Experimental and simulation studies of printability of buried EUV mask defects and study of EUV reflectivity loss mechanisms due to standard EUV mask cleaning processes

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EXPERIMENTAL AND SIMULATION STUDIES OF PRINTABILITY OF BURIED EUV
MASK DEFECTS AND STUDY OF EUV REFLECTIVITY LOSS MECHANISMS DUE TO
STANDARD EUV MASK CLEANING PROCESSES

by

Mihirkant Upadhyaya

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Abstract

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by

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Extreme ultraviolet lithography (EUVL) is a leading candidate for the next generation of lithography in the semiconductor industry. It uses a wavelength of 13.5 nm, and is expected to support the progression of future technology nodes. Experts from industry consider that mask technology is one of the most difficult challenges for EUVL. Masks used for EUVL which are reflective in nature, are inherently distinct from masks which are used for the current 193 nm lithography. Because the exposure wavelength used for EUVL is extremely short, and the critical feature size to be printed is on the order of mere tens of nanometers, there are stringent requirements on EUV mask quality in terms of its flatness, roughness and number of defects that can be tolerated. In this dissertation, we have focused on two aspects related to the performance degradation of the EUV masks namely EUV mask cleaning induced EUV reflectivity losses and the buried EUV multilayer phase defects. By developing a better insight into the mechanisms at play leading to mask damage, we will potentially be able to achieve better quality and more robust EUV masks and hasten the process for commercialization of EUVL.

Standard EUV mask cleaning processes involve various steps and chemistries that lead to degradation of the multilayer structure in turn leading to EUV reflectivity loss, hence impacting
the throughput. In this work, we developed an understanding of the root cause of why different cleaning chemistries cause EUV reflectivity losses, and quantified these losses. Upon subjecting the mask blanks to multiple cleaning cycles, multilayer degradation observed was in terms of multilayer etching and pitting, surface roughness increase and surface oxidation. We studied each of these phenomena through experiments and simulations, and correlated the extent of EUV reflectivity loss to each of the degradation phenomena. We learned about the types of damages that different chemistries cause that led to the EUV reflectivity loss. With a fundamental understanding of the multilayer damage mechanisms, we will be able to better predict the behavior of other chemicals and potentially be able to assess the EUV reflectivity loss caused by them thus determining their compatibility with the EUV mask cleaning processes.

The second aspect of this dissertation addresses the buried multilayer defects in EUV masks. Much work has been done to investigate the printing behavior of these buried defects, both experimentally and through simulations. Printing behavior of the programmed defects has been studied extensively. However, not much work has been done pertaining to the study of printability of native EUV mask defects. Certain models have been developed to simulate multilayer growth over defects, but have their limitations. To overcome these limitations, we evaluated the printability of native defects on EUV mask blanks. EUV mask substrates with native defects were coated with Mo/Si multilayers and were characterized using atomic force microscopy (AFM) and cross-section transmission electron microscopy (TEM) to determine the defect shape and size, and how the multilayer growth evolves over the defect. These EUV mask blanks were imaged under the Actinic Inspection Tool (AIT), at the Lawrence Berkeley National Lab (LBNL) to study the defects’ printability under different focus conditions. Further, using a realistic multilayer growth model that took into account the deposition conditions of the tool
where the multilayer deposition took place, printability simulations were performed and compared with the AIT aerial images. Two software packages namely Sentaurus Lithography from Synopsys and EM-Suite from Panoramic Technology, implementing the finite-difference-time-domain (FDTD) and waveguide algorithms, were used for the defect printability simulation work. A good comparison between the AIT and the simulation results was observed.

Further, we developed an approximate but robust method for investigating defect printability of arbitrarily-shaped native defects given the AFM defect profile on top of a multilayer stack. Given the full-width at half-maximum (FWHM) and height of the defect, as obtained from top layer AFM, we were able to infer the substrate defect profile in terms of FWHM and height, through a systematic study of multiple native EUV mask defects and how they evolve up the multilayer stack. Native, Gaussian and regular-shaped substrate defect profiles (having similar FWHM and heights) were compared for their printabilities, in terms of aerial image intensities, and reasonable comparison was obtained between them. Therefore, irrespective of the substrate defect shape, but having similar FWHM and height, we obtained comparable aerial image intensities. Thus, given an arbitrary defect profile on top of multilayer stack, we can reasonably determine its printability through simulations.

Furthermore, FDTD simulations were performed to investigate the various fundamental aspects associated with a defect, like its height and its slope, and the impact that each of these aspects has on the printability of the defect. Simulations were performed on 32 nm line and space (L/S) absorber patterns with different defect positions relative to the absorber stack. The aforementioned defect parameters were systematically varied to observe their effect on the printability of the defect. The defect printability was observed to be the most sensitive to the slope of the defect, and less dependent on its height.
Dedicated to my Grandparents, Father (Dr. Ramakant Upadhyaya), Mother (Ms. Veena Upadhyaya) and Brother (Mayank) for always believing in me and supporting me in all my endeavors....
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# Table of Contents

1. **INTRODUCTION** ..................................................................................................................1
   1.1 Motivation ..........................................................................................................................1
   1.2 EUV Lithography .................................................................................................................3
   1.3 Reflective Multilayer Mirror .............................................................................................5

2. **COMPONENTS OF EUV LITHOGRAPHY** ........................................................................10
   2.1 Lithography for Semiconductor Manufacturing .................................................................10
      2.1.1 Illumination ..................................................................................................................11
      2.1.2 Photomask ..................................................................................................................11
      2.1.3 Projection Optics .........................................................................................................12
   2.2 Lithography with EUV Light .................................................................................................13
      2.2.1 Illumination for EUV Lithography ..............................................................................13
      2.2.2 Photomask for EUV Lithography ...............................................................................14
      2.2.3 Projection Optics for EUV Lithography .....................................................................15
   2.3 Current Issues in Development of EUVL ..........................................................................15
      2.3.1 Source ........................................................................................................................16
      2.3.2 Photoresist ..................................................................................................................16
      2.3.3 Mask ..........................................................................................................................17
   2.4 Summary and Conclusion ....................................................................................................19

3. **STANDARD WET CLEANING PROCESS FOR EUV MASKS: IDENTIFYING THE DAMAGE CAUSED DUE TO VARIOUS CHEMISTRIES** ..................................................21
   3.1 Introduction .......................................................................................................................21
3.2 Wet Cleaning Process for EUV Mask Blanks.................................................................22
3.3 Experiments..................................................................................................................25
3.4 Experimental Results.................................................................................................26
3.5 Simulations..................................................................................................................33
3.6 Simulation Results.......................................................................................................34
3.7 Observations................................................................................................................47
3.8 Suggested Modification to the Standard Cleaning Process.........................................51
3.9 Summary and Conclusion...........................................................................................55

4. EXPERIMENTAL AND SIMULATION STUDIES OF PRINTABILITY OF BURIED
   NATIVE EUV MASK DEFECTS USING A NOVEL LEVEL-SET MULTILAYER
   GROWTH MODEL...........................................................................................................59
4.1 Overview......................................................................................................................59
4.2 Introduction..................................................................................................................60
4.3 Characterizing Native Defects on EUV Mask Blanks..................................................62
4.4 Multilayer Growth Model............................................................................................62
4.5 Results..........................................................................................................................69
   4.5.1 Comparing Modeled Multilayer Growth with Cross-section TEM and AFM........69
   4.5.2 Comparing the FDTD Simulation and AIT Through-focus Aerial Images..........78
4.6 Summary and Conclusion..........................................................................................89

5. SYSTEMATIC STUDY OF NATIVE EUV MASK DEFECTS.............................................92
5.1 Introduction..................................................................................................................92
5.2 Correlating Multilayer Growth over Native and Gaussian-shaped Defects.................92
5.3 Comparing Printability Performance of Native, Gaussian and Regular-shaped Substrate defects

5.4 Comparing Different Multilayer Growth Models and Correlating Defect Printability
to AIT Aerial Image Intensity Contrasts

5.4.1 Comparison Between Level-set, Stearns and Conformal Growth Model

5.4.2 Aerial Image Contrasts as a Function of Defect FWHM/Height and Volume

5.4.3 Correlating Aerial Image Contrasts to Defect Printability

5.4.4 Affect of Resist Processes on Defect Printability

5.4.5 Proposed Mask Fabrication Process Flow and Caveats

5.5 Summary and Conclusion

6. IMPACT OF THE VARIOUS ASPECTS OF A DEFECT'S SHAPE ON PRINTABILITY

6.1 Introduction

6.2 Impact of Defect Height on Printability

6.3 Impact of Defect Slope on Printability

6.4 Summary and Conclusion

7. CONCLUDING REMARKS AND SUMMARY
CHAPTER 1

1. Introduction

1.1 Motivation

An observation was made by Gordon Moore in 1965 that the number of devices that could be made onto a single integrated circuit would double every 18 months. It was also predicted that this rate of development would continue. This has been made possible primarily due to the technology namely lithography. Current Argon Fluoride (ArF) based lithography technology is almost already beyond its limits and the lithography community has been employing methodologies and "tricks" to continue to scale using the ArF lithography (using 193 nm radiation). The most likely technology to replace 193 nm lithography is extreme ultraviolet (EUV) lithography, which makes use of 13.5 nm light. Unfortunately there are multiple challenges in the path of EUV lithography becoming a mainstream technology to enable lithography.

Lithography is responsible for the mask pattern transfer on the wafer, which is expected to occur in a reliable manner repeatedly. However, if contamination or particle is on the mask, it could potentially be printed on the wafer resulting in reduced yield and throughput. However, not all mask defects result in them getting printed onto the wafer. Different aspects of a defect namely the size, shape, location and material properties determine whether or not the defect will actually be a problem. Studying these defects gets more difficult since in EUV lithography, to attain sufficient reflectivity, multiple layers are stacked on top of one another, so understanding the evolution of multilayer disruption over the defect is important in order to be able to comprehend how the EUV reflectivity would be affected due to this. This type of defect is referred to as a buried defect and it is responsible for altering the phase of the reflected EUV
radiation. Detailed study needs to be performed to understand how the different aspects of an EUV mask defect affect the EUV radiation being reflected, and how that affects the defect being printed. These studies are essential to ensure speedy and quality production of EUV exposure equipment. Since currently the availability of production equipment is limited for such studies, simulations are necessary to produce the needed information during the technology development process.

This dissertation focuses on two of the aspects that result in the degradation of an EUV mask, namely the deterioration impacts of standard mask cleaning processes which, in addition to cleaning the mask surface, also lead to a loss in EUV reflectivity thus resulting in a loss of throughput; and the impact of buried EUV multilayer phase defects on the printability of the mask features onto the wafer.

For the study involving EUV reflectivity loss due to standard mask cleaning process, experiments were conducted to qualitatively determine the degrading impact of each of the steps involved in the mask cleaning process. Further, simulations were performed to quantify and correlate the extent of EUV reflectivity loss to each of the steps involved in the standard mask cleaning process, thus helping to develop a fundamental understanding of the mechanisms behind the mask degradation due to the cleaning processes.

For the buried multilayer defect study, the various EUV mask blanks with native bump and pit defects were imaged at the AIT, an EUV mask-imaging microscope, under different focus conditions to study the through-focus printing behavior of the defects. Further, using the top-surface atomic force microscopy (AFM) data and the transmission electron microscopy (TEM) cross-section images, the growth of the defect through the multilayer was accurately modeled. The model incorporated the various parameters of the deposition tool to accurately
obtain the evolution of the multilayer growth over the buried defect. With a good comparison between the AIT and the simulation printing results, and confidence in our simulations, we performed a systematic study of the various aspects of a native defect that determine the multilayer growth on top of it, and how we can predict the printability of a native mask defect using simulations by just using the top-layer AFM information, thereby reducing the dependence on expensive actinic inspection systems. Finally, we focused on the more fundamental aspects of the defect, like its height and slope that lead to them being printed on the wafer.

With the development of a more fundamental understanding of the underlying mechanisms leading to EUV mask degradation, we can develop better mitigation strategies, thus helping in quicker manufacturability of high quality EUV masks, thus leading to rapid commercialization of EUVL.

1.2 EUV Lithography

The key step in IC manufacturing process is photolithography. Photolithography is the process of transferring geometric shapes on a mask to the surface of a silicon wafer. It uses light to transfer a geometric pattern from a photomask to a light-sensitive chemical photoresist, or simply resist, on the substrate [1]. The resolution and depth of focus (DOF) achievable with photolithography is described in equations below [2].

\[
L_w = k_1 \frac{\lambda}{NA} \quad (1)
\]

\[
DOF = k_2 \frac{\lambda^2}{(NA)^2} \quad (2)
\]

where \(\lambda\) is the radiation wavelength, NA is the numerical aperture seen at the wafer, and \(k_1\) and \(k_2\) known as the “technology factors” are constants that are largely determined by the optical
system and the photoresist, and to an extent the ease of etch processes. Equation 1 implies that a practical solution to increase resolution is to use radiation with a shorter wavelength.

Currently, ArF immersion lithography using 193 nm radiation is used for manufacturing of chips [2-4]. The most promising alternative technology for high volume manufacturing beyond the use of 193 nm is EUVL [1,3,5,6]. EUVL uses 13.5 nm wavelength which as per Equation 1 would help to decrease the feature sizes. Also, there is a paradigm shift in moving to EUV lithography from 193 nm lithography. EUV lithography uses reflective optics as opposed to the transmittive or refractive optics that are used for 193 nm lithography. Reflective optics are used for EUV lithography since EUV radiation gets easily absorbed by most materials. Also, this highly absorptive nature of EUV requires the EUV lithography to take place in clean vacuum conditions.

In order to have sufficient EUV reflectance from the optics, multilayer mirrors are used. The mirrors are manufactured using the principle of Bragg reflection [5]. Also, the maximum reflectance achieved using these Bragg mirrors has been peaked at approximately 69%. So in order to ensure that there is not a significant amount of photon loss, number of mirrors in the photolithography system are limited to ensure high energy on wafer plane, which would in turn result in a higher overall throughput. Figure 1.1 shows an example of a schematic diagram of an EUV lithography optical system.
1.3 Reflective Multilayer Mirror

The EUV reflectivity of any material at normal incidence is usually very low (less than 1%), while the radiation can be transmitted to a depth of several nanometers. Adding multiple layers in such a way that the reflected radiation from the interfaces of these layers adds in phase i.e. constructive interference, will increase the overall reflectivity. Figure 1.2 shows a schematic of such a multilayer structure. Two materials with different refractive indices are deposited alternatively to form the multilayer structure. In order to have a high optical contrast between the two successive layers, the materials are so chosen so that the difference in their atomic number is high.

For obtaining constructive interference for a specific wavelength $\lambda$ which is incident at an angle $\theta$, the thickness of the bilayer ‘d’ has to be made in order to meet Bragg's law [5].
\[ n\lambda = 2d \sin \theta \sqrt{1 - \frac{2\chi}{\sin^2 \theta}}, \chi \ll 1, \alpha \ll \chi \]  

where \( n \) is the order of the Bragg maximum, \( \overline{\chi} \) is the weighted average over one period of the deviation of the real part of the refractive index from unity. The complex refractive index is defined as

\[ n = 1 - \chi + i\alpha \]  

where \( \alpha \) is the imaginary part of the refractive index, also called extinction coefficient.

At a fundamental level, when an electromagnetic wave is incident on any material, the wave’s phase velocity (\( v_{\text{phase}} = c / n \), where \( c \) is speed of light and \( n \) is the refractive index of the material) is slowed in the material since the electric field associated with the radiation creates a disturbance in the electrons of the atoms of the material. This disturbance is directly proportional to the electric susceptibility (indicates the degree of polarization of a dielectric material in response to an applied electric field) of the medium. As the electromagnetic fields oscillate in wave, the electrons in the material will also start to vibrate at the same frequency. The electrons will also radiate their own electromagnetic wave at same frequency (resonance), which is the basic mechanism of how reflection occurs, but this emitted frequency could be out of phase with respect to the incident frequency of the wave. Depending on the relative phase of the incoming wave and the waves radiated as a result of the vibrating electrons, there could be multiple scenarios as described below [7]:

(i) If the electrons emit a light wave which is 90° out of phase with the light wave vibrating them, it will cause the total light wave to travel more slowly. This is the normal refraction of transparent materials like glass or water, and corresponds to a refractive index which is real and greater than 1. The reflection from materials occurs
when the incident radiation shakes (vibrates) the electrons of the atoms of the irradiated surface. The materials with a high reflectivity are usually metals, since they consist of a large number of free electrons not tightly bound to the atoms. Therefore these have a high electric susceptibility, and are free to vibrate and emit radiation.

(ii) If the electrons emit a light wave which is $270^\circ$ out of phase with the light wave vibrating them, it will cause the total light wave to travel more quickly. This is called anomalous refraction, and is observed close to absorption lines, with extreme ultraviolet rays, x-rays, and in some microwave systems. It corresponds to a refractive index less than 1. Here, although the phase velocity becomes larger than $c$, however the group velocity is less than $c$.

(iii) If the electrons emit a light wave which is $180^\circ$ out of phase with the light wave vibrating them, it will destructively interfere with the original light to reduce the total light intensity. This is light absorption in opaque materials and corresponds to an imaginary refractive index.

(iv) If the electrons emit a light wave which is in phase with the light wave vibrating them, it will amplify the light wave.

For the EUV reflection occurring by the Mo/Si multilayer structure, case (ii) mostly applies. In Si, the free electron density is low ($Z = 14$), therefore resonance of electrons by the incoming radiation would be limited, and most of the radiation would just get transmitted. Therefore the real part of the refractive index for Si is close to 1 at EUV wavelengths. Mo, on the other hand has a higher electron density ($Z = 42$), therefore there the incoming radiation sees a lot more electrons in turn vibrating them, thus resulting in emission of radiation by the vibrating
electrons. Therefore Mo and Si are suitable materials to be used for multilayer structure to reflect EUV radiation.

EUV reflectivity of around 69% has been achieved using alternative layers of molybdenum and silicon for photon energy of around 92 eV [8-10]. Figure 1.2 shows a Mo/Si multilayer system, designed for EUV radiation. Silicon acts as a spacer material and Molybdenum acts as a reflector material. Therefore, Mo/Si multilayer structure provides high EUV reflectivity.

![Diagram of Mo/Si multilayer system](image)

**Figure 1.2:** Alternating layers of silicon (low-z material) and molybdenum (high-z material) in a multilayer structure.

Figure 1.3 shows EUV reflectivity plot for a Mo/Si multilayer mirror consisting of 50 periods [10].
**Figure 1.3:** Theoretically calculated reflectance versus wavelength for a Mo/Si multilayer mirror consisting of 50 periods [10].

**References (Chapter 1):**

CHAPTER 2

2. Components of EUV Lithography

2.1 Lithography for Semiconductor Manufacturing

Optical projection lithography is widely used in industry to etch the micro circuits into the silicon wafer. This has various advantages over other technologies like contact printing, where there are contamination concerns due to physical contact between mask and wafer, thereby using projection lithography helps to mitigate defects that can be added during printing. Also, unlike in electron beam lithography, the whole wafer can be printed simultaneously in projection lithography, thus saving time and increasing throughput.

Figure 2.1 shows a generic projection lithography system. This system consists of the illumination system, the photomask, and the projection optics.

![Figure 2.1: Schematic of a generic lithography system.](image-url)
2.1.1 Illumination

There are several different illuminations that are commonly used. Figure 2.2 shows examples of some of the commonly used illumination configurations. White regions indicate where the radiation is allowed to pass and black regions indicate where the light gets blocked.

