Design, Fabrication, and Characterization of an Alternating Phase Shifting Mask for DUV Lithography

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Abstract— **The goal of this project is to design, fabricate, and characterize alternating phase shift masks for 248nm DUV lithography. The characterization of the masks was to include etch depth and sidewall angle measurements via atomic force microscopy (AFM). Etch times were to be varied in order to induce phase changes of 90°, 180°, and 270°; one binary chrome on glass mask was also supposed to be fabricated to show the enhancements offered in processing by the phase shifting masks. The measurements of the etch profiles should not only be useful in determining the achieved phase shift and their correlation to CD in photoresist, but also in the feasibility of using atomic force microscopy on alternating phase shift masks as a form of metrology; a standard profilometer was also going to be used for metrology in comparison to AFM measurements. After characterization of the mask set, minimum CD performance was to be evaluated using PROLITH simulation, followed by experiments in the RIT SMFL.**

Index Terms—**Alternating Phase Shifting Mask (APSM), Atomic Force Microscope (AFM), Levenson Mask.**

I. INTRODUCTION

SINCE the advent of microelectronics manufacturing, the basic design of a photomask for use in lithography has not changed. Essentially masks are binary features (chrome) on glass of the image to be transferred to the wafer. However, these basic masks fail to offer the desired resolution for the small feature sizes desired for modern chips with increasingly smaller transistor gate lengths and greater circuit density. Alternating Phase Shift Masks (APSM, or also known as Levenson-type masks) offer a solution to making smaller features with a greater density (pitch), as well as an enhancement in depth of focus (DOF), while requiring only a few modifications to the "basic" binary mask that has been used in industry for decades.

Although alternating phase shift masks offer resolution enhancement and an increased depth of focus, they can only practically be used in certain situations, and do encounter some limitations/problems. They can generally only be used in applications requiring small feature size and tight pitch, such as the gate level in DRAM manufacturing. Some problems include printing brick-like patterns, second to first level alignment during mask fabrication, inspection, etch depth, phase defects, and mask repair.

Basic chrome on glass, binary masks have been used in the fabrication of integrated circuits for decades. However, as critical dimensions continue to decrease in size, new techniques must be developed to image these features. Using radiation with a smaller wavelength would aid this cause, but that is a rather expensive route to follow, since it would require the purchase of a new stepper/scanner. The use of alternating phase shift masks present a viable solution to increasing resolution, pitch, and depth of focus, while requiring only a few departures from standard binary, chrome on glass fabrication techniques. Although these masks have several benefits, they are not without their caveats.

II. THEORY

Light is an electromagnetic wave comprised of a phase and amplitude. Generally speaking, as the electromagnetic wave encounters smaller opaque features on a chrome on glass mask, the contrast between the opaque and transparent region approaches zero due to constructive interference from fringing fields. Thus, optimizing transmission of light through a chrome on glass mask would require the opaque features to be to be greater in size than the transparent regions. In this type of mask the light has the same phase at all transparent regions. The effects listed above will therefore result in degraded resolution and pitch of CDs. These masks also do not ensure that the electric field at the wafer's surface will go to zero.[1] The electric field at the surface of the wafer is given by equation 1 below:

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$$E(x) = \cos\frac{\pi x}{\lambda} \qquad (1)$$

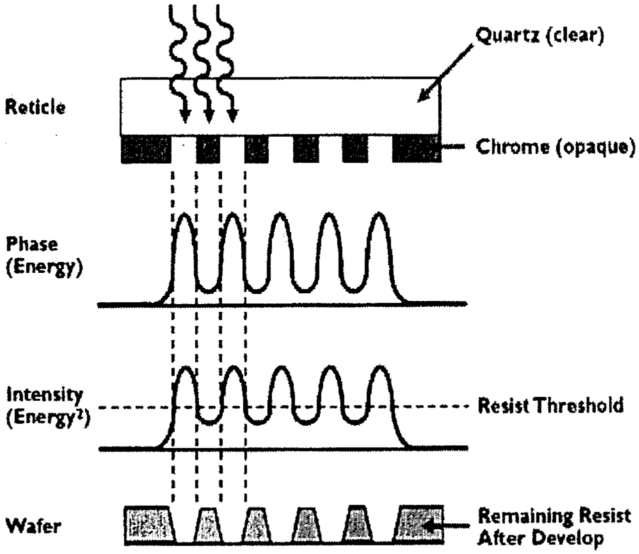

Figure 1: Electric Field for Binary CoG Mask[8]

