0.5 Micron Photolithography using High Numerical Aperture I-Line Wafer Steppers

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Abstract

Results are presented from a new high numerical aperture (NA 0.48) i-line 5X reduction lens which resolves 0.5 micron lines and spaces over greater than 1 micron depth of focus in several commercially available i-line resists. The performance of this lens is contrasted with that of a NA 0.40 i-line lens. The NA 0.40 lens has better depth of focus for 0.7 microns lines and spaces (L/S) and larger, while the NA 0.48 lens has better depth of focus for L/S smaller than 0.7 microns down to a resolution cutoff near 0.35 micron L/S.

Other characteristics of the lens such as its relative insensitivity to absorption heating effects and its behavior as a function of the overpressure of He gas within the lens are explored.

Simulation work suggests that a NA of between 0.5 and 0.55 is optimum for printing 0.5 micron L/S. Further, it suggests that there may be sufficient depth of focus at 0.4 micron L/S to make i-line a competitor to DUV lithography for the 64 Mbit DRAM generation.

1. Introduction

Due to impressive improvements in lens design and manufacturing, it has been possible to support the microelectronics industry throughout the 1980s with successive generations of higher NA, wider field g-line lenses. However, as minimum linewidths shrink to 0.5 um and below, i-line lithography will supplant g-line for IC fabrication. The growing maturity of i-line lithography threatens to forestall the advent of deep UV lithography using excimer laser steppers until the 0.35 micron generation and perhaps beyond.

Figure 1 shows the evolution of pixel count per field for i-line lenses introduced by three different lens manufacturers over the past several years. The pixel count is the number of resolution elements per maximum square field, where the side of one pixel is equal to 0.8 λ/NA. The trend line shows the introduction of lenses capable of 10^9 pixels per field in 1990.

2. Resolution and Depth of Focus for 2500/40 and 5000/50 Steppers

In this paper there will be discussion of two of these lenses, the

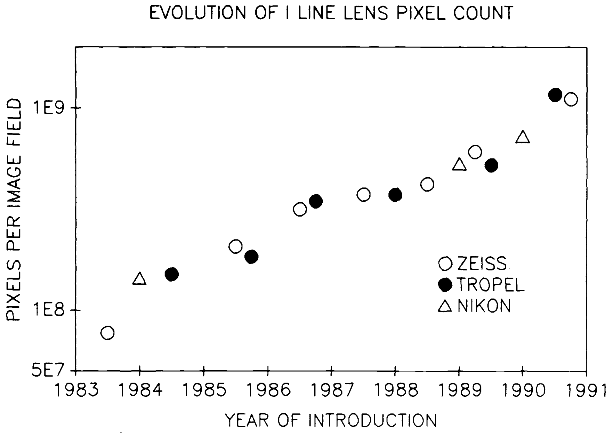


Figure 1. (above)

Table 1. (right)

I LINE LENS SPECIFICATIONS

	Zeiss 10-78-58	Zeiss 10-78-65
Numerical Aperture	0.40	0.48
Wavelength (nm)	365	365
Field Diameter (mm)	21.2	21.2
Partial Coherence	0.54	0.61*
Resolution (k = 0.8)	0.73 um	0.61 um
Rayleigh DOF	± 1.14 um	± 0.79 um
k @ 0.5 um	0.55	0.66
First Lens Recieved	October 1987	August 1989
Stepper	PAS 2500/40	PAS 5000/50

*Other values of partial coherence are available but are not yet characterized.

Zeiss 10-78-58 and the 10-78-65. The operating parameters of the two lenses are given in Table 1. The chief difference between these two lenses is the numerical aperture (NA), 0.40 for the 58 lens and 0.48 for the 65 lens. The 58 lens was first introduced in 1987 and the 65 lens in 1989. The 0.40 NA lens is mounted in the ASM-L PAS 2500/40 wafer stepper and the 0.48 NA lens is mounted in the PAS 5000/50 stepper.

The imaging characteristics of the 10-78-58 lens are exhibited in Figure 2a in which line/space pairs from 0.8 micron down to 0.45 micron are shown in SEM cross section. 1.17 um thick MacDermid 1024 i-line resist was used with a 0.36 um thick, water soluble, contrast enhancement layer on bare silicon. Corresponding contact holes 0.8, 0.7, and 0.6 micron on a side are shown. It can be seen that the linearity cutoff is near 0.45 um L/S and 0.6 micron contact. Figure 2b shows that 0.6 um contacts can be resolved fully with a 20% overexposure.

Figure 3 shows the behavior of linewidth versus defocus for 0.5, 0.6, 0.7, and 1.0 micron L/S for the 0.40 NA lens using 1.23 micron thick i-line resist on silicon. Figure 4 shows the equivalent data for the 0.48 NA lens. The linewidth measurements are made from SEM cross section micrographs.

Note that 0.5 micron imaging is possible for both lenses but that the 0.48 NA lens exhibits better linearity with respect to the 0.6 micron lines and spaces. Also note that the curves for the 0.7 and 1.0 micron features are much wider for the 0.40 NA lens, demonstrating that while the higher NA may have better focus latitude for the smallest features, there is a penalty paid for imaging the larger features.

Figures 5 and 6 show the corresponding resist sidewall angle data, taken from the same micrographs used for linewidth measurements.

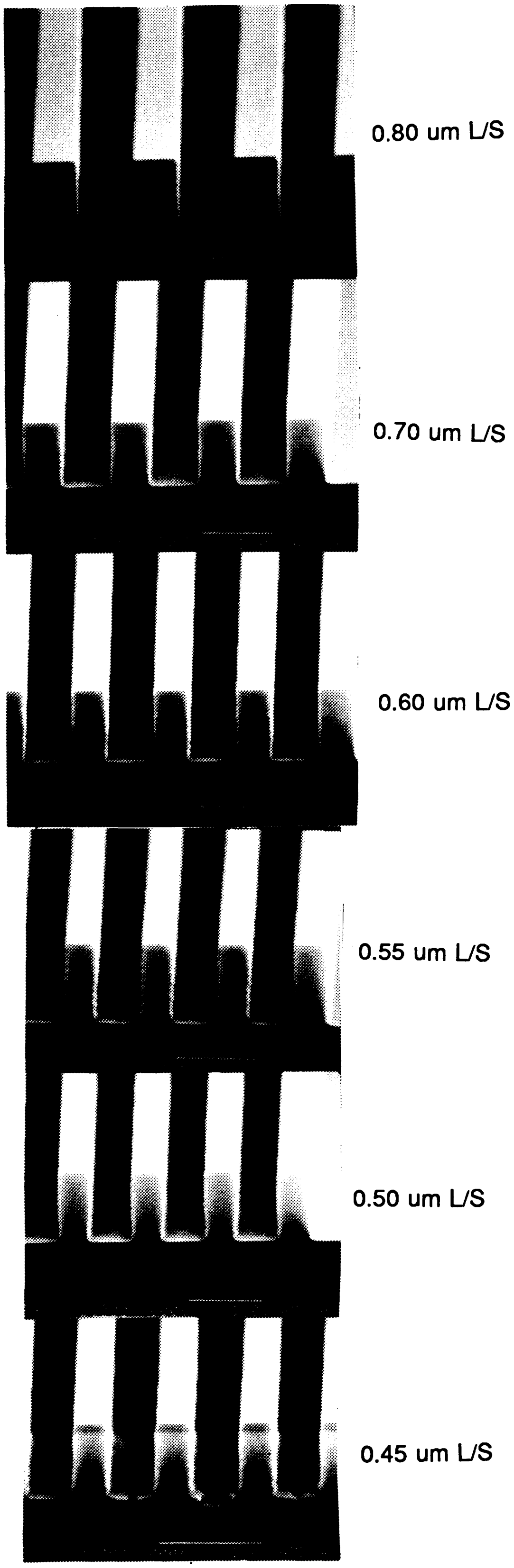


Figure 2a. SEM photographs of 0.80 um down to 0.45um line and space patterns of MacDermid 1024 resist with i-WS-Contrast enhancement material. ASM PAS 2500/40, NA 0.40 I-line, Exposure Dose 330 mJ/cm2

