Investigation of Undercut on Alternating Aperture Phase Shift Mask

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Abstract— **Each new technology node tests the limits of optical lithography. As exposure wavelength is reduced, new imaging techniques are needed to maximize resolution capabilities. The phase-shift mask (PSM) is one such technique that is utilized to push the limits of optical lithography. Altering the optical phase of the light that transmits through a photomask can increase the resolution of a lithographic image significantly. However, intensity imbalances between the etched and non-etched regions due to sidewall scattering can cause resolution, phase and placement errors on the wafer. One method to balance the transmission is to undercut the chrome or retract the quartz underneath the chrome in the etched regions. An alternating aperture phase-shift mask with undercut was successfully fabricated and showed improved intensity balance.**

Index Terms— **intensity imbalance, phase-shift mask, photomask, undercut**

I. Introduction

Altering the optical phase of the light that transmits through a photomask can increase the resolution of a lithographic image significantly. The phase is altered to satisfy the relationship $d = \lambda/2(n-1)$ (in which: d =film thickness, λ = exposure wavelength, n = refractive index). Several types of phase-shifting masks (PSM) have been proposed. Each type has a general characteristic in which some transparent areas of the mask are given 180° shift in optical phase relative to other nearby transparent areas. Therefore the light intensity at a pattern boundary section becomes zero. The interaction of the aerial images between two features with a relative phase difference of 180° create interference regions that can be used to print images much closer together and with an increased depth of focus than that of a standard chrome-on-glass mask[1].

The primary focus will be towards the Alternating Aperture Phase-Shifting Mask (AAPSM).

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An AAPSM consists of alternating transmitting clear areas with relative differences of 180° phase change as shown in figure 1. The phase-shifting regions are defined by another exposure. Then the substrate (quartz) is etched to the required depth to satisfy the equation $d = \lambda/2(n-1)$. Phase differences on the AAPSM create the regions of destructive interference, resulting in a sharp dark image. The interference of the alternating phase spaces allows features to be printed very close together with an increased depth of focus. Ideally, an AAPSM can increase resolution 50% or better than that of a standard chrome-on-glass mask [1].

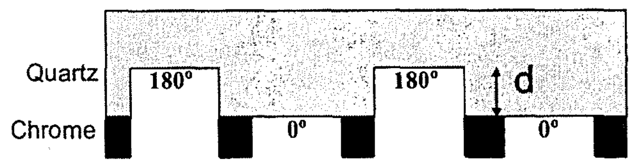


Fig. 1. Alternating Aperture Phase Shift Mask

II. Intensity Imbalance

The AAPSM is fabricated using a subtractive process in which the substrate is etched to a desired depth. This subtractive process causes asymmetrical dissimilarities between the etched and non-etch regions. The asymmetry between the openings is created from sidewall scattering of the etched openings. There will be a higher transmittance at 0° region, which results in a higher image intensity of 0° region. [2]. Therefore an aerial image imbalance occurs between the shifted and non-shifted intensity peaks as illustrated in figure 2. Image imbalances contribute directly to a CD difference between two openings and placement errors[3]. Images that are printed will differ in size between the etched and non-etched openings if the effective phase and transmission of AAPSM are not ideal.

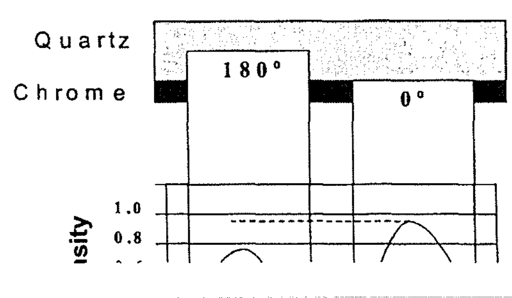


Fig. 2. Intensity Imbalance between etched and non-etched regions

In an ideal phase shift mask, only the $\pm 1^{st}$ diffraction orders are collected by the imaging system as showing in figure 3. Ideally, the 0^{th} order is canceled by the anti-symmetry of the alternating structure. However, non-ideally the AAPSM has some amplitude at the 0^{th} diffraction order. When the 0^{th} order interacts with the $\pm 1^{st}$ orders it constructively or destructively interferes with the fields produced by the $\pm 1^{st}$ orders, causing the aerial image imbalance between the two regions [3].