![Illumination Examples]

**Figure 2.2:** Three examples of source distributions used in lithography.

Illumination is usually described in terms of its coherence, which is denoted by the factor sigma (σ). If σ value is high, then light is incident on the mask at high angles. The value of σ is normally below one. A sigma value of 0 implies that a plane wave is normally incident on the mask.

2.1.2 Photomask

There are two basic types of masks namely the binary and the phase-shifting mask. A binary mask simply blocks the light in some areas of the mask and not in others.

The second basic type of mask is a phase shift mask. A phase shift mask changes the phase of incident light as it is transmitted through the mask. There are two types of phase shift masks namely the alternating and attenuated phase shift masks. In alternating phase-shift masks, certain transmitting regions are made thinner or thicker. That induces a phase-shift in the light traveling through those regions of the mask. When the thickness is suitably chosen,
the interference of the phase-shifted light with the light coming from unmodified regions of the mask has the effect of improving the contrast on some parts of the wafer, which may ultimately increase the resolution on the wafer. In attenuated phase-shift masks, certain light-blocking parts of the mask are modified to allow a small amount of light to be transmitted through (typically just a few percent). That light is not strong enough to create a pattern on the wafer, but it can interfere with the light coming from the transparent parts of the mask, with the goal again of improving the contrast on the wafer [1].

2.1.3 Projection Optics

The role of the projection optics is to deliver the image from the mask on to the wafer. One of the important characteristics of projection optics is the numerical aperture (NA) which is defined as:

\[
NA = n \sin \theta
\]

where \(n\) is the index of refraction of the medium in which the lens is working and \(\theta\) is the half-angle of the maximum cone of light that can enter or exit the lens. The resolution of the lithography system depends on NA, with it being directly proportional to the wavelength of incident radiation and inversely proportional to the NA. Also, the depth of focus (DOF) is directly proportional to the wavelength of incident radiation and inversely proportional to the square of NA.

Two characteristics of the projection optics that are critical to lithography are resolution and the amount of aberrations. The optics in a lithography system are required to have low level of aberrations for good performance. Aberrations cause the printed image to deviate from the expected image. Aberrations fall into two classes namely monochromatic and chromatic. Monochromatic aberrations are caused by the geometry of the lens or mirror and occur both
when light is reflected and when it is refracted. They appear even when using monochromatic light, hence the name. Chromatic aberrations are caused by dispersion, the variation of a lens' refractive index with wavelength. They do not appear when monochromatic light is used.

2.2 Lithography with EUV Light

Industry's prime objective is to shrink the size of the integrated circuits (ICs) or conversely, for the same size IC, pack more functionality into it. This involves improving upon or decreasing the current resolution.

As per Equation 1, to achieve this enhanced resolution, we either have to be able to increase the NA of the system, and/or decrease the wavelength and $k_1$. EUV systems have a lower NA than the existing DUV lithography systems, however we are still able to achieve resolution enhancement with EUV, as the wavelength shrinks by a factor of 14 when moving from 193 nm lithography to EUV lithography. Moving to EUV systems also gives an improvement in the DOF.

2.2.1 Illumination for EUV Lithography

The wavelength of light used for EUV lithography is 13.5 nm. The most common source to produce radiation with this wavelength is a tin plasma source. There are two methods to generate tin plasma namely laser produced plasma (LPP) and discharge produced plasma (DPP). These sources produce a broad wavelength spectrum, and the desired wavelength band i.e. 11 nm - 14 nm wavelength radiation needs to be extracted from this broad range by either tuning the mirror setup between the source and the wafer plane or by using filters.
2.2.2 Photomask for EUV Lithography

The main difference between 193 nm lithography mask and an EUV mask is that masks used for 193 nm lithography are transmissive in nature, and those used for EUV lithography are reflective in nature. This shift in going from transmissive or refractive optics to reflective optics is due to the fact that EUV gets strongly absorbed by most materials, so any mask material would allow little EUV to be transmitted, while absorbing most of it. At EUV wavelengths, all materials have refractive index close to 1, with a large imaginary component. The large imaginary component implies the high absorption of radiation. The structure of the mask is shown in Figure 2.3.

![Figure 2.3: Side view cutline of an EUV mask (left) and the resulting aerial image (right)](image)

An EUV mask consists of a multilayer structure made up of alternating layers of Mo and Si stacked on top of one another, thus forming a multilayer structure. 50 such Mo/Si bilayers are used to ensure that a significant fraction of EUV gets reflected. With 50 bilayers, one achieves an EUV reflectivity of around 69%. On top of the multilayer stack, we have the absorbers which define the feature that is to be transferred to the wafer. The absorber material is typically a Tantalum Nitride (TaN), or an alloy material based on various stoichiometries of Ta and N [2-6]. It is approximately 70 nm in height and absorbs most of the EUV radiation incident on it.
2.2.3 Projection Optics for EUV Lithography

Similar to the EUV mask, the optics used in EUV lithography systems must be reflective. The issue that one faces pertaining to reflective optics is the non-trivial absorption of EUV radiation by the optics. Since the current sources are somewhat limited on power, the number of mirrors that can be used is limited. Although having a large number of mirrors in the system is desirable as that helps to enhance the NA of the system, the finite absorption of EUV power by each of the mirrors limits going to projection optics using large number of mirrors.

In addition to the EUV absorption, EUV mirrors are also be susceptible to aberrations [7-9] which can lead to undesirable pattern printing on the wafer. So the quality of the optics in EUV lithography has to be much more tightly maintained as opposed to those in 193 nm lithography systems.

2.3 Current Issues in Development of EUVL

There are a number of issues that have plagued EUV lithography. Its advancement has been slow over the past several years with its insertion into high volume manufacturing being further pushed out into the future. The major issue in having EUV lithography systems into the chip manufacturing facilities is the cost of ownership. Technically, we could have chips being manufactured using EUV exposure systems, but they wouldn't be sufficient to justify the cost of owning an EUV exposure tool. The economics driving the Moore's Law that require the transistor cost to go down with time would not hold true. So moving to EUV from the current 193 nm lithography systems, would not be a cost effective option. The three primary components that are causing the delay in the implementation of EUV lithography are the EUV source, the photoresist and the photomask. The issues with these three aspects are explained below.
2.3.1 Source

The primary issue with the currents EUV sources is power, which in turn directly impacts the throughput of the system. For example, if we have a high power source, the exposure time for each wafer would be short, however, on the other hand if the power level is reduced, wafer must be exposed for a longer time, hence resulting in a decreased throughput. To be used as a viable technology for manufacturing, EUV sources should be able to operate at a few hundred watts. However until now the best sources have reached approximately 80 watts of usable EUV power [10]. The roadmap for the EUV sources looks promising with power levels of over 200 watts expected in the next year or so.

2.3.2 Photoresist

Photoresist is a light-sensitive material which is deposited onto silicon wafers before each lithography step. When light is incident on the photoresist, its chemical properties get modified which allows the desired pattern to be etched onto the wafer. Photoresists can be broadly classified into two groups, namely positive resists and negative resists. A positive resist is a type of photoresist in which the portion of the photoresist that is exposed to light becomes soluble to the photoresist developer. The portion of the photoresist that is unexposed remains insoluble to the photoresist developer. A negative resist is a type of photoresist in which the portion of the photoresist that is exposed to light becomes insoluble to the photoresist developer. The unexposed portion of the photoresist is dissolved by the photoresist developer [1]. A photoresist’s performance is determined in terms of three metrics namely resolution, line edge roughness (LER) and sensitivity (collectively known as RLS) [11-14]. Resolution is the smallest feature that can be printed on the wafer, and is measured in nanometers. Sensitivity of a resist determines the energy density needed to print the feature on the resist, and is measured in joules.
per centimeter square. LER refers the random deviation of line edges from ideal definition, and is measured in nanometers. Improvement of the photoresist performance gets hampered due to what is known as RLS trade-off as per which any two of the parameters cannot be improved without taking a hit on the third parameter. And improving all three at the same time can be challenging. Current EUV resist performance does not meet the specifications to print tight pitch features in a HVM setting, and significant improvements need to be made in this field.

2.3.3 Mask

A reflective mask used in EUV lithography is prone to certain problems more so than the transmittive mask used in 193 nm lithography. The two biggest issues for EUV masks are defectivity and inspection. Preparation of defect-free masks continues to be one of the top three critical issues preventing the launch of EUVL into HVM. Progress in terms of reducing EUV mask blank (multilayer structure with no pattern printed on it) defect density over the last decade has been relatively slow. The primary reason for this slow progress can be attributed to the existence of phase defects which are embedded within or underneath the multilayer structure. The embedded defects could result from imperfect substrate quality (in terms of scratches, particles and bumps on substrate surface) on which the multilayer deposition occurs, or they could result from particles landing within the multilayer structure due to imperfect chamber components of the ion beam deposition tool where the multilayer deposition takes place. These buried defects could also occur as a result of improper handling of the mask substrates. These defects are often non-repairable and can be challenging to compensate for. In addition to the buried defects, we can also have the contamination and particle defects occurring on top of the mask surface. These however, can be cleaned using mask cleaning processes. However, the standard mask cleaning processes that are currently used, can lead to damage of the multilayer
structure thereby leading to a loss of EUV reflectivity, in turn resulting in reduced throughput. Figure 2.4(a) from Rastegar et al. [15] shows a pristine EUV mask and Figure 2.4(b) shows an EUV mask with all the possible defects.

![Diagram of EUV mask structure](image_url)

**Figure 2.4:** (a) Clean EUV photomask. (b) Types of contamination that could be an issue for EUV photomasks (Rastegar et al. [15]).

Recently EUV mask blank defect density has been brought to acceptable levels with zero defects being reported at 54 nm sensitivity (SiO\(_2\) equivalent) [16]. However the yield for such
high quality mask blanks is low ($\approx 4\%$). Also, as per the SEMATECH's EUV mask blank defectivity roadmap, if EUVL is to become a manufacturing reality in 2015, the roadmap requires that there can be no more than three defects for logic greater than 15 nm in size [17]. Currently, there are no inspection tools that can detect defects at such small size scales. The state of the art optical inspection tools can detect defect having sizes greater than 25 nm on quartz substrate and defect sizes greater than 30 nm on the multilayer top. The defects that can print on the wafer can potentially be smaller than this. Therefore the current EUV mask blank defect densities being reported are potentially a gross underestimation of the actual defect densities. Therefore actinic inspection capability would have to be widely available as it would be essential to detect relatively small-sized defects. Also, fast and accurate simulations would be necessary to determine mitigation and compensation strategies to minimize the deteriorating impact of the defects on the mask blanks.

### 2.4 Summary and Conclusion

Lithography with extreme ultraviolet 13.5 nm light is challenging for several reasons. The 13.5 nm wavelength requires significant new development of source, photomask, optics and photoresist technologies. However, we gain immensely on resolution and also improve on depth of focus by moving to the 13.5 nm-wavelength lithography technique, which is what motivates the industry to strive for successful implementation of this technology. And the work presented as a part of this thesis will hopefully help in realizing this technology as an economically viable solution for the fabrication of the future-generation ICs.
References (Chapter 2):

CHAPTER 3

3. Standard Wet Cleaning Process for EUV Masks: identifying the damage caused due to various chemistries

3.1 Introduction

It has been established that a clean system is essential for the success of EUV lithography. In the context of photomasks, even with the protection of the pellicle for the 193 nm lithography technology, industry has developed mask cleaning strategies for their systems, due to the recognition that pellicle alone is not sufficient. Moving to EUV lithography, where a reliable pellicle is currently not available, it is important for the progression of the technology to develop cleaning strategies for the smaller nodes.

Mask cleanliness is of the utmost importance, and therefore it's essential to establish mask shipping and handling protocols to avoid mask contamination by human error. And although, the clean handling and shipping of masks has been established to a large extent, there can be contamination within the lithography tool, as well as contamination caused due to movement of masks to and from these tools that can lead to masks being contaminated. A few of the mask cleaning methods in use these days are wet cleaning [1-4], laser-induced shockwave cleaning [5-9] and carbon dioxide (CO₂) cleaning [10-13]. These methods are effective in cleaning the contamination on top of the multilayer. Also, the particle removal efficiencies of each are relatively high, approximately 90% or greater, however the potential for substrate and feature damage is also an issue. The current standard EUV photomask cleaning technique, namely the wet clean has a number of deteriorating effects on the mask, namely surface oxidation, increase in surface roughness, and multilayer etching to name a few. In the following sections, we will study each of the steps in the wet clean process in detail and understand the
mask degradation phenomena associated with each of these steps. We will correlate the EUV reflectivity loss to each of these phenomena, and quantify the mask damage being caused due to each step in the mask cleaning process.

3.2 Wet Cleaning Process for EUV Mask Blanks

EUVL is being developed as a promising candidate for high-volume semiconductor manufacturing for 16 nm half-pitch patterning and beyond. One of the top challenges for successful implementation of EUVL into manufacturing is the ability to produce defect-free masks, to which effect mask surface cleaning plays a critical role. Photomask surface cleaning requires that it should be an efficient process with little or no damage to the patterns and no film loss. In addition to this, EUV masks pose further challenges in the cleaning process because they consist of a reflective multilayer mask structure, which is susceptible to surface damage and consequently EUV reflectivity loss [1,2]. The standard reported cleaning process entails wet cleaning, which consists of SPM (sulfuric acid, hydrogen peroxide mix in a 3:1 ratio) and SC1 (ammonium hydroxide, hydrogen peroxide and water mix in a 1:1:5 ratio). However, the use of these harsh chemicals leads to surface damage and introduces particles, all of which lead to a loss in reflectivity.

It has been well established in various studies that the current cleaning methods, when used multiple times, incur a severe EUV reflectivity loss, which is not acceptable and that there is a need to come up with alternative cleaning methods, which would be effective and not have a deteriorating impact on reflectivity [14-16]. To achieve this goal, we need to have a clear and comprehensive understanding of the various cleaning steps and develop an understanding regarding what impact each step has on the mask structure, and how that contributes to the loss
in reflectivity. The current standard process flow for cleaning of EUV photomasks used by SEMATECH is shown in Figure 3.1 which is further explained below.

![Figure 3.1: A diagram of the process flow currently widely used to clean photomasks.](image)

VUV energy is very effective in the breaking of most organic bonds (i.e., C–H, C–C, C–O, and C–N) of surface contaminants. This helps to break apart high molecular weight contaminants. A second cleaning action is carried out by the oxygen species. These species react with organic contaminants to form H₂O, CO, CO₂, and lower molecular weight hydrocarbons.

\[
\text{C}_x\text{H}_y + \text{O} \rightarrow \text{CO}_2 + \text{H}_2\text{O}
\]

These compounds are in turn rinsed away during the DI Rinse step. However, due to the oxygen gas involved in this step, it’s responsible for causing oxidation of the multilayer.

Carbon allotropes are difficult to attack chemically because of the highly stable and typically graphite-like hybridized bonds that surface carbon atoms tend to form with each other. The route by which SPM solution (3:1 solution of H₂SO₄ and H₂O₂) disrupts these stable carbon-to-carbon surface bonds is for an atomic oxygen first to attach directly to a surface carbon to form a carbonyl group [3,4].
Further oxidation, for example, can convert the initial carbonyl group into carbon dioxide and create a new carbonyl group.

\[
\text{C} = \text{O} + \text{C} = \text{O} + 2\text{O}^+ \rightarrow \text{C} = \text{O} + \text{C} = \text{O} + 2\text{C}
\]

\(\text{H}_2\text{O}_2\) in the SC1 solution (1:1:5 solution of \(\text{NH}_4\text{OH}, \text{H}_2\text{O}_2\) and deionized \(\text{H}_2\text{O}\)) promotes the formation of an oxide. \(\text{NH}_4\text{OH}\) slowly etches the oxide. In a typical SC1 solution, the oxide etch rate is \(\sim 0.3\) nm/min at 70ºC. At the alkaline pH value of SC1 solution, most surfaces are negatively charged. Hence, electrostatic repulsion between the removed particle and the oxide surface will prevent particle redeposition. However, owing to their oxidizing \(\text{H}_2\text{SO}_4/\text{H}_2\text{O}_2\) and \(\text{NH}_4\text{OH}/\text{H}_2\text{O}_2\) chemistries, these steps are further responsible for the oxidation and etching of the Mo/Si multilayer structure \([3,4]\).

To understand the extent of oxidation that the above-mentioned chemistries and steps cause, we looked at the standard reduction potentials of each of the chemistries involved. We calculated the standard reduction potentials of the VUV/\(\text{O}_2\) step, SPM chemistry and the SC1 chemistry to be equal to 1.23V, 2.37V and 0.27V respectively. So, we can clearly observe that SPM chemistry is the most oxidizing, followed by the VUV/\(\text{O}_2\) step and then followed by the SC1 chemistry.

High frequency sound waves in a liquid produce positive and negative pressures. In the regions of negative pressures, the liquid pulls apart creating micro/macro bubbles. Collapse of cavitation bubbles creates enough energy to effect particle detachment from a surface. Jet velocities up to 130 m/s have been calculated in water at atmospheric pressure. Pressures of 1000 atm and temperatures of 3000ºK can be reached \([17]\). Erosion occurs as a result of repeated hammer-like blows associated with bubble collapse. This erosion of the top few layers of the
multilayer stack in addition to causing some EUV reflectivity loss makes the multilayer more vulnerable to damage from other cleaning steps.

In this work, comparisons are made between simulated and experimental reflectivity loss results to determine and quantify the contribution of each step to the degradation in reflectivity and multilayer loss. Simulations helped us to correlate the extent of EUV reflectivity loss to each of the degrading factors at play, without the need to perform extensive experiments, thus saving time and resources, as well as yielding more results. Based on the improved knowledge of reflectivity loss mechanisms, and knowledge regarding which cleaning steps cause what type of damage, mask blank cleaning processes can be modified and optimized to reduce their deteriorating impact on the EUV mask blanks.

3.3 Experiment

For the experiment, EUV Mo/Si multilayer mask blanks with Ru capping layers were used. These EUV mask blanks consisted of a 2 nm Ru capping layer and 50 Mo/Si multilayers (ML), each 7 nm thick, on a quartz substrate. Absorber layers were not deposited. This is because we wanted to evaluate the cleaning performance on the Ru capping layer, which is the most sensitive to defect printability and the most delicate to attack by chemicals as compared to the TaN based absorber materials [18]. The blanks underwent multiple cleaning cycles. They were cleaned using a photomask cleaning tool from Hamatech (MaskTrack), which is a spin-spray mask cleaning tool with multiple wet chemistries. Integrity of the multilayer was characterized with an atomic force microscope (AFM) to determine surface roughness, an EUV reflectometer was used to measure reflectivity at EUV wavelength, and TEM was used to look at the multilayer cross section to determine the extent of damage caused to the multilayers by the
cleaning processes. Also, XPS was performed on the multilayer structure to study the extent of oxidation as a result of the cleaning process. To quantify the magnitude of EUV reflectivity drop, reflectivity measurements were taken after every 3 cleaning cycles, up to 50 cleaning cycles and compared with the pre-clean reflectivity measurement to calculate the reflectivity loss. Further, each step in the cleaning cycle was performed 50 times to observe the isolated effect of each step on the reflectivity loss [19]. The experimental work done for this study, besides the XPS characterization of the EUV mask, was performed by SEMATECH.

