out using the standard PROLITH algorithms. Figure 11 is a typical output of the CEL diffraction model showing a negative profile.

The model can now be used to predict the effects of processing variables on the formation of negative profiles. The model accurately predicts that higher optical densities (Ad) of the contrast enhancement layer contribute to greater diffraction effects. Figure 12 demonstrates the experimental results of varying the optical density of the CEL. Figure 12a is a SEM of a resist profile where a CEL of high optical density was used. Note the extreme negative profile. Figure 12b is a SEM of a resist profile where a moderate optical density CEL was used. Figure 12c shows a profile where a lower optical density CEL eliminates the negative profile. The model also predicts that higher numerical aperture (NA) steppers will exhibit greater diffraction effects. Most experimentally observed negative profiles have been on 0.42 NA systems.

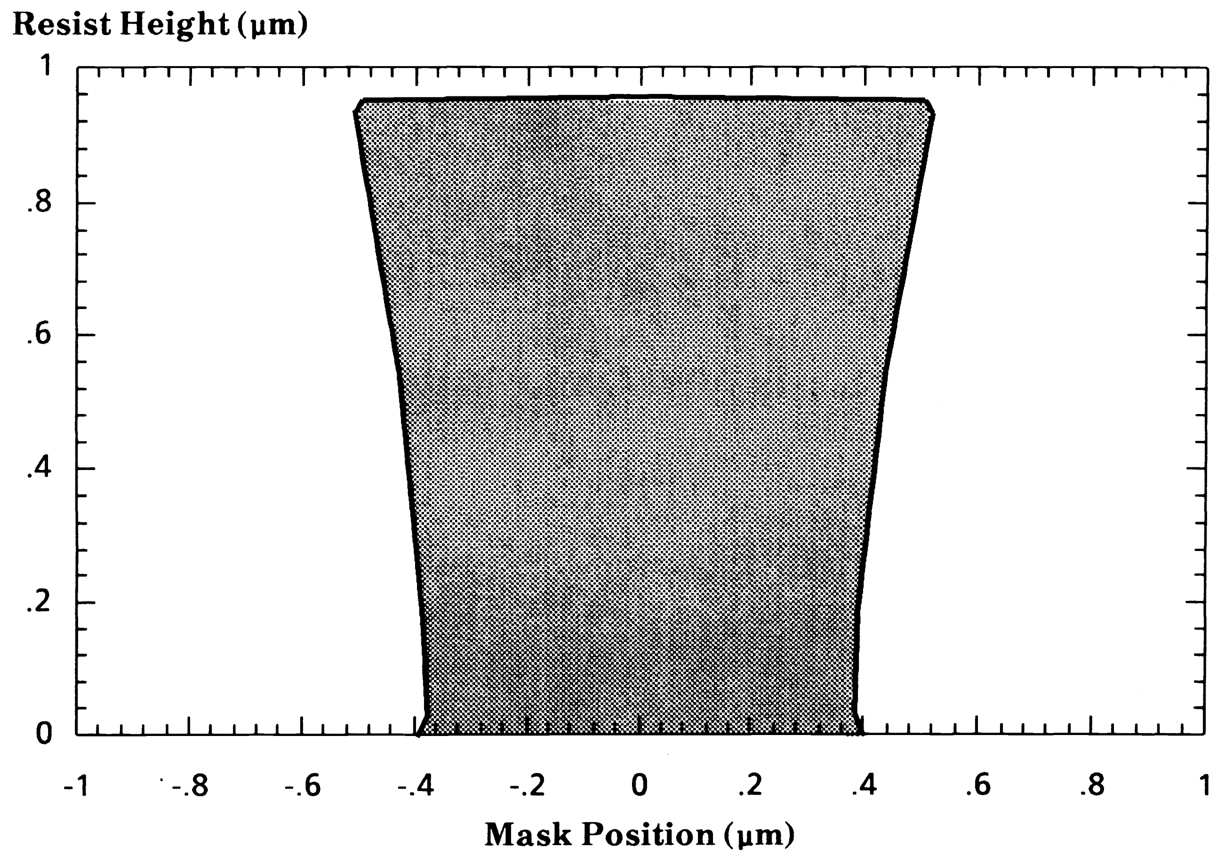


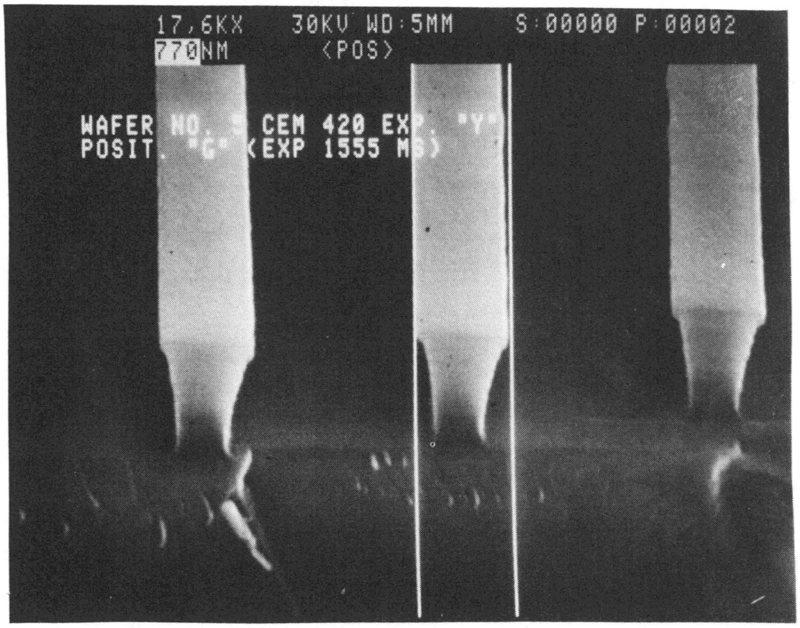
Figure 11: Typical negative profile simulated using the CEL diffraction model.

