EUV Mask Blank Fabrication & Metrology

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Abstract. Extreme Ultraviolet (EUV) lithography is under development to succeed 157nm lithography for commercial IC manufacturing for the 45nm technology node as defined by the ITRS 2001 Lithography Roadmap. EUV masks pose many manufacturing and technical challenges to meet the future commercial needs. Although some EUV mask manufacturing processes can be extended from current optical masks, many new issues arise due to transitioning to all reflective multi-layer mirror system with patterned features versus conventional optical masks. EUV lithography operation at 13.4 – 13.5nm wavelength requires optimal multi-layer performance including peak reflectance, wavelength matching to the optical system, and very low defect levels. The Low Thermal Expansion Material (LTEM) that is used as a substrate for the multi-layer reflector also requires demanding performance levels including Coefficient of Thermal Expansion (CTE), flatness, and roughness to support EUV mask needs. Performance improvements as large as several orders of magnitude are needed for some of these parameters. To aid these developments, specialized metrology tools are needed. These tools fall into two categories: Manufacturing process inspections tools include flatness interferometry, atomic force microscopy, EUV reflectometry, defect inspection, and others. Analytical tools include scanning electron microscopy, X-Ray Diffraction, ion beam milling, and others used for problem solving. Both metrology types will play a major role in the successful development of EUV masks to meet the 45nm node requirements. This paper will review many applicable metrology techniques in addition to those listed, describe the application to EUV mask blank development or manufacturing, show problem solving examples of the techniques, and highlight particular problems or areas of need.

INTRODUCTION

Extreme ultraviolet lithography (EUVL) is a leading next generation lithography technology for integrated circuit (IC) manufacturing for the 45nm technology node and below. EUV technology relies on reflective optics and masks that utilize multilayer (ML) structures. The EUV masks have patterned absorbers features to create the IC features during the exposure process. The ITRS Roadmap for EUV calls for substantial improvements in the quality of both the mask substrates as well as the mask ML film stacks [1].

Two SEMI standard are now available that define the production needs of EUV masks. One standard is for the substrate and another for the ML films. Commercial suppliers are developing polishing processes for Low Thermal Expansion Materials (LTEM) for the mask substrates.

Commercial EUV mask blank suppliers are also developing ML deposition processes for the reflective ML and absorber films. There are several performance requirements that must be improved to meet the production requirements. Most important is the improvement in defects in the ML coating process that is a main concern of mask blanks to attain zero printable defects.

The production requirements of EUV blanks and resulting masks need to support thermal loadings at the mask of up to 6 watts for high system throughputs that require LTEM use. The mask blanks ML reflective performance must match that of the EUV exposure tool projection optic to maintain exposure process windows as well as overall system throughputs. Since EUVL an all reflective optical system the mask focal plane must be maintained in to stringent tolerances therefore mask blank and mask flatness must be on the order of 50nm Peak to Valley.

EUV MASK BLANK PHYSICS

EUV lithography wavelengths are highly attenuating especially at the desired wavelengths of 13.4nm to 13.5nm and only multilayer structures can be used to reflect the energy throughout the exposure system. The EUV mask also uses these ML reflective properties. For reflective properties to work, EUV optics and masks utilize quarter wavelength stack or “Bragg” ML reflection principals. The ML reflectors construction uses alternating pairs of selected materials


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to optimize the refractive index at the EUV wavelength of choice. Alternating layers of Molybdenum (Mo) and Silicon (Si) with thickness of ~4.1nm and ~2.8nm respectively are deposited to build up to 40 or more pairs each having thickness of 6.9nm for 13.40nm EUV wavelength operation. The individual layer thickness and pair pitches can be optimized to center the wavelengths from about 12.0 nm up to 15.0 nm.

Various literatures describe in detail the physics of such ML reflective films [2], [3]. Figure 1 describes the ML stack and the reflective parameters of interest.

\[ b_0 = r_{\text{in(b)}} = \frac{n_1 \cos \phi - n_2 \cos \phi}{n_1 \cos \phi + n_2 \cos \phi} \]  

(3)

And the transmitted photon amplitude energy to the next ML interface is described by equation (4).

\[ a_1 = t_{\text{in(b)}} = \frac{2n_1 \cos \phi}{n_1 \cos \phi - n_2 \cos \phi} \]  

(4)

Depending on the wavelength angle of incidence compared to the critical angle by Equation (1) both reflection and transmission is encountered at each Mo and Si interface.

\[ \theta_c = \sqrt{2\delta} \]  

(1)

Braggs Law (2) relationship provides the wavelength and ML pair "d spacing" (\( \Lambda \)), reflected energy \( b_n \), and layer refractive index (\( n \)) with both reflective (\( \delta \)) and absorption (\( \beta \)) coefficients.

\[ \lambda = 2\Lambda \sin \theta \]  

(2)

The photon reflected amplitude from the first ML interface is described by equation (3).

