GEOMETRY-DEPENDENT LINEWIDTH BIAS: SIMULTANEOUS PRINTING OF CONTACTS AND SPACES

by

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ABSTRACT

This paper discusses the linewidth bias between the printing of different feature types, especially for an isolated space versus a contact (square hole). The bias has been measured by SEM, as well as electrically. With immersion-develop, the bias can be large (~0.3 µm); however, with spray-develop, the bias approaches the theoretical limit predicted by simulations. The bias is also a function of resist thickness, decreasing as the thickness decreases. This result suggests that developer diffusion effects play an important role in determining the final linewidth.

INTRODUCTION

Simultaneous printing of different feature types (e.g., holes, isolated lines, or gratings) and sizes is a challenge in optical lithography. Due to differences in the aerial images, simple theory dictates that, to print these various features at a given nominal design dimension, the dose must differ.[1,3] Exposure-defocus (ED) diagrams have been described for a system with $k_1 = 0.64$ ($k_1 = W * NA / \lambda$, where W is the feature size of interest and NA is the numerical aperture of the exposure system).[2] By comparing the center of the ED trees, printing an isolated resist space requires 25% more exposure dose than printing an isolated resist line where both features are printed at the nominal feature size.[2] Conversely, if the exposure dose is fixed, then the space will be ~10% larger than the line. The amount of bias between different features is a function of the feature type, as well as the k_1 value (which is, in turn, a function of feature size, λ, and NA).

This paper focuses on the biases between contacts (i.e., square holes on the mask) and bars (i.e., clear mask areas) of varying lengths. The contact hole represents an extreme case, which frequently requires significantly increased doses. For a DRAM technology, it may be possible to simply expose a contact level with a higher dose by restricting the types of features on the mask (i.e., only contacts). However, for technologies such as BiCMOS, features (such as emitters) of varying aspect ratios ranging from square (1:1) to long bars (20:1) must be simultaneously printed. For example, it's important to control the area of the emitters. Thus, for a given design width, the printed width must be independent of the length of the emitter, i.e., a square must have the same width as a long bar. The mask design dimensions can be altered to compensate for these biases; however, if there are multiple feature sizes and types on the mask, this procedure may be impractical. Furthermore, the origin of the bias must be understood in order to control it.

EXPERIMENTAL

Selectilux P-3100 resist was spin-coated on wafers with a film stack of either 60 nm SiO_2 or 40 nm titanium nitride (TiN) over 500 nm SiO_2. The resist was coated at thicknesses ranging from 0.5 µm to 1.8 µm. For the thinner coatings, the resist was thinned in diglyme. In all cases (and with both substrate film stacks), thicknesses were adjusted to achieve a reflectivity maximum at 365 nm.

Wafers were exposed on i-line steppers with a numerical aperture (NA) of either 0.35 or 0.45. For the 0.45 NA steppers, a partial coherence, σ, of 0.5 was used. For the 0.35 NA stepper, σ = 0.7 was used. Wafers were developed in 0.18 N TMAH using either static immersion develop or spray-develop; the resist images were then transferred into the substrate, either by buffered HF etch (for the SiO_2 wafers) or by reactive ion etch (for the TiN wafers).

A non-destructive SEM was used to measure linewidths of developed resist or etched oxide patterns. Etched TiN patterns were measured electrically using a bridge resistor test structure.[4]

RESULTS AND DISCUSSION

Immersion Develop Data

Initially, a 4.0 minute immersion-develop was used for the photoresist processing. However, it produced considerable bias between the widths of the square contact holes and the 20 µm-long bars, as shown in Figure 1. For example, when the 1.0 µm space is printed at nominal size, then the 1.0 µm contact is too small, yielding a bias of ~ 0.15 µm. For 0.8 µm features, this bias increases to ~0.25 µm. Conversely, if the contact is printed to size, the space is too large, with a bias ranging from 0.1 µm to 0.15 µm for 1.0 and 0.8 µm features respectively. This data is summarized in Table 1.

To determine if the amount of bias was consistent with theoretical expectations, aerial image simulations were performed using SPLAT.[5] Figure 2 shows 0.8 µm hole and space simulations for a 0.45 NA, 365 nm exposure system with σ=0.5. The hole had higher intensity throughout the image for all intensities higher than 0.02. This higher intensity implies a larger linewidth for the hole. Thus, rather than explaining the observed bias, the aerial image simulations actually predicted a bias in the opposite direction. There are several possible explanations for this discrepancy: 1) the actual aerial image differs from the simulation for either the hole or the space due to non-idealities in the imaging system, such as lens aberrations; 2) the effect of defocus was not considered in the simulation, and for a resist thickness of > 1.0 µm, this may be an important factor; 3) aerial image simulations such as SPLAT are not sufficient predictors — simulations of developed profiles must be considered; and 4) non-ideal develop effects must be considered, such as diffusion of developer into, or by-products out of, the exposed regions. Developer diffusion effects will be especially important in small contact holes.

Spray Develop Data

Immersion-develop was replaced by a spray-develop process to improve the overall manufacturability. Figure 3a shows the linewidth of holes and spaces processed in a spray-develop for 5 minutes. The linewidths were plotted against exposure dose for nominal feature sizes of 0.8 and 1.0 µm. For the 0.8 µm features, the bias was reduced to less than half of that observed with an immersion-develop and, for the 1.0 µm features, the bias was almost eliminated. The bias was decreased even further with shorter spray-develop times (Figures 3b and 3c and Table 1); in fact, with a 1-minute spray-develop time, the bias reversed so that the holes were bigger than the spaces.

Linewidths can be predicted implistically by using just the aerial image simulation; if an ideal resist contrast is assumed, then the linewidth is the distance across an image at a given intensity level. Likewise, bias can be predicted by determining linewidths for the hole and space separately. This approach is simplistic because it ignores resist absorption, bleaching, and develop effects; nevertheless, the bias predicted agrees very well with that observed with the 1-minute spray-develop.

