The Effect of Mask Substrate and Mask Process Steps on Patterned Photomask Flatness

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ABSTRACT

Photomask substrate, blank, and finished mask flatness are becoming more serious concerns for photomask fabrication. Most commercial and captive mask houses now use a combination of mask blanks at various flatness levels from >2.0µm to <0.5µm, measured as total indicated range, or TIR. As mask feature sizes are reduced, depth of focus becomes significantly smaller, driving the need for tighter flatness specifications.

Photomask blank suppliers generally specify mask blank flatness based on measurements of quartz substrates before films are deposited. The mask substrates start with unique, non-flat shapes resulting from polishing and are further deformed by the stress of deposited films. Mask patterning, which removes some of the deposited films, has the potential to change the shape and flatness of the mask. The attachment of a pellicle and frame also has the potential to distort the mask. Since the goal of the mask maker is to provide a finished mask meeting all requirements, including flatness, it is important to understand the effects of each step in the flatness life of the photomask.

This paper provides flatness data from the following process steps: quartz substrate, chromium coating, phase shifter coating, resist coating, patterned mask and pelliclized mask. A correlation is made of substrate and blank flatness and shape to finished mask flatness, with proposed practical guidelines for control of final mask flatness.

Keywords: mask, substrate, mask blank, flatness, pellicle, mask flatness

1. INTRODUCTION

Depth of focus is one of the most critical and rapidly changing parameters in optical lithography. The steady reduction of critical pattern dimensions has driven shorter exposure wavelengths and larger numerical apertures (NA) in steppers. The depth of focus varies linearly with wavelength and as the inverse square of the NA. A numerical example shows the severity of the problem. In the mid-1980s a typical stepper used a 0.35 NA lens with a 365 nm exposure wavelength to produce 0.80 µm images with a 3 µm depth of focus. Today, leading-edge lithography uses 0.85 NA lenses at 193 nm wavelength. Strict scaling would predict that these steppers could produce 0.17 µm images with a focal depth of 0.27 µm. In reality, the development of reticle enhancement technologies has allowed the minimum feature size to go below 0.10 µm, with practical depths of focus around 0.20 µm. The reduction of focal depth by a factor of 10 to 15 over the last 25 years has been a major challenge in lithographic technology.

Major improvements have been made in stepper focus accuracy and stability, and innovations such as chemical-mechanical polishing have improved wafer planarity to support the increasingly tight focus tolerances. Until recently, however, mask flatness was only a minor consideration in the total focus budget. Optical scaling laws show that depth of focus scales as the square of the magnification between the object and image plane of a projection optical system.

Steppers of the 1980s typically used 5x or 10x reduction. A mask with 2 µm non-planarity would detract a negligible 0.02 to 0.08 µm from the total focus range of 3 µm. Today's steppers more commonly use 4x reduction, which increases the effect of a 2 µm mask non-planarity to 0.125 µm in the wafer plane. This represents over half of a 0.20 µm depth of focus.

It is obvious that 2 µm is no longer an acceptable mask flatness tolerance for modern lithography. Mask blank vendors now offer flatness grades of 1 µm, 0.5 µm, and better. However, the tolerance is only specified for the initial fused silica substrate. Absorber films with either tensile or compressive stress can alter the initial shape of the substrate. When the mask pattern is etched into the absorber film some of this stress is relieved, but in an incomplete and pattern-dependent way. Finally, the addition of a protective pellicle can have a marked effect on the final mask flatness. The pellicle frame is a relatively stiff piece of aluminum and is held against the mask surface with adhesive. The flatness of the pellicle frame prior to attachment, and the magnitude and uniformity of the pressure used to mount the pellicle, both contribute to the final shape of the mask.

Much work has been published on various aspects of photomask flatness and the effect on projected image distortion[1-4] but there have been no large scale flatness studies of the entire process, providing flatness information at each process step. Since mask flatness has become a more important component of the lithographic error budget, and because of the many contributions to the final flatness of the mask, it was necessary to study mask flatness through the entire mask-making process from substrate production through film deposition and pattern generation to pellicle application. The major contributions to mask non-flatness are identified in this work, and approaches are discussed for guaranteeing the final, as-delivered flatness to the lithographer.