3.4 Experimental Results

Figure 3.2 illustrates the effect of each step in the mask cleaning process on the EUV reflectivity drop after 50 cleaning cycles. Separate mask blanks were used for the study and they went through the individual steps separately.

Figure 3.2: EUV reflectivity drop due to individual steps in the mask cleaning process after 50 cycles [19].
A mask cleaning process is, in general, required to provide two functions: organic contamination and particle removal. In order to remove organic contamination, SPM is generally used. On the other hand, for the removal of particles on the photomask, a mixture of ammonium hydroxide and hydrogen peroxide or hydrogenated water with megasonic spray is used [20]. One can observe from Figure 3.2 that SPM causes the highest drop in EUV reflectivity among the individual steps. EUV reflectivity drop from SC1 seems to be the least. To understand the negligible drop in reflectivity by SC1 chemistry alone, one has to refer to the TEM images in the upcoming Figure 3.5. It can be seen that almost five bilayers have been removed by cleaning the blank 50 times. This is due to the fact that SC1 is applied along with megasonics for particle removal. Megasonic cavitations along with the desired effect of particle removal will also result in pit formation in the multilayer structure and removal of the top few bilayers. It is well known that EUV reflectivity for the top 40–50 bilayers remains almost the same [21]. Therefore, removal of the top few layers with SC1 and megasonics did not have much impact on the overall reflectivity. On the other hand, when SPM was used along with SC1, there was a further penetration of chemicals into the underlying bilayers, due to the strong oxidizing nature and concentration of chemicals, which resulted in a greater loss of reflectivity. It should also be noted that the combined effect of all chemicals and VUV exposure is cumulative.

Figure 3.3 shows the reflectivity map of the masks after the individual cleaning steps. We observe a slight reduction in EUV reflectivity as a result of the VUV step possibly due to the surface oxidation, as this step uses O₂ gas for surface conditioning. There is negligible reflectivity drop due to the SC1/megasonic step, and it can clearly be seen that the bulk of reflectivity loss is due to the SPM step in the cleaning process.

27
Figure 3.3: Reflectivity maps along with their corresponding reflectivity drop plots for the individual steps in the mask cleaning process after 50 cleaning cycles [19].

The overall reflectivity drop in the mask blank once it goes through the entire 50 cleaning cycles is illustrated in Figure 3.4. The reflectivity measurements were taken after every 3 cleaning cycles.
Cross-sectional TEM was performed on two mask blanks after they had gone through 50 cleaning cycles to evaluate the extent of etching caused due to the cleaning process. In Figure 3.5, we notice that 5–6 Mo/Si bilayers are etched away as a result of the cleaning process. We believe it is the combination of oxide etching and megasonic pitting, which is responsible for the bilayer removal. Here we must note that the bilayer removal is not uniform across the mask structure, and is sporadic as can be seen in the TEM images in Figure 3.5.

**Figure 3.4:** EUV reflectivity loss as a function of the number of cleaning cycles [19].
Figure 3.5: (a) TEM cross section of a mask blank once it has gone through 50 cleaning cycles.

(b) TEM cross section of another mask blank post-50X cleaning cycles [19].

Also, as the mask goes through the numerous cleaning cycles, the overall surface roughness goes up, which in turn causes the overall reflectivity to degrade. AFM measurements were taken on the mask before it went through any cleaning cycle and after it had gone through the cleaning cycles as shown in Figure 3.6.
Figure 3.6: (a) 1 μm X 1 μm AFM scan of pre-cleaned mask blank (rms roughness = 0.1 nm). (b) 1 μm line scan showing the roughness profile in one dimension. (c) 1 μm X 1 μm AFM scan of the mask blank after the cleaning cycles (AFM roughness = 0.15 nm). (d) 1 μm line scan showing the roughness profile in one dimension [19].

The incoming or the uncleaned mask blank had a low root mean square (rms) roughness and as the mask was taken through the cleaning cycles, its rms roughness increased. In this case it went up by 1.5 times after the cleaning cycles, from 0.1 to 0.15 nm.

Finally, XPS was performed on the Mo/Si multilayer structure to evaluate the oxidation of the bilayers as a result of the cleaning process. For this, we first performed XPS on mask blank that didn’t go through any cleaning cycles to look at the extent of oxidation on the
incoming mask blank. As seen in Figure 3.7(a), the XPS depth profile of the mask structure before mask underwent any clean cycles indicates the oxygen content to drop to 0 after 1 sputter cycle, where each sputter cycle etches approximately 2 nm – 3 nm into the mask structure. Figure 3.7(b) shows the spectrum from the Si layer just underneath the Ru cap layer, and we can see that Si layer too is partially oxidized, with most of it being present in its elemental state. Once the mask underwent cleaning cycles, it was again analyzed using the XPS. The XPS spot size used here was 300 µm, so the data as observed through XPS is the average data obtained from a beam spot of 300 µm. As seen in Figure 3.7(c), the XPS depth profile of the multilayer structure after cleaning cycles indicates the oxygen content to drop to 0 after 2 sputter cycles. Figure 3.7(d) shows the spectrum from the Si layer just underneath the Ru cap layer in the post-clean mask, and we can clearly see that the Si layer, that was partially oxidized to begin with on the pre-clean mask has oxidized to a large extent (however, not completely) after the cleaning cycles, thereby indicating the partial oxidation of Si as a result of cleaning cycles.
3.5 Simulations

The experiments performed give us a good insight into the quantification of the reflectivity loss and correlating the loss to the various steps involved in the cleaning process. As discussed earlier, these steps have a number of adverse affects on the mask blanks, namely surface degradation in the form of increased surface roughness and pit formation, oxidation of the bilayer structure, and addition of particles and other contamination from the chemicals used. However, it is not a straightforward task to correlate the reflectivity loss to these individual factors involved. To this effect, simulations were performed to study the impact of each factor namely oxidation, multilayer etching, surface roughness, etc. on the reflectivity loss.
The impact of the various phenomena including oxidation, etching, mask roughness and impurities added on the mask surface for a blank photomask were investigated using the EM-Suite, a lithography software developed by Panoramic Technology Inc., which calculates the intensity reflected from a mask based on a finite difference time domain algorithm [22,23]. The film stack used is a Ru-capped multilayer mirror with 50 Mo/Si bilayers. Optical parameters used for printing experiments are 13.5 nm wavelength and 6° angle of incidence.

### 3.6 Simulation Results

For an unetched, ideal ML structure, we get a reflectivity of 72.5%, as opposed to experimentally observed reflectivity of 66%. This difference between simulated and experimental EUV reflectivity values could be due to various factors namely, simulations assume ideal materials having ideal optical constants (theoretically calculated). Also, no inter-layer diffusion is included as part of the simulations. Studies have shown inter-layer diffusion to occur in Mo/Si systems, which leads to formation of interface defects and voids, and also the formation of different Mo/Si phases and compounds like MoSi₂, Mo₅Si₃ and Mo₃Si to name a few [24-27]. These non-ideal interfaces and phases can further lead to a reduced reflectivity of the multilayer mirror; however, none of these effects were taken into account for our simulation studies. Also, simulations don’t take into account the roughness of the bilayers deposited, and in reality the multilayers deposited may not be perfectly smooth, thus leading to scattering of EUV radiation, and therefore reduced reflectivity. Finally, with reference to the EUV mask materials, there could be a thin oxide and contamination to begin with on the pristine EUV mask blank, therefore resulting in EUV reflectivity loss. Another factor resulting in reduced experimental reflectivity values could be the non-ideal imaging conditions of the EUV mask.
blanks. So, the lower experimental reflectivity value would be a sum total of all the aforementioned effects. Simulation studies performed here give us a qualitative view of what trends to expect for EUV reflectivity loss occurring as a result of the different multilayer degradation processes due to cleaning.

Figure 3.8 shows the impact of uniform etching of the Mo/Si multilayer on the reflectivity drop. With uniform ML etching, we observe an increasing and decreasing reflectivity trend (with the etching of Si and Mo, respectively) with the overall reflectivity decreasing as we etch through the ML structure. Reflectivity increases until 0.6 nm Ru layer is etched, and then it starts to decrease as the Si layer starts to get exposed. This happens because the silicon layer acts as the 'spacer' in the multilayer structure, and absorbs the EUV radiation (explained in section 1.3). On the other hand, as the Si layer gets etched away, the reflectivity increases with Mo layer being exposed, since molybdenum is the 'reflector' (explained in section 1.3) and therefore the EUV radiation increases as Mo starts to get exposed due to the etching. We observe that even after 5 bilayers have been etched, there is a reflectivity drop of ≈ 1%. This result is expected, as the reflectivity that we observe after etching 5 bilayers from the multilayer stack having 50 Mo/Si bilayers, is the same as if we started with a multilayer structure containing 45 Mo/Si bilayers [21].
Figure 3.8: EUV reflectivity drop as a function of ML thickness etched [19].

Simulations were performed to investigate the impact of oxidation of the multilayer structure on the reflectivity loss. Figure 3.9 shows that the effect of oxidation on reflectivity is much worse than etching as the Mo/Si multilayers get gradually oxidized.
Figure 3.9: EUV reflectivity loss as a function of ML thickness oxidized [19].

Ru (n = 0.8863 and k = 0.0171) was oxidized to RuO$_2$ (n = 0.9207 and k = 0.0215), Si (n = 0.999 and k = 0.0018) to SiO$_2$ (n = 0.978 and k = 0.0108) and Mo (n = 0.9238 and k = 0.0064) to MoO$_2$ (n = 0.9341 and k = 0.0168). Here n is the real part of the refractive index of the material and k is the imaginary part (also called the extinction coefficient). Here, we did a direct substitution of the elements with their oxides, keeping the thickness constant (e.g., we replaced 2 nm of Ru with 2 nm of RuO$_2$). In reality, for example, if the complete Ru layer were oxidized to RuO$_2$, the thickness of the RuO$_2$ film would be greater than that of the Ru film. However, for simplicity of simulations, we made the direct substitution. This approximate approach is still valid, since we expect the same trends to be followed for EUV reflectivity loss. We observe that oxidation has a much more severe effect on reflectivity as opposed to simple etching. The reflectivity drop after 5 bilayers have been oxidized is more than 30%.
To reiterate, the above simulations have been performed by doing a direct substitution of multilayer materials with their oxides. Next, we were interested in estimating the expansion of the multilayer materials on being converted to their oxides. For example, we looked at the effect of oxidizing the Ru cap to RuO$_2$ and the underlying Si layer to SiO$_2$. For the simulations, room temperature densities of Ru, RuO$_2$, Si and SiO$_2$ were considered. Ru density was 12.45 g/cm$^3$ (or 0.123 moles/cm$^3$) and RuO$_2$ density was 6.97 g/cm$^3$ (or 0.052 moles/cm$^3$). Molar density of Ru in RuO$_2$ would be 0.038 moles/cm$^3$. So keeping in mind that the number of Ru atoms (or moles) won’t change in the system, we can scale the volume expansion inversely to the molar density, thus indicating that RuO$_2$ would now occupy almost 3.2 times the volume as Ru. Si density was 2.33 g/cm$^3$ (or 0.083 moles/cm$^3$) and SiO$_2$ density was 2.65 g/cm$^3$ (or 0.044 moles/cm$^3$). Molar density of Si in SiO$_2$ would be 0.021 moles/cm$^3$. So keeping in mind that the number of Si atoms (or moles) won’t change in the system, we can scale the volume expansion inversely to the molar density, thus indicating that SiO$_2$ would now occupy almost 4 times the volume as Si.

Here, for example, if we assume that expansion of the oxidized Ru film occurs only in the z-direction (or along its height), since it is bound in length and width, the thickness of RuO$_2$ film would be 6.4 nm. So, in the region of the plot (Figure 3.9) where just the Ru layer is shown to oxidize, going from 2 nm Ru to 2 nm RuO$_2$, it would now go from 2 nm Ru to 6.4 nm RuO$_2$. So, realistically, complete oxidation of 2 nm Ru layer results in 6.4 nm RuO$_2$ and not 2 nm RuO$_2$, therefore leading to a 3.2X higher reflectivity loss as compared to what has been predicted in Figure 3.9 (assuming linear relationship between reflectivity drop and thickness oxidized). So, we get a reflectivity loss of 6.4% as opposed to 2% due to oxidation of Ru to RuO$_2$. This prediction of EUV reflectivity is purely based on the assumption that the reflectivity drop is just
due to the absorption of radiation occurring in a material, and ignores other effects like standing waves etc.

However, experimentally, we observe a reflectivity drop of just 4% after 50 cleaning cycles. And as per the calculations above, we would obtain a 6.4% reflectivity drop if the Ru layer gets completely oxidized. In addition, XPS data suggests that the underlying Si layer also gets oxidized to some extent as well, which would further contribute to the reflectivity loss. Therefore, this suggests that oxidation of both the Ru and Si layer is not complete, and is only partial. Therefore, the oxidation of the different layers in the multilayer structure, although extending within the structure, is only partial. We believe this could be due to the different grain orientations of the same material being present in the layer. Some grain orientations are more susceptible to oxidation as compared to others [28,29].

To understand why oxidation has such a degrading impact on EUV reflectivity, we have to refer to Chapter 1. In Section 1.3, we discussed the fundamental mechanisms by which EUV reflectivity occurs. In the case of oxides, these materials are insulators. Therefore their electric susceptibility is low (electrons are tightly bound to the atoms, are not free to move), therefore the electric field of the EUV radiation is unable to create a disturbance in the charges (electrons) of the atoms. Therefore there is no resonance of electrons in response to the impinging radiation, and therefore no emission of radiation. Thus the absorption coefficient of oxides is high at EUV radiation. Now looking at the optical properties of oxygen at 13.5 nm wavelength, since oxygen has a low atomic number (Z = 16), resonance of the charges (electrons) by the incoming radiation would be limited, and most of the radiation would just get transmitted. This is reflected in the fact that real part of the refractive index for oxygen at EUV wavelength is close to 1. And since oxygen has a low atomic number, the electron density is low, so it doesn’t absorb much
radiation either, which is reflected in the low extinction coefficient (imaginary part of the refractive index) of oxygen. So, oxygen by itself is not responsible for significant EUV loss. The issue with having oxygen in an EUV system is that it would lead to oxidation of the optic surfaces which would in turn absorb EUV radiation.

Although here for the simplicity of our simulations we did a direct substitution of the multilayer materials with their oxides, in reality, as discussed, the conversion to the oxide would result in the expansion of the multilayer materials. This would in turn adversely affect the physical and mechanical integrity of the multilayer structure. Oxidation of the multilayer mirror could easily result in the appearance of cracks and flaking of the material from the multilayer structure.

The combined effect of the multilayer etching and oxidation (assuming a direct substitution of materials with their oxides and assuming complete oxidation of the various layers) on the reflectivity drop is shown in Figure 3.10. We observe that reflectivity drops sharply as the oxide thickness increases. On the other hand, etching has a much milder effect on the reflectivity loss.
**Figure 3.10:** EUV reflectivity drop as a function of oxide thickness and ML thickness etched [19].

If it is approximately known how much oxidation and etching might occur due to a given process, Figure 3.10 can be a useful map to determine the expected reflectivity loss due to the combined effects of oxidation and etching in that process. To obtain Figure 3.10, we started with a multilayer stack which was oxidized up to 9 nm. We then gradually etched into the multilayer stack (in steps of 0.2 nm) and recorded the reflectivity values after every step.

Also, we observed that higher the extent of oxidation, the higher is the reflectivity drop. Figure 3.11 compares the reflectivity drop between the RuO$_2$ and RuO$_3$ oxidation states, and one can see that if Ru got oxidized to RuO$_3$ instead of RuO$_2$, the reflectivity degradation would be more severe. Here again, for simplicity of simulations, we did a direct substitution of Ru by RuO$_2$ and RuO$_3$. Although this approach is approximate, we expect the trends to still hold true.
Figure 3.11: EUV reflectivity drop as a function of oxide thickness for two different oxidation states of Ru namely RuO$_2$ and RuO$_3$ [19].

Further, we performed simulations to observe the effect of a uniform carbon contamination layer growth on top of the mask blank and its gradual etching. In EUVL, a series of chemical reactions, initiated either directly by impinging EUV photons or indirectly by secondary electrons, lead to oxidation or carbon over-layer growth, resulting in degradation of the mirror reflectivity. The reactions involve water and hydrocarbons adsorbed on the surface from an unbaked vacuum environment or from outgassing resists. Photoelectrons generated by incident light striking the mirror are believed to be a major contributor to the dissociation of adsorbed water and hydrocarbons, resulting in oxidation and carbonization, respectively [30-33]. We simulated the effect of having a 10 nm carbon contamination layer on top of the ML stack and etched it uniformly in steps of 0.4 nm and observed its effect on EUV reflectivity, as shown in Figure 3.12.
Figure 3.12: EUV reflectivity as a function of carbon and ML thickness etched [19].

Initially, we observe an increase in reflectivity values as the carbon layer is etched, as would be expected. The reason why carbon leads to EUV reflectivity loss is because carbon absorbs the EUV radiation incident on it. Carbon has a high imaginary component of the refractive index, or extinction coefficient (0.993), at EUV wavelength (13.5 nm), which leads to the absorption of EUV by carbon. This trend continues up to 3.4 nm after which reflectivity starts to go down, which is contrary to a simplistic model that would predict the reflectivity to keep increasing as the contamination gets etched. This decrease in reflectivity goes on until the remaining carbon thickness is 5.2 nm, after which the reflectivity starts to go up again until all the carbon gets etched. The temporary downward trend in reflectivity that is witnessed here is we believe the result of what is known as the standing wave effect. The position of the standing wave can be controlled both by deliberately varying the thickness of the Si terminating layer (of the Mo/Si stack) and by depositing C films of various thicknesses as was demonstrated in the
The standing wave occurs in a stationary medium as a result of interference between two waves traveling in opposite directions. So in a multilayer mirror system, a standing wave is formed by the superposition of two waves of the same frequency propagating in opposite directions (since EUV masks are reflective). The effect is a series of nodes (points of zero displacement) and anti-nodes (points of maximum displacement). Depending on whether the node or anti-node coincides with the surface of the multilayer, the reflectivity of the EUV can vary. By changing the thickness of the capping layer, we can tune the reflectivity we want to obtain from the EUV masks. In the given case, where we would have expected to see a trend of increased EUV reflectivity with the etching of surface carbon layer, we observe the reflectivity values to decrease. We believe that at that thickness, the node of the EUV standing wave coincides with the surface, thereby not impacting the EUV reflectivity, therefore resulting in the counter-intuitive trend.

However, we observe the reflectivity values to not just flatten out, but slightly decrease as well. Such not-so-obvious effects have been reported in other studies as well, with a non-linear response in EUV reflectivity of the multilayer structure with the change in thickness of either the capping layer, the top oxide layer, surface contamination layer or any combination of these [34-36]. In a study conducted by S. Oestreich et al. [36], they studied the effects of different thicknesses of amorphous carbon layers on the reflectance of a multilayer mirror as a function of the carbon film thickness. For specific thicknesses of the capping layers, they observed that the EUV reflectivity went up as the carbon film starts to grow on top of them. We observe a similar trend (Figure 3.9) of reflectivity values slightly dropping with the etching away of carbon layer. This is explained by the fact that the reflection occurring from the multilayer structure occurs as a consequence of constructive interference from the multiple Mo/Si interfaces, and the growth of
an absorbing film of certain thicknesses can enhance the positive interference and lead to an increase in EUV reflectivity. Similar effect occurs with the growth of every Mo layer in the stack. Therefore, this effect also partially explains the enhancement in EUV reflectivity when Si layer gets etched away and Mo layer gets exposed (as observed in Figure 3.8), in addition to the fact that as Mo layer gets exposed, reflectivity is expected to increase since Mo is the reflective material of the multilayer structure (owing to its high Z value).