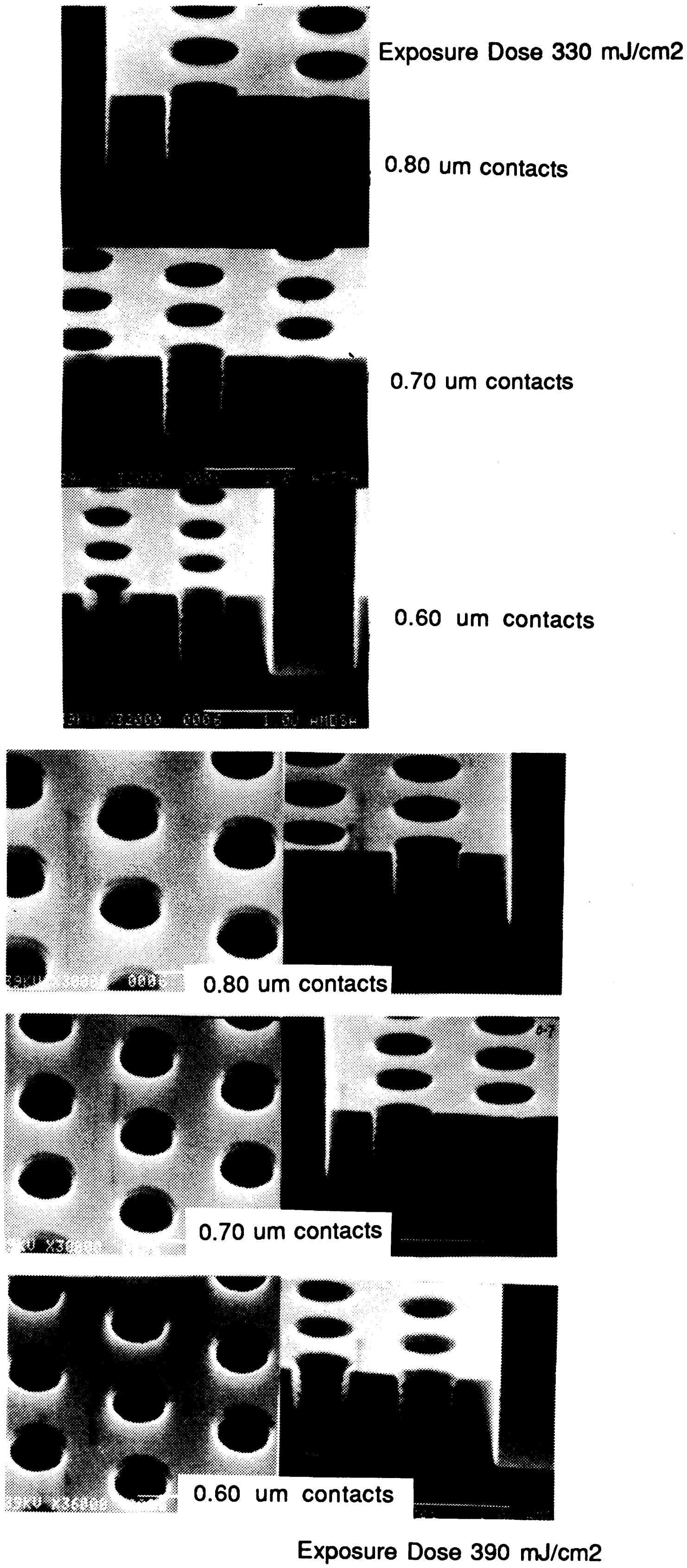
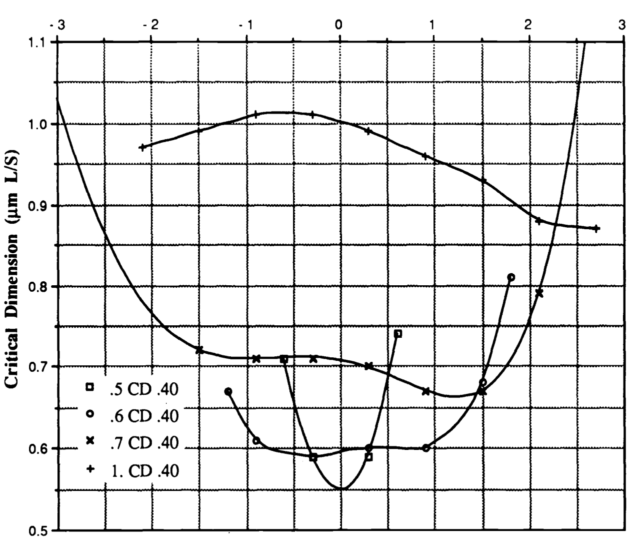


Figure 2b. SEM photographs of 0.80 um, 0.70 um and 0.60 u contact hole patterns with i-WS -contrast enhancement material. ASM PAS 2500/40, NA 0.40 I-line

D.O.F for ASM PAS 2500/40
1.23µm Resist

Figure 3.



D.O.F for ASM PAS 5000/50
1.23µm Resist Thickness

Figure 4.

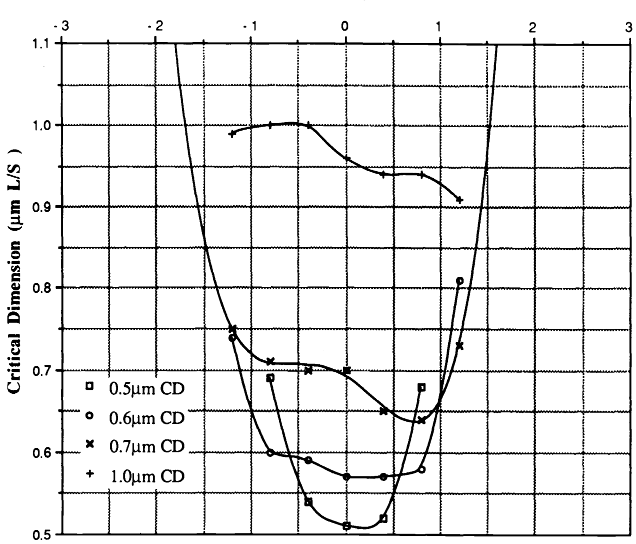


Figure 5.

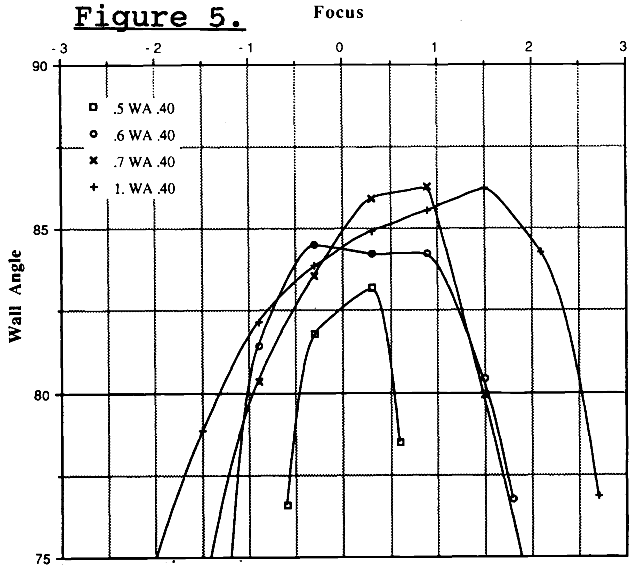
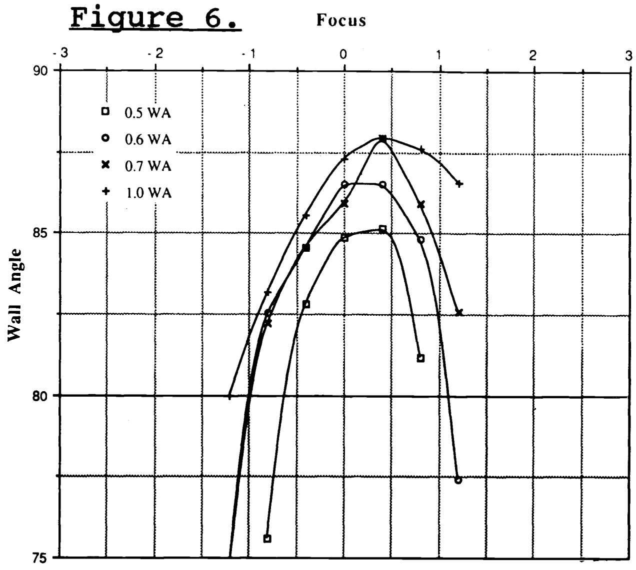


Figure 6.