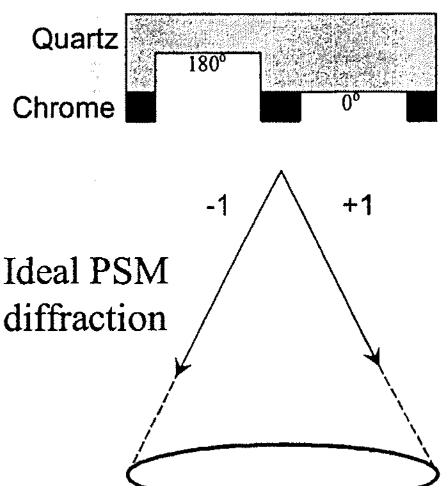
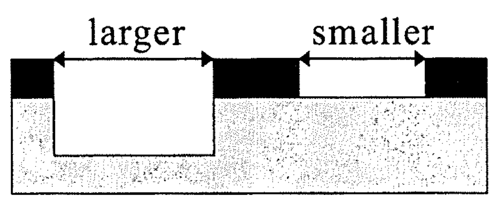


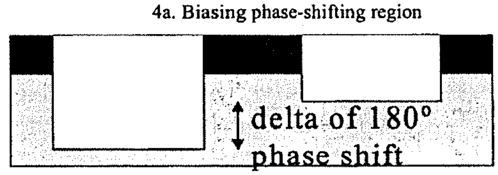
Fig. 3. Phase-shift mask diffraction

In addition to transmission imbalance between phase regions, sidewall scattering also creates phase errors. Even if the trenched is etched to a given depth, the effective phase difference will be somewhat different from 180° due to diffraction at the glass and chromium edges. The combination of phase and transmission error results in a focus-dependent CD and placement error and the peak intensities at the best focus are not balanced due to transmission errors. In the presence of phase and transmission errors, the focus can be offset, such that the intensities are balanced but at the expense of image quality of both etched and non-etched. It has been shown that the contributions of phase and transmission error are orthogonal thus both errors must be eliminated to remove the 0^{th} diffraction order [3].

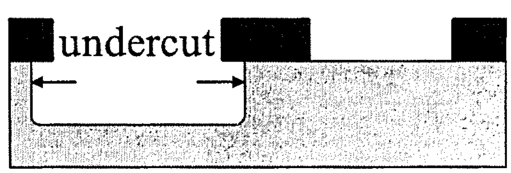
There are three general methods to balance the intensity between the phase shifted and non-shifted regions. Referring to figure 4, the first method is to bias the phase-shifting region. Additional light is able to get through the etched trench as a result of enlarging the etched region and therefore balancing the intensity between the etched and non-etched regions. The second technique is a dual-trench approach. This method involves adding an additional etch step in which both regions are etched into the quartz, but still maintaining the 180° shift between the two regions. The dual-trench process will balance the intensity; however the intensity at the etched and non-etched portions will be considerably reduced than that of the other two methods. The third technique is to undercut the chrome or "pull-back" the quartz underneath the chrome. This is accomplished by anisotropically dry etching the quartz to a desired depth followed by an isotropic wet etch. This causes the quartz to be retracted underneath chrome, therefore reducing sidewall scattering and balancing the intensity of etched and non-etched areas [1]. In addition, combinations of all three methods can be used to balance the intensity. The focus of this project is on the undercut method.



4a. Biasing phase-shifting region



4b. Dual-trench approach



4c. Single-trench with undercut

Fig.4. Techniques to balance the intensity.