In a separate experiment performed by Mertens et al. [37], it was observed that 1 nm of carbon corresponds to $\approx 1\%$ relative reflection loss. From our simulations we observe that, on an average, adding a 10 nm carbon layer gave us a reflectivity of 62\%, which is $\approx 10\%$ less reflectivity than when no contamination is present, which closely matches the experimental results obtained by Mertens et al.

Next, we performed simulations to study the impact of mask roughness on the EUV reflectivity. The roughness data, as seen in the AFM line scan [Figure 3.6(d)] consists of low frequency as well as high frequency profiles over a large range (1 $\mu$m). Although the AFM data may contain periodic structures based on the physical process, this cannot be confirmed for a fact, and the measurements might very well contain only noise at a large range of frequencies.

We were interested in understanding how the spatial frequencies of the surface variation would affect the optical response. To this effect, we simulated periodic roughness profiles and varied their periodicity to observe the impact on EUV reflectivity. For the simplicity of our simulations, we simplified the roughness profile to an elliptical pattern. Figure 3.13 illustrates the roughness profile used for simulation.
Figure 3.13: Roughness profile used for the simulation.

Figure 3.14 shows the effect of varying half-period length of the elliptical pattern on EUV reflectivity.

![EUV Reflectivity Graph](image)

**Figure 3.14:** EUV reflectivity as a function of half-period length of the elliptical roughness profile having an amplitude of 0.4 nm. EUV reflectivity drop observed here is less than 0.2%.

Simulations were performed at varying half period lengths of the elliptical pattern keeping the amplitude fixed at 0.4 nm. Here we must note that realistically the roughness profile would not have an isolated spatial frequency and would be a combination of multiple
frequencies. However, here we studied the impact of a single frequency in isolation on the EUV reflectivity. Also, the simplification of the actual roughness profile to an elliptical shape is not realistic, since an elliptical shape has sharp edges, as can be observed in Figure 3.13, and we wouldn’t expect to come across such well-defined sharp edges in an actual roughness profile. Ideally, sinusoidal shape would be a better representation of the actual roughness profiles. However, elliptical profiles were chosen for simplicity of simulations. Amplitude of 0.4 nm was chosen since the AFM line scan post-clean cycles [Figure 3.6(d)] shows spatial profiles with maximum amplitude of 0.4 nm. Only the top Ru layer was made rough, since the AFM line scans post-cleaning cycles indicate that the amplitude of the roughness, as measured on the mask surface was 0.4 nm over a relatively long range of 1 µm, thus indicating that the roughness increase is limited to only the 2 nm thick capping Ru layer. For the imaging parameters, for this simulation, a mask side numerical aperture of 0.08 was chosen. This numerical aperture here is just an estimate, and indicates what angles might be getting collected in an EUV reflectometer tool. This estimate is based on the typical value of numerical aperture being used in an EUV mask review system [38]. In Figure 3.14 we observe the maximum reflectivity drop of around 0.1%. This reflectivity drop is negligible, and is within the range of statistical noise. Therefore the EUV reflectivity loss due to surface roughness occurring as a result of cleaning cycles is negligible.

3.7 Observations

On comparing the reflectivity trends obtained from experiments and the simulations performed, we can draw a number of inferences.
From the experiments, we observe the reflectivity to slightly increase after the first 3 cleaning cycles (Figure 3.4). From simulations we notice the same trend when the top carbon contamination layer gets etched (Figure 3.12). We can infer from this that the initial few cleaning cycles lead to the cleaning of the top carbon contamination layer without causing much etching, oxidation or surface roughness increase as these phenomena lead to reflectivity losses.

TEM images (Figure 3.5) show that after 50 cleaning cycles we lose up to 5 Mo/Si bilayers, and the experimental reflectivity loss after 50 cleaning cycles is $\approx 4\%$. Simulations show that etching 5 bilayers causes a reflectivity drop of $\approx 1\%$ (Figure 3.8). So, etching alone cannot explain the reflectivity drop that we get after 50 cleaning cycles.

Using the roughness profiles from the AFM images (Figure 3.6), we simulated reflectivity loss due to surface roughness. The reflectivity drop as a result of surface roughness was observed to be negligible. So, just etching of multilayers and surface roughness is not able to account for the 4\% reflectivity drop observed.

Coming to oxidation, we attempted to understand the effect of multilayer oxidation on reflectivity loss by gradually oxidizing the multilayer structure. Our simulations were based on two simplistic assumptions. First, the multilayer can be replaced by its oxide in a 1:1 thickness ratio i.e. substitution of 2 nm Ru with 2 nm RuO$_2$, which we clarified is not true. Second, the layers are assumed to oxidize completely, which is not the case either. Even with these simplistic assumptions, we believe that the reflectivity trends that we observe with multilayer oxidation would still hold true. Keeping these assumptions in mind, in Figure 3.9, we observe a 2\% reflectivity loss as the Ru capping layer gets oxidized to RuO$_2$, and a reflectivity drop of $\approx 7\%$ as both the Ru capping layer and the top Si layer are oxidized completely. This helps better explain the 4\% reflectivity loss that we observe experimentally as seen in Figure 3.4. However, the
experimental loss in reflectivity is only 4% compared to 7% drop in reflectivity observed from simulations; thus suggesting that the underlying Si layer does not get completely oxidized. This is confirmed by the XPS data illustrated in Figure 3.7 that shows that the oxidation is limited to the Ru capping layer and the underlying Si layer, which gets partially oxidized. The oxygen content drops to almost zero beyond the top 4 nm – 6 nm, i.e., beyond the top Ru layer and the underlying Si layer, as observed in the XPS depth profile [Figure 3.7(a)].

The observation stated above is for the simple case of direct substitution of the material with its oxide with a thickness ratio of 1:1. However, when we incorporate the effect of material expansion on oxidation, we observe that, although oxidation penetrates through the capping Ru layer to the Si layer underneath, oxidation of layers is only partial, and the linear relationship between EUV reflectivity drop and multilayer thickness oxidized might not be completely accurate. So, although clearly oxidation has a much more severe impact on EUV reflectivity compared to multilayer etching and surface roughness increase, we cannot quantify the exact depth of oxide formation within the multilayer structure or even the extent of oxidation of each layer. The assumption of direct substitution of materials with their oxides and the assumption of complete oxidation of the material helps us to better understand, at least qualitatively the reflectivity trends to expect as a result of multilayer oxidation.

Since majority of the EUV reflectivity drop observed is due to oxidation, we would like to approximately assess the multilayer thickness oxidized after each cleaning cycle. However, this is not a straight forward task, since we made the observation that oxidation of the multilayer structure, although penetrating the capping Ru layer to the underlying Si layer, is only partial for both the Si and Ru layers. Therefore, since oxidation occurring as a result of cleaning cycles is not a linear front, with the different layers getting partially oxidized, it’s difficult to precisely
determine the multilayer thickness oxidized with progressive cleaning. However, if we make the simplistic assumptions of oxidation being a linear front, and that the materials get substituted by their oxides in a 1:1 thickness ratio (as assumed for plotting Figure 3.9, which we understand is not true by simple conservation of mass logic), then combining the results plotted in Figure 3.9 (simulated EUV reflectivity versus multilayer oxide thickness) with those as shown in Figure 3.4 (experimental EUV reflectivity versus number of cleaning cycles), we obtain Figure 3.15 showing the oxide thickness as a function of number of cleaning cycles. Although based on non-ideal assumptions, the plot gives us a qualitative picture of the trends to expect for multilayer thickness oxidized as a result of the cleaning cycles. Initially, the oxide thickness increase is somewhat linear in nature and then saturates towards the end, which we believe would hold true in reality. Again, the data presented in Figure 3.15 does not take into account either the expansion of material on being oxidized or the fact that materials only get partially oxidized as a result of the cleaning process.

![Graph](image.png)

**Figure 3.15:** Multilayer thickness oxidized as a function of number of cleaning cycles.

When looking at the individual steps involved in the cleaning process, 50 SC1/megasonic steps cause a reflectivity drop of less than 1%, suggesting that this step causes multilayer etching and removal, and/or increase of the surface roughness. NH₄OH/H₂O₂ concentrations in SC1 step
are far less than $\text{H}_2\text{SO}_4/\text{H}_2\text{O}_2$ concentration used in the SPM step and therefore we should expect less oxidation with SC1 steps. On the other hand, 50 SPM cycles cause $\approx 3\% - 4\%$ reflectivity drop; thus strongly indicating that this step is primarily responsible for the oxidation of the Ru cap layer and the underlying Si layer.

The reflectivity loss observed after the cleaning process is possibly a combination of multilayer etching, surface contamination growth, surface roughness and oxidation. Oxidation is responsible for a majority of the reflectivity loss compared to multilayer etching or surface roughness increase.

3.8 Suggested Modifications to the Standard Cleaning Process

Based on the conclusions drawn in the previous section, we understand that oxidation is the biggest culprit responsible for causing the most severe EUV reflectivity loss ($\approx 4\%$) amongst the various other degradation factors like multilayer etching/pitting and surface roughness increase that occur as a result of standard mask cleaning processes. These other factors put together cause 1\% - 2\% reflectivity loss, which is almost 4 times less than loss caused due to oxidation alone. So, oxidation occurring as a result of the standard mask cleaning chemistries/processes is a problem.

Also, as mentioned in the previous section, the chemistry or process step that causes the highest amount of oxidation (3\% - 4\%) is the organic removal step that involves the SPM chemistry. As discussed in Section 3.2, the highly oxidizing chemistries are used to break the strong carbon-to-carbon bonds that are formed on the contamination layer on the EUV mask surface; however they also cause an oxidation of the multilayer structure that has a severe negative impact on EUV reflectivity. Alternatives to the strong oxidizing chemistries are needed.
if we want to protect the EUV masks from the undesirable EUV reflectivity losses that get compounded over multiple cleaning cycles and exposure processes.

So, until now, there hasn’t been any radical change in the standard EUV mask cleaning processes, with the traditional chemistries (as studied above) being still in wide use for EUV mask cleaning. New multilayer materials and cleaning chemistries are being explored in order to ensure the feasibility of EUVL at 14 nm half-pitch nodes and beyond [39-41]. In a study conducted by Lee et al. [42] they investigated the adhesion forces between the common contaminant particles and the various capping layers, and concluded that the various capping materials (Ru, Si) promote particle adhesion to some degree at a wide range of pH values. Also, photo-induced defects or haze defects have been an issue due to the cleaning chemistry residues being left behind on the masks [43,44]. So, based on our study, as well as studies mentioned above, we ideally want to find alternatives to the standard mask cleaning chemistries. Lytle et al. [45] had explored the use of helium (He) plasma to remove the contamination layer as well as the particles from the EUV mask surface. One of the drawbacks to using plasmas for cleaning is that the high energy ions generated in a plasma can result in damage to the surfaces. Especially in case of EUV masks, where nanometer-level control of mask surface roughness is needed, using gas plasmas for cleaning might not be entirely suitable.

In this section, we propose and show some preliminary results of using a hydrogen radical based cleaning approach. Hydrogen radical cleaning has been shown to effectively remove the carbon contamination from the surfaces of optics. This technique is likely to be used inside a real EUV exposure system [46-48]. At our site at CNSE, we study the cleaning of ruthenium coated silicon wafers (witness plates) under hydrogen radical flow [49,50]. Figure 3.16 shows a schematic of the hydrogen cleaning system at our site.
In the hydrogen cleaning system in our lab, we have a flow of hydrogen gas that dissociates into hydrogen radicals on coming in contact with the hot tungsten wire. These radicals then react with the carbon contamination layer on top of the witness plates, forming volatile species that get pumped away. Witness plates that are deliberately contaminated to study the extent of contamination caused by EUV resist outgassing are cleaned using a hydrogen radical cleaner system (developed at our site). Carbon is the major contamination element present on the witness plate samples, which is effectively removed using the hydrogen radical cleaning. This has been shown by the X-ray photoelectron spectroscopic technique (XPS) studies performed at our site [51]. At our site, we get contamination cleaning rates of ≈ 1 nm/hour and higher cleaning rates have been reported as well [52,53]. After cleaning, thickness of the contamination layer is negligible (∼ 0.1 nm) as determined by the ellipsometry technique [51]. Also, the hydrogen radical cleaning technique does not cause any degrading effects on the optics' multilayer structure. It has been reported that the EUV reflectivity drop of Ru capped Mo/Si multilayer structure (uncontaminated) after 20 hour exposure to hydrogen radical clean was less
than 1%, thus showing that Mo/Si optics exhibit fairly good resilience to degradation by atomic hydrogen exposure [53].

Although the above-mentioned studies were performed to study the cleaning of carbon contamination of the optics caused as a result of EUV resist outgassing, we expect the carbon cleaning mechanism to be similar for EUV masks, since the composition of both the optics and the masks is the same. So, using the atomic hydrogen clean method to get rid of carbon contamination on the mask surface might be a feasible alternative to reduce our dependence on the SPM chemistries, or maybe even make them obsolete, for getting rid of the carbon contamination growth on top of the EUV mask surfaces.

However, there are a number of potential hurdles to using the hydrogen radical cleaning technique as a replacement to SPM chemistry. The standard cleaning process takes place inside a track-based tool, where one step follows the other in a sequential manner without human intervention. So, substituting the hydrogen cleaning system in place of the SPM step would either require manual transfer of mask from the track-tool to the hydrogen cleaning system and back, or would involve somehow integrating the hydrogen cleaning system to be a part of the track-based tool. The former approach could potentially lead to contamination of the EUV mask due to handling, transport and transfer of the mask to and from track-tool as well as the hydrogen cleaning system, and the latter approach would require coming up with clever engineering solutions in order to integrate the hydrogen cleaning system within the existing track-based cleaning flow. This would require some effort on part of the mask cleaning industry to move forward in this direction.
3.9 Summary and Conclusion

In this study, we attempted to correlate the amount of reflectivity loss of EUV mask blanks occurring due to the cleaning process, to the various mechanisms at play during cleaning. We observed the effect of the various steps namely SPM, SC1/megasonic, and vacuum-ultraviolet, in isolation, on the EUV reflectivity loss. AFM analysis and TEM cross section studies were used to look at the integrity of the multilayer structure. XPS was performed to study the extent of oxidation of the multilayer structure.

Simulations were performed to analyze the impact of cleaning process steps on the reflectivity degradation of the mask blank. The factors studied here were uniform carbon contamination on top of the multilayer, multilayer etching, oxidation, and surface roughness.

By comparing the reflectivity loss results obtained through experiments to those calculated through simulations, we were able to qualitatively and, to some extent, quantitatively determine the impact of each step of the cleaning process on EUV mask blank durability. With this information, one can work toward modifying or even changing the mask cleaning process steps to mitigate EUV reflectivity losses currently observed. This could be by way of altering cleaning chemistries, duration of each step, or the total number of steps to reduce the impact of reflectivity loss on the mask blank, without having to compromise on the cleaning efficiency.

We proposed an alternative to the organic contamination cleaning step (involving SPM chemistry), that is responsible for causing oxidation of the multilayer stack, which in turn is responsible for the majority of the EUV reflectivity loss during the mask cleaning process. We discussed the role of atomic hydrogen cleaning to effectively remove organic contamination without causing a loss of EUV reflectivity. Hydrogen radical cleaning is a promising technique that could reduce dependence on, or even replace the standard SPM chemistry to get rid of the
carbon contamination growth on the surface of an EUV mask, without causing a drop in the reflectivity of EUV radiation.

References (Chapter 3):

CHAPTER 4

4. Experimental and Simulation Studies of Printability of Buried Native EUV Mask Defects using a Novel Level-set Multilayer Growth Model

4.1 Overview

As studied in Chapter 2, the availability of defect-free masks is considered to be a critical issue for enabling extreme ultraviolet lithography (EUVL) as the next generation technology. Since completely defect-free masks will be hard to achieve, it is essential to have a good understanding of the printability of EUV mask defects. In this work, we wanted to study the printability of native mask defects using a novel level-set multilayer growth model that took into account the tool deposition conditions where the multilayer deposition took place. For this study four native mask blank defects were characterized using atomic force microscopy (AFM) and cross-section transmission electron microscopy (TEM), and the defect printability of these defects was evaluated using simulations implementing the finite-difference time-domain (FDTD) and the waveguide algorithms. The simulation results were compared with through-focus aerial images obtained at the SEMATECH-Berkeley Actinic Inspection Tool (AIT), an EUV mask-imaging microscope at Lawrence Berkeley National Laboratory (LBNL). We obtained a good match between the through-focus aerial image intensities obtained at AIT and those obtained using simulations. To model the Mo/Si multilayer growth over the native defects, which served as the input for defect printability simulations, a level-set technique was used to predict the evolution of the multilayer disruption over the defect. Unlike other models that assume a constant flux of atoms (of materials to be deposited) coming from a single direction, this model took into account the direction and incident fluxes of the materials to be deposited, as well as the rotation of the mask substrate, to accurately simulate the actual deposition conditions existing inside the ion beam deposition tool. The modeled multilayer growth was compared with the
cross-section TEM images through the given defects, and there appeared to be a good agreement between them through visual inspection.

Further (as will be discussed in Chapter 5), we developed an approximate but robust method for investigating defect printability of arbitrarily-shaped native defects given the AFM defect profile of a native defect on top of a multilayer stack. Given the FWHM and height of the defect, as obtained from top layer AFM, we were able to infer the bottom defect profile in terms of FWHM and height, through study of multiple native EUV mask defects. Multilayer growth over native, Gaussian and regular-shaped substrate defect profiles (having similar FWHM and heights) was simulated using the level-set multilayer growth model and their printability performances were compared, in terms of aerial image intensities, and reasonable comparison was obtained between them. Thus, given an arbitrary defect profile on top of multilayer stack, we can reasonably determine its printability through simulation.

4.2 Introduction

EUVL is the leading next generation lithography technology to succeed optical lithography for the future technology nodes [1-3]. The reflective masks used in EUVL consist of a low thermal expansion material coated with a Mo/Si multilayer and a patterned absorber layer. The availability of defect-free mask blanks is one of the most critical technology gaps hindering the commercialization of EUVL [2,3]. The defects namely the pit or particle, can originate either on the substrate, during multilayer deposition, or on top of the multilayer stack [4-6].

The physical structure of a defect produced by a particle within the multilayer coating of an EUVL mask can be complex. In order to determine the smallest particle capable of producing a printable defect, it is crucial to be able to model the growth as well as the printability of the
defects accurately. Modeling is also essential in determining strategies to mitigate the printability of such defects by employing various techniques like defect smoothing [7], multilayer defect compensation technique [8], or using additional buffer layer [9], to name a few.

The most commonly used model, namely the non-linear continuum model or the Stearns model [10] used to simulate the multilayer growth over a defect, assumes the deposition and etch fluxes to be at normal incidence to the mask surface (thereby ignoring the shadowing effects due to the defect), which is not the case. The model used here takes into account the tool deposition conditions which include the angular flux of atoms incident on the substrate, the chamber geometry and various other deposition factors such as substrate and target angle, substrate and target size, and the distances.