The fact that depth of focus decreases for larger features with increasing NA is not intuitive at first. To visualize the effect, think of viewing in an optical microscope as one changes the objective, from 5X (low NA) to 10X, to 40X, and then to 100X (0.9 NA). With each increasing magnification (NA), the resolution for the smallest features increases but the overall depth of focus decreases.

There is an optimum NA to print a given feature size, as discussed in a previous paper[1]. Suzuki also has written on this point[2]. Mack has addressed this idea in a paper in this same journal[3]. At too low a NA, the first spatial frequency does not appear in the image and there is effectively zero depth of focus. At very high NA, the depth of focus for all spatial frequencies is small, on the order of one wavelength. At intermediate NAs, the depth of focus is comparable to the Rayleigh depth and is a maximum at a given NA.

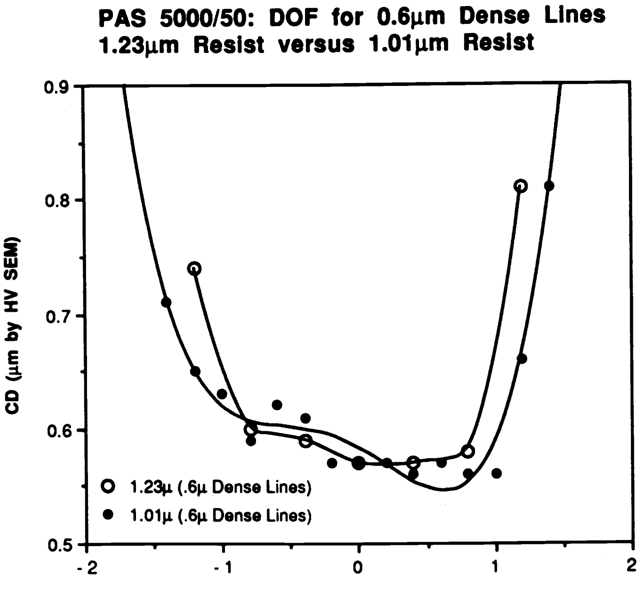


Figure 7a.

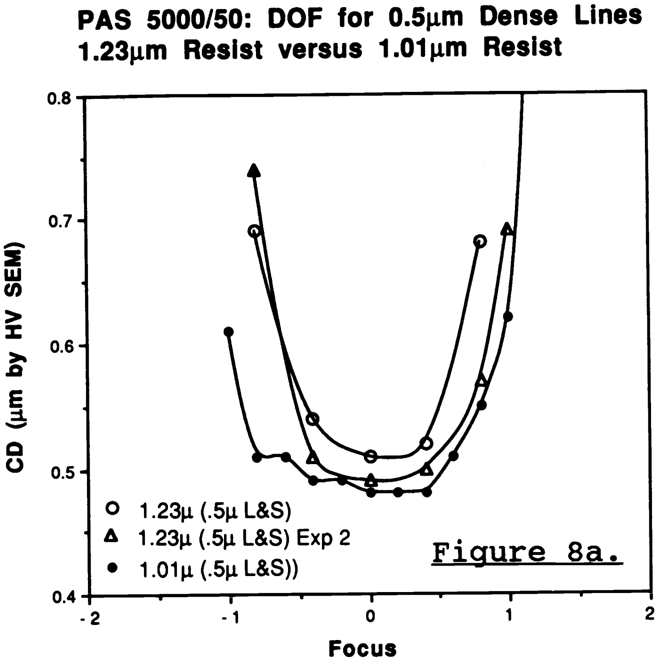


Figure 8a.

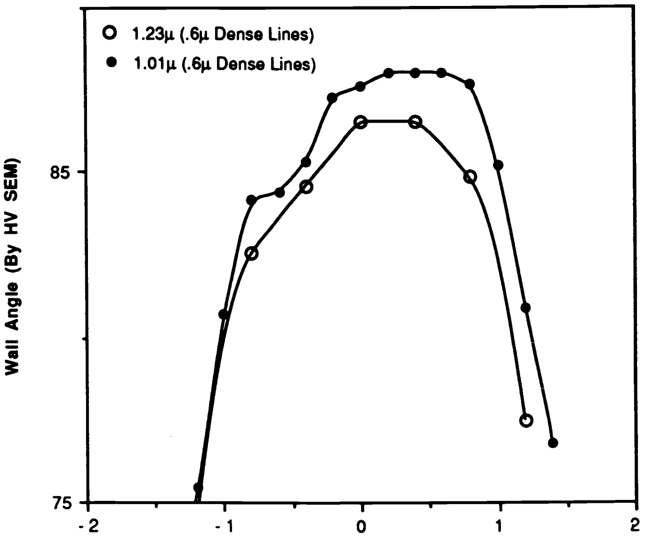


Figure 7b.

Focus

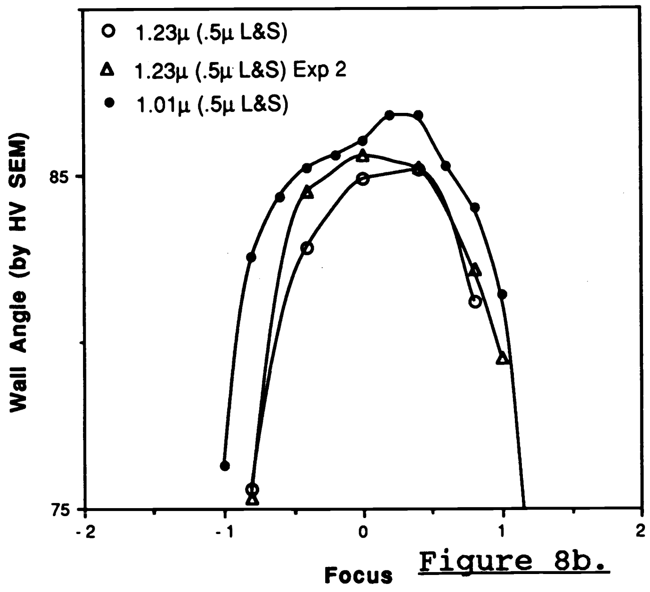


Figure 8b.

We have worked for two years with resist thicknesses near 1.2 microns to pattern 0.7 micron design rule devices. With the advent of 0.5 micron devices the resist aspect ratio becomes more than two, making development as well as linewidth metrology more difficult. A thinner resist coating can improve depth of focus as long as etch and coating integrity requirements can still be met. Evidence for this improvement can be seen in Figures 7 and 8, where linewidth and wall angle for 0.6 micron L/S are shown as they vary with defocus for both 1.01 and 1.23 micron thick resist coatings. It is clear that the 1.01 micron thick resist exhibits better focus depth by 0.2 to 0.4 micron.

Resists from different manufacturers will exhibit variations in depth of focus depending on their chemistry and the processing they undergo. Linewidth and wall angle versus defocus for 0.6 micron L/S

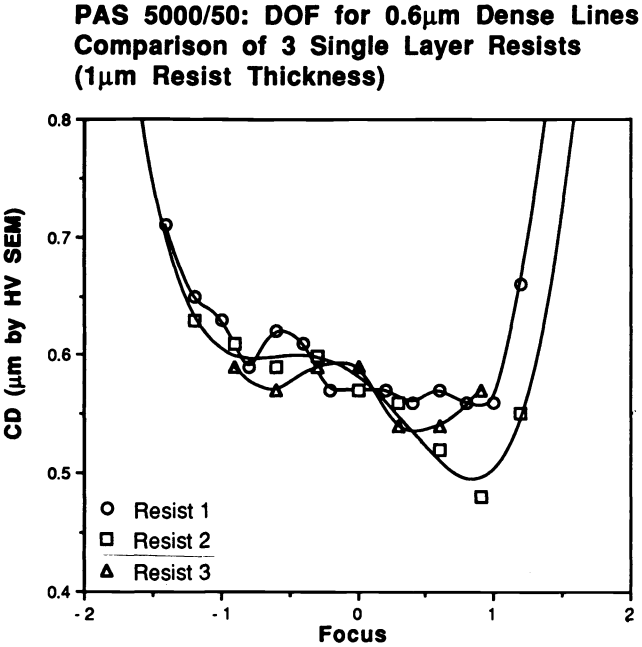


Figure 9.