III. OBJECTIVES

The object of this experiment was to fabricate two alternating aperture phase-shift masks (AAPSM) for comparison purposes. The first is a standard AAPSM (fig.1) and the second is an AAPSM with approximately 75nm of undercut on each side (fig.4c). The desired

etch depth for each mask is 2440 Angstroms following the equation $d = \lambda/2(n-1)$, where the DUV imaging wavelength, λ is 248nm and the refractive index is 1.5. Upon completion of the mask fabrication process; phase, depth, etch profile and intensity balance, have been measured for each mask.

IV. General Procedure

1. Obtain two standard chrome-on-glass mask blanks
2. First write level – Opens up chrome areas to be quartz etched (180° regions)
3. Develop
4. Dry chrome etch

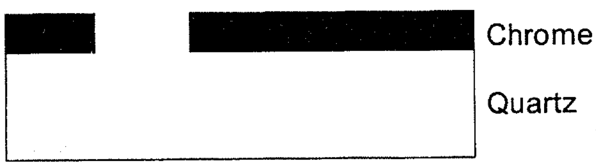


Fig.5. Masks after first level write

5. Anisotropic dry quartz etch
   - 1st mask depth of 2440A
   - 2nd mask depth of 1500A
6. Isotropic wet quartz etch – 2nd mask only
   - 2nd mask wet etch an additional 940A (1500 + 940 = 2440A total depth)

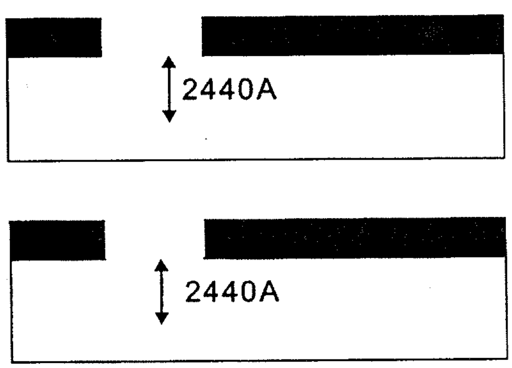


Fig.6. After quartz etch

7. Strip resist/clean
8. Spin coat resist for 2nd level
9. Second write level – Opens up chrome areas not to be quartz etched (0° regions)
10. Develop
11. Dry chrome etch
12. Strip resist/clean

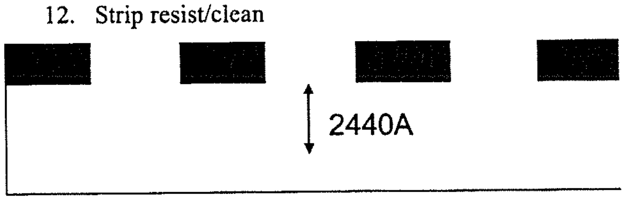


Fig.7. First mask completed

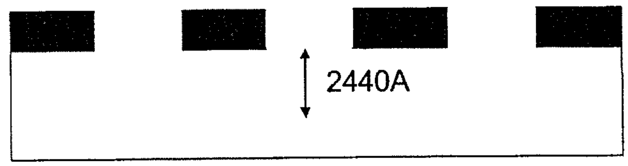


Fig.8 Second mask completed with undercut

13. Measure phase – MPM248
14. Measure aerial image transmission – AIMS
15. Measure depth and profile – SNP

V. Results and Analysis

The two varying alternating aperture phase shift masks were fabricated satisfactorily. The phase is the first attribute to look at when dealing with a phase-shift mask. Tables I and II show the phase across each of the masks, along with deduced depth in angstroms. Figures 9 and 10 shows the phase uniformity across each mask.