The model developed (also true for the Stearns model) overcomes the limitations of techniques like the single surface approximation (SSA) and the conformal multilayer growth technique which attempt to approximate the defect propagation through the multilayer stack. In SSA, the defective multilayer structure is replaced by a single reflecting surface with the shape of the top surface of the multilayer. This approximation is valid only for sufficiently low aspect ratio defects [11]. The conformal multilayer growth assumes the defect to be uniformly propagated through the multilayer stack. Again, this approximation only holds true for relatively small defects [10].

The aim of our work was to draw comparisons between the aerial images obtained using AIT tool at LBNL and those obtained using the FDTD and waveguide simulations that used the level-set modeled multilayer growth as the input. We obtained a good match between them.
4.3 Characterizing Native Defects on EUV Mask Blanks

Once the multilayer deposition process on the mask substrate was complete, the mask blank was analyzed for defects using a Lasertec M7360 inspection tool which uses light scattering as a means to detect defects present on the substrate surface. The defect locations were marked with the help of fiducials to easily locate the defects for AFM, TEM and AIT printability studies. AFM was performed at the defect locations to observe the defect profile on top of the mask blanks. The masks were then sent to LBNL to undergo inspection at the AIT where the aerial images of the defect sites were obtained at multiple focus conditions. TEM cross-section studies were then performed on the defects to observe how the multilayer disruption due to the defect propagates up the multilayer stack. The defect profile at the substrate obtained from the cross-section TEM was used as one of the inputs into the multilayer growth model.

4.4 Multilayer Growth Model

The multilayer growth model, as developed [12,13], looked at the deposition conditions of the Veeco Instruments’ Nexus low defect density (LDD) tool located in the SEMATECH cleanroom facility. The tool consists of an ion source, Si, Mo and Ru targets, and an electrostatic chuck to hold the mask substrate. The schematic of the tool is shown in Figure 4.1. Ar ions extracted from the ion source strike the target liberating the atoms to be deposited. The sputtered atoms travel to the mask substrate where they get deposited, creating the multilayer reflector. The mask substrate is electrostatically chucked to the mask fixture, which precisely positions the substrate relative to the target and spins the substrate around its normal direction.
**Figure 4.1:** Top-down schematic of the Ion Beam Deposition tool. TA and SA are the target angle and the substrate angle respectively.

The multilayer growth model uses kinetic Monte Carlo method for calculating angular distribution of sputtered atom flux, and level-set method for determining multilayer growth. The simulation method takes into account the sputtered flux, energy of the sputtered atoms, and gas scattering inside the chamber. It takes into account the probability of striking an ambient gas atom along the atom’s trajectory and predicts the energy and direction of the atom after the collision. The scattering gas in the initial simulations was assumed to have a Boltzmann’s velocity distribution at 50°C and to be comprised of argon atoms at 0.14 mTorr, which is the typical pressure inside the Veeco chamber during deposition. Modeling the deposition rate throughout the chamber requires estimates of several parameters, such as the number of atoms ejected from the target at each location on the target, which was estimated using measured target erosion profiles; the angular distribution of atoms reaching the substrate, which was estimated by measuring the deposition rate on substrates mounted on a hemispherical surface around the center of the target; the gas scattering behavior between the target and substrate, which was estimated using a kinetic Monte Carlo method and scattering cross sections. A collision kinetic
theory with a random impact parameter was used to determine the post-collision velocity of the atom. The substrate rotation that is commonly used to improve uniformity in the Veeco Nexus tools is modeled by rotationally averaging the number of atoms that strike the substrate. Typically 40 million atoms are launched in the simulation to get reasonable statistics on substrate uniformity.

After determining the growth rates and uniformity on the multilayer, multilayer growth on a given defect profile can be simulated. The study of multilayer growth on defects helps one to understand the total phase change and the effect of curvature change for a given defect profile under given deposition conditions. The net phase change adds to the intrinsic effect of the core defect and its influence on the growth of the multilayer stack during deposition. Therefore, identifying this influence is critical.

One of the ways to study the evolution of surfaces is by numerically simulating the growth of dynamic implicit surfaces and reproducing multilayer growth on defects. Existing simulation theories can be used such as the fast marching method, front tracking method, and level-set method. The level-set method is a powerful technique based upon an implicit description of evolving surfaces and, hence, it can account for any topological changes in any number of dimensions. The level-set method was implemented by level-set initialization, development of the level-set by numerical integration, and level-set visualization. The surface of interest is the contour for which the function $\varphi(r, t)$ is zero. This is called the zero level of the level-set function and describes the surface implicitly. Since the surface is always defined as the same contour of $\varphi(r, t)$, it follows that any level-set function $\varphi(r, t)$ obeys the Hamilton-Jacobi evolution equation as given in Equation 6.

$$\frac{d\varphi(r,t)}{dt} + \nabla \cdot \mathbf{V} \varphi + a|\nabla \varphi| = b \kappa |\nabla \varphi|$$ (6)
where \( \varphi(r,t) \) is the definition of the interface given by the initial pit or particle geometry, \( \vec{V} \) is the external velocity vector of the deposition fluxes, \( \nabla \varphi \) defined as \( \left( \frac{d\varphi}{dx}, \frac{d\varphi}{dy}, \frac{d\varphi}{dz} \right) \) is gradient of the interface in three dimensions, \( \vec{V}\nabla \varphi \) is deposition by the vector of direct line of sight, \( a|\nabla \varphi| \) is deposition due to the flux of atoms reaching the surface by scattering, \( \kappa \) defined as \( \nabla \left( \frac{\nabla \varphi}{|\nabla \varphi|} \right) \) is Laplacian of the interface defining the curvature \( \varphi(r,t) \), and \( b\kappa|\nabla \varphi| \) is the curvature-driven force dominant in a large adatom diffusion growth regime.

The initialization for the level-set method includes initializing a function \( \varphi(r,t) \) and setting up boundary conditions. The initialization of the level-set in our case will depend upon the shape of the defect profile on the substrate. Hence the function was initialized in such a way that the zero level-set represents the shape of defect. The defect profile can be imported from an image recognition profile of transmission electron microscopy (TEM) images, in addition to function initialization representing the defect profile. Further, interface evolution was studied with the discretized level-set data obtained for each time step. The derivative of \( \varphi \) can be approximated by multiple schemes such as first order ENO (essentially non-oscillatory), second or higher order ENO, or weighted ENO (WENO). The combination of forward Euler time discretization with the upwinding difference scheme provides a consistent finite difference approximation to the partial derivatives; however, special caution should be taken while stepping the \( \delta t \) to get convergent calculations. Stability of the solution to Equation 6 was enforced by using Courant-Friederichs-Lewy (CFL) conditions, which are given by Equation 7.

\[
\Delta t_{\text{max}} \left( \frac{|V|}{\Delta x}, \frac{|V|}{\Delta y}, \frac{|V|}{\Delta z} \right) \leq C
\]  

(7)
where $\Delta t_{\text{max}}$ is the maximum allowable time step to obtain convergence for solution to Equation 7, $|V|$ is the magnitude of velocity vector (whose dimension is length/time) as given in Equation 6 and C is the Courant number, which in this case is equal to 1.

In the level-set approach, we define the 2-D level-set function (outline of the defect as seen in cross-section TEM image) in the XZ plane. The equivalent 3-D defect shape, for which the 2-D level-set multilayer growth simulations would hold true, is the 2-D defect shape (defect interface) rotated in the XY plane by 180 degrees about the center of the 2-D level set surface, to represent a rotationally-symmetric 3-D defect shape. The rotation here is done about the center of the level-set surface, and the defect shape is so defined such that its maximum height or depth coincides with the center of the level-set surface. Here, it must be made clear that the level-set multilayer growth simulations are 2-D in nature, simulating the evolution of the 2-D interface of the defect. Also, the 2-D simulations assume the deposition conditions to be isotropic, with the XZ and YZ planes being identical. There can be potential issues in performing 2-D simulations to replicate the growth over a 3-D defect shape which is not rotationally symmetric. If the real defect is not symmetric about its peak, we would not obtain an ideal result. Figure 4.2 shows an example of a non-symmetric defect, and the equivalent 3-D defect shape that the growth model assumes.
**Figure 4.2:** (a) Level-set interface of the defect shape in XZ plane (cross-sectional view). (b) Equivalent 3-D defect shape as defined by the 2-D level set interface (top-down XY plane view).

Figure 4.2(a) shows the 2-D level-set interface (defining a substrate defect shape) that serves as the input into the growth model. So, we observe that when this 2-D defect shape gets rotated 180 degrees about the lowest point of the defect, we obtain the shape as seen in Figure 4.2(b). We know that this is not an accurate representation of the real 3-D defect shape on the mask substrate. Therefore this model doesn’t assume the correct 3-D defect shape (for the defined 2-D interface) if the defect is not rotationally symmetric. However, conversely, we can obtain a reasonably accurate 2-D representation of the defect shape by taking the cross-section (from the 3-D defect shape) across the vertical line as shown in Figure 4.2(b). Therefore, although the 3-D representation of the defect shape is not real, it would yield an accurate (or real) 2-D defect interface. After simulating multilayer growth over the defect, we obtain a 2-D output of the interface growth. For performing the defect printability simulations, we want to be able to
use a 3-D defect shape to attempt to mimic the actual defect shape. For that, we employed an average-based smoothing algorithm to the 2-D defect shape output from the growth model, wherein we obtained the corresponding average depth values on either side of the defect peak and applied those average values to either side of the peak. We then rotated this averaged 2-D defect shape by 180 degrees to obtain the 3-D defect shape that we then input into our defect printability simulations. We must note here that even for our defect printability simulations we assume rotationally-symmetric defects, and this approach won’t be valid for simulating defects that are grossly non-symmetric.

The process of defect profile definition that served as an input into the level-set model (the level-set function) was an iterative one. The outline of the defect shape, as observed in the TEM images was traced and the function defining the traced shape was input into the growth model. The FWHM and height of the defect at top of the multilayer stack, as obtained through the model were then compared with those as determined by the AFM measurements on top of the multilayer stack. Since the TEM slice may not be exactly through the center of the defect, the traced outline of the defect would underestimate the FWHM and height of the defect at the substrate, and hence the resulting profile at the multilayer top. So, the bottom defect profile was iteratively adapted until the modeled defect profile matched the AFM defect profile at the multilayer top. This was done since the top few layers of the multilayer structure reflect the majority of the EUV radiation, thus making it critical to model their growth more accurately.
4.5 Results

4.5.1 Comparing Modeled Multilayer Growth with Cross-section TEM and AFM

Four defects, two bump and two pit, were characterized and studied for this work. The level-set growth model was able to predict the deposition rate and uniformity of the material deposited on the mask substrate. The TEM cross-sections of the defect growth for all four of the defects appear to agree with the simulated multilayer growth over the defects as shown in the upcoming Figure 4.4 [14,15]. AFM was performed post multilayer deposition to look at the defect profiles on top of the multilayer stack. AFM scans of two defects along with the modeled defect profiles at the multilayer top are shown in the upcoming Figure 4.5 [14,15]. Since the defects studied here are native and non-symmetric, measurements of FWHM were made along four directions (x-axis, y-axis and the two 45° diagonals). The AFM measurements of the "A" bump defect performed at the top of the multilayer stack yielded a maximum height of 6 nm and an average FWHM value of 58 nm, with a standard deviation of 1 nm. AFM measurements of the "B" pit defect at the multilayer top yielded a maximum depth of 8 nm and an average FWHM value of 51 nm, with a standard deviation of 4 nm, indicating a non-rotationally symmetric defect. Even though the asymmetry was about 10%, we modeled a rotationally symmetric defect. The AFM measurements of the "C" bump defect performed at the top of the multilayer stack yielded a maximum height of 42 nm and an FWHM value of 68 nm (raw AFM data unavailable to perform the FWHM measurement in different directions for this defect, so we used the SEMATECH reported average values for FWHM and height). AFM measurements of the "D" pit defect at the multilayer top yielded a maximum depth of 7 nm and an average FWHM value of 44 nm (again, raw AFM data unavailable to perform the FWHM measurement in different directions for this defect, so we used the SEMATECH reported average values for FWHM and
depth). The FWHM and height information for the above-mentioned defects has been summarized in Table 4.1.

<table>
<thead>
<tr>
<th>Defect Type</th>
<th>FWHM (nm)</th>
<th>Height/Depth (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;A&quot; Bump</td>
<td>58</td>
<td>6</td>
</tr>
<tr>
<td>&quot;B&quot; Pit</td>
<td>51</td>
<td>8</td>
</tr>
<tr>
<td>&quot;C&quot; Bump</td>
<td>68</td>
<td>42</td>
</tr>
<tr>
<td>&quot;D&quot; Pit</td>
<td>44</td>
<td>7</td>
</tr>
</tbody>
</table>

Table 4.1: FWHM and height/depth information pertaining to the characterized defects.

The modeled defect profiles at the multilayer top were in agreement within 1 nm for height and FWHM compared to the average AFM measured profile, after iteratively adapting the substrate defect profile (as explained in section 4.4). As an example, Figure 4.3 illustrates the iteration process followed to determine the substrate defect profile for the “A” bump defect. For this defect, the initial defect profile as outlined in the TEM cross-section image had led to an underestimation of the top-layer FWHM and height by approximately 20% as compared to the AFM measurements of the defect at the multilayer top. Figure 4.3 shows the outline of the initial defect profile for "A" bump defect (in red) and the adapted outline of the defect profile (in orange), that was eventually used.
Figure 4.3: TEM showing the iterative process of outlining the defect profile to match the top-layer AFM for FWHM and height. In red, we see the initial traced outline of the defect, and in orange we have the adapted traced outline of the defect so as to match the modeled growth on multilayer top with AFM measurements at multilayer top.

After following the iteration process for the various defects, multilayer growth of 40 Mo/Si multilayers was modeled with each bilayer being approximately 7 nm thick. The TEM cross-section and modeled cross-section of the multilayer growth over the defects are shown in Figure 4.4. Although the parameters used here were those of the Veeco Nexus tool, the model can be adapted to simulate multilayer growth under different deposition conditions in different tools.
Figure 4.4: (a) TEM cross-section of the "A" bump defect on the EUV mask. (b) Simulated multilayer growth over the "A" bump defect using our model. (c) TEM cross-section of the "B" pit defect on the EUV mask. (d) Simulated multilayer growth over the "B" pit defect using our
model. (e) TEM cross-section of the "C" bump defect on the EUV mask. (f) Simulated multilayer growth over the "C" bump defect using our model. (g) TEM cross-section of the "D" pit defect on the EUV mask. (h) Simulated multilayer growth over the "D" pit defect using our model [14,15].

Following steps were followed for the TEM sample preparation to characterize the defects:

(i) First, the defect was imaged using the FIB-SEM (tool combining the capabilities of a focused ion beam and a scanning electron microscope). For this, a FEI Helios NanoLab tool was used.

(ii) Thereafter, the mask is tilted at an angle of 52 degrees to observe if the defect is a surface defect or is it propagating from within the multilayer stack (embedded defect).

(iii) Once it’s established that the defect is embedded, platinum is deposited on top of the defect using e-beam Pt deposition.

(iv) Then the Ga ion beam in the FIB-SEM tool is used to put fiducial marks close to the defect, which would aid in identifying the defect during the sample preparation steps.

(v) Next, the characterized defect needs to be cross-sectioned using the milling functionality of the FIB-SEM tool. The tool recognizes the fiducial marks and starts the milling process to prepare the cross-section of the defect. The accuracy of the FIB tool to prepare the cross-sections is 30 nm.

(vi) So, if the dimension of the defect (in the direction perpendicular to the ion beam direction) is less than 30 nm, we may very well miss the defect. Therefore, we can only control the accuracy of the cross-section being drawn to an accuracy of 30 nm.
Hence, we are not able to ensure that the cross-section would be at the center of the defect. The thickness of the cross-sectioned sample containing the defect is approximately 100 nm.

(vii) The cross-section containing the defect is then imaged using the FEI Titan TEM tool.

(viii) Sample damage can occur as a result of the FIB sample preparation, as the ion impact on specimen surface may not only lead to material removal due to sputtering by ion beam, but also to the formation of a damaged layer that may extend several tens of nanometers into the material.

Top layer AFM scans of the "A" bump and "B" pit defects along with the top layer modeled growth are shown in Figure 4.5. Raw AFM data for "C" bump and "D" pit defect was not available.
Figure 4.5: (a) AFM image of the "A" bump defect at top of the multilayer stack. The bump defect has an average FWHM of 58 nm and a maximum height of 6 nm. (b) Top of the multilayer stack as predicted by level-set multilayer growth model (after iterating bottom defect profile to get agreement with top AFM profile within 1 nm). (c) AFM image of the "B" pit defect at top of the multilayer stack. The pit defect has an average FWHM of 51 nm and a maximum depth of 8 nm. (d) Top of the multilayer stack as predicted by level-set multilayer growth model (after iterating bottom defect profile to get agreement with top AFM profile within 1 nm) [14,15].

For the AFM measurements, a Digital Instruments 5000 AFM was used. A sharp carbon-based tip (Nanotools SSE-NT-RTESPA) was used to measure the defects which had a nominal tip radius of 2 nm. One limitation of AFM is the fact that the data acquired is convoluted with information of the probe tip (size, asymmetry etc.). This phenomenon is called “tip imaging”. Depending on the size and geometry of the tip, features appear broader than they are in reality. In a very simplified model, assuming spherical tip apex and a spherical object, it can be shown how the width is overestimated. Typical tip radii are anywhere between a few to several tens of nanometers; thus, for smaller objects and features, this effect must be taken into account. For our work, the dimensions of most of the defects that were measured were much larger, both in terms
of width and height (or depth) as compared to the AFM tip radius of 2 nm. Still, we wanted to estimate the maximum error in measurement of the defect profile due to the size of the AFM probe tip. If we assume the tip to be a sphere of radius $r_{\text{tip}}$ (for our AFM system, $r_{\text{tip}} = 2$ nm), and we want to image a feature (assuming it to be spherical) of radius $r_2$, as shown in Figure 4.6, the maximum measured width ($w$) of the feature is given as Equation 8 [16].

$$w = 2(r_2 + r_{\text{tip}}) \quad (8)$$

So, the maximum error in measurement of width of a defect would be $2r_{\text{tip}}$. The error in measurement of the height would be zero, and for a pit defect, as long as the aspect ratio of the pit is not larger than that of the tip (which is equal to 100 for the tip used), and the bottom of the pit does not have a curvature smaller than that of the AFM tip, error in measurement of the depth of the pit would also be zero.

The maximum error in width measurement being equal to $2r_{\text{tip}}$ would hold true for measurement of widths where the tangent line passing through the points across which width is to be measured, is perpendicular to the surface. For example, this would be the case for measuring the diameter of a sphere in the horizontal direction. However, in our case, we did not have spherical defects, but had approximately Gaussian-shaped defects and we were interested in
finding out the error in determining their FWHM. Using basic geometry, we inferred that the maximum error in determining the FWHM of an assumed Gaussian-shaped defect would be equal to $2r_{tip}\sin\theta$, where $\theta$ is the angle the tangent lines make with the surface across which width is to be measured. This angle was determined for each of the defect shapes using the raw data obtained from the modeled multilayer growth of the defects. Table 4.2 shows the defects and their corresponding dimensions along with the absolute and percentage errors in determination of the defect widths.