**EUV MASK BLANK MANUFACTURING**

There are many processing steps required to manufacture high performance EUV mask blanks from the raw LTEM to the final coated and inspected blank. Figure 2 describes the general processing steps in such a process. A particular blank supplier may use alternative process steps however most of these steps are consistent from supplier to supplier. Within the process flows the first half of the processes support getting the LTEM into a format ready for multilayer depositions. The definition of this unit is called the "mask substrate". There are many specifications that the substrate must meet and are defined in the SEMI P37-1101 Specification for Extreme Ultraviolet Lithography Mask Substrates [4].

The second half of the process defines the final mask blank with ML depositions, defect inspections, repair strategies, and other steps. There are many specifications that the ML films must meet and are defined in the SEMI P38-1102 Specification for Absorbing Film Stacks and Multilayers on Extreme Ultraviolet Lithography Mask Blanks [5].

The combination of P37-1101 and P38-1102 standards together total over 30 separate specifications some of which allow particular levels or “grades” of performance. The needed specification improvements in many of these specifications will require the successful use of capable process related metrology and
Table 1 outlines most of the key inspection metrology technologies required for the measurements needed and whether it is targeted as a process monitor or an analytical tool to be used for problem solving. Many of the specific metrology tools in Table 1 will be described in detail and its application.

Table 1. EUV Mask Blank Process Flow

<table>
<thead>
<tr>
<th>Metrology System</th>
<th>Performance / Need</th>
<th>Process</th>
<th>Analytical</th>
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<td>Dilatometer</td>
<td>LTEM CTE mean &amp; uniformity</td>
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<tr>
<td>Optical microscope</td>
<td>Gross defects</td>
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<td>•</td>
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<tr>
<td>Tensile test</td>
<td>LTEM stiffness</td>
<td>•</td>
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<td>SEM with EDX</td>
<td>Defect analysis</td>
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<tr>
<td>Flatness Interferometer</td>
<td>Substrate &amp; blank flatness (LSF)</td>
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<tr>
<td>Phase Contrast Micro (PMM)</td>
<td>Substrate mid spatial frequency (MSF)</td>
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</tr>
<tr>
<td>Atomic Force Micro (AFM)</td>
<td>Substrate roughness &amp; defect analysis</td>
<td>•</td>
<td>•</td>
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<tr>
<td>Defect Inspection</td>
<td>Defect count, location, size, other</td>
<td>•</td>
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<tr>
<td>Trans. Elect. Micro. (TEM)</td>
<td>ML film structure, defect analysis</td>
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<td>EUV Reflectometer</td>
<td>ML film EUV reflectivity performance</td>
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<td>X-Ray diffraction</td>
<td>ML film structures, film thickness uniformity</td>
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<td>Ellipsometer</td>
<td>ML film thickness</td>
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**METROLOGY TOOLS**

The following section will highlight the major metrology tools that are used to support the EUV mask blank manufacturing developments. Most, but not all of the entire specific tools listed in Table 1 will be mentioned. A brief overview of the metrology operation, performance metrics and impacts to EUVL operations, and examples where appropriate to demonstrate the tools effectiveness will be provided.

**Dilatometer**

Dilatometers are used to measure a materials impact to thermal loadings through changes in length dimensions. The rate at which materials expand or contract under temperature changes is defined as it’s Coefficient of Thermal Expansion (CTE). EUV masks as well as projection optics require LTEM materials with very low CTE. Dimensional length changes from heat loadings (up to 6 Watts for masks) in production EUVL systems will create image placements errors or distortions on the printed wafer. The development of very low CTE materials to meet “Class A” requirements of ± 5 ppb/°K along with a spatial uniformity of 6 ppb/°K requires dilatometer methods with uncertainty of at least less than 5 ppb/°K and preferably 1-2 ppb/°K.