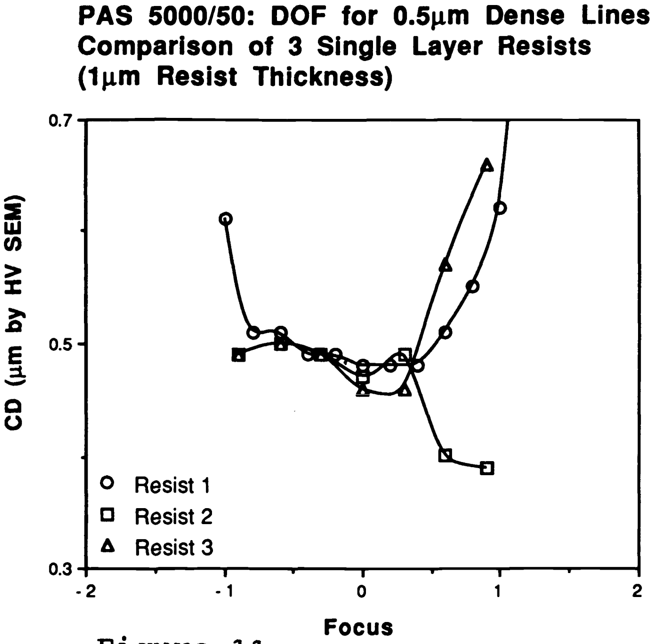


Figure 11.

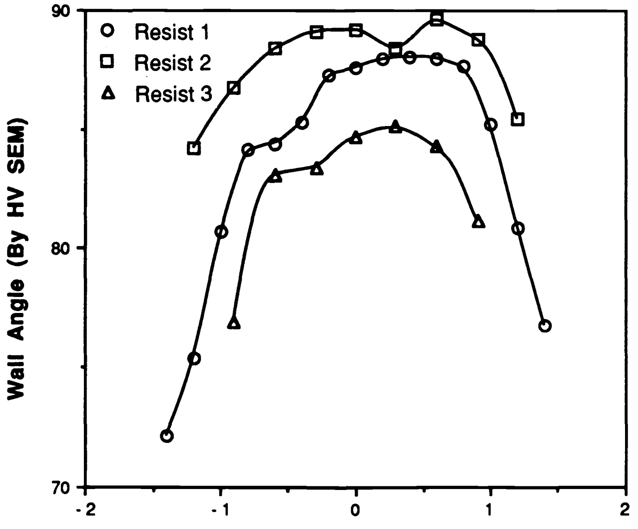


Figure 10.

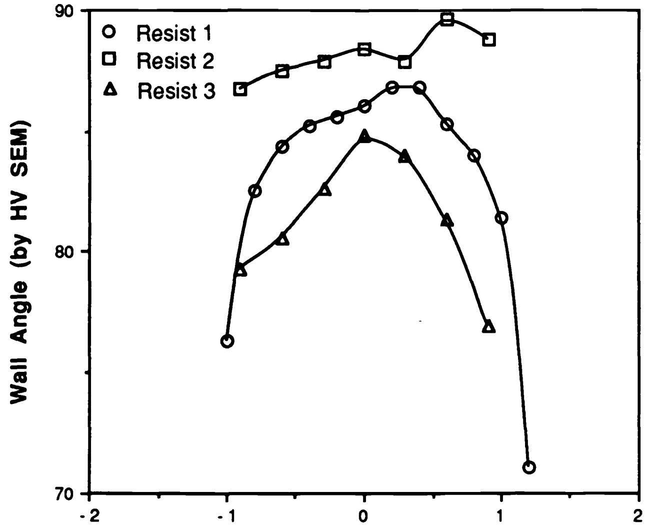


Figure 12.

for three different i-line resists are shown in Figures 9 and 10. The same for 0.5 micron L/S is shown in Figures 11 and 12. The data are for 1.01 micron thick resist coatings on 4200 Å thick poly silicon films on silicon substrates. Each resist was processed similar to the manufacturer's recommendations. For 0.6 micron L/S, all of three resist exhibited a substantial amount of linewidth variation as a function of defocus (see Figure 9). For 0.6 micron L/S, Resist 1 exhibits the best line width control (2.25 microns with 0.6 micron ± 10%) and intermediate wall angle control (1.8 microns with wall angle greater than 83°) , while Resist 2 exhibits only intermediate linewidth control (2.0 microns) but superlative wall angle control (2.5 microns - see Figures 9 and 10). The data plotted in Figures 9-12 were derived from the micrographs in Figure 13.

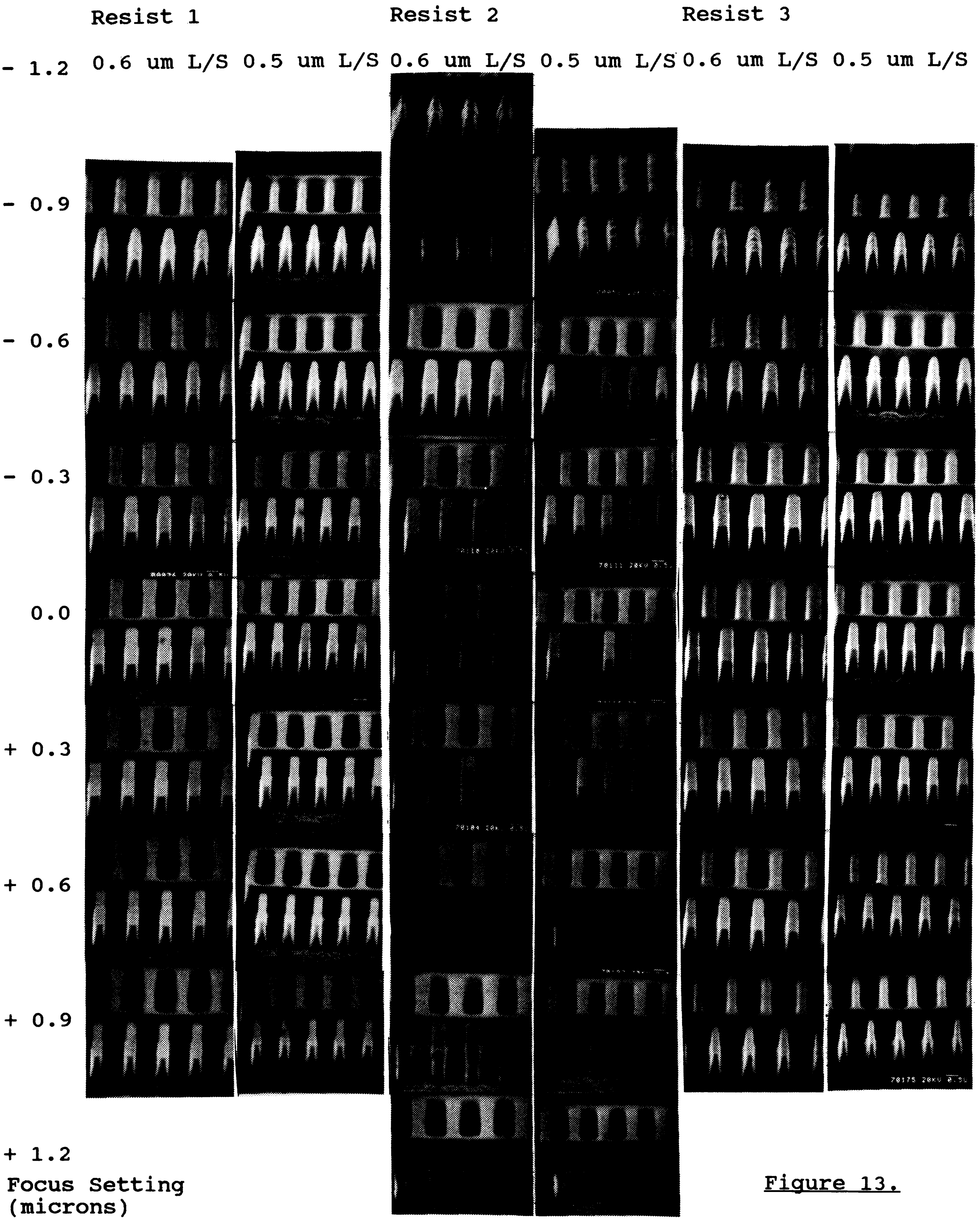

Resist 1
Resist 2
Resist 3
0.6 um L/S
0.5 um L/S
0.6 um L/S
0.5 um L/S
0.6 um L/S
0.5 um L/S
- 1.2
- 0.9
- 0.6
- 0.3
0.0
+ 0.3
+ 0.6
+ 0.9
+ 1.2
Focus Setting
(microns)

Figure 13.