Alternating phase shift masks offer a solution to these problems. These masks introduce a π, or 180°, phase shift in the electric field at the surface of the mask at alternating apertures, unlike the binary chrome on glass mask whose electric field at the surface has the same phase at all apertures. This phase shift is introduced by etching a certain distance into the transparent material of the mask (this could also be accomplished by depositing a particular thickness of the same transparent material onto the mask). The etch depth required in fused silica (quartz) to induce a π phase shift in 248nm radiation is 247nm. This depth can be calculated from equation 2,

$$\Delta\phi = \frac{2\pi}{\lambda}(n-1)t \qquad (2)$$

where t is the thickness to be etched, ϕ is the desired phase shift, λ is the wavelength of incident radiation, and n is the refractive index of the transparent media.

As mentioned previously, binary chrome on glass masks do not ensure that the electric field at the wafer's surface will be zero, resulting in a degraded image and therefore a decreased resolution and pitch. However, in the case of an alternating phase shift mask, the electric field at the mask swings from +1 in regions with no phase shift to -1 in apertures with a π phase shift, thus forcing the electric field at the wafer to pass through zero.

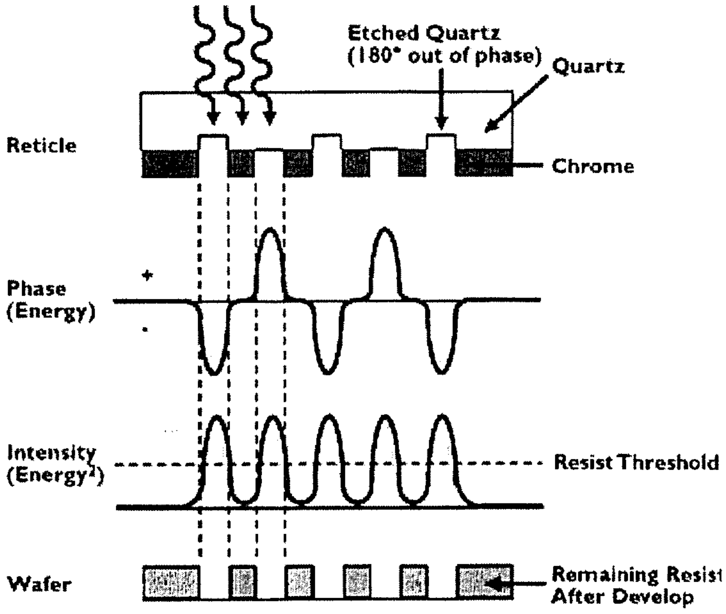

Figure 2: Electric Field for Alternating Phase Shifting Mask[8]

The aerial image intensity can be approximated by equation 3 below:

$$I(x) = 0.5(1 + \cos\frac{2\pi x}{\lambda}) \qquad (3)$$

This allows alternating phase shift masks to exhibit greater contrast, thus leading to better resolution and pitch. In fact, the resolution of an alternating phase shift mask is twice that of a chrome on glass mask, represented by equation 4.

$$\frac{0.25\lambda}{NA} \qquad (4)$$

Despite the advantages offered by alternating phase shift masks, there are several negative aspects. Alternating phase shift masks perform best in applications requiring small CDs and a tight pitch, such as the gate level in DRAM manufacturing. Certain types of features, however, make it difficult to use alternating phase shift masks. High density brick-like patterns do not allow for neighboring features to have phases opposite one another, and patterns that are not repetitive are also difficult to assign phase shifts to that meet the alternating phase shift mask specifications.[3] Additionally in clear field masks, regions where phase shifted and non-phase shifted regions meet will cause an undesired printed line in the photoresist.