**Dilatometer Operation**

Although dilatometers basic operation is reasonably straightforward the implementation can be demanding. Many variations of dilatometers have been discussed in literature with potentials and limitations [6]. Dilatometers major components include use of reference surfaces between the two ends of the material under test, a measurement system to record linear changes, and the frame that connects the measurement system to the reference surfaces.

**Figure 3** shows one of the many dilatometer concepts for potential EUV LTEM CTE measurement accuracies to meet P37-1101 requirements. Using Fabry–Perot narrow band pass filter strategy laser light transmitted when the LTEM resonance matches that of the wavelength can be directly correlated to the LTEM change in length. Very accurate temperature controlled fluid bath provides control of the LTEM test sample and cavity.

**Flatness Interferometer**

Flatness interferometers are used to measure the substrate and mask blank flatness error. Flatness or figure interferometers have been used in optical lens manufacturing for many decades. Evolutionary improvements over time have allowed this technique to be used today. Due to the tight tolerances of the EUV mask needing to be held within the focal plane in an all-reflective system, masks need to have flatness control of 50nm (peak-to-valley) (P-V). Masks having flatness control exceeding this level will introduce image distortions and image placement errors on the printed wafer. The performance of flatness needs to be measured over a spatial frequency range of 100mm down to 1mm.

Multiple types of interferometer systems have been designed to measure substrate flatness. Fizeau, Twyman-Green, Shack, Haidinger or other interferometer variants have been improved upon as described by Malacara [7]. The general systems comprise of a light source that is reflected off a tests unit whose wavefront is intentionally interfered against a reference flat and additionally through a beam splitter. The resulting interference wavefront is a measure of test surface flatness error and then is captured on a camera for analysis (e.g. CCD).

**Figure 4**: Interferometer diagram based on Fizeau architecture as described by Chiayu Ai [8]. Elements of system are laser (10), spatial filter (16), collimator optics (18), reference flat optic (20), test piece (22), cubic beam splitter (24), CCD camera (26), and zoom lens (28).

Flatness interferometers are used in several points within the EUV substrate and mask blank
process as initial rough lapping steps, followed by double sided polishing, and any sub aperture finishing steps. Incoming part flatness quality to a particular finishing step is very important especially when local areas need to be identified for local figuring.

In order to achieve needed substrate flatness performance for EUV blanks of 50nm P-V or better the flatness interferometers require overall system accuracies of better than 20nm P-V including condenser optics, fixturing, temperature and airflow controls.

**FIGURE 5:** Interferometer 3D surface profile of LTEM substrate with a) 660nm P-V fronstide surface variation after initial coarse figuring and b) 300nm P-V after final figure and polishing.

**Phase Contrast / Measuring Microscope**

A Phase Measuring Microscope (PMM) is used to measure the substrates “Mid Spatial Frequency Roughness” (MSFR). This attribute in EUVL is the main contributor to system flare or light scattering due to rough surfaces. Excessive flare will degrade the point spread function or aerial image of the printed feature on the wafer. Figure 6 shows a generic description of a PMM that utilizes phase contrast from the test surface against a reference surface in which a diffraction pattern is captured by a camera. This figure is a concept described by Leslie Deck in U.S. patent #5,402,234. Additional system variations can take the form of Michelson, Mirau, Linnik, and Fizeau based traditional interferometers described in detail by Malacara [10].

The performance of MSFR for EUV projection optics is less than 0.2nm rms and is to be held over a spatial frequency between 1mm and 1 um. For EUV masks and blanks MSFR error is additionally important as it contributes to surface local slope changes. Large local slope variations will cause localized image placements introduced by the reflective masks as described by SEMI P37-1101 standards. Recently MSFR errors in the mask blank can contribute to printed features “line edge roughness” (LER). Figure 7 shows PMM surface maps of the same substrate measured using three different aperture magnifications.

**FIGURE 6:** Description of Phase Measuring Microscope concept outlined by L. Deck [9]

**Atomic Force Microscopy (AFM)**

AFMs are used to measure the substrates “High Spatial Frequency Roughness” (HSFR). AFM descriptions or operations can be found in various literature. The HSFR attribute in EUVL is a main contributor to maintaining system reflectivity. As discussed previously the desire to have well defined ML boundaries for good contrast provides high reflectivity. As the surface on which ML’s are deposited become rougher this can impact the ML as small surface perturbations can be replicated throughout the ML stack. The performance of HSFR for EUV mask substrates calls for less than 0.15nm rms over a spatial frequency region of 10 um down to about 20nm.