2. MASK BLANK FLATNESS

A mask blank consists of a highly polished quartz substrate and several films deposited on top of the substrate as shown in Figure 2.1. In the illustration below, a phase shifting material (PSM) has been deposited directly on top of the quartz substrate, followed by a chromium absorber film and finally a photoresist.

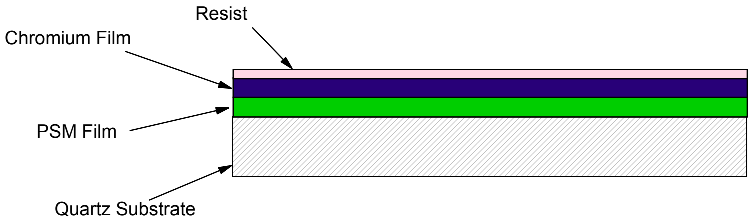

Figure 2.1. Typical example of a mask blank

In a typical mask fabrication facility there are generally many different types of mask blanks used for mask fabrication. Often several types of photoresists are used to enhance imaging capability with various mask writers and for specific mask features. Many chromium absorbers and phase shifting materials for both 248nm and 193 nm stepper illumination are available from mask blank suppliers. The combinations of these various films results in 20 to 30 different mask blanks available for mask fabrication. Various combinations commonly used in commercial and captive mask houses are described in Table 2.1.

We began this work by measuring the flatness of mask blanks incoming from our suppliers. Measurements were performed using a commercial near normal incidence interferometer system with phase analysis techniques and 20nm measurement uncertainty. For all work described in this paper, the area measured was 142 x 142mm, since the blanks are purchased to specifications within this area.

Over 70 blanks were measured, representing types A, B, B1, B2, C, C2 and D, and comprising 3 substrate flatness specifications (0.5, 1.0, and 2.0µm). The blank shapes varied through concave, flat, convex, saddle and higher order twisted shapes dubbed "flying carpet". Examples are shown in Figure 2.2.

Mask Blank Type	**Composition**
A	**Cr Type 1** **Flatness = 2.0µm**
B	**Cr Type 2** **Flatness = 2.0, 1.0, 0.5µm**
B1	**Cr Type 2 / 248nm PSM** **Flatness = 2.0µm**
B2	**Cr Type 2 / 193nm PSM** **Flatness = 2.0, 0.5µm**
C	**Cr Type 3** **Flatness = 2.0, 0.5µm**
C2	**Cr Type 3 / 193nm PSM** **Flatness = 2.0, 1.0, 0.5µm**
D	**Cr Type 4** **Flatness = 2.0, 0.5µm**

Table 2.1. Description of commonly used mask blank types

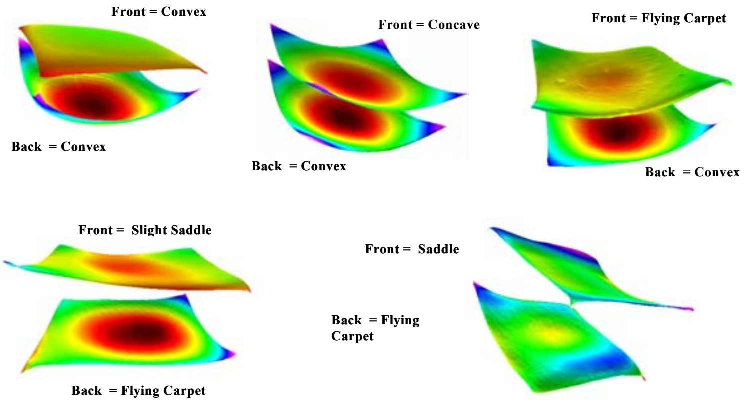

Figure 2.2. Examples of mask blank shapes

The flatness distribution of blanks measured during this work is presented in Figures 2.3 and 2.4. For the 0.5µm blanks, the measured flatness values ranged from 0.31 to 0.92µm with an average of 0.50µm. Seven of seventeen 0.5µm blanks exceeded a 0.5µm guideline. It should be noted that many of these blanks would have significantly flatter results if measured in a slightly smaller area since the shapes were generally flat to slightly concave across most of the top surface with increased variation only near the edges or corners of the measured area. Since the suppliers measure the substrates prior to film deposition, one may suppose that the increased flatness may largely be the result of deposited film stress. Additional work will be necessary to further minimize the flatness of blanks at the 0.5µm specification and beyond.