As mentioned above, there are at least four possibilities for the observed bias with an immersion develop to occur in the opposite direction from that predicted by aerial image simulations. Given that the shortest spray-develop process does give a negative bias (i.e., holes are bigger than spaces), it appears that the bias observed with the immersion develop is unrelated to non-ideal aerial images. The effect of defocus would be expected to be the same for both spray and immersion develop; and, even at 1.0 µm of defocus, the hole still has a higher intensity than the space throughout most of the image (Figure 4). Expanding the model to include develop, such as with SAMPLE,[6] would not be expected to make any difference since the hole has a higher intensity throughout the image. This leads to the fourth possibility — developer diffusion effects (not included in SAMPLE). For 1.6 µm of resist, the aspect ratio for a contact hole is 2:1; diffusion of fresh developer into the bottom of this region, or diffusion of depleted developer or developer by-products out of this region, may become important factors. The fact that a spray-develop process produces less bias than immersion develop is also suggestive of a diffusion effect being important.

One observation not readily explained is that the bias decreases as develop time decreases. Simplistically, one would expect diffusion effects to be less important with a longer develop time because there is more time to diffuse material in and out. Possibly, the different resist chemistries (i.e. lower concentration of converted photoactive compound) obtained with lower doses (longer develop times) are important. It may also be that the aerial images are not ideal; rather, they may cross over so that the space has a higher intensity at the center, and the hole has a higher intensity at the edge. At higher doses (corresponding to the lower intensity portion of the aerial image), larger holes would be predicted; and, at lower doses, larger spaces would be predicted.

Varied Resist Thickness

The possibility of developer diffusion was studied further by using varied resist thicknesses to alter the aspect ratio of the contact hole. The assumption was that, for thinner resists, diffusion would be less important. Wafers for this experiment were coated with either 0.5, 0.9, or 1.6 µm of resist. For exposures on the 0.45 NA stepper, SiO_2 wafers with a 1 minute spray-develop were used. Measurements were made on the SEM after develop as well as after oxide etch and resist strip (Table 2). As expected, no significant bias was observed with any of the resist thicknesses, either after develop or etch. If the spray-develop process shows less bias due to reduction of diffusion effects, decreasing the thickness would be expected to only further improve the situation. However, since the biases obtained with thick resist were close to the theoretical limit, as defined by the aerial images, the thinner resists should not have much effect.

Wafers were also processed under conditions where a bias would be expected, i.e., immersion-develop. They were exposed on the 0.35 NA stepper and immersion-developed for 1 minute. TiN substrates were used to allow both SEM and electrical linewidth measurements. The width of a 5 μm bar with spaces on both sides at the feature size of interest, was measured. The space width was then calculated: (space width) = (pitch) – (actual width of the 5 μm bar). The pitch was taken as 5.00 + W, where W is the feature size of interest. The contact holes were measured using a test structure and algorithm derived by B. Lin et al.[7] The average width of the contact holes can be determined by comparing the resistance of two 10 μm wide bars (one contains an array of contact holes). In the original work, an empirical modification of the analytically derived equation was required to achieve a good fit to the larger contact holes. No attempt was made to further modify the equation, aside from comparing electrical and SEM linewidth measurements. Both 0.7 and 1.0 μm feature sizes were measured. The 1.0 μm features were chosen because they represent the same k_1 factor as for 0.8 μm features exposed on a 0.45 NA stepper. The smaller features were chosen to represent the case of printing at the resolution limit of the tool.

The electrical linewidth data for 0.7 μm holes and spaces is shown in Figure 5 for 0.5 μm thick resist. The linewidth versus exposure curves are much smoother than the SEM measurements shown in Figures 1 and 3, due to the higher precision of the electrical measurements. The bias between 0.7 μm spaces and holes was plotted versus hole width for three resist thicknesses (Figure 6); Figure 7 shows the same information for 1.0 μm features. This data is summarized in Table 3 for both 0.7 and 1.0 μm features. Several observations can be made: 1) the bias decreases with increasing hole width, especially for the 0.7 μm features; 2) the bias is larger with the 0.7 μm features; and 3) the bias decreases with decreasing thickness.

Aerial image arguments can be used to explain the first two observations. Figures 8 and 9 show aerial images obtained from SPLAT for 0.7 and 1.0 μm features, respectively. Since the contact-hole test structure consists of an array which is four contacts wide in a 10 μm wide bar, both edge and center contacts were simulated; the differences were negligible (intensity was within 0.002 throughout the image), so only the center contacts are shown. Figure 8 illustrates that, by using the simplistic approach discussed earlier, the hole prints at the nominal 0.7 μm, for a threshold intensity of 0.27. For the same intensity, the space is 0.04 μm wider. If a higher intensity is used so that the hole prints at 0.50 μm, the bias increases to 0.09 μm. This could explain increased bias at lower dose, but not to the extent shown in Figure 6. Another important factor is that intensity in the center of the image is much lower for a hole than for a space (Figure 8); This could lead to slower development in the center, which would cause a smaller linewidth. The effect of a difference in the central intensity upon the development process can be predicted using SAMPLE. Figure 10 shows simulated developed images for contact holes and spaces as a function of develop time. The simulations were done using the AZ1370 photoresist optical parameters (A, B, and C) and develop-rate constants (E_1 - E_3)[8] because those parameters were unavailable for the Selectilux resist. The simulations were performed for a film stack of 1.6 μm of resist / 40 nm TiN / 500 nm oxide / silicon; the bias, measured at the bottom of the images, decreased with increasing develop time. Figure 11 shows the bias predicted by simple aerial image calculations and SAMPLE, along with the measured bias, as a function of contact-hole size. Although the SAMPLE predictions were closer to the measured bias, there was still an offset, especially with the thicker resist. The choice of optical parameters and develop-rate constants will undoubtedly have an effect on the bias. For example, the addition of a surface inhibition in the develop model might increase the bias because it could exaggerate the effect of the difference in central intensity. Developer effects not included in SAMPLE may be important, and could result in increased bias due to developer diffusion effects. It is also possible that, at least at low doses, some of this increased bias is due to other factors such as partially etched holes, leading to erroneous electrical linewidth measurements or improper calibration of the contact hole to electrical measurements.[4]

