Simulation Study of a New Phase-Shifting Mask: Halftone-Rim

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ABSTRACT

This paper reports the simulation study of a new phase-shifting mask (PSM), quartz-etch halftone-rim, applied on one and two dimensional patterns, such as contact hole, line/space and polylayer using positive-tone resist (optical parameters focused mainly on λ=365nm, NA=0.5, sigma=0.6, halftone chrome T=4%). When apply this halftone-rim PSM on 0.35μm dense contact holes, the simulations indicated that optimized rim width is 0.15 λ/NA (0.11 μm). Optimized single side width for biased contact is 0.1μm (0.9 x optimized rim width). Optimized biased contact is 0.55μm (0.35+0.1+0.1μm) which is 1.57 times larger of 0.35μm design rule. Exposure latitude is 9.9 %. Total depth of focus (DOF) is about 1.2μm. Compared with sized-rim PSM (chrome T=0%), this halftone-rim PSM has lower operation exposure dose; higher exposure latitude and larger DOF. When apply it on the 0.35μm dense and isolated line/space, optimized rim width is 0.12 λ/NA (0.09μm). Optimized single side width for biased space is 0.08μm (0.9 x optimized rim width). The total DOF is about 1.0 μm for line/space. By using combination of halftone-rim PSM and off-axis illumination (OAI), the total DOF will reach 1.2~1.5μm for 0.35μm dense line/space. However, the improvement for line/space is insignificant if compared with sized-rim PSM. Halftone-rim PSM has advantages on patterning of contact holes but not on line/space in this study.

Keywords: Phase-Shifting Mask, Halftone, Rim, Halftone-Rim, Simulation, Off-Axis Illumination, Submicron Lithography.

1. INTRODUCTION

Phase shifting mask (PSM) could improve both resolution and depth of focus (DOF) without changing much to the exposure system except using lower degree of coherence (sigma) for stepper. The resolution could reach 0.35~0.40 μm with the combination of PSM technique and conventional i-line (365 nm) process. Different PSMs suit for different circuit patterns because each has its advantages and disadvantages in optical pattern transfer. Rim PSM has the advantage of self-aligned shifter layer and minimal design impact. However, the exposure light intensity is weakened. It means that the higher exposure dose, in other word, longer exposure time, is needed. Attenuated (halftone) PSM has the advantages of higher aerial image intensity and edge sharpness in the pattern transfer, but it has only marginal improvement (10~20%) and also its total DOF is limited.

We first reported a new type of PSM, namely, halftone-rim, which combines the merits of halftone (attenuated) and rim PSMs[1]. This paper is a follow-up of previous paper. The optimization of design rules for 0.35 μm contact hole, line/space and polylayer is simulated. Regular stepper and stepper with annular off-axis illumination are used in this simulation study. Due to the difficulties and reproducibility of fabrication of this kind of PSM, no meaningfully experimental results could be compared with simulations, therefore, not reported in this paper.

0-8194-1788-2/95/$6.00

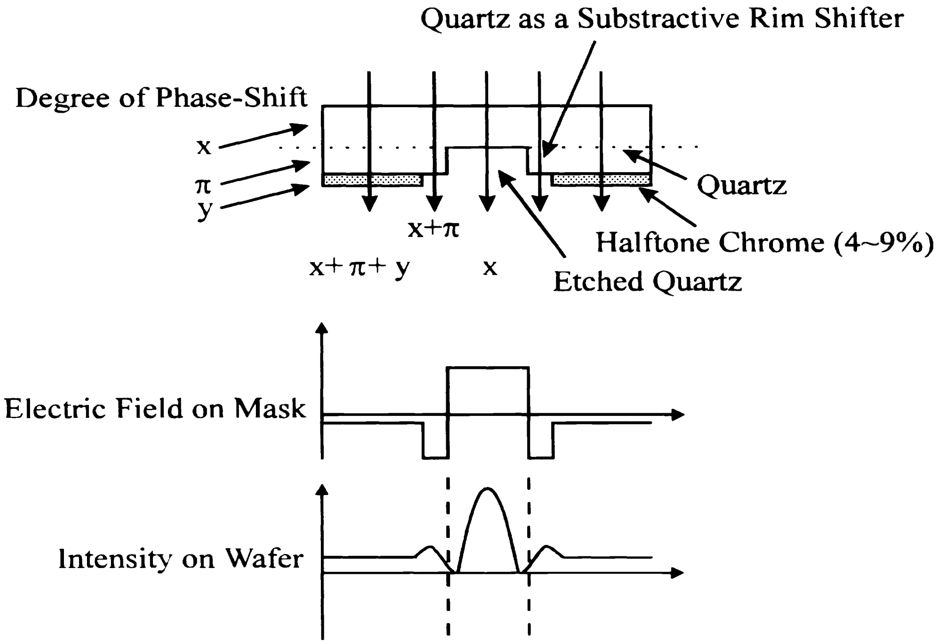
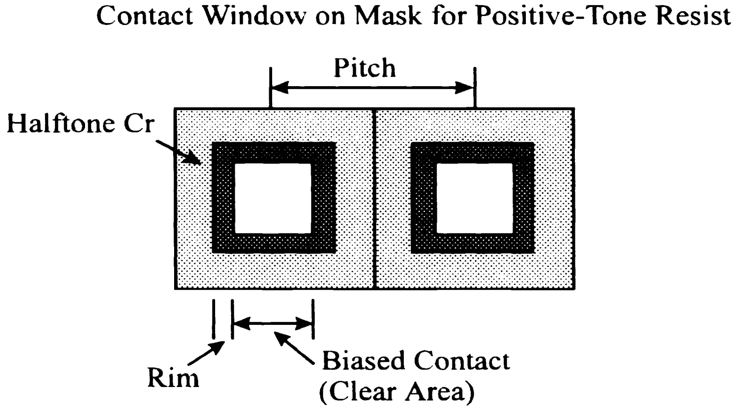