TABLE I
STANDARD AAPSM PHASE AND DEPTH

Phase @ 248nm					
	174.5	175.9	176.6	175.3	173.3
	177.3	178.8	179.4	178.6	176.9
	178.5	179.7	179.9	179.5	177.9
	177.8	179.7	180.1	179.4	177.3
	174.9	177.1	177.4	176.5	174.0
Average		177.4			
Std dev		2.0			
Range		6.8			
Deduced Depth					
	2365.6	2384.4	2393.2	2376.6	2349.2
	2403.7	2423.6	2431.3	2420.9	2398.5
	2419.8	2435.8	2438.5	2433.1	2411.4
	2410.3	2435.9	2441.9	2431.2	2403.3
	2370.7	2400.0	2405.0	2393.0	2358.0
Average		2405.4			
Std dev		26.7			
Range		92.7			

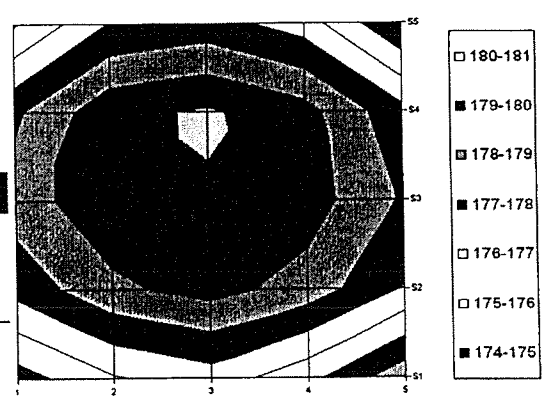


Fig.9. Standard AAPSM phase uniformity

The phase for each mask yielded tolerable results. The average phase for the standard AAPSM is 177.4 degrees while a couple of degrees from the desirable 180 degrees. The AAPSM with undercut yielded a little better phase average of 181.5 degrees. However, the undercut AAPSM uniformity was not quite as good as the standard AAPSM. This can be attributed to the additional wet etch step adding more degrees of variation.

TABLE II
UNDERCUT AAPSM PHASE AND DEPTH

Phase @ 248nm				
175.9	177.4	180.6	180.3	178.4
181.2	183.8	186.1	183.6	181.3
179.6	185.4	186.6	185.7	182.9
180.4	182.4	186.8	184.5	181.8
176.3	177.7	181.8	179.4	178.4
Average	181.5			
Std dev	3.2			
Range	10.9			
Deduced Depth				
2384.3	2404.2	2447.5	2444.1	2417.8
2455.6	2491.9	2523.2	2488.7	2457.6
2433.9	2513.3	2529.3	2517.5	2479.6
2445.8	2472.9	2531.8	2500.9	2463.9
2389.8	2409.1	2464.3	2431.3	2418.7
Average	2460.7			
Std dev	43.9			
Range	147.5			

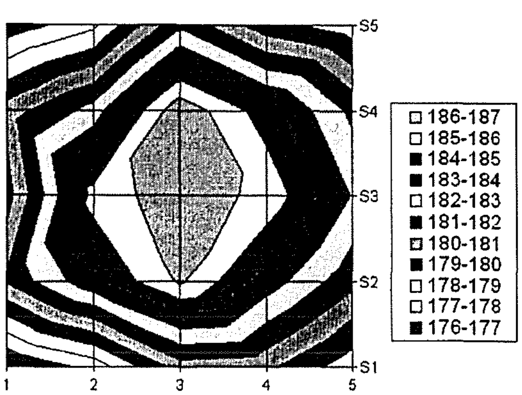


Fig.10. Undercut AAPSM phase uniformity

After determining each mask had the appropriate phase, the next step was to look at the etch profile using an SNP profilometer. The deduced depth from the phase was also verified using the SNP. The next step was then to look at the image intensity for each mask. Figures 11 and 12 are set-up to show where the image intensity peaks are in comparison to the actual etched profile. The AIMS image intensity was measured at the 248nm wavelength, with an NA of 0.5 and sigma of 0.3.

From these results it can be determined that the undercut did indeed help to improve the intensity imbalance. Looking at the standard AAPSM intensity, we can see the intensity imbalance between etched and non-etched regions does exist. Then looking at the undercut AAPSM intensity peaks, we can see the peaks come up and are starting to balance with the non-etched regions. Tables III and IV show the intensity image results at three different feature sizes and the percent imbalanced.