Comparing Figures 8 and 9, it is apparent that a larger bias was predicted for the 0.7 μm features. From the simplistic approach, however, negative bias (i.e., larger holes) would be expected for 1.0 μm features. Even when using a more complete model such as SAMPLE, a negative bias will still be predicted for the 1.0 μm features since the hole has a higher intensity throughout the aerial image (Figure 9). Therefore, while the simulations predict a bias for the 0.7 μm features, they do not predict the bias observed with the 1.0 μm features. These discrepancies, coupled with the observation that the bias decreases with decreasing resist thickness, lead to the probability that developer-diffusion effects can play a strong role in determining line sizes. Another possibility is that actual aerial images might differ from those simulated using SPLAT, due to lens aberrations. The fact that the measured bias can approach the bias predicted with the ideal aerial images (Figure 3c and Table 1) suggests that non-ideal aerial images do not play a major role. Other factors also support this conclusion: data for X- and Y- oriented lines show little difference, suggesting negligible astigmatism; measurements come from the center of the field, where lower-order aberrations should be minimized; and the same effect is observed on two different lens types (low and high NA).

Previous reports have suggested that there might be an offset between electrical and SEM linewidth measurements due to effects such as the slope in the sidewall of the conducting line.[9] Other factors, such as grain structure in the conductor, might also contribute to a measurement offset. To characterize this offset, SEM measurements were made. The 0.7 μm holes and spaces were measured (Figure 12) and compared to electrical line-width measurements from the same wafer; there was considerable offset between the measurements, ranging from 0.1 to 0.2 μm. The offset between SEM and electrical measurements was comparable for both spaces and contacts. SEM measurements of 1.0 μm features gave similar results.

Other measurements suggest that the electrical measurement offset is less than 0.1 μm; therefore, some of the offset in Figure 12 may be due to improper SEM calibration. The actual amount of the offset does not at all change the conclusions any because the offset is roughly the same for contact holes and spaces.

SUMMARY

The biases between spaces and contact holes were studied for varying image sizes on two different stepper systems and were found to be significant with an immersion-develop; the spaces were from 0.10 to at least 0.35 μm larger. For an immersion-develop, the bias decreased with decreasing resist thickness and increased with decreasing feature size. Spray-develop can reduce the bias to levels consistent with that predicted by theory. The reduction of bias with spray-develop or with decreased resist thickness appears to be due to the reduced importance of developer-diffusion effects under these conditions. The increased bias with smaller feature sizes can be partially explained with theoretical considerations, as seen from aerial image and SAMPLE modelling. However, developer-diffusion effects are also felt to be important considerations.

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Feature Size (µm)	Resist Thickness (µm)	Bias (Space-Hole), Nominal Hole Width (µm)	Bias (Space-Hole), Nominal Space Width (µm)
0.7	0.5	0.15	0.21
0.7	0.9	0.25	0.35
0.7	1.6	0.35	(Hole Not Open)
1.0	0.5	0.09	0.09
1.0	0.9	0.15	—
1.0	1.6	0.20	0.26

Table 1. Linewidth bias between contact holes and spaces, for various develop conditions. Biases were determined from SEM measurements a least-squares fit to the actual data.

Resist Thickness (µm)	Measurement Type	Bias (µm)
0.5	Resist Image	0.03
0.9	Resist Image	0
1.6	Resist Image	0
0.5	Etched Image	0
0.9	Etched Image	<0.03
1.6	Etched Image	<0.02

Table 2. Linewidth bias between contact holes and spaces, for varied resist thickness. Biases were determined from SEM measurements after develop or after oxide etch and resist strip. The biases were the same regardless of whether the space or contact hole was printed at nominal size.

Feature Size (µm)	Develop Conditions	Bias (Space-Hole), Nominal Hole Width (µm)	Bias (Space-Hole), Nominal Space Width (µm)
0.8	Immersion, 4 min	0.16*	0.24
1.0	Immersion, 4 min	0.10*	0.35
0.8	Spray, 5 min	0.08	0.07
1.0	Spray, 5 min	0.01	0.01
0.8	Spray, 2 min	0.02	0.02
1.0	Spray, 2 min	0	0
0.8	Spray, 1 min	-0.03	-0.03
1.0	Spray, 1 min	-0.04	-0.04

*Extrapolations were needed to obtain the bias.

Table 3. Linewidth bias between holes and spaces, for varied resist thickness. Biases were determined from electrical linewidth measurements.