Alternating phase shift masks also have the potential for quartz patterning errors, where the desired etch depth is not achieved, resulting in an incorrect phase shift. The light intensity that passes through the transparent regions remains constant regardless of phase shift/etch depth. Inspection tools that merely observe light intensity through the mask to verify the pattern will not notice this phase error. Additionally, there are no systems currently available to repair these quartz patterning defects.[4]

Other phase shifting masks types do exist, however they generally do not exhibit the same increase in resolution as alternating phase shift masks offer. Rim phase shifters also force the zero intensity at the wafer surface, but also allow for arbitrary feature types to be fabricated. Chromeless phase shifting masks can be fabricated from a blank quartz mask with only one patterning step, as opposed to two patterning steps for alternating phase shift masks; each phase transition results in a zero intensity reading at the wafer surface. Attenuated phase shift masks (also known as embedded attenuating phase shift masks or leaky chrome phase shifting masks) utilize partially transmitting regions with transmission values in the range of 4-15% that also induce a π phase shift, resulting in a zero intensity reading at the wafer surface. Similar to binary chrome on glass masks, attenuating phase shift masks require only one patterning step.

Atomic force microscopy allows for the inspection of both etch depth (and therefore phase shift), as well as the feature's sidewall angle. The measurement of etch depth using an AFM is solely dependent upon the length of the probe tip in use; clearly the probe needs to be longer than the depth of the feature to be measured.

Although AFM can be used to measure sidewall angle, certain criteria need to be met in order to do so. All atomic force microscopes are equipped with feedback in the Z direction, which allows for surface height measurements. However, not all atomic force microscopes are equipped with feedback in the X and Y directions, which is required to accurately measure sidewall angle. In addition, the measurement of sidewall angle requires an algorithm to account for the non-linear response of the piezoelectric actuators (used to scan the probe) to applied voltages. Ultimately, if there is an algorithm to account for the piezoelectric actuators, and the AFM being used has feedback in the X and Y directions, the sidewall angle that can be measured must be less than the half-angle of the probe tip. If the sidewall angle is greater than that of the half-angle of the probe tip, the angle measured will be that of the probe.

Atomic force microscopes have two main modes of operation: contact and non-contact. In the contact mode, the probe tip and sample surface are kept at a very close distance from one another; this distance is regulated by repulsive forces that are encountered when the probe tip is brought into close proximity with the sample surface. The advantage to this mode of operation is that atomic resolution can be achieved. This advantage does not come without a price. When the probe tip encounters sudden changes in surface height (such as sidewall angles), it undergoes severe deformation, which over time could result in tip damage or destruction.

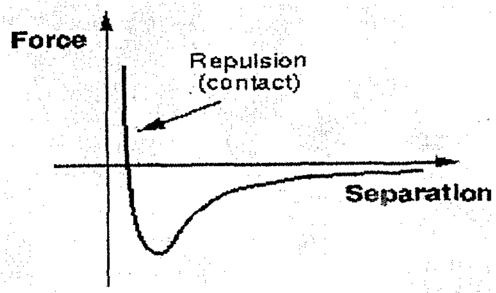

Figure 3: AFM Regions of Operation[9]

The other mode of operation for an AFM is the non-contact mode (also referred to as tapping mode). In this mode of operation, the probe tip and sample surface are kept at a distance an order of magnitude larger than that in the contact mode; this distance is regulated by attractive forces between the probe tip and sample surface. The advantages to this mode are that attractive forces from approaching sidewalls can be fed-back to the system thus reducing probe deformation, tip shape and measurement stability are maintained, and high aspect ratio critical dimensions can be measured.

Current atomic force microscope tip technologies are small enough to be extended for approximately four generations, allowing for the development of new technologies in that time period. Several different types of probe tips exist. Standard tips are typically long, slender, have a sharp apex, and are used in contact mode; an example of a standard tip is shown in figure 4.

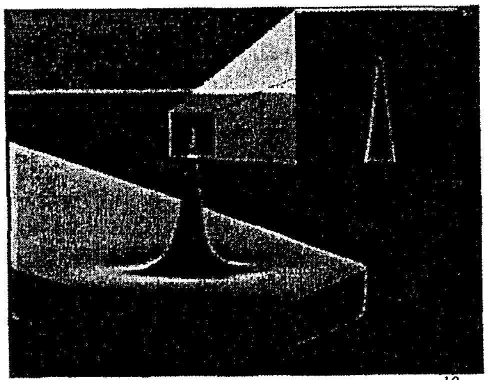

Figure 4: Standard AFM Probe Tip[10]

In addition to the standard probe tips, CD mode probe tips also exist; there are two main types. One type of

CD mode probe tip is conical, which allows for the accurate measurement of critical dimensions.