<table>
<thead>
<tr>
<th>Defect Type</th>
<th>FWHM (nm)</th>
<th>Height/Depth (nm)</th>
<th>$\theta$ at FWHM</th>
<th>Abs. error of FWHM ($2r_{tip}\sin\theta$)</th>
<th>% age error</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;A&quot; Bump</td>
<td>58</td>
<td>6</td>
<td>8°</td>
<td>0.6 nm</td>
<td>1%</td>
</tr>
<tr>
<td>&quot;B&quot; Pit</td>
<td>51</td>
<td>8</td>
<td>12°</td>
<td>0.9 nm</td>
<td>1.8%</td>
</tr>
<tr>
<td>&quot;C&quot; Bump</td>
<td>68</td>
<td>42</td>
<td>42°</td>
<td>2.6 nm</td>
<td>3.8%</td>
</tr>
<tr>
<td>&quot;D&quot; Pit</td>
<td>44</td>
<td>7</td>
<td>10°</td>
<td>0.7 nm</td>
<td>1.6%</td>
</tr>
</tbody>
</table>

**Table 4.2:** Table showing the errors in measurement of the defect width occurring as a result of tip broadening due to the AFM tip having a finite radius (in our studies $r_{tip} = 2$ nm).

Although here we are able to estimate the error occurring due to the tip broadening effect, we chose not to take this effect into account, since even the maximum possible the error due to this, as can be observed from Table 4.3 was less than 4% for the worst case, so we chose to ignore this effect for our studies.

**4.5.2 Comparing the FDTD Simulation and AIT Through-focus Aerial Images**

The simulated multilayer growth was used as the input for the defect printability simulations. To perform the simulations, we used two lithography simulation software packages namely Sentaurus Lithography (S-Litho) from Synopsys and EM-Suite from Panoramic Technology Inc. EM-Suite was used to perform simulations implementing the FDTD [17,18]
algorithm while S-Litho was used to perform simulations implementing the FDTD as well as the waveguide [19] algorithms for the rigorous modeling of EUV masks. The optical and imaging parameters used for the simulations were chosen to match the parameters used for the AIT imaging, which were 13.5 nm wavelength radiation incident on the mask at an angle of 6 degrees, top-hat illumination with a sigma value of 0.2, and a numerical aperture (NA) of 0.35 for a demagnification factor of 4 used in our simulations. The actual NA of the AIT zoneplate used for imaging the characterized defects was 0.0875. Figure 4.7 [14,15], Figure 4.8 [14,15], Figure 4.9 and Figure 4.10 [19] show the aerial images from the AIT along with the aerial images obtained using the FDTD and waveguide simulations for the "A" bump, "B" pit, "C" bump and "D" pit defects respectively. All the 1-D aerial image intensities were scaled according to their respective average intensities (as obtained from the 2-D aerial image intensity plots). The 1-D aerial image intensity plots presented here were obtained by taking a cross-section through the x-axis of the 2-D aerial image intensity maps. The AIT aerial image intensity FWHMs measured across four directions agree to within 6% for all focus conditions for all the four defects. Therefore, the AIT aerial image intensities were approximately symmetric for all the four defects, thereby allowing the choice of direction of cross-sections to be arbitrary. Also, the AIT background, although negligible on the days when the defects were inspected, was subtracted from the raw AIT aerial image intensities prior to our analyses. The difference in contrast (calculated by dividing the difference of maximum and minimum intensities by their sum) between AIT and simulated aerial image intensities for the various focus conditions, was observed to be approximately 5% on average for the four defects. Simulations overestimate the contrast as compared to the AIT. This contrast difference between AIT and simulated aerial image intensities can be partially accounted for by the tip broadening effect occurring as an
artifact of the AFM measurements of our characterized defects, which would have led to the worst-case overestimation of defects’ widths by typically around 2% (worst-case overestimation of 3.8% for “C” defect), which corresponds to around 2% overestimation of contrast values [as inferred from Figure 5.6(a), from Chapter 5, in the range of defect dimensions studied here]. For the printability simulations, we would have ended up modeling a higher value of a defect’s width than what was real, which would then have led to the non-ideal match of the aerial image intensity contrasts between AIT and simulations. This mismatch in contrast is not significant, and we believe can be at least partially accounted for by the tip broadening mechanism associated with AFM measurements. We will investigate whether this contrast mismatch (error) between AIT and simulated aerial image intensities is critical or not in terms of detecting printable defects in Chapter 5 (Section 5.4.3) in some detail. The FDTD simulations took almost 12 hours to run while the waveguide simulations ran in around 1.5 minutes for simulating the 0.5μm × 0.5μm × 0.5μm mask volume containing the characterized defects. The grid size used for all our simulations was 1nm × 1nm × 0.7nm.

(a)
Figure 4.7: "A" bump defect (a, b) (i) 2-D aerial image intensity data obtained at AIT. (ii) 2-D aerial image intensity data obtained with FDTD simulations performed using EM-Suite from Panoramic Technology Inc. (iii) 2-D aerial image intensity data obtained with FDTD simulations performed using S-Litho from Synopsys. (iv) 2-D aerial image intensity data obtained with waveguide simulations performed using S-Litho from Synopsys. (v) 1-D aerial image intensity data extracted from the 2-D aerial image intensity maps obtained at AIT, and those obtained using FDTD and waveguide simulations [14,15].
Figure 4.8: "B" pit defect (a, b) (i) 2-D aerial image intensity data obtained at AIT. (ii) 2-D aerial image intensity data obtained with FDTD simulations performed using EM-Suite from Panoramic Technology Inc. (iii) 2-D aerial image intensity data obtained with FDTD simulations
performed using S-Litho from Synopsys. (iv) 2-D aerial image intensity data obtained with waveguide simulations performed using S-Litho from Synopsys. (v) 1-D aerial image intensity data extracted from the 2-D aerial image intensity maps obtained at AIT, and those obtained using FDTD and waveguide simulations [14,15].
Figure 4.9: "C" bump defect (a) 2-D aerial image intensity data obtained at AIT (b) 2-D aerial image intensity data obtained with FDTD simulations performed using EM-Suite from Panoramic Technology Inc. (c) 2-D aerial image intensity data obtained with FDTD simulations performed using S-Litho from Synopsys. (d) 2-D aerial image intensity data obtained with waveguide simulations performed using S-Litho from Synopsys. (e) 1-D aerial image intensity data extracted from the 2-D aerial image intensity maps obtained at AIT, and those obtained using FDTD and waveguide simulations.
Figure 4.10: "D" pit defect (a) 2-D aerial image intensity data obtained at AIT (b) 2-D aerial image intensity data obtained with FDTD simulations performed using EM-Suite from Panoramic Technology Inc. (c) 2-D aerial image intensity data obtained with FDTD simulations performed using S-Litho from Synopsys. (d) 2-D aerial image intensity data obtained with waveguide simulations performed using S-Litho from Synopsys. (e) 1-D aerial image intensity data extracted from the 2-D aerial image intensity maps obtained at AIT, and those obtained using FDTD and waveguide simulations [20].

So, we believe we achieved a good comparison between the aerial image intensity contrasts obtained at AIT and those through simulations. Here, we must note that the match between the aerial image intensity spreads obtained at AIT and through simulations was not ideal. However, it is the aerial image contrast that is relevant, and which would determine if the feature gets printed on the wafer. As for the intensity spread, as long as the resolution of the
EUV resist (which is typically less than 20 nm on wafer-plane) is narrower than the feature width (as is the case for our characterized defects), width of the intensity spread is not critical in determining the printability performance.

The AIT imaging of pit defect "D" was performed in early 2009, when LBNL reported some amount of aberrations in its AIT tool. The predominant aberration in the tool was astigmatism having a value of 0.08 $\lambda$ [21]. We performed simulations to look at the impact of astigmatism on the aerial image intensity. Figure 4.1 shows a comparison of AIT aerial image intensity of "D" pit defect, with the aerial image intensity obtained using simulation with 0 astigmatism and simulation with 0.08 $\lambda$ amount of astigmatism. Comparison was made at the best focus condition and we observe that the contrast difference between aerial image intensities obtained from the two simulations is around 3% (lower contrast for aerial image intensity with aberrations), and the intensity spread obtained using simulation incorporating the aberration is approximately 15% more as compared to the simulation with no astigmatism. So, we obtain a slightly better match between aerial image intensities obtained at AIT and those obtained using simulations for the "D" defect, in terms of the aerial image intensity spreads, when we incorporate the aberrations that were present in the AIT tool at that time.
Figure 4.1: Plot showing the impact of astigmatism on the simulated aerial image intensity for "D" pit defect.

4.6 Summary and Conclusion

A realistic multilayer growth model was developed for the study of printing behavior of buried multilayer defects in EUV masks that took into account the deposition conditions of the ion beam deposition tool where the multilayer deposition took place. We obtained a good match between the cross-section TEM profile of the multilayer disruption caused by the defect and the defect evolution up the multilayer stack as predicted by the growth model. Using the modeled multilayer growth as the input for our defect printability simulations, we achieved a good match between the through-focus aerial image intensities obtained at AIT and those obtained using simulations, for the characterized native mask defects. The native mask defects had heights ranging from 6 nm to 42 nm, and FWHMs ranging from 44 nm to 68 nm, and based on the good match between AIT and defect printability simulations, we demonstrated that the level-set growth model can simulate multilayer growth with a good degree of accuracy, over real native defect shapes having a wide range of widths and heights. We were therefore able to establish the
capability of defect printability software packages employing various algorithms to reliably simulate the printability of real defect shapes occurring on mask blanks, thus potentially making the simulation approach a viable option to be used as an inspection tool to determine printability of native defects occurring in mask blanks. We will elaborate on this point and propose a mask blank inspection process flow in the next chapter of this thesis. The waveguide simulation was nearly 500 times faster than the FDTD simulations for our characterized defects and yielded comparable results. We were able to prove the robustness of the FDTD and waveguide algorithms to simulate the through-focus printability behavior of arbitrarily-shaped native EUV mask defects.

References (for Chapter 4):


CHAPTER 5
5. Systematic Study of Native EUV Mask Defects

5.1 Introduction

In the previous chapter, we have demonstrated the accuracy of the level-set multilayer growth model and that of the various defect printability algorithms. Next, we wanted to develop a reliable method to estimate the printability of a given native EUV mask defect given the AFM profile on the multilayer top. Studies have been done that have looked at multilayer growth over programmed defects using non-linear continuum growth models [1-5], and have attempted to predict the printability of native defects. However, a systematic study correlating the ML growth over a native defect versus a programmed defect, and showing the comparisons between their printabilities has been lacking. Here, we have developed an approximate but relatively accurate and robust method for investigating defect printability of arbitrarily-shaped native defects given their AFM profiles on top of the multilayer stack.

5.2 Correlating Multilayer Growth over Native and Gaussian-shaped Defects

First, we wanted to establish a clear correlation between the defect profiles at the substrate and the defect profiles at the top of the multilayer, for the given deposition conditions for our ion beam deposition tool, the Veeco Nexus. In a study conducted at SEMATECH by Il-Yong Jang et al. [6], AFM measurements for native defects were performed at the substrate as well as at the multilayer top, and a graph showing the substrate defect width versus the multilayer top defect width was obtained. 15 bump and 15 pit defects were characterized for this study. The native defects chosen for this study all had shallow heights (or depths), approximately equal to 3 nm. The reason why the shallow defects were characterized for this study was so that the height or depth of the defect does not have a significant impact on the propagation of defect
width up the multilayer stack. For our study, we used Gaussian substrate defect profiles having similar profiles (in terms of FWHM), to the native defects used in the above-mentioned study. The Gaussian defects used for our study had a height or depth of 3 nm, similar to that of the native defects. We then simulated multilayer growth over these defects using the level-set multilayer growth model, and obtained the defect profiles on the multilayer top. We then plotted the multilayer top defect FWHM as a function of the substrate defect FWHM and compared this to the results obtained by Il-Yong Jang et al [6]. The comparison has been shown in Figure 5.1 [7]. We observe a good comparison between the simulation (performed using Gaussian defect profiles) and experimental results (obtained for native defect profiles), thus showing that multilayer growth over a defect shape is primarily a function of its FWHM and height. This led us to hypothesize that irrespective of the arbitrary shape of the substrate defect, the initial few layers that get deposited on top of the defect, smooth out to assume a regular shape, and the subsequent top layers getting deposited also acquire a regular shape based on the initial layers deposited. So, multilayer growth over substrate defects of a given width and height will evolve in a similar way, irrespective of their shapes. We will show evidence in support of this hypothesis in the next section of this chapter.
Figure 5.1: Defect FWHM on multilayer top as a function of substrate defect FWHM for (a) bump defect and (b) pit defect [7].

Since the experimental study had been performed using the Veeco Nexus IBD tool and our growth model was developed for that tool itself, we could draw a fair comparison between the experimental and our simulation results.

Next, proceeding with the assumption that multilayer growth over an arbitrarily-shaped native defect is similar to that over a Gaussian-shaped defect having similar width and height at the substrate, we wanted to fully map the defect profile at multilayer top as a function of the substrate defect profile, for our deposition tool. Figure 5.2(a) shows the top defect FWHM as a function of the substrate defect FWHM and height for a Gaussian bump defect, and Figure 5.2(b) shows the top defect height as a function of the substrate defect FWHM and height for a Gaussian bump defect. Figure 5.2(c) shows the overlay of the two maps as shown in Figure 5.2(a) and Figure 5.2(b) in the form of a contour plot. Given the top FWHM and height of a bump defect (as determined by AFM scan), the contour plot can be used to determine the Gaussian-equivalent-FWHM-and-height (GEFH) of the defect at the substrate. Figure 5.2(c),
Figure 5.2(d) and Figure 5.2(e) show the same information as Figure 5.2(a), Figure 5.2(b) and Figure 5.2(c) respectively, for a Gaussian pit defect.

**Figure 5.2:** (a) Map of top defect FWHM and (b) map of top defect height as a function of bottom (substrate) FWHM and height of defect for Gaussian bump defect. (c) Contour plots showing top FWHM (dashed-line contours) and top height as a function of substrate FWHM and height of defect for Gaussian bump defect. (d) Map of top defect FWHM and (e) map of top defect depth as a function of bottom (substrate) FWHM and depth of defect for Gaussian pit defect. (f) Contour plots showing top FWHM (dashed-line contours) and top height as a function of substrate FWHM and height of defect for Gaussian pit defect [7].

So, given an AFM scan of a native defect, we can now infer the substrate defect profile, in terms of GEFH using the contour maps shown in Figure 5.2. Starting with the Gaussian defect
at the substrate (having FWHM and height as determined by GEFH obtained from the contour plots), we can then simulate the multilayer growth over this defect using the level-set multilayer growth model, which would in turn be imported into the defect printability simulation software to obtain the printability result in terms of the aerial image intensity. In the next section, we determine whether the printability performance for the Gaussian-shaped substrate defects matches that of the corresponding native substrate defects having similar profiles in terms of their widths and heights.

5.3 Comparing Printability Performance of Native, Gaussian and Regular-shaped Substrate Defects

Next, we wanted to investigate the impact of FWHM and height of the defect on the defect printability (in terms of the aerial image intensity). For this, we identified two native substrate EUV mask defects, and compared their AIT aerial image intensities with the simulated aerial image intensities. Printability simulations were performed using waveguide algorithm. Multilayer growth simulations were performed over 3 substrate defect profiles corresponding to each of the characterized native mask defect. First, multilayer growth was simulated over the native defect shapes as obtained from the cross-section TEM images (as per the procedure defined in "Multilayer Growth Model" section i.e. Section 4.3). Second, Gaussian substrate defect shapes were used as input into the multilayer growth model. We determined the FWHM and height of the characterized native defects at multilayer top using the AFM scans. Then the maps shown in Figure 5.2 were used to determine the GEFH of the defects at the substrate, which were then used as inputs into the multilayer growth model. Third, to demonstrate (as per our hypothesis in the previous section) that a truly arbitrarily-shaped defect can be completely
defined just in terms of its FWHM and height for the purpose of predicting its printability, we simulated multilayer growth over defects that were rectangular in shape. FWHM and height values used for Gaussian defects, were used for rectangular defects as well, except that FWHM that was used to define Gaussian defects simply translated into the width of the rectangle-shaped defects. Figure 5.3(c) shows the comparison of the 1-D AIT aerial image intensities for the pit native defect with the simulated aerial image intensities for the modeled native, Gaussian and rectangle-shaped defects. The modeled defect growths are shown in Figure 5.3(a). We observe a good match between the AIT and simulated aerial image intensities (for the rotationally symmetric simulated defect growths), with the AIT-to-modeled native contrast difference being equal to 1%, AIT-to-modeled Gaussian contrast difference equal to 3% and AIT-to-modeled rectangle contrast difference equal to 8%.

(a)

(b)
**Figure 5.3:** (a) Cross-section of native EUV mask defect, simulated native mask defect, simulated Gaussian mask defect and simulated rectangular mask defect (left to right), and (b) corresponding 2-D aerial image intensity maps shown underneath. (c) 1-D aerial image intensity comparison between native defect and simulated defects. Defect printability simulations performed using waveguide algorithm [7].

Figure 5.4(c) shows the comparison of the 1-D AIT aerial image intensities for the bump native defect with the simulated aerial image intensities for the modeled native, Gaussian and rectangle-shaped defects. The modeled defect growths are shown in Figure 5.4(a). We observe a good match between the AIT and simulated aerial image intensities (for the rotationally symmetric simulated defect growths), with the AIT-to-modeled native contrast difference being negligible, AIT-to-modeled Gaussian contrast difference equal to 1% and AIT-to-modeled rectangle contrast difference equal to 6%.

It could be argued that one obtained similar printability results for the Gaussian-shaped and rectangular-shaped defects since volumes for both the defects are comparable. However, this is not the case. In the section coming up, we will study the impact of volume of a defect on the aerial image contrast, and also investigate how the contrast changes as a function of the defect’s width and height.
Figure 5.4: (a) Cross-section of native EUV mask defect, simulated native mask defect, simulated Gaussian mask defect and simulated rectangular mask defect (left to right), and (b) corresponding 2-D aerial image intensity maps shown underneath. (c) 1-D aerial image intensity comparison between native defect and simulated defects. Defect printability simulations performed using Waveguide algorithm [7].
The aerial image intensities shown in Figure 5.3 and Figure 5.4 are at best focus conditions i.e. defocus equal to zero. Thus, we conclude that the critical top few layers of the multilayer are not much affected by the defect shape at the substrate having similar FWHMs and heights, and evolve in a similar manner up the multilayer stack, thus resulting in similar printability performance.

5.4 Comparing Different Multilayer Growth Models and Correlating Defect Printability to AIT Aerial Image Intensity Contrasts

5.4.1 Comparison Between Level-set, Stearns and Conformal Growth Model

Next, we wanted to compare the defect printability performances of the defects by using different multilayer growth models on the substrate defect profiles. In Figures 5.3 and 5.4, we looked at the printability results obtained by propagating the Gaussian-equivalent substrate defects up the multilayer stack using the level-set growth model. So, using the same substrate profile, we propagated the defect up the multilayer stack using the conformal multilayer growth model. To model multilayer growth using Stearns model, we used the growth parameters used by Stearns et al. [8] to deposit Mo/Si multilayers over defects in sample V1284. Stearns et al. determined the growth parameters by studying the actual defect growths under AFM and TEM, which are summarized in Table 5.1.
Table 5.1: The values of growth parameters used in the multilayer defect simulations of localized defects in Mo/Si multilayer coatings nucleated by lithographically patterned substrate particles [8].