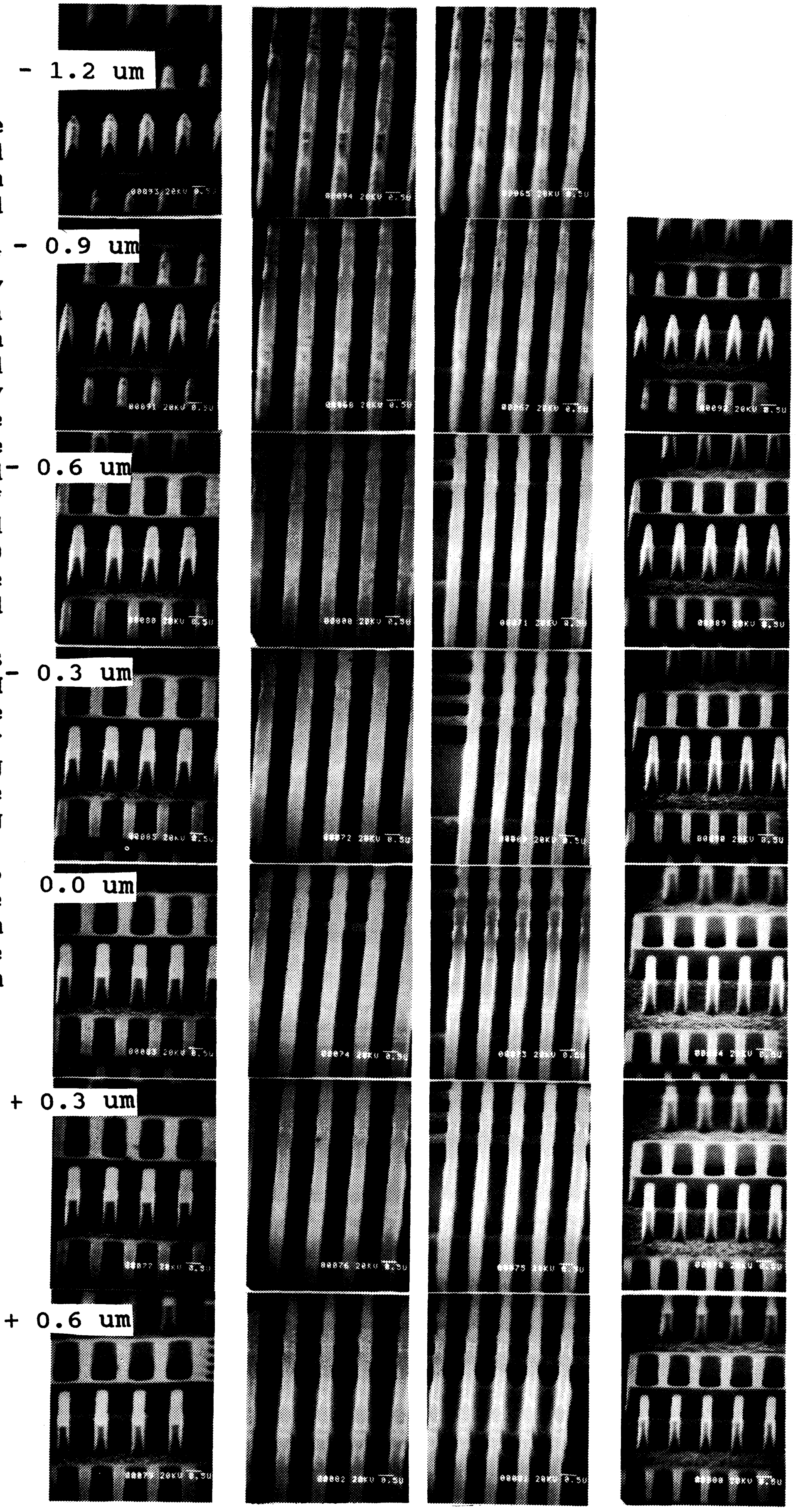


Figure 14.

Effect of substrate topography and stepper focus on linewidth control and best operating point. Substrate consists of 420 nm of poly silicon, into which a 0.7 um deep trench has been etched through the poly silicon and into the silicon. The substrate was coated with 1.01 um of Resist 1, and printed with the 5000/50 keeping the exposure dose constant and stepping the focus. At each focus position, four SEM micrographs were taken of four neighboring structures from the same die (reading left to right): (a) 0.6 um L/S; (b) 0.6 um L/S across the trench; (c) 0.5 um L/S across the trench; (d) 0.5 um L/S.

The effect of substrate topography on linewidth control and best focus operating point was also investigated. For these experiments, substrates were fabricated consisting of 4200 Å thick poly silicon films, into which a 0.7 micron deep trench was etched through the polysilicon and into the underlying silicon substrate. The substrate was coated with 1.01 micron thick films of Resist 1, and printed with the PAS 5000/50 keeping the exposure dose constant and stepping the focus (see Figure 14). Because of the trench width (about 5 microns) is fairly small, the resist tends to planarize the trench. At each focus position, four SEM micrographs (A,B,C and D) were taken of four neighboring structures from the same die: (A) 0.6μm line and space; (B) 0.6μ line and space across trench: (C) 0.5μm line and space; and (D) 0.5μm line and space (see Figure 14). Position of best focus for the 0.5 micron line (see Figure 14 C) across the trench appears to be between -0.6 microns and -0.3 microns, while the position of best focus for the 0.5 micron line appears to be at about 0.0 microns (see Figure 14 D). The overlap in focus for printing both structures acceptably is from -0.6 microns to 0.0 microns. Taking 0.3 microns of lens field curvature from this amount leaves very little focus margin indeed. Taming substrate topography will be one of the most challenging problems for 0.5 micron i-line lithography.

3. Other Aspects of the 5000/50

Light absorption in i-line lenses can lead to large focus shifts[4] depending on the choice of i-line glasses and glues. An experiment was performed to determine if the 65 lens suffered from this defect. 50 silicon wafers were exposed with focus-exposure matrices centered at the optimum focus determined from an independent test at the

Figure 15a.

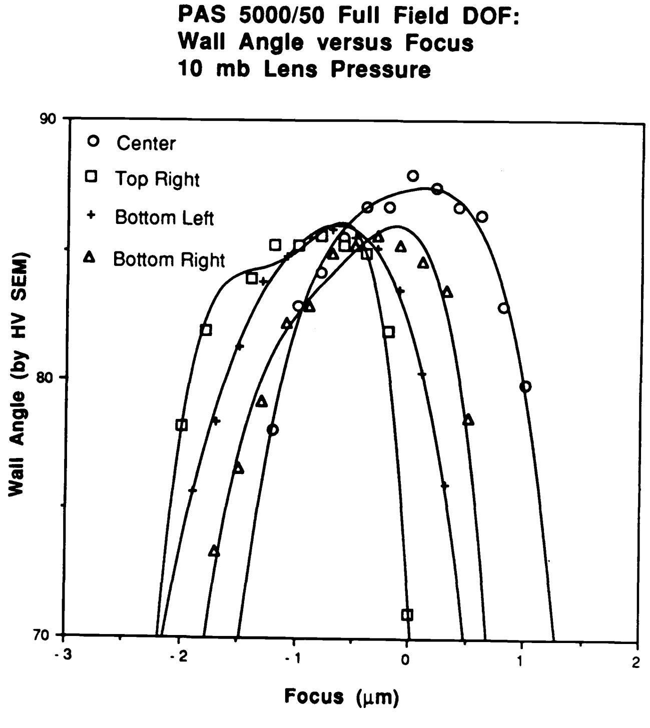
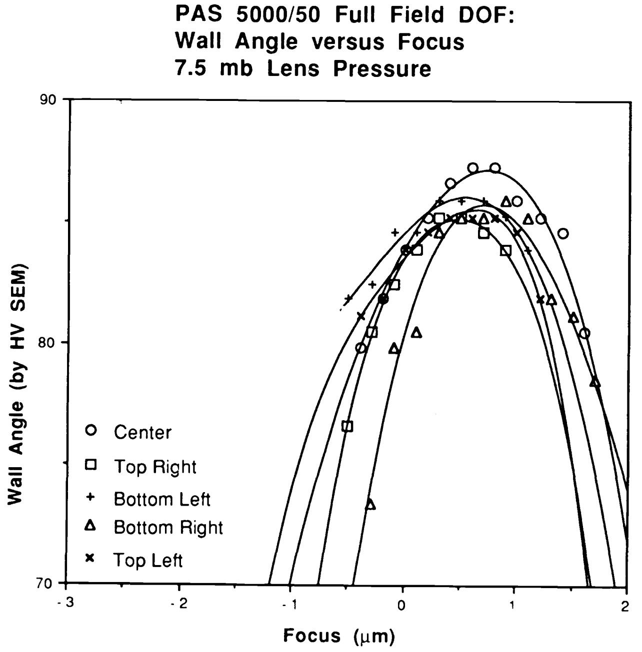