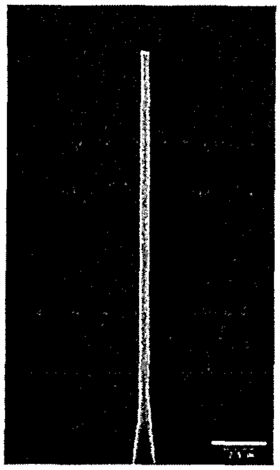

Figure 5: Conical CD Mode Probe Tip[10]

Additionally, flared tips are also available, which in systems that have feedback in X and Y directions allow for the measurement of reentrant sidewalls.

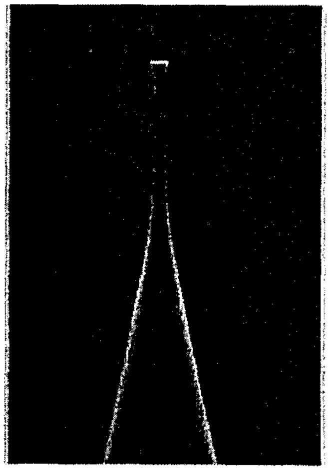

Figure 6: Flared CD Mode Probe Tip[10]

The measurement of pitch for critical dimensions is not affected by the probe width; however, the measurement of lines and spaces is affected by the probe width (lines become larger, spaces become smaller). It is possible to measure the width of the probe tip by using a standard mode sharp-apex tip. The width of the CD mode tip can then be subtracted from CD measurement data to obtain proper measurements.

Some general advantages to atomic force microscopy over other forms of metrology are that it can be performed in normal environmental conditions (does not require operation in a vacuum), can measure phase shift (etch depth) unlike other mask inspection tools which simply measure transmitted light intensity which remains constant regardless of phase, non-contact, 3-dimensional, potential to accurately measure sidewall angles, and no change in CD size due to measurement. Some general disadvantages are that it is very slow, only small areas can be measured (5x5µm areas and smaller are typical), long and slender probes are desired for maximum resolution and feature height measurements but probe tip aspect ratios greater than 10:1 are prone to breaking easily, and degradation of the probe must be tracked since tip erosion creates measurements to deviate from the mean.

III. DESIGN

The mask design consisted of a resolution chart comprised of 2.0µm down to 0.13µm feature sizes, which correlate to 10.0µm to 0.65µm feature sizes on the mask, since the ASML 248nm stepper being used is a 5X reduction stepper. The mask consists of both clear and dark field regions, meaning that in the clear field regions, alternating spaces in the resolution chart received a phase shift, whereas in the dark field, alternating lines received a phase shift. Other features were included on the mask, but only the resolution chart received a phase shift; the resolution chart is shown in figure 7:

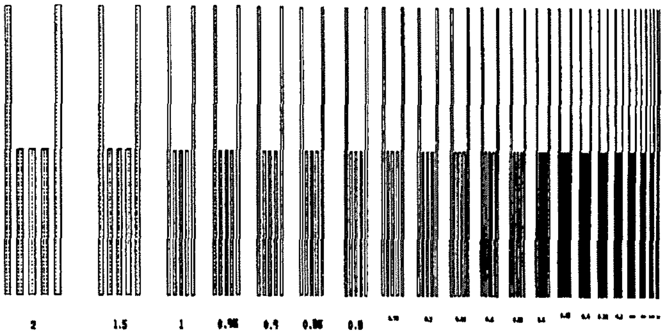

Figure 7: Resolution Test Chart[7]

The resolution test chart was incorporated into the mask design shown in figure 8:

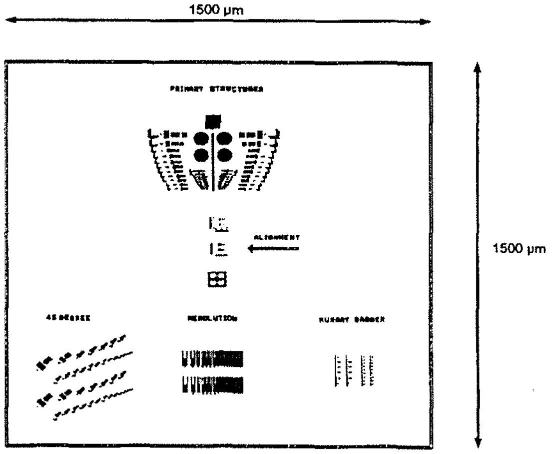

Figure 8: All features on mask[7]

A single die is comprised of the design shown in figure 8 repeated five times, one in the center of the die, and one in each corner of the die. The mask consists of a 3X3 array of die, resulting in nine total die to be printed in one exposure. This was done to allow for multiple sites to be measured on the mask, allowing for good characterization of the quartz etch process. The mask itself is 6"x6".

IV. RESULTS AND DISCUSSION

To fabricate the mask, the design was submitted to the RIT SMFL mask house. The mask fabrication process requires two levels. The first level is made using the standard RIT process: a standard chrome on glass mask blank coated with photoresist is patterned on the MEBES using a 0.25µm dot size, after which the photoresist is developed and the chrome is wet etched (followed by photoresist strip). The 0.25µm beam diameter limits the minimum resolvable feature size to 0.50µm. However, it is not the beam diameter that is the ultimate limiting factor, but the wet chrome etch. The wet chrome etch limits the minimum resolvable feature size to 0.75µm on the mask, which would correlate to a 0.15µm line/space in photoresist.

The second level of the mask requires the mask to be coated again with photoresist; this step presented a challenge to the mask house, since it did not possess 6"x6" edge-handling chuck to coat the mask. However, it was possible to spin the mask at a low RPM without vacuum on a standard chuck, allowing for the mask to be coated with photoresist for second level exposure.

After photoresist coating, the mask was placed into the MEBES for exposure of the second level, after which the photoresist was developed. Unfortunately, the alignment and overlay of the mask was a failure, with gross rotational and translational error.

A dry quartz etch process developed by Jun Yang was to be used to etch the quartz if the second level of the mask been successfully made. The quartz etch process details are: 330-400W, CHF3~130SCCM, Ar~50SCCM, O2~5SCCM, pressure ~70torr. These process parameters resulted in an etch rate of approximately 500A/min. Therefore, to achieve the desired π phase shift (2470A into quartz), the quartz would need to be etched for approximately 5 minutes. Figure 9 shows a cross section of an etched SiO_2 profile which was made to characterize the quartz etch process. Although it is difficult to see, the resulting sidewall angle is approximately 80 degrees.

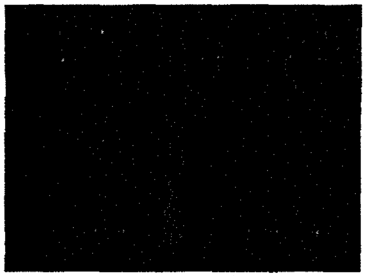

Figure 9: Etched SiO_2 profile (courtesy of Jun Yang)

Atomic force microscopy analysis of the quartz etch was not possible due to a lack of AFM probe tips.

V. CONCLUSIONS

The theory governing phase shifting masks and atomic force microscopy is well understood. However, there is much future work to be performed on this project. Without the procurement of certain parts, such as a useable mask and atomic force microscope probe tips, the work outlined in the abstract cannot be completed.

ACKNOWLEDGMENT

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Andrew C. Estroff obtained his B.S. in Microelectronics Engineering from the Rochester Institute of Technology in May, 2003. He has worked as a DUV Lithography Process Engineer for IBM, a Researcher studying process integration problems with Resonant Interband Tunneling Diodes, and at Karl Suss as an Applications Engineer working on Resist Coating Systems. Mr. Estroff is also a member of MESA, the Microelectronic Student Association, at RIT, where he has helped to create a MEMS gear, for the students, by the students.