Fig. 1 **Illustration of a quartz-etch halftone-rim phase-shifting mask. Y denotes the degree of phase-shift from halftone chrome under i-line and is 33.8° by calculation (Thickness 350 Å, Refractive Index 1.98, T=4%). Useful T% range is 1~9 in our study.**


Contact Window on Mask for Positive-Tone Resist

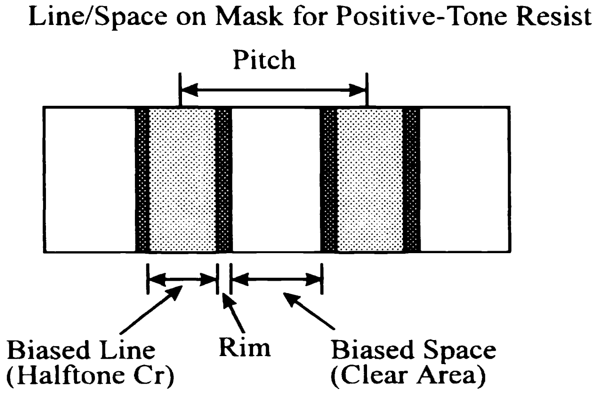

Line/Space on Mask for Positive-Tone Resist

Fig. 2 **Schematic of contact hole and line/space designs on halftone-rim mask.**

2. EXPERIMENTAL

The simulation tool is Depict-3 from Technology Modeling Associates, Inc. (TMA). Parameters used for calculation and simulation are as follows unless specifically remarked:

A. Hoya attenuated blank mask :
  Intensity transmittance (T%): 4 (Amplitude transmittance: 20%)
  Thickness of halftone Cr: 350 Å
  Refractive index of halftone Cr: 1.98 (at 365 nm)
  Refractive index of quartz: 1.48
B. Stepper : i-line (365 nm), NA: 0.5, Degree of coherence (σ): 0.6
C. Degree of phase-shifting by halftone chrome
  $\theta_{ht} = T_{ht}\ 2\ \pi\ (n_{ht}-1)\ /\ \lambda$
  $\theta_{ht} = 350\ \text{Å} \times 2 \times 180\ \times (1.98-1)\ /\ 3650\ \text{Å} = 33.8$
  $\theta_{ht}\ +\ \theta q\ = 33.8\ + (180 - 33.8\ ) = 180$
D. Thickness of quartz needed to be etched:
  $Tq = \lambda\ \theta q\ /2\ \pi\ (nq-1) = 3650\ \text{Å}\ (180 - 33.8\ )\ /\ 2 \times 180\ \times (1.48-1) = 3088\ \text{Å}$
E. Photoresist : TOK IP-3100 (positive-tone, non-dyed), thickness 1.05 µm
  Dill's parameters: A=0.90, B=0.08, C=0.02
F. Resist Development: U.C.-Berkeley Mode, R1=14, R2=0.001, R3=9, R4=0.1, R5=0.9, R6=0.8

3. RESULTS AND DISCUSSION

The steppers with λ 365 nm (i-line), NA 0.5, sigma 0.6 are still the work-horse of IC industries in Taiwan, Republic of China. Blank mask with halftone chrome T 4% is readily available from Hoya and suitable for printing both dense and isolated patterns. Hence, the above optical parameters are focused in these simulation studies.