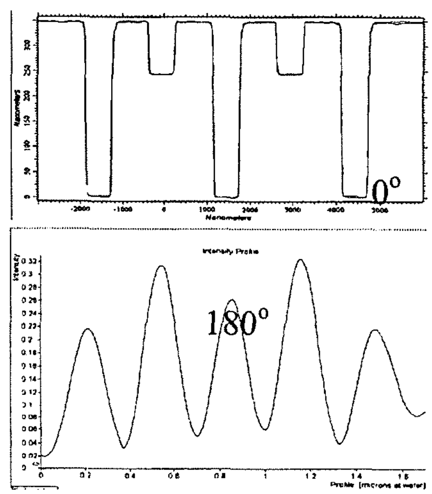


Fig.11. Standard AAPSM profile and intensity peaks

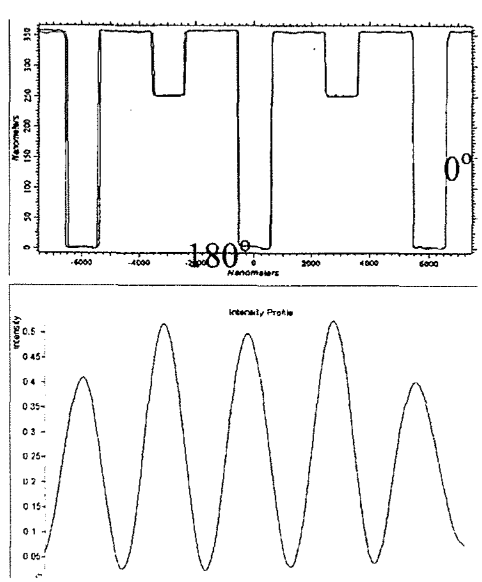


Fig.12. Undercut AAPSM profile and intensity peaks

TABLE III. STANDARD AAPSM INTENSITY RESULTS

Site #	Feature Size	Left	Center	Right	% Imbalance
1	600 nm	0.317	0.262	0.323	18.1%
2	700 nm	0.454	0.390	0.464	15.0%
3	800 nm	0.498	0.430	0.503	14.1%

TABLE IV. UNDERCUT AAPSM INTENSITY RESULTS

Site #	Feature Size	Left	Center	Right	% Imbalance	Delta
1	600 nm	0.343	0.295	0.359	16.0%	2.2%
2	700 nm	0.479	0.448	0.484	7.0%	8.1%
3	800 nm	0.519	0.496	0.524	4.9%	9.2%

There are few things to keep in mind with this type of technique used to balance the intensity. The first is the sidewall profile with an undercut feature. The profilometer used in this experiment is not able to locate or retrieve an undercut type profile. The profile shown fails to show some of the isotropy of the actual etched feature. Stripping the chrome off would reveal a feature with an undesired decreased slope towards the bottom of the etched feature. The fact is a trade-off between sidewall angle and the amount of undercut exist. That is a deep anisotropic dry etch yields better sidewall profile at the expense of less undercut and ultimately not as good intensity balance. Furthermore, there may be some peeling or chrome lift-off at the small feature sizes. If a large undercut is desired, there may not be enough area for small chrome areas to adhere to the quartz and lift-off of these features may occur.

VI. FUTURE PLANS

The undercut AAPSM has shown some promising results in balancing the intensity peaks. However, this doesn't mean much, if the results can't be shown on the wafer level. The next step would to actually expose wafers and compare results between the masks at the wafer level. A full focus exposure matrix should be performed to show ideally how effective the undercut is on balancing the intensity peaks. In addition, further investigation of other balancing techniques can be explored.

VII. CONCLUSION

In conclusion, two alternating aperture phase shift masks have been fabricated with satisfactory phase and depth measurements. The AAPSM with undercut showed promising results for balancing the intensity between the etched non-etched areas. Further experimentation of the undercut AAPSM should be performed to evaluate the system at the wafer level.

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[3] H. Kokubo, US Patent Publication No.: US 2001/0044056 A1, (2001)