One of the most important variables in forming negative profiles is the development characteristics of the photoresist. Figure 13 is a contour plot showing lines of constant PAC within the resist after exposure through a CEL as predicted by the diffraction model. Depending on the threshold of PAC conversion needed by the photoresist/developer system for development, anything from positive to negative profiles can result. Resist/developer systems with a low PAC threshold concentration do not exhibit negative profiles. Also, over-exposure increases the degree of negative profiles.

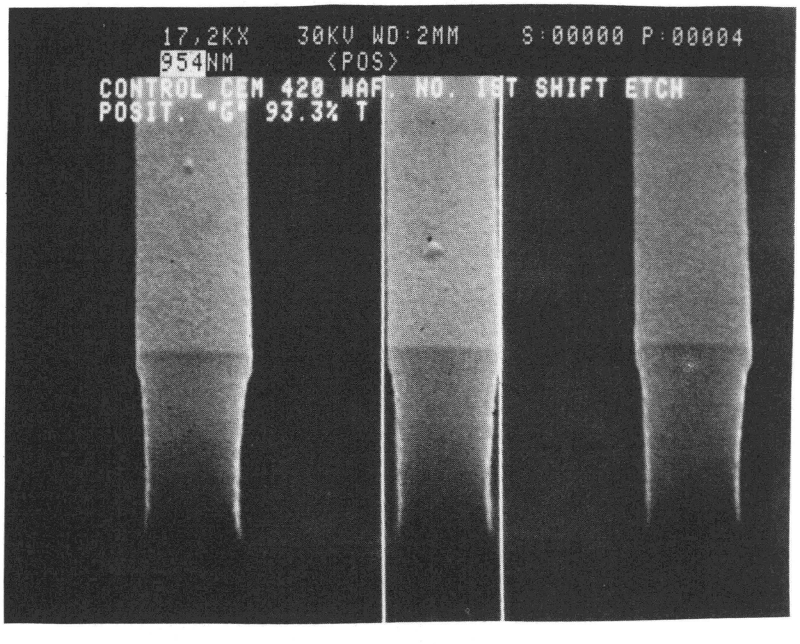
The new CEL diffraction model presented here has accurately predicted the contributors to negative profiles. By using this model, it was possible to quickly screen several possible variables for their effect on the profile shape. Negative profiles can be best controlled by adjusting the optical density of the CEL, or the development parameters of the photoresist. Since in many cases the properties of the photoresist are fixed for all practical purposes, G. E. has introduced a new material, ALTILITH™ CEM-420Z, which has a reduced optical density. This material has been successful in controlling negative profiles.