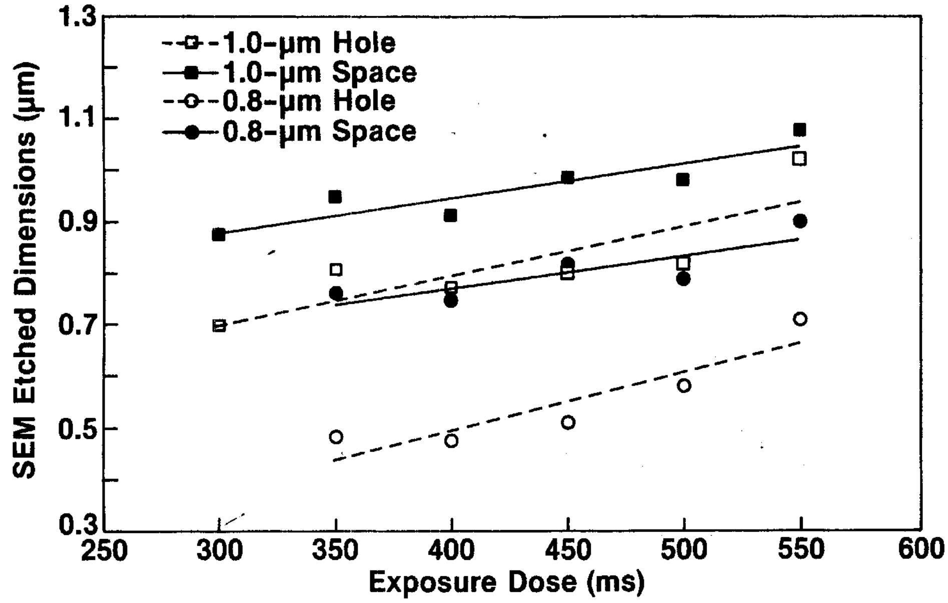


Figure 1. SEM linewidth vs. exposure-dose curves for nominal feature sizes of 0.8 and 1.0 μm. A 4-minute immersion develop was used.

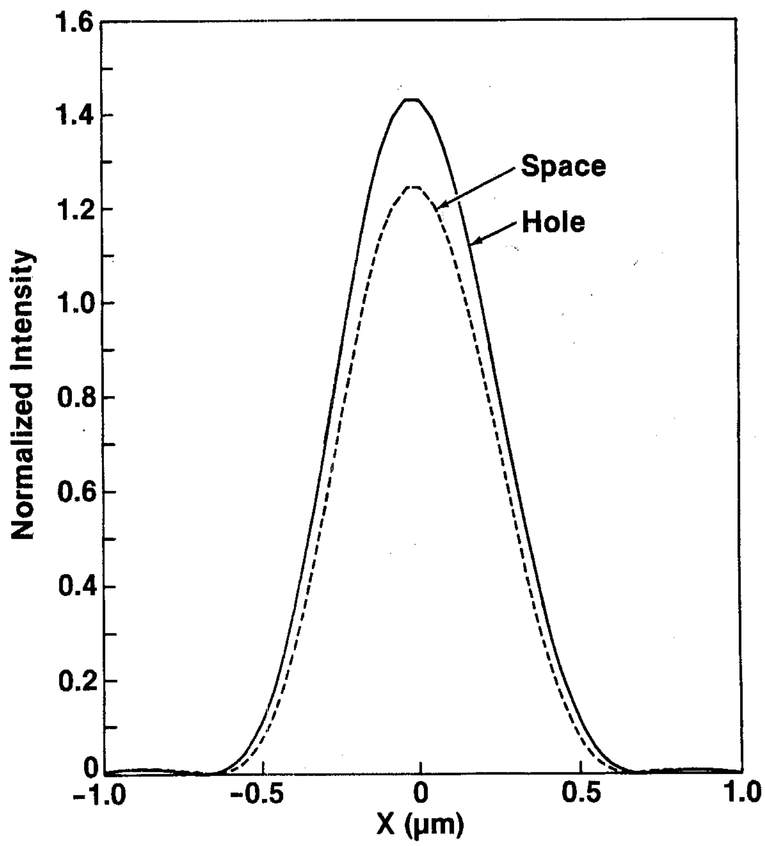
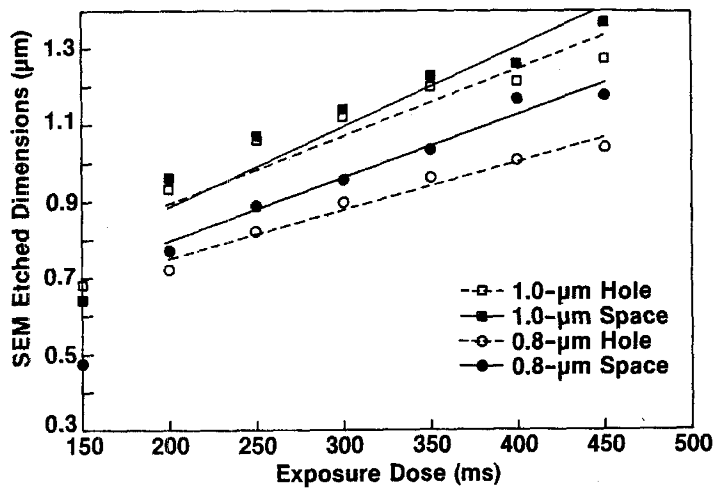
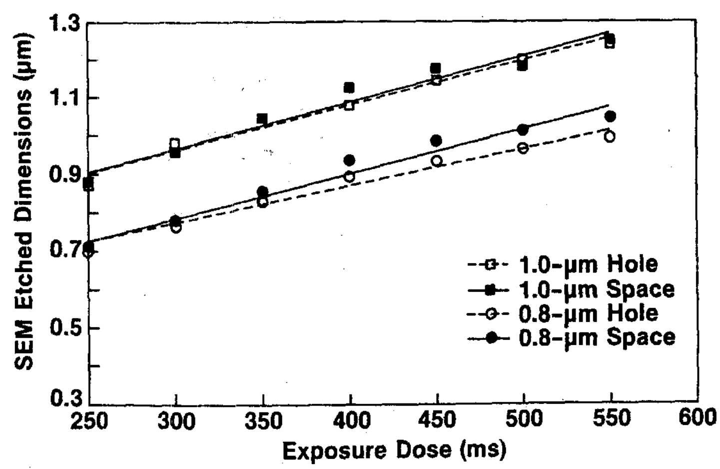