Figure 15b.



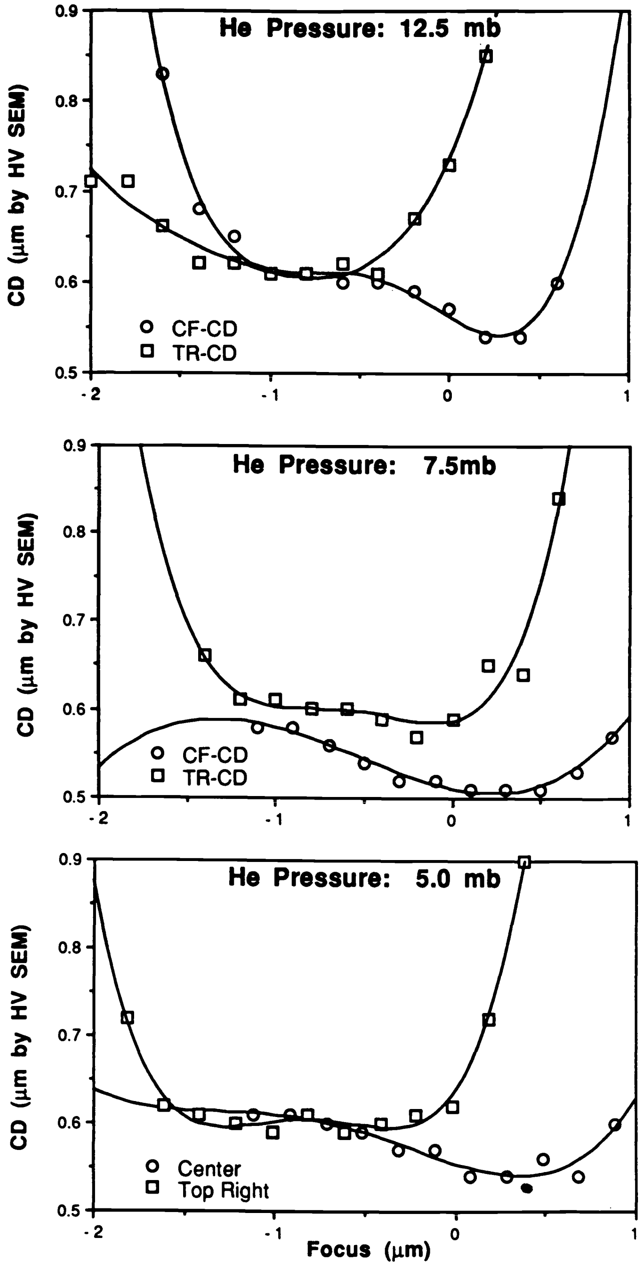


Figure 15c.

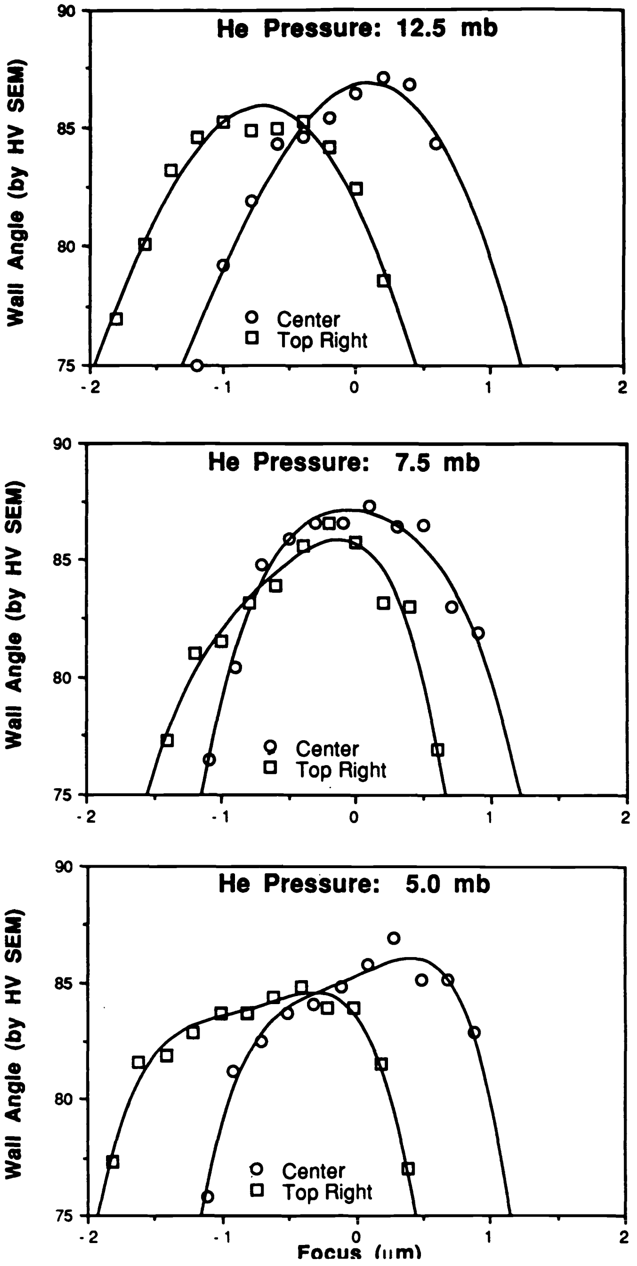


Figure 15d.

beginning of the experiment (when the stepper was "cold"). A dark field resolution test reticle which comes with the stepper as standard (Steekvar) was used for best focus determination. The wafers were then exposed using an approximately 50% transparent reticle. It was determined from microscopic inspection of small resolution patterns, "focus verniers", equivalent to those described by Gemmink[5] that the plane of best focus hadn't shifted from wafer to wafer and during the time necessary to expose the 50 wafer lot, to within the ± 0.3 micron precision of the inspection technique. At the completion of 50 wafers the standard focus test mentioned above was repeated. No change in focal plane position was observed. This demonstrates that

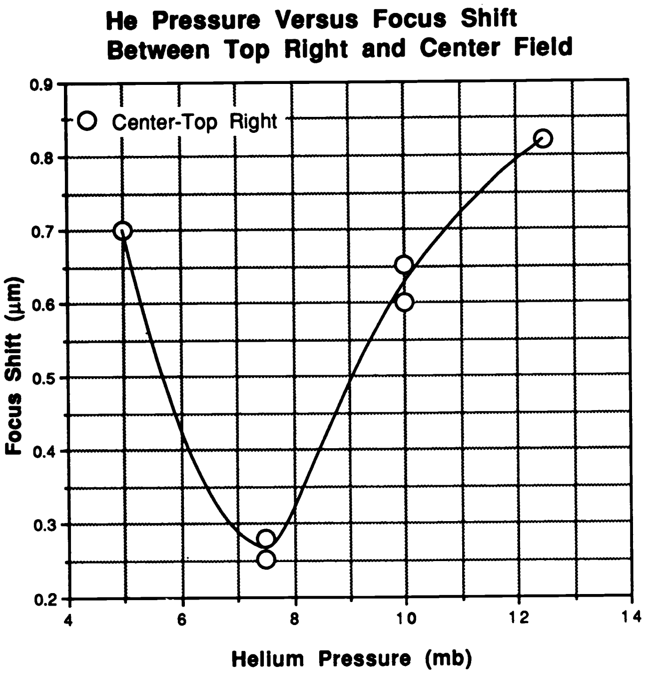


Figure 16.

if the effect does exist it is at least an order of magnitude or smaller than that reported for a similar i-line lens from a different manufacturer.