The 2.0µm blanks ranged from 0.37 to 2.1µm with an average of 1.0µm. Only two of fifty-five 2.0µm blanks were found to be slightly greater than 2.0µm, while more than half were less than 1.0µm. Six 1.0µm specified blanks were measured and all were less than 1.0µm flatness.

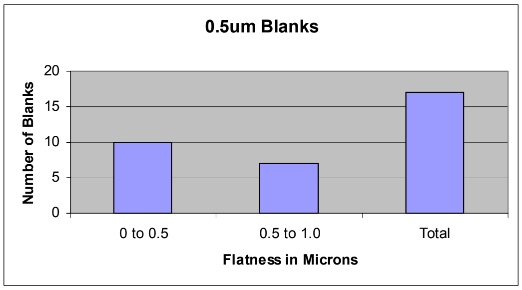

Figure 2.3. Performance of 0.5µm blanks

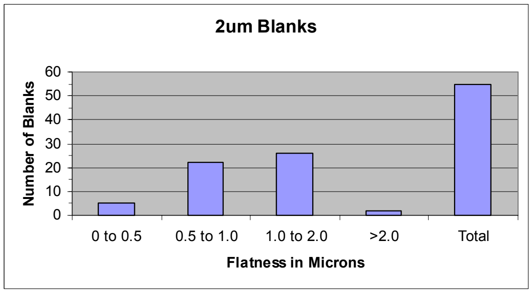

Figure 2.4. Performance of 2.0µm blanks

In addition, the back side flatness was measured on each of the blanks discussed above. For the 0.5µm blanks, the back side shape was generally convex and masks ranged from 0.49 to 2.41µm with an average of 1.8µm. The 2.0µm blanks ranged from 0.43 to 3.7µm flatness on the back, averaging 2.0µm. Mask back surfaces also varied through concave, flat, convex, saddle and flying carpet shaped.

3. CORRELATION OF QUARTZ SUBSTRATE AND MASK BLANK FLATNESS

Since mask blank suppliers generally measure and specify flatness after polishing of the substrate but before deposition of films and resist, there is some possiblility of the flatness of the finished blank differing from the flatness of the substrate due to film stress. Mask fabricators are most interested in the flatness of the final blanks as they are used in the mask process. Thus, it is important to understand the shape altering effects of each film type as well as the combined effect of all the films present in a given mask. To compare substrate and mask blank flatness, we stripped all the films from several blanks, leaving the original quartz substrate. The flatness was measured both before and after removal of films, so that the original substrate flatness could be compared with the flatness of the blanks as received. The correlation data are presented in Figure 3.1 for all three flatness specifications. While the correlation between substrate and finished blank (substrate minus blank) flatness was quite good, there are some instances where the substrate flatness was either better or worse than the finished blank flatness. This is due to the initial shape of the substrate combined with the shaped induced by the stress of the films deposited to make the blank. If the initial shape of the substrate was perfectly flat, the shape and flatness of the blank would be expected to be a combination of stress due to the Cr film, the PSM film and the resist. If no measurement of flatness is performed on the final blanks, the mask blank supplier must rely on careful control of the film deposition processes and exact matching of film stresses to assure final blank flatness within specifications.