The principle and function of halftone-rim PSM is shown in Fig. 1. Its difference from conventional rim or sized-rim PSM is that the chrome layer is not opaque. Useful intensity transmittance of halftone chrome is within the range of 1~9%. Intensity transmittance higher than 9% will generate unacceptable side-lobe maximum (ghost line); less than 1% will not have significant improvement if compared with rim or sized-rim PSM. Halftone chrome with T 4% has 33.8 phase-shift by calculation. The mask design for contact and line/space is shown in Fig. 2. Although negative-tone resist is more convenient for patterning line/space from the viewpoint of mask design, however, positive-tone resist is still used for patterning and simulation because of the advice of IC industry people.

Summaries of simulated results of halftone-rim PSM for contact hole and line/space are shown in Table 1. The optimized rim widths for contact and line/space are 0.15 λ/NA and 0.12 λ/NA, respectively. The optimized single side widths for biased contact and biased space in line/space are both 0.9 rim width. The optimization was decided by considering the following parameters from aerial images: log-slope of center peak; side-lobe maximum; maximum intensity of center peak; threshold intensity of center peak. The contact, space, line and rim are all biased to obtain optimized resist profiles.

The optimization of sized-rim PSM was also studied by applying the same method as for halftone-rim PSM. Comparing the results from halftone-rim and sized-rim, the improvement for contact hole is meaningful. However, the improvement for line/space is insignificant. Their results are nearly identical.

Table 1. Summaries of simulated results of halftone-rim PSM for contact hole and line/space.

1. Contact hole : Pitch = 1.0 μm (Dense pattern)

Design rule (μm)	Optimized single side width for biased contact (μm)	Optimized biased contact (μm)	Optimized rim width (μm)	Energy (Eop) (mJ/cm^2)	Energy latitude (%)	DOF (μm)
0.35	0.9 rim width (0.10)	0.35+0.1+0.1 (0.55)	0.15 λ / NA (0.11)	158~174	9.9	1.2
0.40	0.9 rim width (0.10)	0.40+0.1+0.1 (0.60)	0.15 λ / NA (0.11)	120~141	16.0	1.5

* Optimized biased contact is approximately 1.5~1.57 times larger of design rule.

* Pitch 0.70 μm can not be used for 0.35 design rule for dense contact, since the rims from each side will overlap and mask becomes functioning as an attenuated PSM.

2. Line/Space:

Design rule for line/space (μm)	Optimized rim width (μm)	Optimized single side width for biased space (μm)	Optimized biased space (μm)	Energy (Eop) (mJ/cm^2)	Energy latitude (%)	DOF (μm)
0.35/0.35	0.12 λ / NA (0.09)	0.9 rim width (0.08)	0.35+2(0.08) (0.51)	146~163	11.1	1.13
0.60/0.40	0.12 λ / NA (0.09)	0.9 rim width (0.08)	0.40+2(0.08) (0.56)	124~149	18.4	1.18
1.60/0.30	0.12 λ / NA (0.09)	0.9 rim width (0.08)	0.30+2(0.08) (0.46)	163~175	7.1	0.92

Table 2. Comparisons of simulated results of sized-rim and halftone-rim for contact hole optimization.

Design rule (μm)	DOF (μm)		Energy latitude (%)		Energy (Eop) (mJ/cm^2)	
	Sized-rim	Halftone-rim	Sized-rim	Halftone-rim	Sized-rim	Halftone-rim
0.35	1.1	1.2	9.8	9.9	165~182	158~174
0.40	1.3	1.5	15	16	125~145	120~141