The Stearns model was developed at the Lawrence Livermore National Laboratory (LLNL), which has been using a low defect density (LDD) ion beam deposition tool developed by Veeco since early 2000s for its multilayer coatings [9]. We therefore believe that the nature of deposition conditions in the LDD Veeco tools in use at SEMATECH and LLNL, having only deposition fluxes, would be similar in nature, thereby enabling us to do a fair comparison between the Stearns and the level-set model. We particularly used the growth parameters used for V1284 masks, since it purely consists of deposition fluxes with etch fluxes being zero, as is the case in the Veeco Nexus IBD tool that we used for our study. The Gaussian substrate defect profiles had to be slightly adapted (they had to be reduced by approximately 20\% in width and height/depth) to make the top defect profiles match (which as discussed in Section 4.4, is more critical). Figure 5.5 shows the comparison of the printability results between Gaussian-shaped defects propagated using level-set growth model, conformal growth model and the Stearns
growth model. Here, we must note that printability simulations for defects grown using level-set and Stearns model, were performed using waveguide simulations. Printability simulations for the defects grown using conformal growth model were performed using FDTD simulations. We believe the results would still be consistent, since we’ve shown a good comparison between aerial image intensities using the different printability simulation algorithms in Chapter 4 for the various characterized native defects.

![Figure 5.5](image)

**Figure 5.5:** (a) Comparison between printability results obtained for (a) the pit Gaussian-shaped substrate defect (from Figure 5.3) and (b) the bump Gaussian-shaped substrate defect (from Figure 5.4) evolved up the multilayer stack using level-set and conformal growth models.

We observe the contrast difference in aerial image intensities between level-set and Stearns growth model to be approximately 20% for both the defects, and between level-set and conformal growth model to be approximately 35% for both the defects. Here it must be noted that had we used the same substrate profile as used for level-set and conformal growth models for the Stearns model, the mismatch to the latter would have been even larger. So we can clearly observe that for the two defects characterized, level-set model provides a better match to AIT aerial images as opposed to the other growth models.
### 5.4.2 Study of Aerial Image Contrasts as a Function of Defect FWHM/Height and Volume

Next, we wanted to perform a systematic study of how the aerial image contrast varies as a function of the substrate defect profile. For this, we simulated multilayer growth over Gaussian-shaped substrate defect profiles using the level-set multilayer growth model and performed defect printability simulations using the waveguide algorithm. Figure 5.6(a) shows a map of the aerial image contrast as a function of the substrate Gaussian defect’s FWHM and height. Also, we wanted to look at the aerial image intensities for defects as a function of their volumes. Figure 5.6(b) shows the graph where we’ve plotted the aerial image contrast versus the defect volume.

![Figure 5.6:](image)

**Figure 5.6:** (a) Map showing the aerial image contrast as a function of the height and FWHM of the Gaussian-shaped bump defect at the substrate. Multilayer growth was simulated using level-set model and waveguide algorithm was used to perform the printability simulations. (b) Aerial image contrast as a function of defect volume. ‘w’ in the legend refers to the width of the defect.

We can observe from Figure 5.6(a) that the aerial image contrast worsens as the width and height of the substrate defect increases, as would be expected. However from Figure 5.6(b) we observe a range of aerial image intensity contrasts for the same defect volumes. This shows
that aerial image contrast cannot be reliably determined in terms of the SEVD, and the individual width and height information should be known for a defect. Also, from Figure 5.6(b), the contrast change caused by the defects with smaller widths is lower as compared to the contrast change caused by the defects having larger widths, thus showing that for the same volume, defects having a larger width would result in a larger aerial image contrast.

5.4.3 Correlating Aerial Image Contrasts to Defect Printability

Finally, we wanted to study the affect of various-sized defects on defect printability in a patterned mask structure. For this we simulated 32 nm L/S features containing Gaussian-shaped defects of different dimensions, and studied the effect on printability for the defects located at either the center or edge of the absorber features. 2-D simulations were performed using waveguide algorithm. Imaging conditions used were 0.3 NA (wafer-side) and top-hat illumination with coherence (σ) of 0.2. Defect dimensions were so chosen so as to have a uniform spread about the average defect dimensions as obtained for the native defects characterized in Chapter 4. Stearns’ growth model was used to simulate growth over the Gaussian-shaped defects (due to certain constraints, level-set growth model could not be used for this work, however we would expect the defect printability trends to be similar for defect growth modeled using level-set model as well). Growth parameters as outlined in Table 5.1 were used as inputs into the Stearns’ model to simulate the multilayer growth.

Figure 5.7 shows example layout of the center and edge defects used for the defect printability simulations. Edge defects were so positioned so as to have the edge of the absorber coincide with the height of the Gaussian defect across which FWHM is measured.
Figure 5.7: Layout of (a) center defect and (b) edge defect in 32 nm L/S pattern (wafer plane).

Figure 5.8 shows the impact of defect’s FWHM and height on defect printability as well as on the contrast obtained for the defect when imaged in clear field. Change in CD was determined using the aerial image threshold model. Both FWHM and height of the defects plotted here are as measured at the mask substrate. Also, the defect printability obtained here is for the non-shadowed case (no shadowing from the absorber features). 10% relative change in CD was chosen as the defect printability criterion.
**Figure 5.8:** Effect of defect’s FWHM and height (at substrate) on printability as well as aerial image contrast (for defect in clear field) for (a) center defect and (b) edge defect. H denotes substrate height of defect.

The idea behind this study was to draw a correlation between the contrast of the aerial image of the defect in clear field and the change in CD that the same defect would cause in a dense 32 nm L/S feature. In Figure 5.9 we have plotted the relative change in CD that occurred due to the defects in 32 nm L/S features versus the contrast and also versus the intensity change caused in the aerial image intensity by the defects when they are in the clear field i.e. away from any patterns.

(a) (b)

**Figure 5.9:** Relative change in CD plotted as a function of (a) contrast of defect’s aerial image intensity in clear field for center defect, (b) contrast of defect’s aerial image intensity in clear field for edge defect. FWHM of the substrate defect increases progressively from 8 nm to 16 nm to 32 nm with the increasing contrast and intensity change values. We observe that a defect becomes printable for a clear field contrast of approximately 45% for the respective defect.

We clearly observe from Figure 5.9 that the defect printability gets progressively worse as a function of contrast of the defect’s aerial image intensity, and a defect transitions into the
printable region from the non-printable region for a clear field contrast value of approximately 45% for the respective defect. To reiterate, this result for open field contrast value of 45% to cause a 10% CD change has been drawn for 32 nm L/S features with 0.3 NA (wafer-side) using a top-hat illumination ($\sigma = 0.2$). As we will see in the study discussed below, this open field contrast value of 45% has been shown to hold true for different-CD L/S features under different imaging conditions. We also observe that on an average, the defect printability is worse for the center defects as opposed to the edge defects.

In a joint study conducted by SEMATECH and LBNL [10,11], different types of native defects (bumps and pits) were characterized and their printability predicted based on the aerial image intensities obtained at AIT. For this study 52 native defects were characterized and their profiles recorded with the help of AFM measurements. Figure 5.10 shows the plot of printability of defects as a function of their heights/depths and widths at different focus conditions. From the figure we can clearly observe that pits are more printable at negative focus and bumps at positive focus values.
Figure 5.10: Defect printability at (a) -50 nm focus, (b) best focus and (c) +50 nm focus [10].

Intensity threshold values for the various defects as obtained at AIT were used to define the printability of defect for each node (with the 10% CD change as the defect printability criterion). As per the study, if the intensity drop due to the defect in clear field was more than 60%, then the defect had the potential of being printed on the wafer. Intensity drop of 60% corresponds to around 45% contrast in the aerial image intensity. Simulations were conducted with different defect widths and heights for the 32 nm, 22 nm and 16 nm nodes. These simulations were performed under different illumination conditions (using top-hat and annular illumination schemes) at different numerical apertures (ranging from 0.25 to 0.45).

For all the defects simulated, the intensity loss thresholds for printable defects were near 0.4 (60% intensity drop or 45% contrast) as determined in the clear field. The summary of simulation parameters used and the intensity thresholds obtained for these various parameters have been summarized in Table 5.2. This almost constant value of intensity drop at the various CDs and imaging conditions is because of the large $k_1$ factor of EUV lithography. So there is little change in intensity threshold without resist processes. Consequently for the study, the printable intensity threshold was set at 0.4 [11].
Table 5.2: Simulation conditions and intensity threshold values [10].

<table>
<thead>
<tr>
<th>Property</th>
<th>Illumination condition</th>
<th>NA</th>
<th>Intensity threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td>32nm 1:1</td>
<td>Conventional, $\sigma : 0.5$</td>
<td>0.25</td>
<td>0.39</td>
</tr>
<tr>
<td>22nm 1:1</td>
<td>Annular, $\sigma : 0.3/0.5$</td>
<td>0.35</td>
<td>0.395</td>
</tr>
<tr>
<td>16nm 1:1</td>
<td>Annular, $\sigma : 0.3/0.5$</td>
<td>0.45</td>
<td>0.39</td>
</tr>
<tr>
<td>21nm 1:2</td>
<td>Conventional, $\sigma : 0.5$</td>
<td>0.25</td>
<td>0.37</td>
</tr>
<tr>
<td>15nm 1:2</td>
<td>Annular, $\sigma : 0.3/0.5$</td>
<td>0.35</td>
<td>0.38</td>
</tr>
<tr>
<td>11nm 1:2</td>
<td>Annular, $\sigma : 0.3/0.5$</td>
<td>0.45</td>
<td>0.39</td>
</tr>
</tbody>
</table>

The results obtained in the above-mentioned study compare well to those obtained through our study that looked at the intensity drop in the aerial images due to the defects in clear field versus the defect printability (Figure 5.9), where we observe the defect to be printable (keeping in mind the 10% CD change as printability threshold) when the contrast of the aerial image intensity due to the defect in clear field is approximately 45%.

The motivation behind the above study was that an actinic blank inspection tool must be able to fully quantify the printability of each defect. All defects on a blank need to be detected regardless of what they are; their exact locations should be recorded; their aerial images quantified; and finally based on the above information it must be decided which blanks must be discarded or can be repaired or where smart pattern placement can help. Mask shops can use this information to sort for the layer used by the number of defects. For example, a blank with many printable defects can be used for the contact layer, while one with few defects could be used for the gate poly layer.
5.4.4 Affect of Resist Processes on Defect Printability

Next, we wanted to develop an understanding regarding how the defect gets printed in the resist. The defect specifications that we derive from the aerial image printability studies have to be coupled with the resist parameters and properties to understand how the defect would print in the resist. Simulations with the aerial image threshold model are typically used to decouple the effects originating from the exposure projection optics and the wafer resist process. There have been a number of studies conducted which have looked at printability of defects in resists for absorber pattern defects by fabricating programmed defects on test masks [12-16]. These studies showed that the resist printability results do not correlate too well with those from the aerial image simulations. These works suggest that some defects may also have a chance of being non-printable depending on resist characteristics in contrast to aerial image based simulation.

In one such study [15] which looked at absorber point defects (opaque programmed square-shaped defects on the mask surface), it compared the experimental results for resist printed images to the aerial image intensities which allowed the separation of effects originating in the projection optics and the wafer resist processes. The experimental wafer printing was carried out at the Micro Exposure Tool (MET) at the LBNL. The patterns were printed in MET-1K resist from Rohm and Haas which is a positive-type, chemically amplified resist. At the time of printing, this resist showed the best performance in terms of simultaneous high resolution ($\approx 30$nm), good sensitivity ($20$mJ/cm$^2$ for $112$nm thickness) and low LER ($\approx 4$nm 3$\sigma$). Resist thickness was $125$ nm and the resist process followed the baseline process established at the LBNL. Figure 5.11(a) shows the mask structure (with the point defects) used for experiments as well as for simulations. A $60$ nm L/S (wafer-side) mask was used. Figure 5.11(b) shows the defect size (defect size was computed as simply the change in CD of the L/S features) obtained
through simulations of the mask structure. For the CD evaluations, a threshold model was applied to the aerial image. FDTD algorithm was used for performing simulations with grid size of 1 nm. Figure 5.11(c) shows the defect size obtained from actual wafer printing in the MET. The mask was printed with an annular illumination with an inner and outer sigma of 0.3 and 0.6, respectively. NA was equal to 0.3 (wafer-side) and 0.06 (mask-side).

![Figure 5.11](image)

**Figure 5.11:** (a) Schematic view of (i) dark and (ii) clear defect types. (b) Printed defect size versus mask defect size for the dark and clear defects as derived from simulation of mask layout. Black line is the ideal demagnification by a factor of 5. (c) Printed defect size versus mask defect size as derived from actual wafer printing [15].

From Figure 5.11(b), one observes that the defect shapes on masks (measured using SEM), and in the aerial image are very similar to each other. It seems that the mask defects are almost identically transferred into the aerial image by the projection optics. In contradiction to the aerial image, from Figure 5.11(c) one observes that the appearance of defects in the wafer resist is much different. Small defects cannot be observed in the resist, and there is a bridging of the space or line break for larger defects.

To summarize the results above, we observe a strong impact of resist process on defect printability. There are multiple reasons for discrepancy between resist printed defects and aerial
image printed defects. The most obvious fact is the limitation of defect printing to defects larger than 100 nm on mask (this implies resist processes have the capability to limit the printed defect size due to their limited resolution). The resolution of the lithographic process in general is driven by the resolution of both the projection optics (aerial image) and the resist process (whichever one is limiting). This total resolution must be compared to the pattern to be printed. Then, the process of transfer of aerial image to the resist, which also goes to explain the reasons for difference in results obtained, involves the following: the exposure of resist to the EUV radiation generates a concentration profile of photo acid in the resist which approximately follows the intensity distribution of the aerial image. Scattering and flare also generate small amounts of photo acid and these generally result in image degradation. The photo acid then starts diffusing proportionally to the concentration gradient especially during the post-exposure bake. In a balanced resist, the diffusion process can to an extent be counteracted by the proper amount of an added base (quencher). In effect, the image in the resist is blurred which is also a consequence of effects like mask LER, corner rounding of features etc. [15].

In another study by T. Liang et al. [16], they studied the printability of the point defects (opaque programmed square-shape) in resist, and compared the resist printed results to the simulated printability results. For the study Rohm and Haas MET-1K (same resist as used in the study above) was used. 70 nm L/S (wafer-side) features were used for the defect printability experiments. Two types of point defects namely protrusion and intrusion, same as the ones depicted in Figure 5.11(a)(i) and Figure 5.11(a)(ii) respectively, were studied. Plot comparing the defect printability performance in resist and that determined using simulated aerial images is shown in Figure 5.12.
Figure 5.12: Plot of CD change versus point-defect size. The resist printing experiments were performed on 0.3 NA MET. The AI in the legend above stands for Aerial Image simulations for the exact 5X mask and MET conditions used for the experiments [16].

Aerial image simulations predict a higher printability than the experimental data. The main cause for such significant differences is the resist, which has limited resolution for resolving localized defects. Due to this, we can observe from the plot that the data and the simulation curves are converging as the defect size increases. Therefore, resist effects must be considered in simulations in order to provide more accurate results.

There are two rows of defect sizes on the x-axis for the plot: the first row labeled ‘For 70nm PL1’ indicates the measured defect sizes on the mask printed on the 5X MET with 0.3NA. The scaled defect sizes on a 4X mask can be extrapolated from these experimental data to predict the printability of defects on 25nm resist lines printed on a 4X stepper with 0.25NA. These scaled defect sizes are shown in the second row labeled as ‘For 25nm PL1’. For example, if a 10% resist CD change is chosen as the criterion to define a printable defect, such a defect will be 25nm x 5 = 125nm on the 5X mask for printing 70nm PL1 resist lines on the MET and 8.6nm x
4 = 34.4nm on a 4X mask for printing 25nm PL1 resist lines on a 0.25NA stepper, respectively. This scaling is only valid for low MEEF (mask error enhancement factor) which is expected to be the case for $k_1 \approx 0.5$ [17] and improved resist performance. Besides the fact that printable defects sizes can be extrapolated from the experimental data currently attainable with available resist performance, there is significance in such scaling: the extrapolated predictions encompass the scaled effect of resist resolution [16].

Here it must be noted, that the above-mentioned studies comparing resist printing performance to aerial image printing performance were performed for mask surface programmed opaque defects and not for defects buried in multilayer stack, however, we would expect the same trends to be true for the buried phase defects as well. Based on the two resist printability studies shown above, we can conclude that simply performing the aerial image simulations is not sufficient to determine the true defect printability. In fact, aerial images overestimate the defect printability, especially for the smaller defects. So, using the simulated aerial image intensity would lead to a really conservative estimate of number of printable defects in a mask blank. The estimation of 60% drop in aerial image intensity for a defect in clear field as a criterion for defect printability has to somehow be convolved with the resist parameters, for different resists to get a more realistic estimate of the defect printability criterion for the different resists. Also, the two studies, which studied the resist printing behavior of defects (for the same resist on the same tool studying similar L/S features with square-shaped defects) agree well with one another, with both predicting similar defect size (125 nm mask side) to be printable on the wafer (as per the 10% relative change in CD criterion).
5.4.5 Proposed Mask Fabrication Process Flow and Caveats

In our work, our goal was to achieve a good comparison between aerial image intensities of native mask blank defects obtained at AIT and through simulations, so as to minimize our dependence on the AIT to determine the aerial image contrast of a defect. In our comparisons made between AIT and simulated aerial image intensities in Chapter 4, we observed a mismatch in the aerial image contrast between the AIT and simulated aerial images to be around 5%. Assuming that this contrast mismatch is purely due to some fundamental differences between the mechanisms by which aerial images are obtained at AIT and through simulations (ignoring the effect of tip broadening), we want to be able to infer the effect on defect printability due to this difference in contrasts. We have inferred from Figure 5.9 that an aerial image contrast of approximately 45% would potentially result in the defect getting printed (as per the 10% relative CD change criterion). So if a defect yields a contrast of around 43% in clear field as per AIT, the 5% contrast error (overestimation) by simulations would yield a contrast of 45% thereby resulting in the defect being considered as printable, even though it might have been just unprintable. Therefore, the error of 5% in determining aerial image contrast by the simulations may result in an error in classification of a defect as “printable” or “non-printable” if it’s close to the “Printability Threshold”.

So, below we propose an approximate, but robust process flow to determine the aerial image contrast caused by native defects on EUV mask blanks, and consequently determine the likelihood of the defect getting printed on the wafer. This would save time and resources involved in the use of actinic inspection tool, as our approach relies solely on simulations. We propose a mask fabrication process flow as shown in Figure 5.13.
The process flow proposed above comes with a number of caveats, pertaining to the use of modeling and simulations for predicting defect printability. First, the 3-D defects simulated in this work to show comparison to AIT, were assumed to be rotationally symmetric, while in reality we know that the native defects can have an arbitrary shape. Second, there could be a number of errors occurring as a result of defect characterization itself. As we saw in Chapter 4, the TEM cross-section that we used to define the level-set function of the defect might not be perfect, and there could be damage to the TEM sample as a result of the sample preparation procedure, thereby leading to errors in defect shape definition. The level-set model itself is a 2-D growth model that simulates multilayer growth over a 2-D defect interface, assuming a rotationally-symmetric 3-D defect shape, which might not be the case for real native defects. It also assumes deposition condition to be isotropic i.e. similar in the XY and the YZ plane, which might not be true. The AFM technique, which is used to characterize a defect’s width and height can suffer from tip broadening effects (due to the finite tip radius), and depending on the profile and dimensions of the defect, it can be a source of overestimation of a defect’s width. Then the defect printability simulations might not be ideal, as they are based on approximate solutions to Maxwell’s differential equations, as well as they assume a discretized simulation domain with user-defined grid spacing which may not be ideal. Further, the process flow proposes using Gaussian-equivalent substrate defects as substitutes to the real native defects, which could again be a source of error due to approximation of a native defect shape with a Gaussian shape. And

Figure 5.13: Proposed automated process flow for mask blank inspection.
finally, the defect printability in the resist itself can depend on a number of factors such as the accurate estimation of resist sensitivity (therefore the dose of exposure), its LER/LWR characteristics as well as the resist resolution, all of which have to be considered and combined with the aerial image results to get a true understanding of defect printability, and to enable us to use just the simulated aerial images to define printability of a defect. Errors in estimation in any of the above-mentioned parameter space could result in inaccurate prediction of printability of the defect in the actual resist. Therefore, the proposed process flow should be used with a conservative approach.