Conclusions

A study using both experimentation and computer simulation was initiated to determine the benefits of contrast enhancement lithography. An increase in development latitude was predicted by the modeling and observed experimentally. This increase is due to a higher than normal exposure of the center of a space causing a greater PAC gradient near the line edge. Experiment and model also agreed that CEL reduced the feature size effect, allowing better reproduction of the mask size for submicron features. The proximity effect was seen to be reduced with CEL, but PROLITH simulations failed to predict this trend.

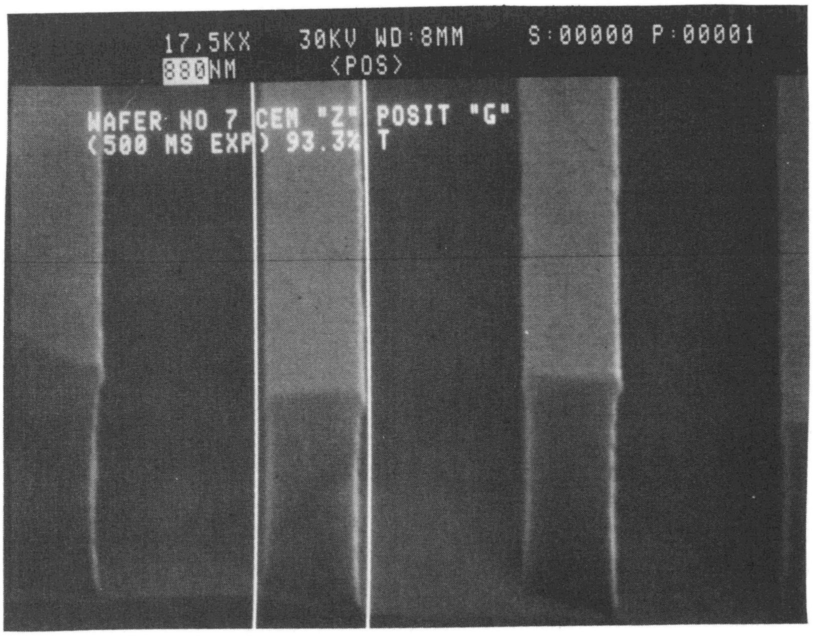


(a)



(b)

Figure 12: SEM micrographs depicting negative profiles for CEL materials with: a.) high optical density, b.) moderate optical density, and c.) low optical density.



(c)

Figure 12: SEM micrographs depicting negative profiles for CEL materials with: a.) high optical density, b.) moderate optical density, and c.) low optical density.

The effect of CEL on exposure latitude is still in question, with simulations and previous experimental data predicting an improvement and current data showing little discernable difference. CEL was found to have greater depth-of-focus, though only slightly, using linewidth as a measure, and significantly greater depth-of-focus using sidewall angle as the metric. Under certain circumstances negative profiles have been observed experimentally and a diffraction mechanism has been proposed to explain the phenomenon. Using a new diffraction model, the effects of the CEL, photoresist, and exposure tool on the onset of negative profiles has been accurately predicted. Based on this analysis, a new material, ALTILITH™ CEM-420Z has been introduced to control negative profiles.