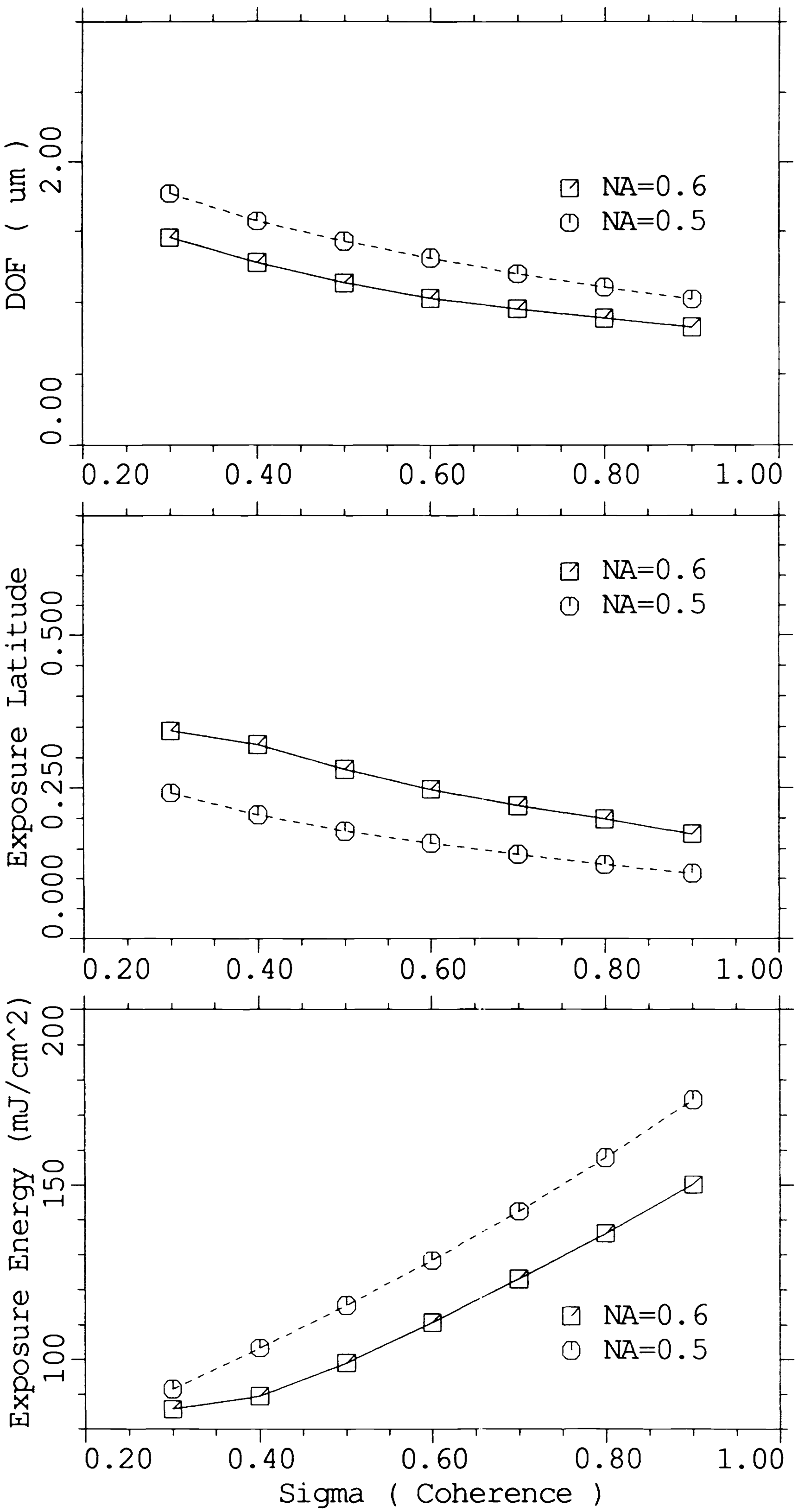


Fig. 3 The effects of sigma and NA on DOF, exposure latitude (EL) and exposure energy (Eop) for patterning dense contact hole. (contact=0.35 μm, pitch=1.0 μm, T=4%)