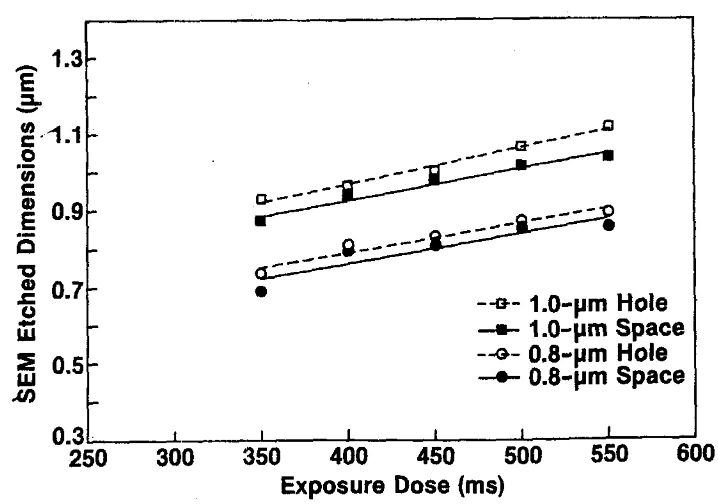
Figure 2. Aerial image simulations for both a 0.8-μm hole and space ($\lambda = 365$ nm; NA = 0.45; $\sigma = 0.5$; defocus = 0 μm). The intensity, I, was nomalized such that I = 1.0 in large clear (no chrome) areas on the mask.



a)



b)



c)

Figure 3. SEM linewidth vs. exposure-dose curves for spray-develop times of (a) 5 minutes, (b) 2 minutes, and (c) 1 minute.

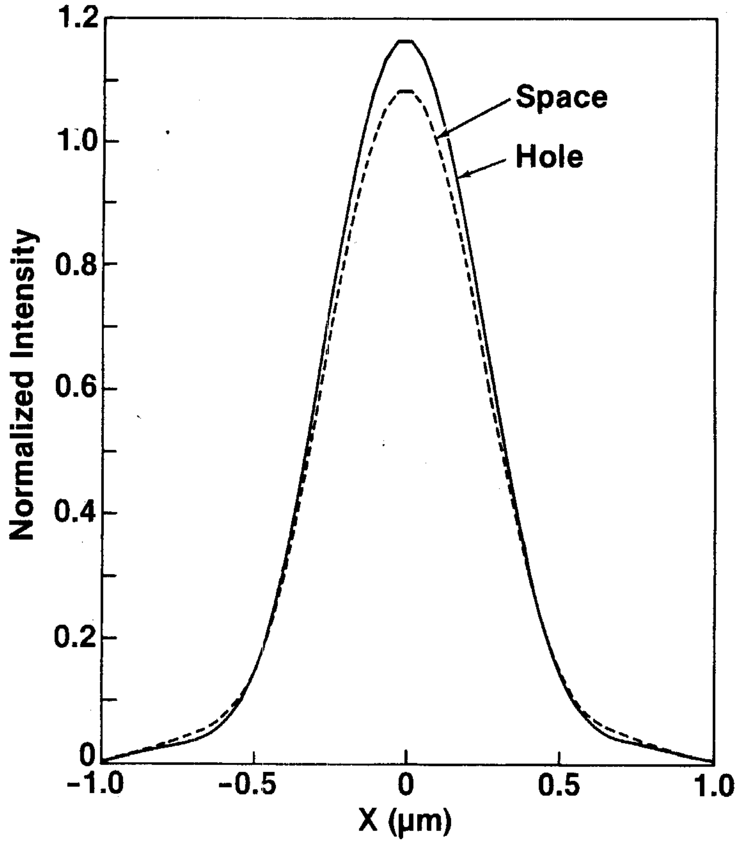


Figure 4. Aerial image simulations for both a 0.8-µm hole and space ($\lambda = 365$ nm; NA = 0.45; $\sigma = 0.5$; defocus = 1.0 µm).

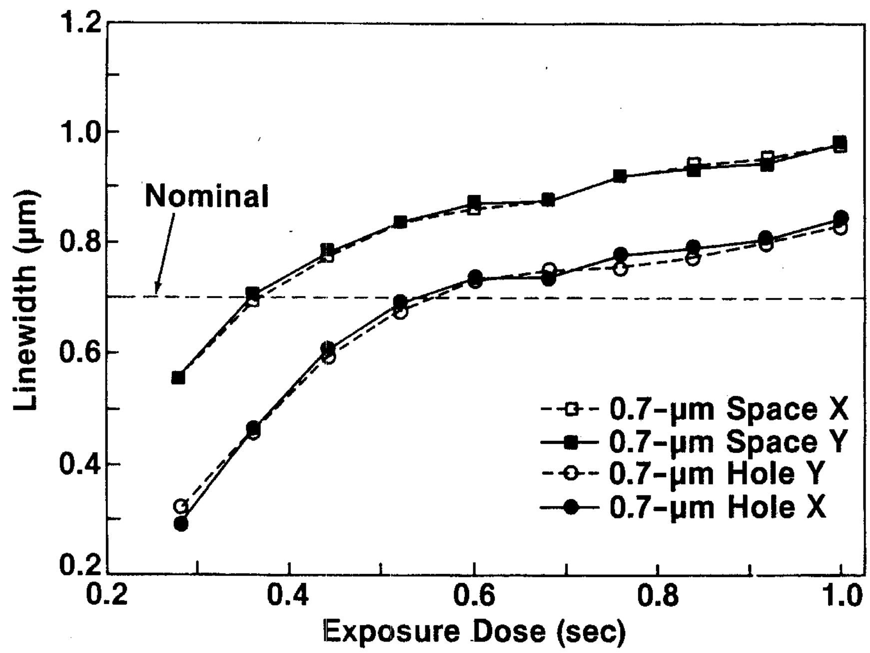


Figure 5. Electrically measured linewidth vs. exposure dose for 0.7-µm features. Data was obtained using 0.5-µm resist.