The 65 lens is the first Zeiss i-line lens filled with pure helium to make it less sensitive to changes in atmospheric pressure and ambient temperature. The lens column is also cooled by a water jacket, so that the temperature of the column is controlled to ± 0.1° C.

It was determined in our initial experiments with the stepper after installation that field curvature was anomalously large. (Field curvature as defined for stepper lens testing is the difference in focus between the center and the average of the four corners). This is shown in Figure 15a, where resist wall angle for 0.6 um lines versus defocus for center of the field and the four corners (15 mm square) is plotted. Note the large displacement of the best focus for the four corners of the field versus the center. Investigations revealed that the helium pressure over ambient (overpressure for short) was 2.5 mbar greater than its design value (10 mbar vs. 7.5 mbar design). When the helium overpressure was reduced to 7.5 mbar, the field curvature was reduced, as shown in Figure 15b.

This led us to question whether 7.5 mbar was indeed the best overpressure value so field curvature was also measured at 5 and 12.5 mbar. This data is shown in Figures 15c and 15d. For reasons of

Figure 17.

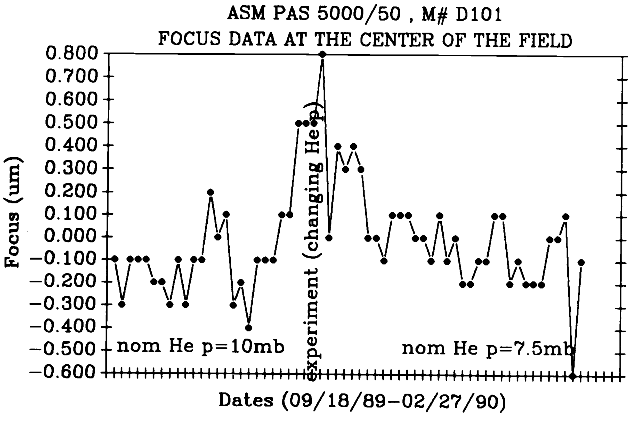
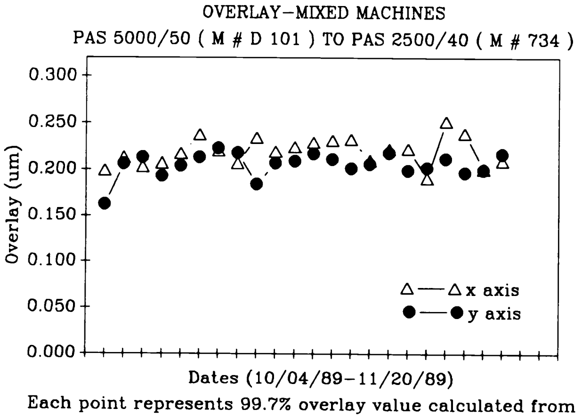


Figure 18.



Each point represents 99.7% overlay value calculated from 306 measurements : 2 wafers , 9 fields per wafer , 17 points per field.

simplicity, emphasis was placed on minimizing the difference in focus between the center and the worst of the four corners, known conventionally as the focal plane deviation (FPD). The dependence of FPD on helium overpressure determined from these experiments is shown in Figure 16, showing that the best overpressure is indeed about 7.5 mbar.

The stability of the position of best stepper focus is a key parameter for system productivity. Best stepper focus over time is plotted in Figure 17. The data is gathered daily using a focus exposure matrix which is inspected by optical microscopy. Steekvar resolution patterns are printed and inspected to determine the position of best focus. The unstable period in the middle period seems correlated with the experiments with helium overpressure, which occured in the same time period.

Overlay stability of the stepper over time measured against a reference printed on a 2500/40 stepper in the same fab is plotted in Figure 18. The data points represent the error in x and y at the 99.7% level, using the ASM-L stepper's autometrology package to acquire the data. The overlay error is consistently measured at between 210 and 230 nm, 99.7%, for both axes. Experiments run to determine the stepper's ability to align to patterns printed by itself show 99.7% overlay error of less than 110 nm both axes.

4. Prospects for I-Line at 0.5 and 0.4 Micron : Optimum NA

An important question is, given i-line lithography, what is the best NA for 0.5 micron? And further, can i-line lithography be extended to 0.35 or 0.4 micron, the resolution expected for the 64Mbit DRAM? What NA would be best for 0.4 micron?

Simulation can help to answer such questions before the lenses are actually designed and built. Of course, the results of the simulation are only as good as the underlying theory and the quality of the assumptions made for material properties and operating parameters which are input to the simulation. In this study, Prolith[6] Version 1.5 was used to find the optimum NA for i-line lithography to produce 0.5 and 0.4 micron lines and spaces, respectively.

Linewidth versus defocus for 0.5 micron L/S is plotted in Figures 19a and 19b for two lenses, NA 0.48 and NA 0.60. All other parameters were held constant. The simulation assumes a fairly average i-line resist process, .955 micron thick, on bare silicon. A post exposure bake is used. In Figures 20a and 20b the resist wall angle is plotted versus defocus for the same data set. Note how much narrower the focus latitude is for the NA 0.60 lens, for both linewidth and wall angle criterion. The higher NA lens does produce a better best focus image, with steeper wall angle, and exposure latitude at best focus is very good compared to the lower NA lens. On the other hand, its images degrade much faster with defocus.

If all the detractors to the focus budget (optical aberrations, wafer nonflatness, circuit topography, focusing errors, etc.) could be

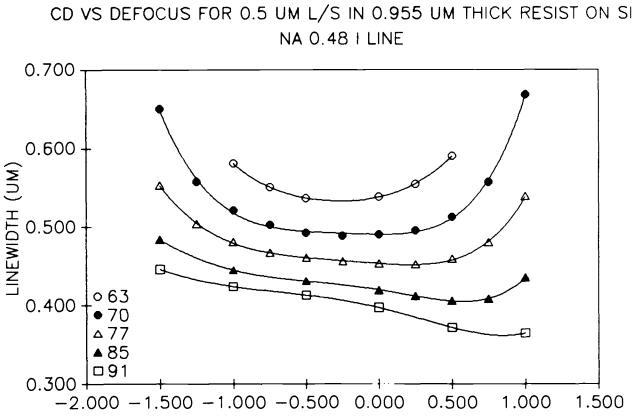


Figure 19a.

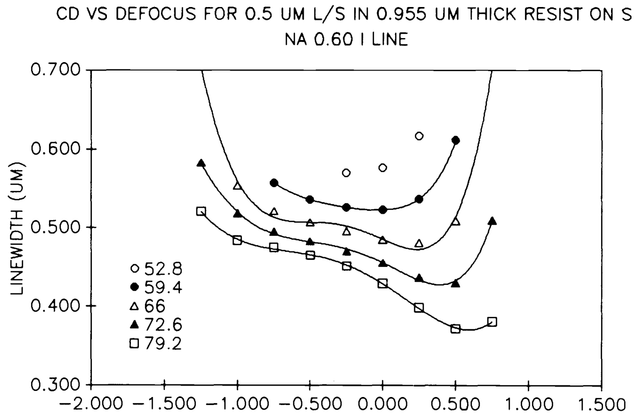


Figure 19b.

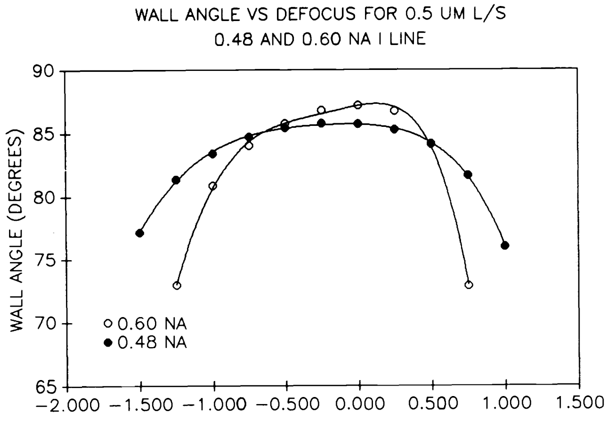


Figure 20.