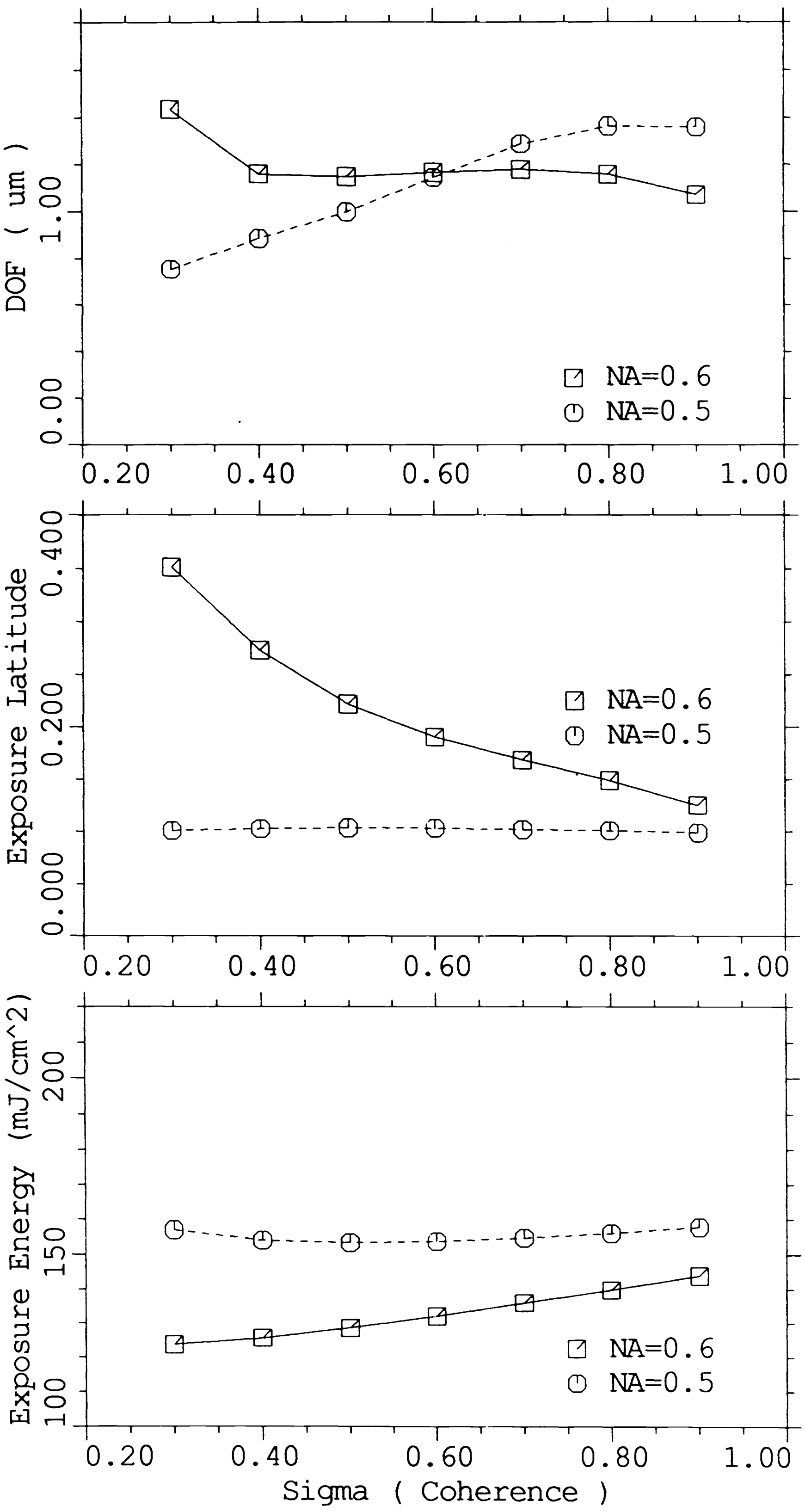


Fig. 4 The effects of sigma and NA on DOF, exposure latitude (EL) and exposure energy (Eop) for patterning dense line/space. (line=0.35 µm, space=0.35 µm, T=4%)

Table 3. Summaries of optimized parameters of halftone-rim PSM applied to contact hole and line/space.

1. Contact hole

CD(μm)	NA	Sigma	T%	DOF(μm)	EL%	Eop(mJ/cm^2)
0.35	0.5	0.3	4	1.8	15	118
0.40	0.5	0.3	4~9	>1.8	20	110

2. Line/Space

L/S(μm)	NA	Sigma	T%	DOF(μm)	EL%	Eop(mJ/cm^2)
0.35/0.35	0.50~0.65	0.3~0.5	1~9*	1.2	40	120
0.60/0.40	0.5~0.6	0.55	1~4	1.7	30	110
1.60/0.30	0.5~0.7	0.5	4	1.0	10~20	120~140

*almost independent of T% within this range.