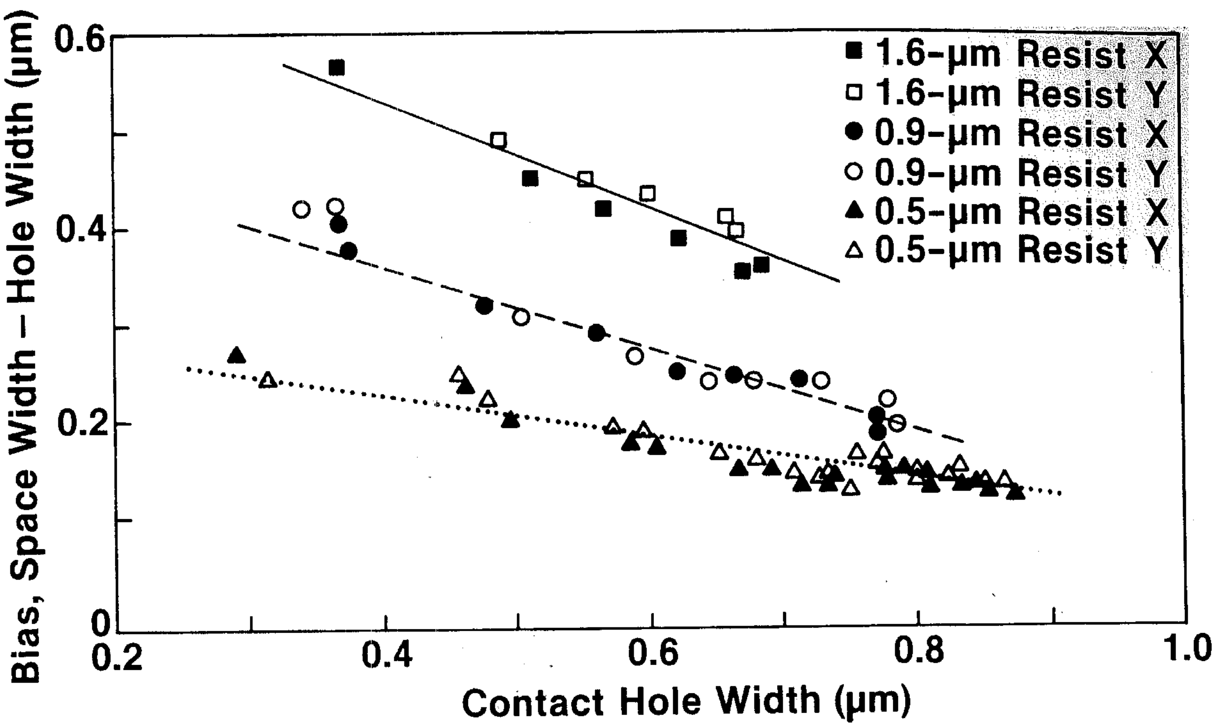


Figure 6. Bias (space width - contact width) vs. contact-hole width for 0.7-µm features, for three different resist thicknesses. Data is based upon electrical linewidth measurements.

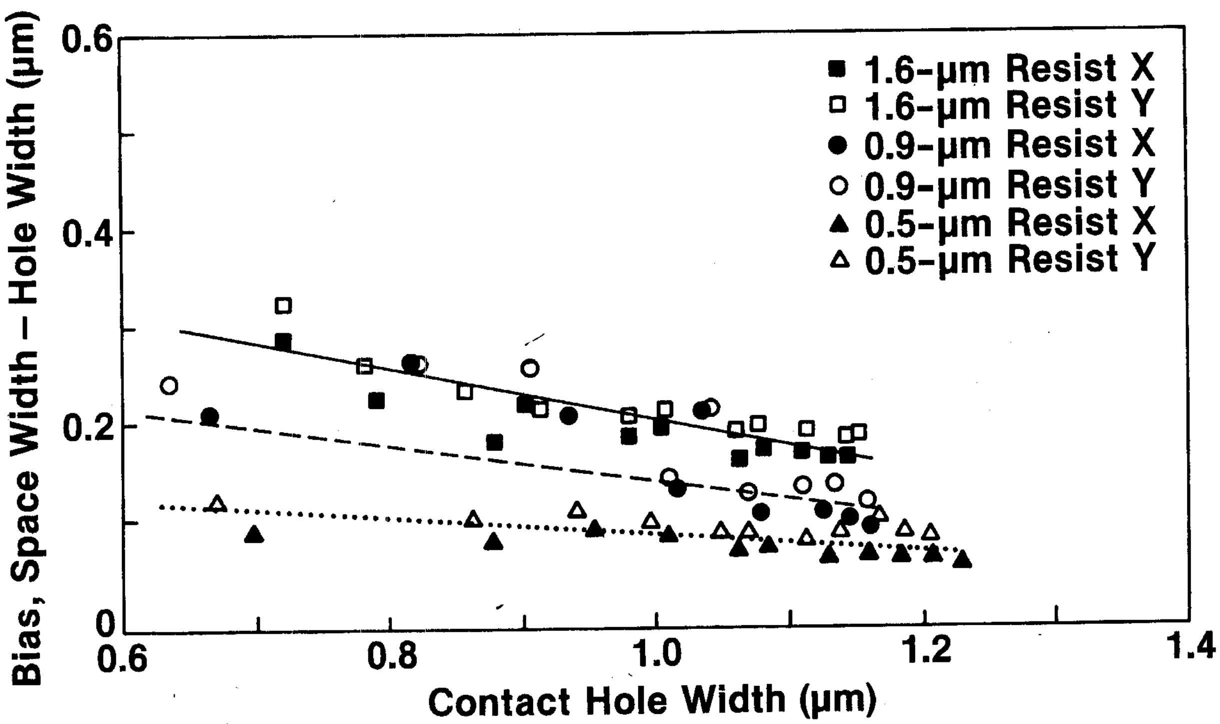


Figure 7. Bias (space width - contact width) vs. contact-hole width for 1.0-µm features, for three different resist thicknesses. Data is based upon electrical linewidth measurements.