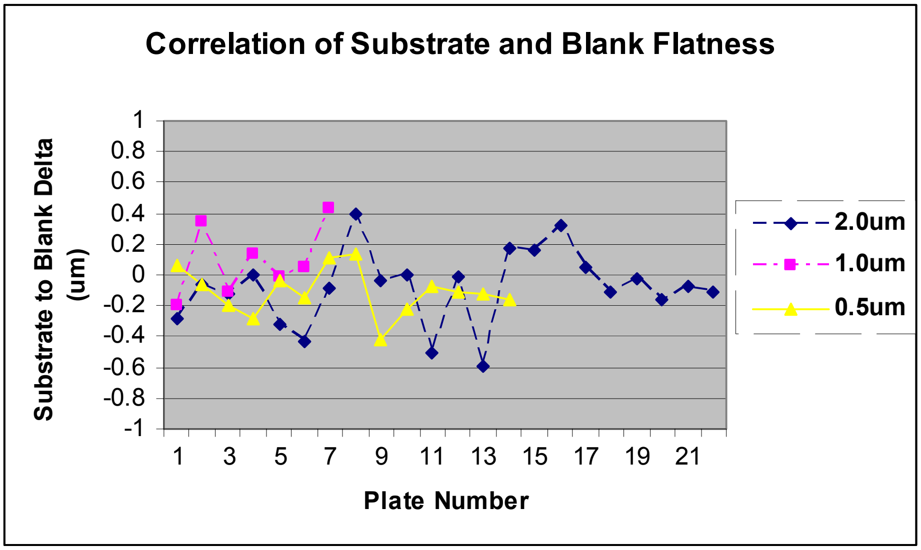

Figure 3.1. Correlation of substrate and mask blank flatness

By carefully looking at several mask blanks of one type, one can observe that the Cr film produces a concave effect on the substrate while the phase shifting film produces a convex effect. This is expected since sputter deposited Cr film stress is generally tensile, while the PSM film stress is generally compressive. Since the substrate is never exactly flat but always has some residual shape, the deposition of one or both films produces a shape that is the algebraic addition of the flatness surface of the substrate and the predictable deformation induced by the film stress. We collected data on each film type's contribution to the final blank shape by selectively removing the films and measuring the intermediate blank's shape before and after each step. This work is discussed in Section 4.

4. FILM CONTRIBUTION TO MASK BLANK FLATNESS

In order to determine the contribution of the various film types to the overall flatness of the mask blank, each film was selectively removed and the blank re-measured until the bare quartz substrate was revealed. In this manner it was possible to determine the shape and flatness of the quartz substrate, the Cr coated substrate (COG blanks), the PSM coated substrate, the Cr and PSM coated substrate, and the full mask blank. The effect of each film was mathematically calculated and the shapes plotted. Figure 4.1 illustrates the complete process for an example of a 0.5µm specification blank and demonstrates the effect of the Cr and PSM films in mask blank formation. While the shapes depict a true representation of the surfaces, the color and intensity of each shape were selected automatically by the plotting software and do not show true scaling from one image to another.

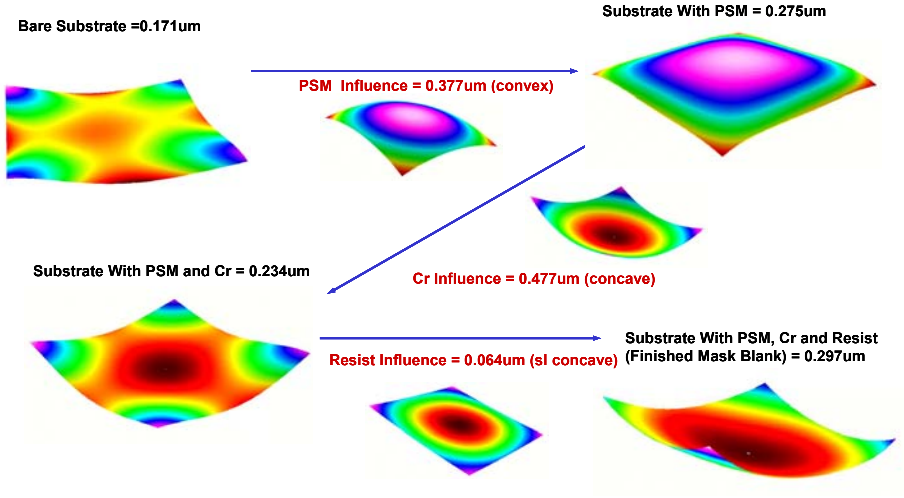

Figure 4.1. Example of the various flatness steps in mask blank formation

Over forty blanks were measured with films sequentially stripped. Over the 142x142mm fiducial area, the average flatness influence of Cr was found to be 0.43µm concave with a range 0.23 to 0.70µm for all Cr film types measured. All Cr film types produced a strong concave shape effect on the quartz substrate due to the tensile stress inherent in the sputter deposited Cr film. The average flatness influence of the two PSM film types was 0.44µm convex and the range was 0.33 to 0.69µm. Both PSM film types exhibited a strong convex shape effect on the substrates due to the compressive stress resulting from the sputter deposition process for these films. Table 4.1 and 4.2 summarize the Cr and PSM data collected during the film stripping process. In general, the effects due to resist are small (<0.1µm) and can be ignored for most purposes.