AFM’s can also show very high definition surface quality of LTEM such as processing artifacts (e.g. sleeks) or material inhomogeneity such as inclusions that have penetrated the surface. Improvements to LTEM substrate processing using AFM feedback can dramatically improve surface quality that may not show up in HSFR rms values alone. The following Figure 8 shows AFM scans with such results.
This relationship further supports that through conventional ML deposition technologies such as conventional Ion Beam Deposition (IBD) or magnetron sputtering that HSFR for masks need to be held to less than 0.15 nm rms.

The amount of HSFR has been correlated to overall EUV reflectivity loss in ML through the "Debye-Waller" factor.

\[ R_{(\theta)} = R_0 e^{-\left( \frac{2\pi^2}{\Lambda} \right)^2} \]  

(5)

**FIGURE 7:** Three different PMM 2D surface maps of same LTEM substrate: a) 2D surface map using a 2.5x objective measuring a 0.50 nm rms error. b) 2D surface map using a 10x objective measuring 0.26 nm rms error. c) 2D surface map using 50x objective measuring 0.12 nm rms error (apparent sleeks caused by polishing process).

**FIGURE 8:** Two separate AFM scans on two different LTEM that both have HSFR of 0.15 nm rms however improved polishing processes have eliminated sleeks.

**Defect Inspection**

Particle defects and defect detection on the LTEM substrate surface or on the ML blank are the most critical to EUV performance. Defects that are on
or near the surface of the ML blank usually will absorb the EUV wavelengths and cause a printed defect on the wafer. This type of defect is termed an “amplitude” defect. The other type of defects is ones that are either on the LTEM substrate surface or near the bottom of the ML film stack. These defects disrupt the uniform ML thickness locally and can cause unwanted surface propagations. Since the local ML films in the vicinity of such a defect are either affected in thickness, d spacing, or λ/4 periods, EUV reflected light could be driven out of an 180° in phase condition, cause destructive interference, and produce a “phase” defect. Defect printability simulations have shown that sizes down to about 25nm in diameter have high probability to print by E. M. Gullikson et al [11] (see Figure 9).

There are two types of defect inspection technologies for EUV blanks one using optical wavelength inspection and the other is “actinic” or at wavelength EUV inspection. Both approaches have their merits and limitations and trade-offs between defect size detection sensitivity and throughput. Optical inspection techniques generally have higher throughput at the expense of defect size sensitivity compared to actinic techniques.

**Optical Defect Inspection**

Optical defect inspection techniques vary widely however two such techniques will be discussed here. One is based on light scattering principals as discussed by Seong-Ho Yoo et al [12]. The other technique uses confocal microscopy. Figure 10 shows the comparisons of the two approaches. Paramount in either inspection technology are the algorithms used once either scattering or imaging information is captured by the cameras or other sensors (Charged Coupled Device -CCD). Current inspection systems can output information in discrete defect coordinate locations, defect maps, and size histograms as seen in Figure 11.

**Actinic Defect Inspections**

Actinic defect inspection may be required if there is a higher occurrence of printed defects on the wafer that is not detected through optical techniques. There continues to be debate whether actinic inspection is required in EUV blank manufacturing. Currently actinic defect inspection studies have been performed using modified optical systems on research synchrotron beamlines (e.g. Lawrence Berkeley National Labs). Using synchrotron radiation by modifying it to 13.4nm wavelengths is accomplished through undulators. EUV wavelength are scanned at near normal angles on the mask blanks and resulting scatter is recorded both in “dark field” and bright field” mode simultaneously. Such techniques can be seen by Park et al [13] and Yi et al [14].
X-Ray Diffraction

Shallow hard X-ray reflectivity (0.154nm) analysis or diffraction can be used to obtain valuable information about ML interfaces, individual film thickness, and d-spacing periods. X-ray diffraction analysis uses the property of crystal lattices to diffract monochromatic X-ray light. This involves the occurrence of interferences of the waves scattered at the successive planes within the ML. With the use of Bragg’s Law equation (2) and understanding the ML material property d spacing, individual film thickness, and calculated EUV reflectivity can be generated.