Computer simulation is helpful in predicting trends in contrast enhancement lithography and in identifying the physical causes of these trends. With the exception of the proximity effect, the computer model PROLITH was found to closely match the observed behavior of contrast enhancement lithography.

Acknowledgments

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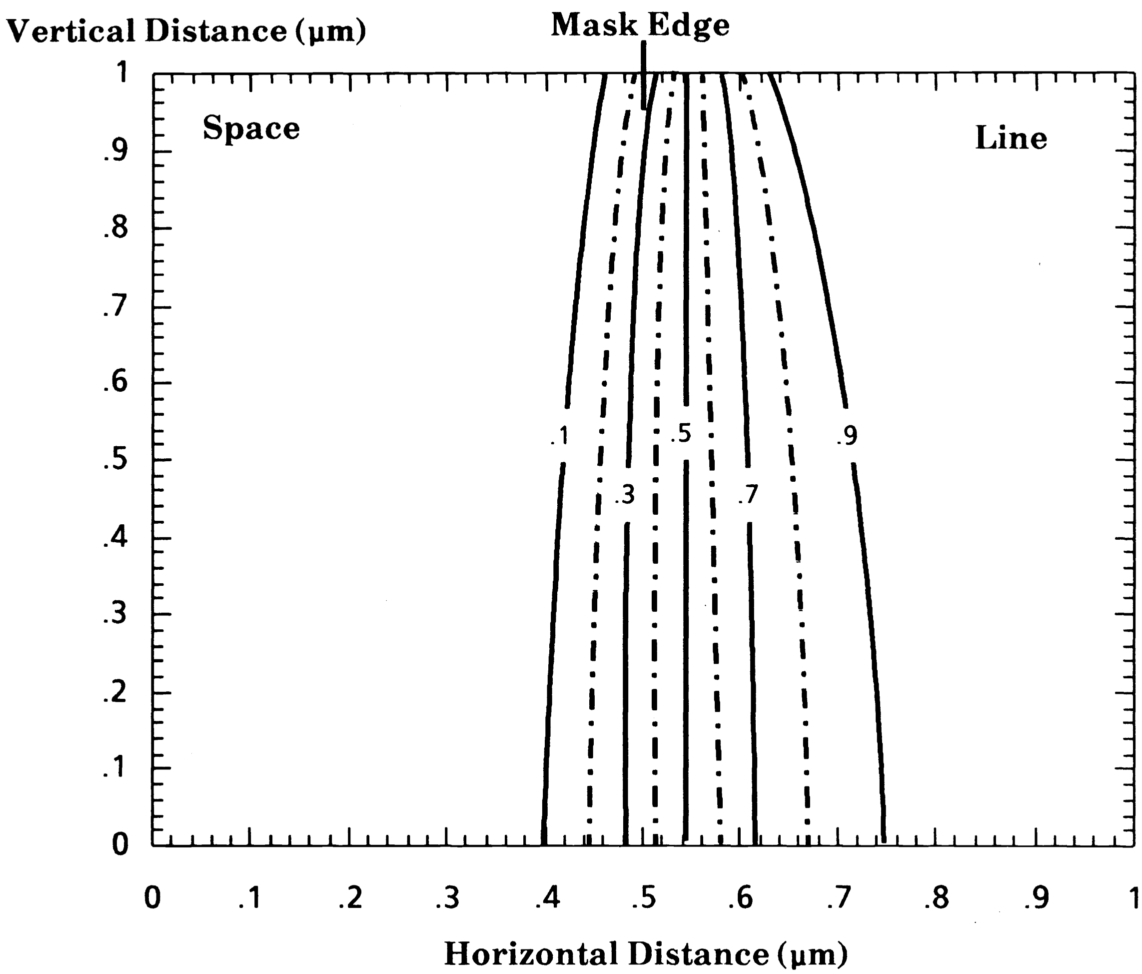

Figure 13: Contour lines of constant PAC concentration simulated using the CEL diffraction model.

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