Several observations can be made from a review of the data by Cr and PSM film type. First is that the Cr film types exhibited different magnitudes of flatness effect on the substrates due to their differences in thickness and stress. The variation in the magnitude of the effect within a film type is higher than expected, especially for Cr film type 2 both by itself and on top of 248nm PSM material. Cr film types 1, 3 and 4 had much smaller variation as shown by their smaller standard deviations. Since Cr film types 3 and 4 are used primarily for masks with tighter specifications, including CD and flatness control, this is a positive result. This type of information would be useful in a predictive modeling effort relating substrate and mask blank shape and flatness to final mask flatness.

The second observation is that the magnitude of the Cr film effect increased when the Cr was deposited on PSM materials. This can be seen in both Cr film types 2 and 3 deposited on PSM materials. This is probably due to variations in film stress resulting from the sputtering process. Metal films often exhibit differences in stress when deposited on different surfaces, particularly if the surfaces have different roughness. This effect should be considered by mask blank suppliers when attempting to control or match Cr and PSM film stress effects.

Third, the two PSM materials exhibited different magnitudes of shape effect on the substrate, with the 248nm film averaging 0.63µm and the 193nm films averaging 0.35µm. The 193nm film exhibited a lower standard deviation for the films measured indicating that there is better film thickness and/or stress control in this film. Comparison of the magnitudes of Cr type 3 on 193nm PSM (average = 0.50µm) and 193nm PSM (average = 0.35µm) would suggest that better control of film thickness/stress is necessary to control mask blank flatness, particularly if the control process uses substrate shape/flatness measurements rather than final mask blank flatness. This will certainly be required for 45nm node masks where 0.25µm flatness is needed. A predictive model which takes account of substrate shape, Cr film type stress/thickness (shape/magnitude effect) and PSM film type stress/thickness would be useful in better control of mask blank flatness. Alternatively, one could measure the blank flatness after resist coat and sort blanks into various flatness categories to achieve the same result. However, this process would require a clean, fully automated flatness measurement system which would not expose the resists currently in use for mask fabrication.

	Cr Type 1 (µm)	**Cr Type 2 (µm)**	**Cr Type 2 on 248nm PSM (µm)**	**Cr Type 3 (µm)**	**Cr Type 3 on 193nm PSM (µm)**	**Cr Type 4 (µm)**
	0.460	0.233	0.667	0.339	0.516	0.392
	0.373	0.310	0.646	0.299	0.534	0.332
	0.403	0.280	0.702	0.293	0.477	0.330
	0.419	0.287	0.655		0.494	0.331
	0.422	0.350	0.462		0.487	0.414
		0.337			0.466	0.447
		0.472			0.412	0.363
		0.529			0.477	0.370
		0.471			0.510	0.375
		0.476				
		0.499				
		0.282				
		0.252				
Average	**0.415**	**0.292**	**0.626**	**0.310**	**0.502**	**0.360**
Minimum	**0.373**	**0.233**	**0.462**	**0.293**	**0.412**	**0.330**
Maximum	**0.460**	**0.529**	**0.702**	**0.339**	**0.534**	**0.447**
St Dev	**0.032**	**0.106**	**0.094**	**0.025**	**0.035**	**0.040**

Table 4.1. Summary of Cr flatness effect data for several Cr film types

	248 nm PSM (µm)	**193nm PSM (µm)**
	0.683	0.332
	0.558	0.344
	0.6	0.377
	0.621	0.347
	0.694	0.341
		0.396
		0.366
		0.364
		0.338
		0.341
Average	**0.631**	**0.348**
Minimum	**0.558**	**0.332**
Maximum	**0.694**	**0.396**
St Dev	**0.057**	**0.020**

Table 4.2. Summary of PSM flatness for 2 film types

5. PATTERNED MASK FLATNESS

Over 150 patterned masks, fabricated from mask blanks with 3 flatness specifications (0.5 to 2.0µm), were measured to determine the relationship between finished mask flatness and mask blank flatness specification. Examples of the front and back shapes of three finished masks without pellicles are shown in Figure 5.1. As with the mask blanks, some patterned masks have both surfaces either convex or both concave while others have one surface convex and one concave. Still others have one or both surfaces twisted out of plane on one or more corners ("flying carpet") or have a distinct saddle shape (less common).