It is important to note that although XRD is a very useful tool the reflectivity performance at 0.154nm wavelength as seen in Figure 13 does not assure EUV wavelength performances at 13.4nm. Film contamination or other effects would not influence the 0.154nm radiation. XRD reflectivity curves such as Figure 15 can provide useful information as the “Bragg Peaks” occurring at the correct angle of incidence can be well correlated to the Ion Beam Sputter (IBS) deposition process.

Transmission Electron Microscope (TEM)

High resolution TEM analysis of the ML structures can be very informative as an analytical
inspection technique to understand issues within ML. The first area is the analysis of the interface between Molybdenum and Silicon layers within the ML stack. As mentioned previously keeping the ML interfaces uniform with sharp contrast supports high EUV reflectivity. Effect of crystalline or silicide diffusion of SiO$_2$ between the Silicon and Moly can be readily seen in TEM’s. Figure 14 shows when Mo/Si ML are heated above 200°C there is intermixing and the Mo thickness appears to increase causing a change in Mo / Si “d-spacing.

The second important information that TEM’s provide is the effects of buried defect within the ML stack and how conformal or smoothing the ML is over such defects. Such IBS process improvement experiments can greatly aid to understanding such effect. Figure 15 shows how a buried defect on the LTEM substrate can affect the Mo/Si ML very sharply. Depending on the IBSD process smoothing or lack of it such a defect would become a printable “phase” defect.

FIGURE 14: Cross-sectional HRTEM images of Mo/Si multilayer samples. (c) IBS sputtered Mo/Si below the transition at $T_{Mo} = 1.89\pm0.10$ nm. (d) IBS sputtered Mo/Si above the transition at $T_{Mo} = 2.14\pm0.10$ nm. The thicker Mo in bottom picture effects overall “d” spacing and EUV reflectivity performance [15]

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FIGURE 15: Cross-sectional transmission electron microscopy image of a Mo/Si multilayer coating deposited by ion beam sputtering at off-normal incidence on a ~60 nm diameter gold spheres. [16]

EUV Reflectometer

A EUV reflectometer measures the absolute peak reflectivity and spectral output performances of the Mo/Si ML stacks. Reflectometers have been developed using two approaches one utilizing synchrotron electron storage rings with filters and undulators to modify the hard X-ray wavelengths into EUV wavelengths (e.g. 13.4nm) and the other using a plasma generated source. For dedicated use and high utilization in a blank manufacturing line it is anticipated that the smaller dedicated plasma or discharge source EUV reflectometers will be used. There are some commercial suppliers developing such dedicated systems.

Figure 16 is a diagram showing a generic reflectometer for dedicated high utilization. The major subcomponents of such systems use a laser that strikes a solid metal target either of Sn, Au, or other element to create plasma in which EUV radiation is generated. This energy is collected and filtered through use of collimator and spherical grating elements. The energy then is measured once before it is reflected off of the test piece and then after. Due to the energy variation of each plasma discharge on the solid target the reflected energy measurement accuracy requires both the
incoming energy “pre” and the reflected energy “post” intensities. Description details of EUV reflectometer operation are found in Gullikson et al [17].

The measured output of EUV mask blank as recorded by reflectometers provides the full EUV spectra, peak reflectivity, median, centroid, and full width half maximum (FWHM) performance. The measurement spot size is on the order of 1 – 3 mm and reflectivity uniformity of the test piece is accomplished though multiple measurements across the plate. Figure 17 shows a typical EUV reflected spectral measurement from an EUV reflectometer.

FIGURE 16: Simple diagram of a plasma discharge EUV reflectometer where solid target is replenished through use of reel-to-reel metal tape.

FIGURE 17: Typical spectral output of reflected EUV as measured by an EUV reflectometer.

SUMMARY

Metrology systems will continue to play a major role in the further development of EUV mask blanks to meet production specifications described by SEMI P37 and P38. Most important are the systems that detect defects and provide information on the location, composition, and impacts to the ML performance and potential printability in the exposure systems.

REFERENCES

[5] Semiconductor Equipment and Materials International (SEMI); Microlithography Volume, P38-1102 “Specification for Absorbing Film Stacks and Multilayers on Extreme Ultraviolet Lithography Mask Blanks” ; www.semi.org