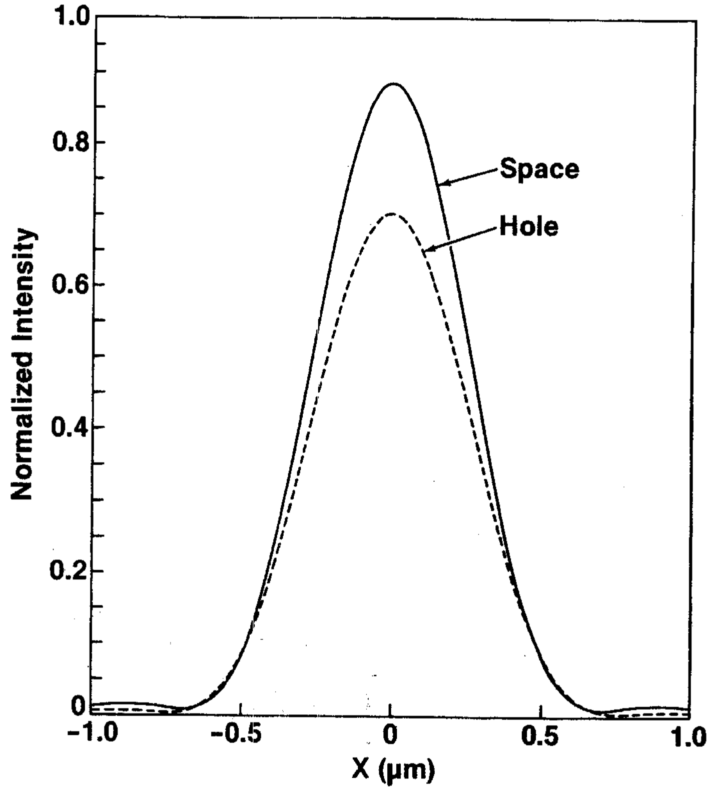


Figure 8. Aerial image simulations for both a 0.7-μm hole and space ($\lambda = 365$ nm; NA = 0.35; $\sigma = 0.7$; defocus = 0.0 μm).

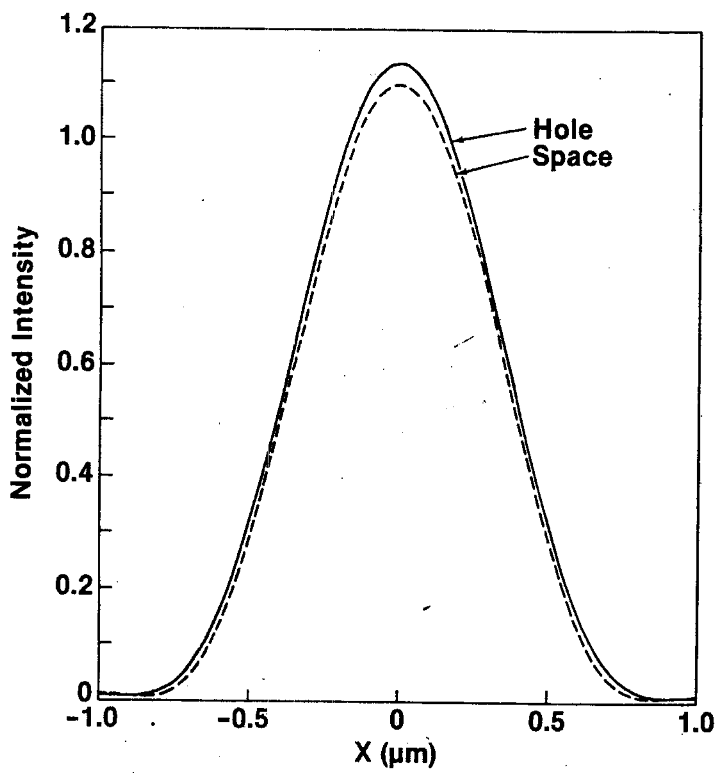


Figure 9. Aerial image simulations for both a 1.0-μm hole and space ($\lambda = 365$ nm; NA = 0.35; $\sigma = 0.7$; defocus = 0.0 μm).

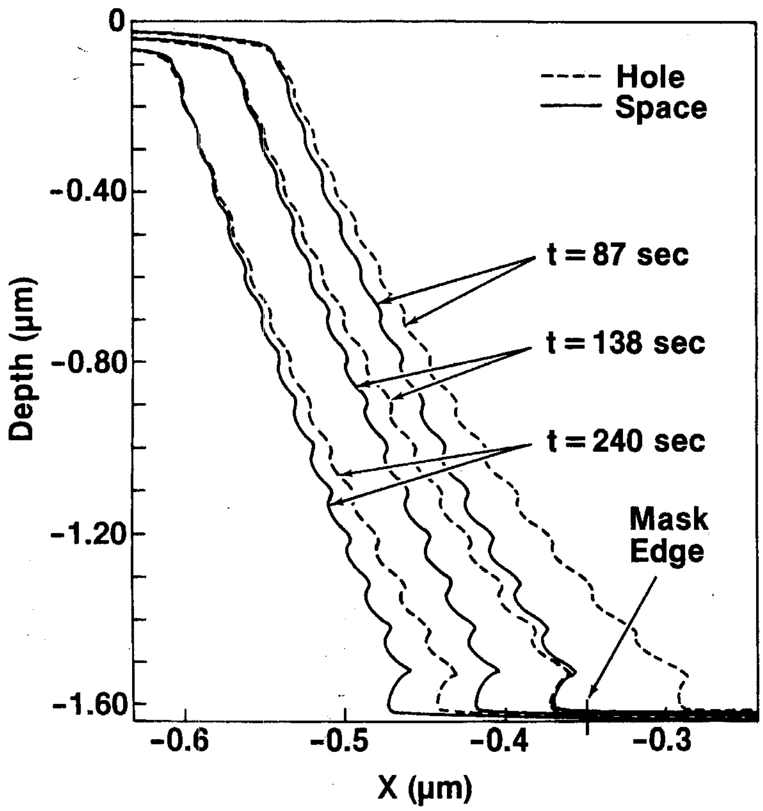


Figure 10. SAMPLE simulations of developed profiles for contact holes and spaces for three different develop times. The aerial images in Figure 8 were used as input for these simulations.