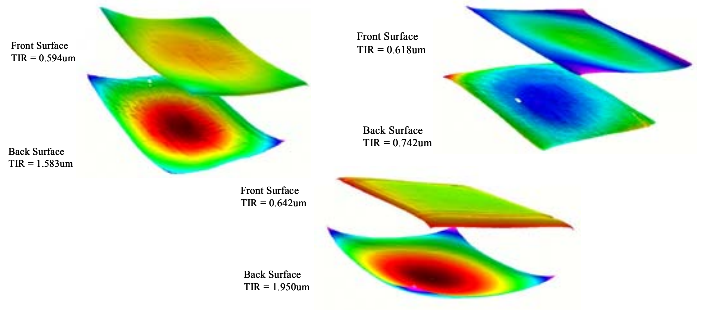

Figure 5.1. Masks fabricated from 0.5µm flat blanks

The flatness data for the patterned masks are presented graphically by mask blank type in Figures 5.2 through 5.4. Approximately 44% (23 of 52) of the patterned masks fabricated with blanks purchased to 0.5µm flatness specifications had measured flatness greater than 0.5µm. (range 0.25 – 0.94). For masks fabricated with 1.0µm specified blanks, 5 of 34 (15%) were greater than 1.0µm, the population having a range of 0.25 – 1.25µm. Almost all masks fabricated with 2.0µm blanks had flatness of less than 2.0µm. One out of 67 (1.5%) were found to exceed 2.0µm with the range of measurements being 0.3 – 2.75.

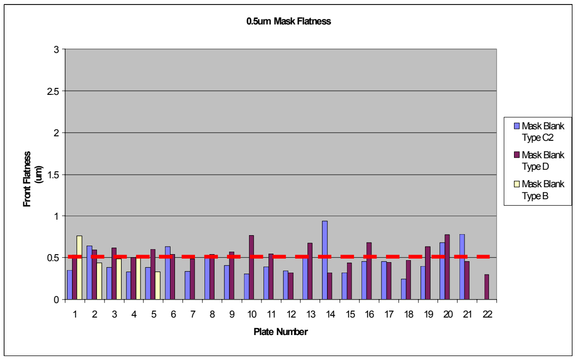

Figure 5.2. Flatness of masks fabricated to 0.5µm guidelines

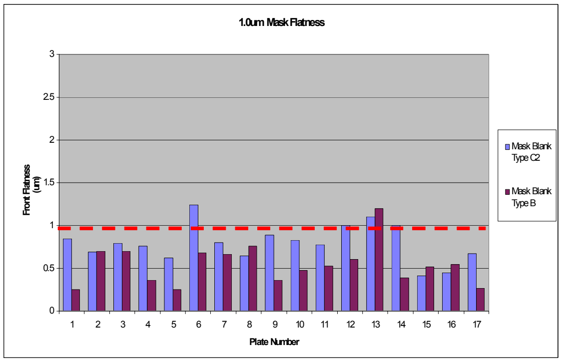

Figure 5.3. Flatness of masks fabricated to 1.0µm guidelines

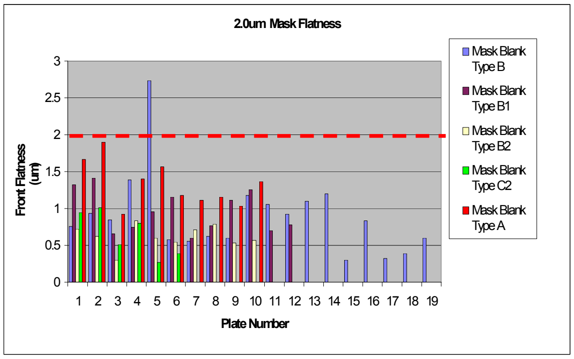

Figure 5.4. Flatness of masks fabricated to 2.0µm guidelines

Clearly most attention needs to be paid to masks fabricated to the tighter flatness guidelines. Since the populations of blanks and patterned masks measured in this study were different, a direct correlation cannot be made between blank and patterned mask flatness. One can expect that there is a close relationship between substrate, blank and patterned mask flatness generally. However, patterning may improve flatness if the substrate flatness was worsened by deposition of stressed film and that film is largely removed during patterning. Alternately, patterning could worsen flatness when the blank flatness was very low and a large amount of highly stress film was removed during patterning.