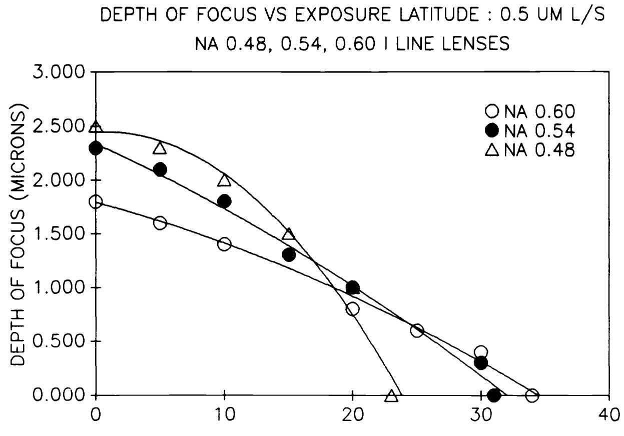


Figure 21.

held to zero, then the 0.60 NA lens would be superior to the 0.48 NA lens for printing 0.5 um L/S, on the basis that the best focus image exceeds the quality criterion over a greater range of exposure. On the other hand, if all the detractors to the exposure dose budget (illumination nonuniformity, reflectivity variations, proximity effects, etc.) could be held to zero, then the opposite would be true (i.e., 0.48 better than 0.60), since the lower NA image at the optimum exposure maintains its acceptability over a greater range of defocus. For finite focus and exposure budgets, the question of which NA is better becomes more complicated.

Figure 21 shows the depth of focus versus exposure latitude for the two lenses, plus that of an intermediate lens with an NA of 0.54. In choosing the best lens for the job, an estimate for both the exposure variation and the focus variation expected in a given process should be made. For example, if it is possible to work with a focus budget of 1.5 um or less (which includes field curvature, astigmatism, wafer flatness, circuit topography , and focusing error) and an exposure budget of 15% (which includes illumination nonuniformity, resist thickness and substrate reflectivity variations, and dose control errors), then, referring to Fig.21, both the 0.48 and 0.54 NA lenses can meet these requirements, while the 0.60 NA lens does not have sufficient depth of focus. The higher NA lens will be more

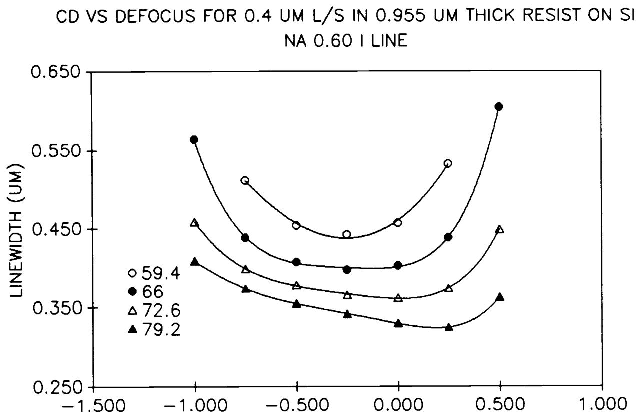


Figure 22.

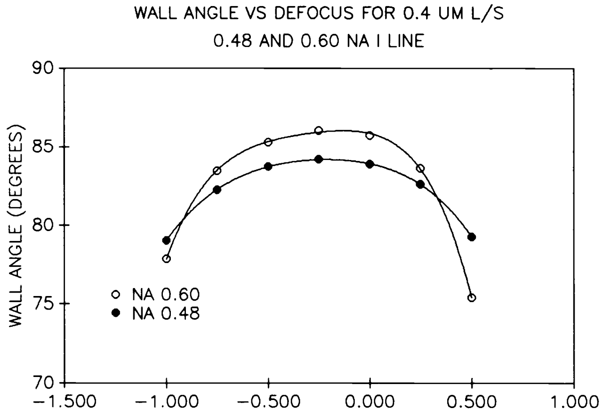


Figure 23.

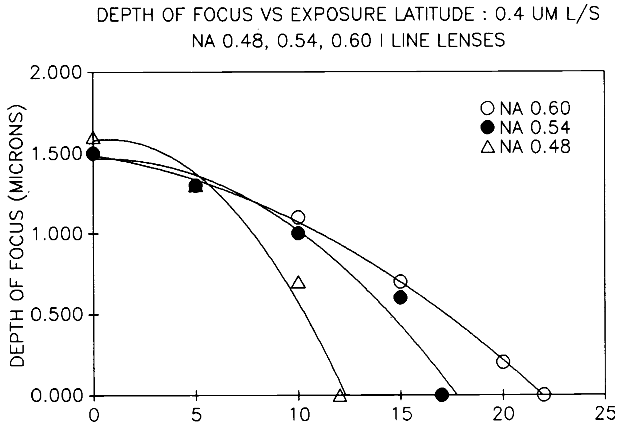


Figure 24.

effective where exposure variation is more of a problem than focus variation.

Looking forward in time, Figure 22 shows the linewidth versus defocus for 0.4 micron L/S printed with the 0.60 NA lens. Figure 23 compares the wall angle versus for the 0.48 and 0.60 NA lenses for 0.4 um L/S. Figure 24 shows the depth of focus at different values of exposure latitude for the same three lenses, but now for 0.4 um L/S. According to the simulation, it's possible to define 0.4 um L/S with 1.2 um DOF and 10% exposure latitude with a perfect 0.60 NA lens.

These simulations show only the behavior of line/space patterns, long known to exhibit better depth of focus than isolted spaces or contact holes. Lin has long shown that one must consider the common overlap of all types of features actually used on the reticle[7]. An exhaustive study reported last year by Petersen[8] and Lin for the common overlap of lines and spaces, isolated lines, isolated spaces, contact holes and islands suggests that a k factor of 0.74 is nearly optimum for submicron optical lithography. This is equivalent to a 0.54 NA i-line lens for 0.5 micron lithography.

In summary, the simulation results seem to imply an optimum NA for 0.5 micron L/S in the range of 0.5 to 0.55. This is equivalent to a k factor range of 0.69 to 0.76, less than the conventional process k factor of 0.8. It is now fairly certain that optical lithography will have to push the k factor down, to 0.7 and lower to forestall the advent of X ray lithography or other rivals for far submicron imaging.

These results also suggest that i-line may be used effectively at 0.40 micron, sufficient for the first generation of 64 Mbit DRAM production. With resist process improvements and innovations such as phase shifting masks[9,10,11] and FLEX[12], it may be possible to shrink i-line capabilities to 0.35 micron, forestalling the introduction of deep UV lithography to the 256 Mbit DRAM generation at 0.25 micron. It is clear that the extra capital cost and operational costs of excimer steppers make them unattractive for 0.5 micron production and the same may be true at 0.35 micron.

5. Summary and Conclusions

Imaging characteristics of the new Zeiss 10-78-65 (NA 0.48) i-line lens have been presented. Depth of focus for varying feature sizes has been contrasted with the Zeiss 10-78-58 (NA 0.40) i-line lens. It has been found that the 0.40 NA lens has better depth of focus for 0.7 micron L/S and greater, while the 0.48 NA lens has better depth of focus for less than 0.7 micron L/S.

Resolution and depth of focus at 0.6 and 0.5 micron L/S for the 65 lens using three different resists was investigated. Depth of focus limitations for 0.6 and 0.5 um L/S crossing a 0.7 um deep trench in silicon were presented.

Focus shifts due to absorption heating in the lens were searched for but not observed. Field curvature's behavior as a function of the overpressure of helium gas within the lens was measured and presented. The variation of best stepper focus over time was also monitored and described.

Simulation work suggests that a NA of between 0.5 and 0.55 is optimum for printing 0.5 micron L/S. Further, it suggests that there may be sufficient depth of focus at 0.4 micron L/S to make i-line a competitor to DUV lithography for the 64 Mbit DRAM generation.

6. References

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