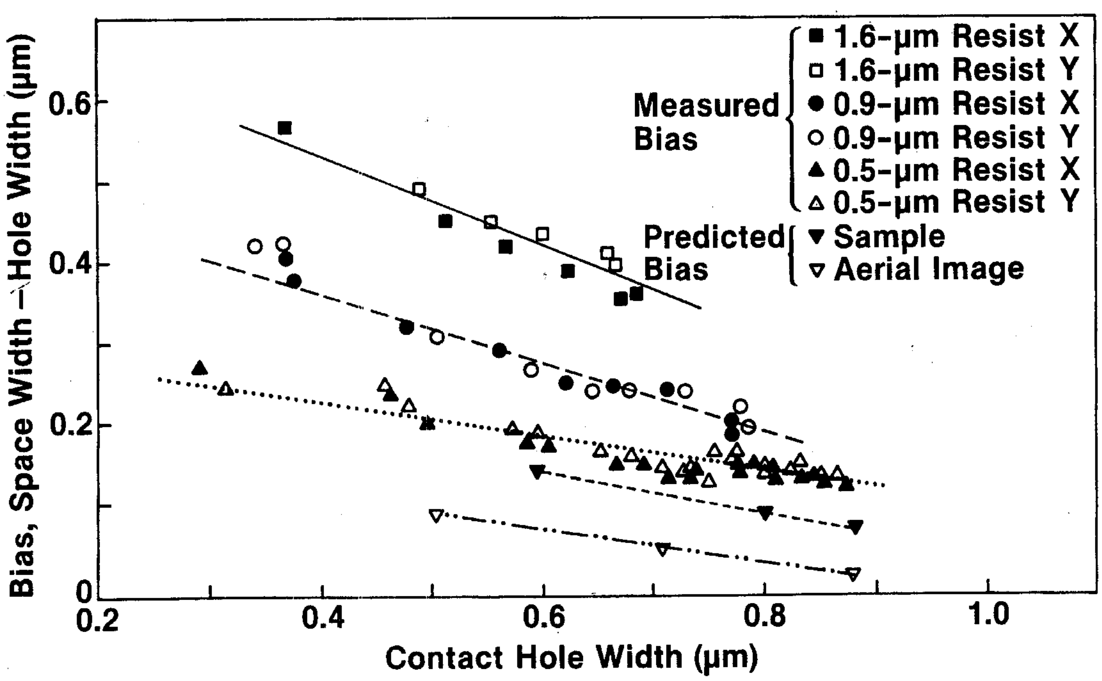


Figure 11. Predicted and measured biases as a function of contact-hole width, for 0.7-μm features.

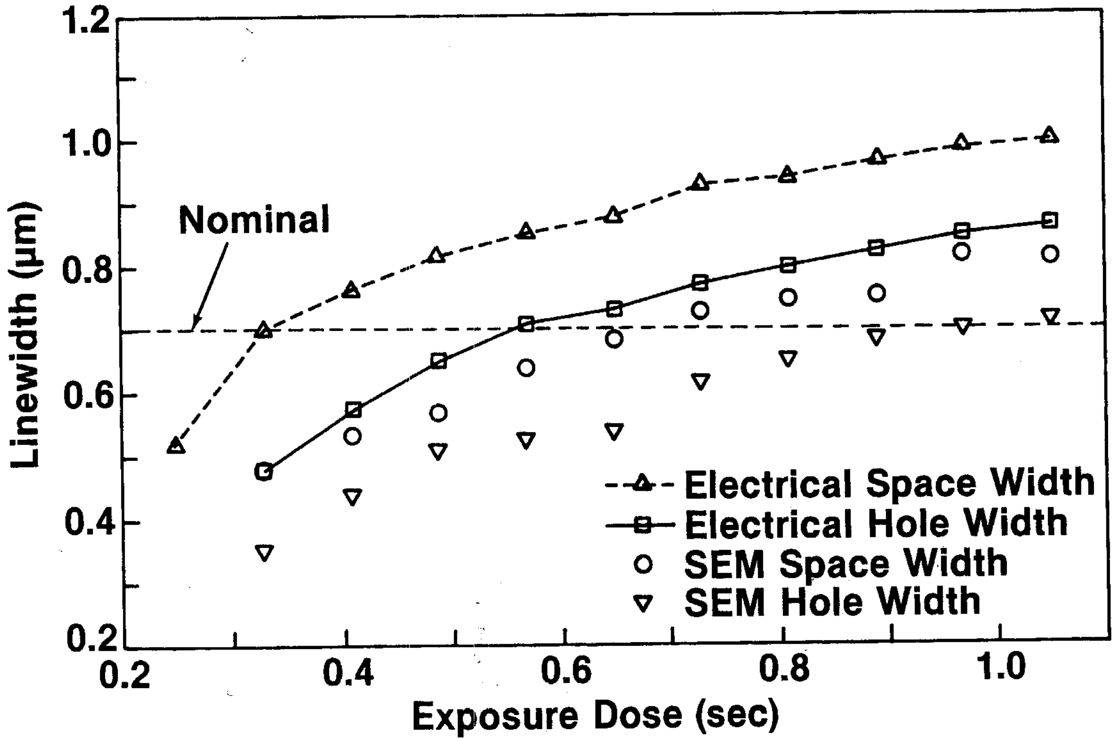


Figure 12. SEM and electrical linewidth measurements vs. dose, for 0.7-µm features.