Additional data needs to be gathered on masks and blanks from the same population with various mask patterns to better understand the effect of mask blank flatness and patterning effects on finished mask flatness. Application of this data in conjunction with models predicting mask distortion could be very effective in improving final mask flatness. However, an immediate improvement in patterned mask flatness should be achievable by measuring and sorting the 0.5µm blanks and using the flattest blanks for the most critical mask levels.

6. PELLICLE CONTRIBUTION TO MASK FLATNESS

Optical masks are usually fitted with a pellicle to protect the pattern array from foreign material. These typically comprise an aluminum frame with a polymer membrane stretched across the top. The pellicle and frame are attached to front surface of the mask with flexible adhesive. A diagram of a pelliclized mask is shown in Figure 6.1 below.

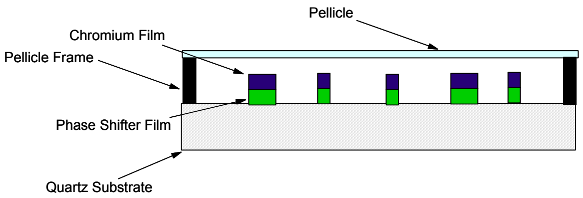

Figure 6.1. Diagram of patterned mask with pellicle attached

Attachment of the aluminum frame to the mask surface may additionally distort the mask shape, resulting in either improved or worsened flatness. The effects of pelliclization will depend on at least two factors: the shape of the aluminum frame before attachment and the nature of the attachment process. The relative importance of these effects have been evaluated through modeling and measurement of in plane distortions.[2, 3, 4]

To demonstrate the potential effects of pellicle attachment, several mask blanks were measured both before and after pellicle attachment. The photoresist was removed from the blanks before measurement, the blanks were measured, and then pellicles were attached and the blanks were re-measured. Examples of the effects of the pellicle attachment are shown in Figures 6.2 - 6.6. and the numerical results for these examples are presented in Table 6.1