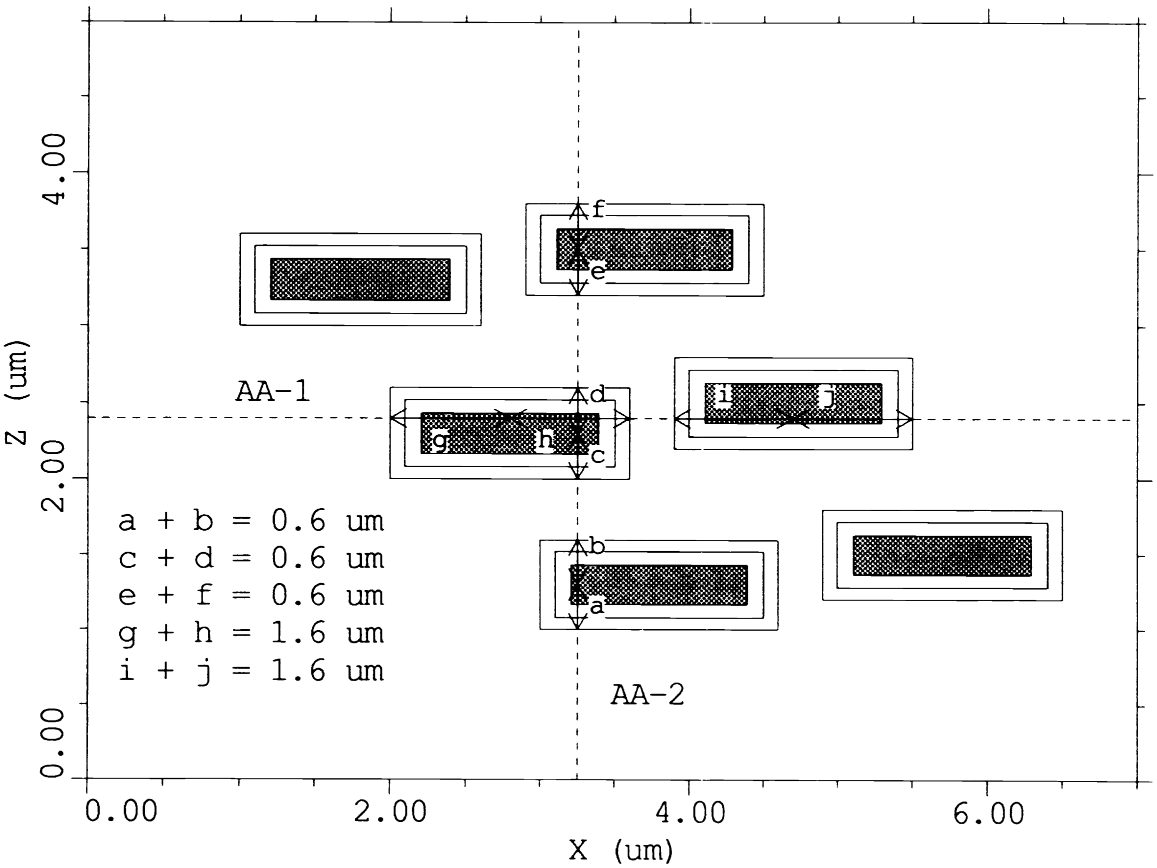


Fig. 5 Layout of polylayer studied. Hatched area indicates the area of halftone chrome (dark) on mask and therefore lines on photoresist. Positive-tone resist is used for simulation.