5.5 Summary and Conclusion

We were able to show that a defect can be completely characterized in terms of its FWHM and height for the defect printability studies. With the information of the defect profile at the multilayer top (using AFM scan), we can infer the multilayer evolution over the defect from the substrate up, with the help of the top dimensions-to-substrate dimensions defect profile maps and contour plots (Figure 5.2) used in conjunction with our level-set multilayer growth model. We showed that native, Gaussian and rectangular-shaped substrate defect profiles having similar FWHMs (or widths in case of rectangle) and heights yield similar aerial image intensities. This could have potential applications in further developing or improving multilayer defect compensation (MDC) techniques as well as being an aid to the actinic photomask inspection or qualification systems, like the EUV actinic aerial image metrology system (AIMS).

We then showed the comparison between the printability results obtained using level-set growth model, Stearns model and the conformal growth-model on the pit and bump Gaussian-shaped substrate defects, and demonstrated the level-set growth model to be more accurate as
compared to the other growth models. Then we mapped the contrast in aerial image intensities as a function of a defect’s height and width, as well as a function of the defect’s volume, and observed that intensity contrasts can widely vary even for defects having the same volume, and concluded that both the height and width information is necessary to determine a defect’s printability performance. We finally investigated defect printability on 32 nm L/S features and correlated the aerial image intensity contrast to the printability of the defect, and suggested the use of modeling and simulation, as described in our work, to ideally be a stand-alone solution to determining the defect’s printability. We proposed a process flow which would reduce our dependence on actinic imaging for qualifying EUV mask blanks. We also outlined the limitations and caveats that should be kept in mind in order to use this process flow.

References (Chapter 5):


CHAPTER 6

6. Systematic Study of Impact of the Various Aspects of a Defect's Shape on Printability

6.1 Introduction

Next, we wanted to investigate the various aspects associated with a defect, like its height and its slope, and the impact that each of these aspects has on the printability of the defect. FDTD simulations were performed on 32 nm line and space (L/S) absorber patterns with different defect positions relative to the absorber stack. The aforementioned defect parameters were systematically varied to observe their effect on the printability of the defect. In Chapter 5 we looked at the aerial image intensity drop due to defects in mask blanks, and attempted to draw a correlation between the aerial image contrasts due to defects in clear field and defect printability caused by them in 32 nm L/S features. In this chapter, we develop a fundamental understanding of the trends of how the defects (having different heights and slopes) result in printability.

There are two attributes associated with any defect shape, namely its height and its slope. We wanted to study the impact of each of these aspects on defect printability in isolation. There are studies that have looked at the printability of programmed Gaussian defects through simulations and have looked at its various aspects such as its FWHM and depth [1-5] (including the work presented here) as well as its spherical equivalent volume diameter (SEVD) [6-11], and how these aspects impact the defect getting printed. However, the height and the slope are convolved in a Gaussian shape, or any other commonly used shape for that matter, and it is not a straightforward task to separate the impact of these aspects on defect printability. In this study, we have attempted to isolate the height and slope aspects associated with any defect shape to
observe the trends in defect printability with their systematic variation. Although not representative of the real defect shapes, this study gives us a good insight into the defect printability trends that can be expected from the various defects with varying heights and slopes. We performed simulations on a 32 nm L/S absorber patterns with defects placed at different locations with respect to the absorber stack. For the purpose of our study, defects were assumed to propagate uniformly through the multilayer stack. All simulations performed were for 2-D domains (not 3-D) to save time, and since we expect that trends obtained for 2-D defects would hold true for domains simulating 3-D defects as well. Also, all simulations were performed at best focus, and through-focus behavior was not studied. NA of 0.3 was used (mask-side) with a top-hat illumination having coherence (σ) of 0.2.

### 6.2 Impact of Defect Height on Printability

First, we tried to isolate the phase effect associated with a defect, by varying the height of a section of the multilayer structure systematically to observe its impact on the printability. Figure 6.1 shows the layout of the simulated defect.

![Figure 6.1: (a) Layout of a defect centered between the absorbers (mask-plane). (b) Layout of a defect located at the edge of the absorber (mask-plane).](image-url)
From Figure 6.2, we observe that the change in CD, in case of defects centered between the absorbers is approximately an oscillatory function of the height of the defect, with the periodicity approximately equal to half the wavelength of the incident EUV radiation. This is due to the phase shift in the radiation reflected by the defect with respect to the radiation reflected from the regions having no defect. The phase difference between the radiation reflected from the defect and the rest of the multilayer stack is given by Equation 9.

\[
\Delta \phi = 2 \left[ 2\pi \left( \frac{\delta}{\lambda} \right) \right] 
\]

(9)

where \( \Delta \phi \) is the phase difference between the radiation reflected by the defect and the radiation reflected from the rest of the multilayer stack, \( \delta \) is the path difference and \( \lambda \) is the wavelength of the incident radiation, in our case 13.5 nm.

When the path difference is a multiple of \( \lambda/2 \) i.e. \( n\lambda/2 \) (where \( n \) is a whole number), we get the phase difference to be equal to \( 2n\pi \) giving us constructive interference between radiation reflected from the defect and the non-defect regions of the multilayer stack, resulting in the least delta CD. We therefore see an oscillatory nature of the delta CD with the changing defect heights with a periodicity of \( \lambda/2 \) or approximately 7 nm, consistent with Equation 9.

We observe the worst printability behavior when the defect covers half (\( L = 64 \) nm) the space between absorbers, and the printability result is also relatively bad when the defect covers one-fourth (\( L = 32 \) nm) the space between absorbers, as opposed to when the defect covers the entire space (\( L = 128 \) nm) or three-fourth (\( L = 96 \) nm) the space between the absorber patterns. This is due to the fact that for the defect covering half (\( L = 64 \) nm) the space between absorbers, half of the non-defect region between absorbers reflects light which is "in-phase" and half region reflects light which is "out-of-phase" with respect to the light reflected from the non-defect regions of the multilayer stack. Therefore, printability performance on an average is the worst for
this case. On the other hand, when the defect is covering the entire (L = 128 nm) space between the absorber regions, the entire region between absorbers reflects light which is "out of phase" with respect to light being reflected from non-defect regions of the multilayer stack. However, since 100% of light is "out of phase" within that localized space between the absorbers, it does not locally interact much with radiation having a phase different than the "out of phase" phase from the neighboring L/S, thereby not having a significant impact on printability. Also, as the defect becomes smaller and covers one-eighth (L = 16 nm) the space between the absorbers, the printability performance improves. This is due to the fact that the resolution of the imaging system is finite and not infinitesimally small. At the mask plane, the resolution of the EUV imaging system is approximately 80 nm. Therefore features much smaller than 80 nm cannot be resolved well by the optics of the EUV imaging system. Therefore although the defect is present, it does not significantly impact the printability, thus making it a non-resolvable defect not impacting printability. Finally, the defects located in the center of the absorber patterns do not cause the L/S pattern to shift as long as just the height of the defect is changing.

![Center Defect (delta CD vs Height)](image_url)

**Figure 6.2:** Graph showing the change in CD as a function of defect height for a given defect length.
From Figure 6.3(a) and 6.3(b), we observe that the change in CD as well as the pattern shift for the defects at the edge of the absorber patterns are approximately an oscillatory function of the defect height, with the periodicity approximately equal to the period of the multilayer structure i.e. 7 nm. Also, we observe the worst printability behavior when the defect covers half (L = 64 nm) the space between absorbers as opposed to when the defect covers the entire space (L = 128 nm), three-fourth (L = 96 nm) the space or one-fourth (L = 32 nm) the space between the absorber patterns, following the same reasoning given in the previous paragraph. Also, we observe the CD change to be approximately equal for defects covering one-fourth (L = 32 nm) the space and three-fourth (L = 96 nm) the space between absorber patterns for the same height of the defects. Further, the pattern shift in the L/S features caused by these defects is approximately equal in magnitude but opposite in direction. This is due to the fact that for the defect covering one-fourth the space between absorbers, three-fourth of the non-defect region between absorbers reflects light which is "in-phase" and one-fourth region reflects light which is "out-of-phase" with respect to the light reflected from the non-defect regions of the multilayer stack. Exactly the opposite is true for the defect covering three-fourth the region between the absorber patterns. This results in approximately equal CD change and equal and opposite pattern shifts for the same defect height for the two defect lengths. Also, as the defect becomes smaller and covers one-eighth (L = 16 nm) the space between the absorbers, the printability performance improves, following the same reasoning given in the previous paragraph.
Figure 6.3: (a) Graph showing the change in CD as a function of defect height for a given defect length. (b) Graph showing the pattern shift as a function of defect height.

6.3 Impact of Defect Slope on Printability

Next, we tried to isolate the slope aspect of the defect by tilting a section of the multilayer stack with respect to the rest of the multilayer stack as shown in Figure 6.4. Again, although this is not a representation of the real defect shape, this helps us to study the slope aspect of the defect shape in isolation. All simulations were performed at best focus, and through-focus behavior was not studied.

Figure 6.4: (a) Layout of a defect centered between the absorbers. (b) Layout of a defect located at the edge of the absorber.
From Figure 6.5(a) and 6.5(b), we observe that for the center defects, for the defects having the same slope, those covering the entire space between the absorbers (L = 128 nm) have a worse impact on the change in CD as well as the pattern shift than the defects covering three-fourth (L = 96 nm) the space between absorbers, which in turn is worse than the defects covering half (L = 64 nm) and one-fourth (L = 32 nm) the space between the absorber patterns. This is because for defects covering entire length between absorber features (L = 128 nm), all the EUV radiation falling in that space will get reflected off at angles larger than can be captured by the lens. However, if the defect is not covering the entire length between absorbers (say L = 64 nm), although it might have the same slope as that of the defect covering entire space between absorbers (L = 128 nm), some of the EUV radiation will be incident on the flat multilayer structure within that space and would therefore get collected by the lens, therefore causing less of a CD change. For defects covering one-fourth (L = 32 nm) the space between absorber patterns, we observe the change in CD to flatten out and become almost constant at a particular value of the slope of the defect.
Figure 6.5: (a) Graph showing the change in CD as a function of defect height for a given defect length. (b) Graph showing the pattern shift as a function of defect height. (c) Same graph as depicted in (a) with a smaller slope domain.

The results as seen in Figure 6.5 are consistent with our understanding that if light reflected by a defect is at angles greater than those that can be captured by the lens, then that defect will cause a significant change in CD. Since we have investigated the effect of defect slope in isolation here, we can predict the slope of the defect which would lead to the defect being printed. The expression for the slope above which the defect printability rapidly starts deteriorating is given by Equation 10.

\[ \text{Slope} \geq \left( \frac{\text{N.A.}}{2D} \right) \quad (10) \]

Where N.A. is the numerical aperture used, which is 0.3 in our case, and D is the demagnification factor which is 4. Substituting these values in the equation above, we infer that defects with slopes greater than 0.04 radians will lead to progressively worse defect printability, which is what we observe in Figure 6.5(c). Here, we must note that for this condition to be true, the defect width should be close to the resolution of the optical system. This is the reason why
the defect with a width of 32 nm (L = 32 nm) in Figure 6.5(c) does not follow the trend as predicted by Equation 10, since the optical resolution of the system is around 80 nm (mask plane).

From Figure 6.6(a) and Figure 6.6(b), we observe that for the edge defects, for the defects having the same slope, those covering the entire space between the absorbers (L = 128 nm) have a worse impact on the change in CD as well as the pattern shift than the defects covering three-fourth (L = 96 nm) the space between absorbers, which in turn is worse than the defects covering half (L = 64 nm) and one-fourth (L = 32 nm) the space between the absorber patterns, following the same explanation as given in the previous to last paragraph. For defects covering half (L = 64 nm) and one-fourth (L = 32 nm) the space between absorber patterns, we observe the change in CD as well as the pattern shift to flatten out and become almost constant at a particular value of the slope of the defect, following the same explanation as given in the last paragraph.
Figure 6.6: (a) Graph showing the change in CD as a function of defect slope for a given defect length. (b) Graph showing the pattern shift as a function of defect slope for a given defect length. (c) Same graph as depicted in (a) with a smaller slope domain.

6.4 Summary and Conclusion

We studied the various aspects of a defect shape namely its height and its slope, and what impact each of them has on the printing behavior of the defect. We observed that the printing behavior of the defect is much more sensitive to the slope of the defect than the defect height.

References (Chapter 6):


CHAPTER 7

7. Concluding Remarks and Summary

As per the 2013 ITRS (international technology roadmap for semiconductors) roadmap for lithography, EUV lithography was projected to be the go-to technology for realization of technology nodes 16 nm and below. And this was predicted to occur at end of 2014 / beginning of 2015. However we have not witnessed EUVL's introduction yet and it's not likely that EUVL would take over at the onset of 2015 as well.

There have been a number of issues that have plagued EUVL over the past decade or so with not-so-significant improvements being made over these past years. The first and the foremost issue has been EUV source power. The EUV peak power for ASML NXE 3300B exposure tools is currently around 80W at intermediate focus, and approximately 225W is what is required for HVM.

The second issue over the years has been the lack of sufficient infrastructure to support the development of EUV masks. There exist challenges in aspects ranging from defect inspection and verification to the ability to get to defect-free mask blanks with a high yield. The primary reasons why progress has been slow in getting to defect-free masks have been lack of good quality mask substrates (on which multilayer gets deposited), as well as improper handling of mask substrates and mask blanks leading to EUV mask blank defectivity. A significant milestone was recently (May, 2014) achieved by SEMATECH with zero-defect mask blanks being reported at 54 nm sensitivity (SiO₂ equivalent). However the yield for such high quality mask blanks is relatively low (≈ 4%). Also, as per SEMATECH's EUV mask blank defectivity roadmap, if EUVL is to be launched into HVM, for logic applications, no more than 3 defects greater than 15 nm size can be tolerated. The defect inspection systems currently in place are just
not that sensitive to detect defects at these small size scales. The state-of-the-art defect inspection tools using optical scattering technique for defect detection have a defect detection sensitivity of 25 nm on the quartz substrate and a sensitivity of 30 nm on multilayer top. So going forward, commercial actinic inspection systems would need to be available to ensure that the relatively small defects, which can still be printable on the wafer, are not overlooked. This would need huge investments and collaboration on the part of the EUVL industry.

Third issue has been in the field of developing EUV resists which meet the resolution, LER and sensitivity requirements to ensure tight-pitch features (high resolution) can be reliably printed on the wafer with good mechanical and physical integrity (low LER) at a high enough throughput (high sensitivity) to ensure that the overall cost per wafer is kept within check, hopefully as required by or predicted by Moore's Law.

In this dissertation we focused on the second of the three issues described above, namely understanding and mitigating the adverse affects of EUV mask defects, and devising methodologies and simulation techniques which would be an aid to (or hopefully replace) the expensive actinic mask inspection equipment. We studied two aspects pertaining to degradation of EUV mask blanks. First, we looked at the EUV reflectivity losses occurring due to the standard wet cleaning process for EUV mask blanks. Second aspect was broadly dedicated to the study of native buried multilayer phase defects in EUV mask blanks.

For the EUV mask blank cleaning study, experiments were performed to look at the type and the extent of mask damage caused as a result of the standard wet cleaning chemistries and processes used. Multilayer damage observed was in terms of multilayer etching and pitting, surface roughness increase and surface oxidation. Simulations were performed to quantify and correlate the extent of EUV reflectivity loss to each of the aforementioned factors. EUV
reflectivity was found to be the most affected by the oxidizing chemistry of the SPM step, with the multilayer oxidation causing the majority of the EUV reflectivity loss (≈ 4%) observed. Other factors such as multilayer etching and pitting, and surface roughness increase, primarily caused due to the megasonic step, did not have a significant impact on EUV reflectivity causing approximately 1% EUV reflectivity loss. With a fundamental understanding of the multilayer damage mechanisms, we would be able to predict the behavior of other chemicals towards EUV mask materials and assess the EUV reflectivity loss caused by them, thereby being able to determine their compatibility with the EUV mask cleaning processes. In this work, we proposed a hydrogen radical-based cleaning system to substitute the SPM chemistry for the purposes of cleaning the organic contamination layer on top of the multilayer mask surface. We reported data showing that atomic hydrogen cleaning can be effective in removing the carbon contamination without causing a loss in EUV reflectivity. However, industry collaboration and clever engineering designs would be required to incorporate this technique in the current standard mask cleaning process flow.

The study of native buried phase defects in EUV mask blanks comprised of three aspects. First, we developed an accurate multilayer growth model to simulate multilayer growth over native defects. This model, which was based on the level-set technique, took into account the tool deposition conditions of the ion beam deposition tool where the multilayer deposition took place. Using the modeled growth, we performed defect printability simulations using FDTD and waveguide algorithms and compared simulation results to those obtained at AIT for the characterized defects. We obtained a good match between the two sets of results, thus demonstrating the accuracy of the growth model as well as the accuracy of the algorithms used to perform the defect printability simulations. Second aspect of this study was related to performing
a systematic study of the native mask defects. We correlated the actual multilayer growth over native substrate defects to the modeled multilayer growth (using level-set growth model) over well-defined defect shapes having similar profiles to the native defects in terms of width and height. We then compared printability results obtained for actual native defects (from AIT) to the ones obtained for modeled defect geometries (from FDTD and waveguide simulations). The purpose behind this study was that given an AFM scan of a native EUV mask defect on multilayer top, we would be able to infer the defect profile at substrate, and using our level-set multilayer growth model over the substrate defect profile, we would be able to perform accurate and fast defect printability simulations thereby reducing dependence on as well as being an aid to actinic inspection tools. The biggest caveat to this (as seen in Section 5.4.3 of Chapter 5) is the disconnect between simulated aerial image printing results and the resist-printing results (primarily due to the limited resist resolution). Therefore there is an urgent need to come up with ways to correlate aerial image printability to the resist printability for the various resists, so as to have a complete and robust picture of defect printability. The third and the last aspect of the EUV mask defect study involved looking at the various aspects of a defect shape, and investigating the impact that each of them have on the printability. A point on any physical shape can be completely defined in terms of height and slope. So, we looked at the defect printability trends by varying these fundamental aspects of a defect shape. First, we observed how the printability of a defect gets affected if just its height is varied (phase change). And then we did the same study by varying just the slope of the defect in isolation. Defect printability was found to be much more sensitive to the change in slope of the defect as opposed to the change in its height.
We hope that the work presented here on improving the quality of EUV mask blanks will help to mitigate some of the issues that EUV mask manufacturers currently face, and help in the production of high quality EUV mask blanks with a good yield. Overall, we hope that this would bring EUV lithography closer to being an HVM process to aid in the progression of the future technology nodes.