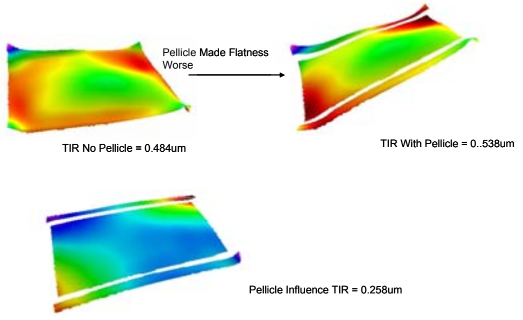

Figure 6.2. Plate 1 - example of pellicle worsening mask flatness

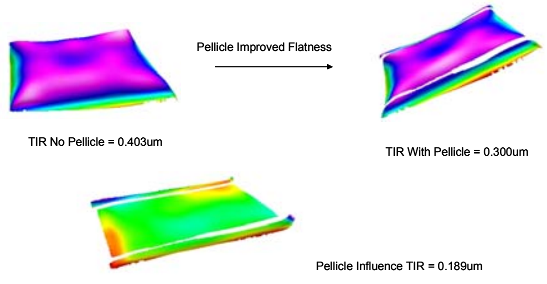

Figure 6.3. Plate 2 - example of pellicle improving mask flatness

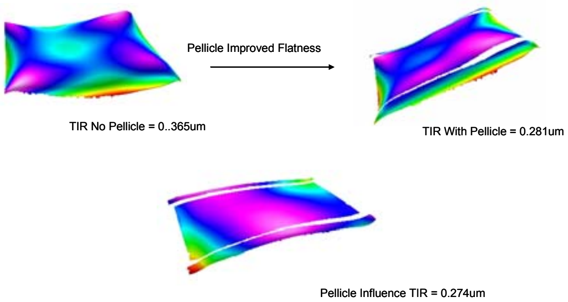

Figure 6.4. Plate 3 - example of pellicle improving mask flatness

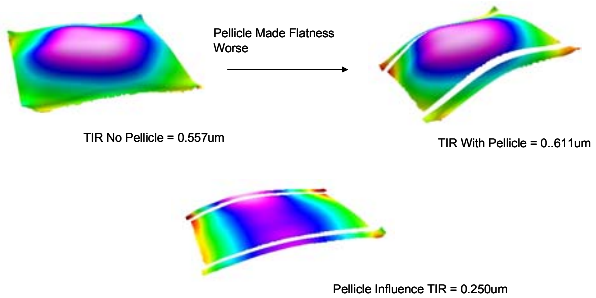

Figure 6.5. Plate 4 - example of pellicle worsening mask flatness

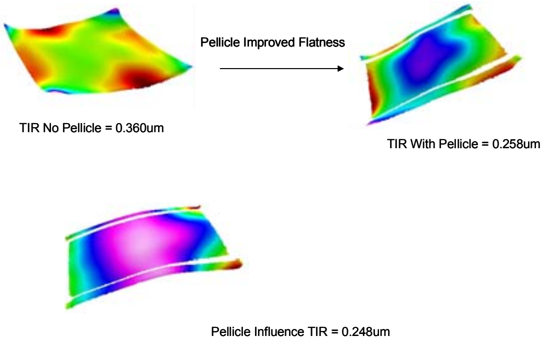

Figure 6.6. Plate 5 - example of pellicle improving mask flatness

Plate	Flatness of Blank (µm)	Flatness of Blank with Pellicle (µm)	Effect of Pellicle on Flatness	Numerical Value of Pellicle Effect (µm)
1	0.484	0.538	Worsened	0.258
2	0.403	0.300	Improved	0.189
3	0.365	0.281	Improved	0.274
4	0.557	0.611	Worsened	0.250
5	0.360	0.258	Improved	0.258
Average	-	-	-	0.246

Table 6.1. Effect of pellicle attachment on Cr coated mask blanks

For the five mask blanks used in this evaluation, three were found to improve (deltas = 0.084 - 0.103µm) in flatness upon attachment of the pellicle and frame. Two were found to worsen (deltas = 0.054µm) in flatness with pellicle attachment, resulting in final flatness greater than 0.5µm. The last column of Table 6.1 shows the numerical value of the "pellicle effect" for each blank. The average of this value was 0.246.

Several things can be done to mitigate pellicle effects on final mask flatness. First, tighter specifications on pellicle frame flatness would reduce the effects of frame attachment to the mask. Alternatively, both the mask and frame flatness and shapes could be measured and frames could be paired with the appropriate mask to minimize shape mismatches. Combined with mask blank sorting to improve patterned mask flatness, frame/mask matching could significantly improve final mask flatness and performance. However, the cost and time associated with the additional mask process steps would limit the application to all but the most critical mask levels.

6. SUMMARY AND CONCLUSIONS

This work has demonstrated several interesting and useful points relating to mask blank and final mask flatness improvements. First, mask blanks have a myriad of shapes ranging through concave, flat, convex, saddle and flying carpet and may not always meet the specifications to which they were purchased, especially for blanks with the tightest specifications. Back surface flatness is usually higher than front surface and can sometimes exceed 3.0µm. There is a correlation between the substrate flatness and the blank flatness but is not always 1 to 1. Cr films produce concave effects on the substrate shape while PSM materials produce convex effects. Resist effects are generally negligible. Improved Cr and PSM film stress control is needed to reduce their effect on the substrate in blank formation and the consequent effect on patterned masks where part of one or more films has been removed to form the pattern. Ideally, for the most advanced masks with tighest specifications, suppliers would make flatness measurements on the final mask blanks and provide data to mask fabricators.

Patterned mask flatness has been shown to be largely the result of mask blank flatness and film stress relief. The effect of various patterning combinations with specific mask blank types has not been demonstrated but should be considered in effectively meeting the strictest mask specifications. The pattern density and layout will affect both the shape and magnitude of patterned mask flatness.

Attachment of the pellicle can either increase or decrease the final mask flatness, depending on the shape and flatness of the patterned mask, the shape and flatness of the pellicle frame and the characteristics of the attachment process. Improvements in frame flatness and adhesive flexibility in pellicles, frame bonding processes and patterned mask flatness should reduce final mask flatness significantly. Measurement and matching of frame and patterned mask shapes can also provide improved mask flatness control for the most critical mask levels. Improvements in all these areas are needed to meet the strict requirements for 45 and 32nm node photomasks.

Lastly, a predictive model incorporating all steps of photomask processing including substrate shape, film effects, pattern density and layout effects, pelliclization effects and stepper chucking effects together with large sample size verification would be extremely useful in controlling and guaranteeing flatness requirements for all aspects of the photomask process.

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