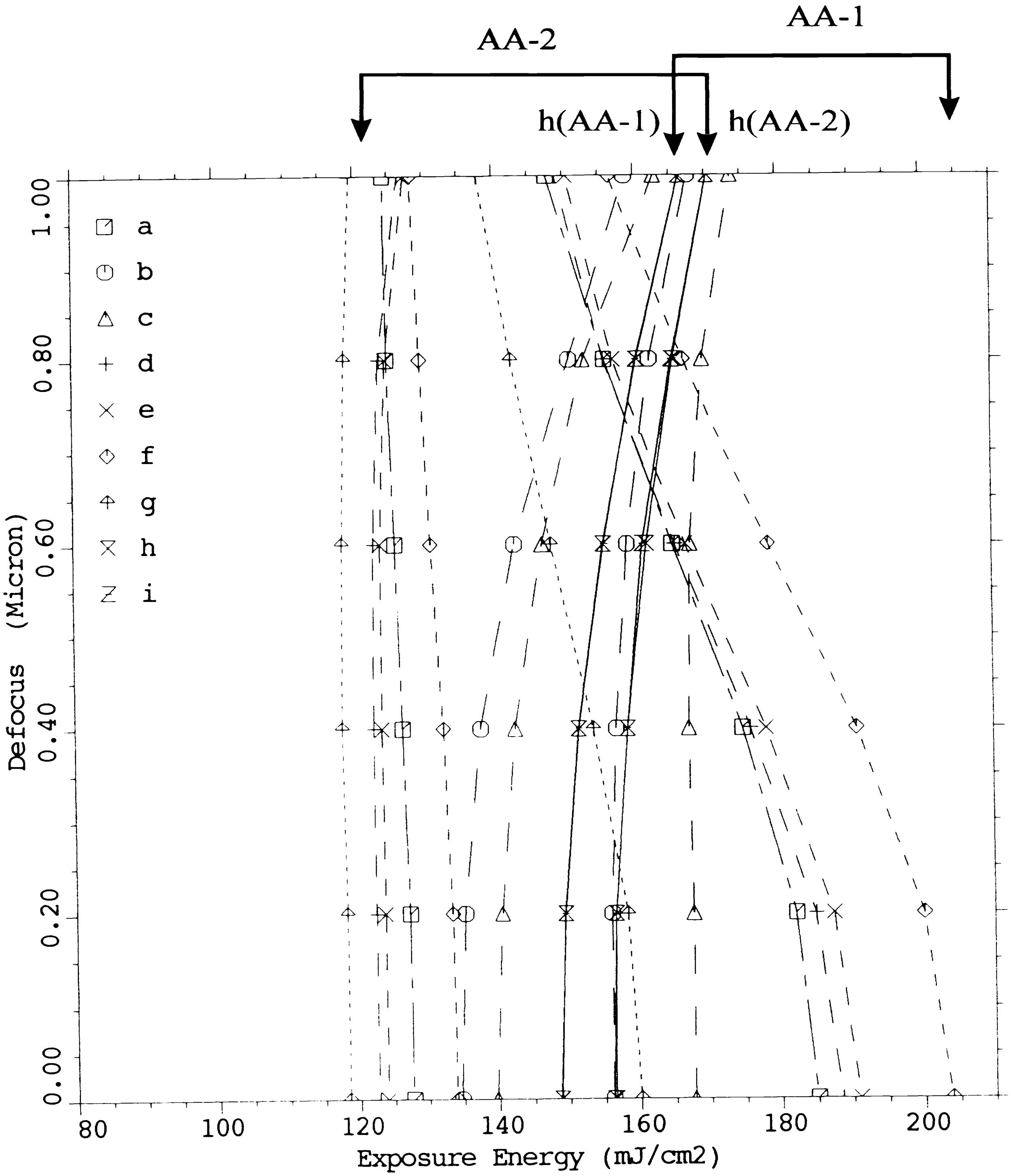
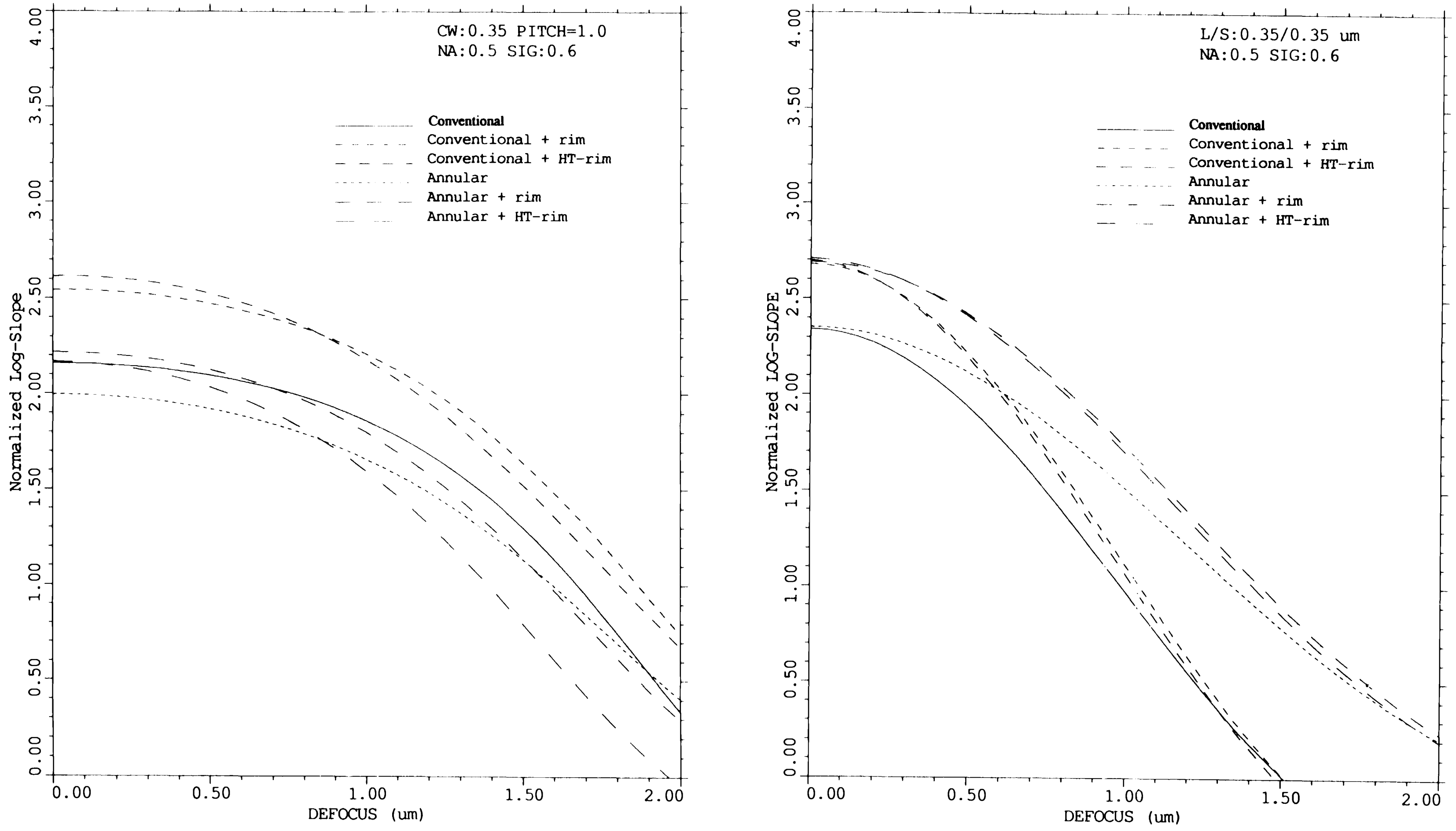


Fig. 6 E-D tree of the polylayer. The exposure energy needed for dimension AA-1 (higher energy) and dimension AA-2 (lower energy) overlapped between two h lines. Please note that lines of h symbol and i symbol are at same position.



(A) **(B)**

Fig. 7 Normalized log-slope of center maximum of aerial images against defocus using various steppers and masks. Conventional: regular stepper without function of OAI. HT: halftone.
(A) patterning dense contact hole (NA 0.5, sigma 0.6, contact 0.35, pitch 1.0).
(B) patterning dense line/space (NA 0.5, sigma 0.6, L/S 0.35/0.35, pitch 0.70).

Table 2 indicates the comparisons for contact hole optimization. The halftone-rim PSM has larger total DOF; higher energy or exposure latitude (EL) and less operation exposure energy (Eop). Simulation studies with Depict-3 simulation tool indicate that halftone-rim is suited better for the making of contact hole, but not for line and space.

The effects of sigma and NA on DOF, exposure latitude (EL) and exposure energy (Eop) for patterning dense contact hole (contact=0.35 μm, pitch=1.0 μm, T=4%) is shown in Fig. 3. Lower degree of coherence (sigma) is favored in this case. NA 0.5 is favored than 0.6 except for exposure latitude. The effects of sigma and NA on DOF, exposure latitude (EL) and exposure energy (Eop) for patterning dense line/space (line=0.35 μm, space=0.35 μm, pitch=0.70 μm, T=4%) is shown in Fig. 4. On the contrary to contact hole, higher degree of coherence (sigma) is favored in this case. Again, NA 0.5 is favored than 0.6 except for exposure latitude.

The summaries of optimized parameters of halftone-rim PSM applied to contact and line/space are shown in Table 3. These parameters are not limited to NA 0.5 and sigma 0.6. For dense line/space 0.35/0.35, T% seems nearly independent of the results within the range 1~9%.

The application of halftone-rim PSM on polylayer is also studied. The layout of polylayer studied is shown in Fig. 5. The layout is a pattern with two dimensions as illustrated by AA-1 and AA-2. The smallest line is 0.3 μm. One exposure dose is needed to printing this two dimensional layout and to meet the design rule. The E-D tree for this polylayer is shown in Fig. 6. By using best fitted biases of line, space and rim, exposure energy of 150~155 mJ/cm^2 from the overlapped energy range of AA-1 and AA-2 are found.

The effects of off-axis illumination (OAI) on rim (sized-rim) PSM and halftone-rim (HT-rim) PSM are shown in Fig. 7. In general, combination of annular OAI and regular rim has sharper log-slope of center peak of aerial image than combination of annular OAI and halftone-rim. Halftone-rim has no advantage by using stepper with function of OAI.

4. CONCLUSIONS

The simulation studies from previous[1] and this papers both indicated that halftone-rim PSM has a better resolution and larger total DOF for 0.35 μm contact hole compared with rim and attenuated PSMs. The experimental results of preliminary pattern transfer studies so far using this new type PSM could not reach the results of resolution and DOF from the simulation, therefore, are not reported in this paper. The control of thickness of etched quartz; vertical sidewall profile of etched quartz by RIE; the etching of halftone chrome, the width of rim; the exposure dose for pattern transfer, etc. are all critical to this study. Further experimental works on optimization of lithographic processes are needed to improve both resolution and total DOF. The applications of halftone-rim PSM for patterning dense and isolated line/space with or without OAI did not show meaningful improvement if compared with rim (sized-rim) PSM.

5. ACKNOWLEDGEMENT

This work was financially supported by the National Science Council and National Nano Device Laboratory of Republic of China.

6. REFERENCES

1. Wen-an Loong, Shyi-long Shy, Guey-chi Guo and Yueh-lin Chou, "Simulation and Fabrication of a New Phase-Shifting Mask for 0.35 μm Pattern Transfer: Halftone-Rim", SPIE Vol. 2087, pp. 380~389 (1993).