

Extreme Ultraviolet Lithography: status and challenges ahead

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ABSTRACT

The purpose of this article is to provide an update of the current status and most recent advances in each of the specific areas of sources, masks, optics, photoresists and microexposure tool for extreme ultraviolet lithography. The article is therefore organized according to these topics, with a brief discussion of the issues surrounding each, the current development status, and future outlook. A sustained study on the development of industry infrastructure for EUVL is underway at International SEMATECH. Although significant challenges remain, progress is being made on various technical fronts.

Introduction

Background

Extreme ultraviolet lithography (EUVL) is the exposure technology of choice to succeed optical lithography for volume semiconductor manufacturing at feature sizes below 50 nm. EUVL uses radiation at 13.5 nm from a plasma source to project an image using reflective optics and a reflective mask.

Compared with competing next-generation lithography (NGL) options, such as X-ray proximity, electron projection, ion projection and direct-write, EUVL offers the solution that is most likely to meet the most important industry requirements, which include the following:

- Minimum feature size resolution, including critical dimension and overlay control.
- Throughput capable of supporting volume manufacturing.
- Compatibility with existing mask-making and resist-manufacturing infrastructure.
- Extensibility to at least three generations to allow recovery of development costs.

In addition, EUVL tools have mask and wafer scanning, alignment and

focusing architectures that are similar to those found in current optical exposure tools.

According to the International Technology Roadmap for Semiconductors (ITRS), EUVL will be targeted for application at the 45-nm lithography node, although recent plans by some IC manufacturers indicate its implementation at the 32-nm node. Based on International SEMATECH's (ISMT's) current estimates of industry timing, volume production at this node is likely to begin in approximately 2009. While exposure-tool suppliers are developing tools to be ready to meet this demand, it is just as important that the supporting infrastructure also be developed in time.

In the case of EUVL, this means that mask and mask blanks must be commercially available at production specifications, EUV photoresists must be available with adequate resolution, sensitivity, line-edge roughness and outgassing performance, and in-fab support items such as reticle handling, inspection and storage must be readily available. In addition to focused projects designed to yield solutions for each of the above items, International SEMATECH's EUVL program is also directed at supporting the development of key enablers to identify and resolve remaining critical issues for the technology. These include achieving reliable high-power EUV sources, and mitigating the degradation of optical components. Standards also play an important role in the infrastructure for an emerging technology, and International SEMATECH is at the forefront of efforts to establish key standards in the areas of EUV masks, source metrology and calibration.

A brief history of EUVL

Early concepts for EUVL emerged from research in Japan and the US during the 1980s, using so-called "soft X-rays" in the 10 to 30 nm range. During the 1990s, research in the US was focused at Lawrence Livermore and Sandia National Laboratories in Livermore, CA, with industry support from AT&T, Intel, AMD, and others. In

1997 the EUV Limited Liability Corporation (EUV LLC) consortium was formed and eventually expanded to include Intel, AMD, Motorola, Micron, Infineon and IBM. From 1997 to 2002, the EUV LLC program at Lawrence Berkeley, Lawrence Livermore, and Sandia National Laboratories achieved many significant milestones, including demonstrations of 100 nm lithography over a 24 mm × 32.5 mm scanning field using a fully integrated 0.1 numerical aperture (NA) exposure system known as the engineering test stand (ETS).

Meanwhile, significant advances in EUV technology were being made under the Association of Super-Advanced Electronics Technologies (ASET) consortium in Japan, and the Microelectronic Developments for European Applications (MEDEA+) and PREUVE consortia in Europe. Today, exposure tool development is in progress at the "big three" of ASML, Nikon, and Canon, while Exitech in Cambridge, England is building microfield tools for multiple customers. Six or more companies are in a race to develop high-power EUV sources that will find their way into production exposure tools. EUV-mask and mask-blank technology is being developed in the US, Europe, and Japan, and International SEMATECH is establishing an advanced EUV Mask Blank Development Center and Resist Test Center in collaboration with the University at Albany – SUNY in Albany, NY.

Overview

The above discussion has provided insight into some of the important topics relevant to EUVL. Since there exists a wealth of technical literature as well as numerous previously published overview articles on EUVL, only a brief explanation of the underlying technology is given here and the reader is invited to consult other sources for more detailed information.

Instead, the purpose of this article will be to provide an update of the current status and most recent advances in each of the following specific areas:

- Sources
- Masks
- Optics
- Photoresists and microexposure tool.

The remainder of this article is therefore organized according to these topics, with a brief discussion of the issues surrounding each, the current development status, and future outlook.

EUV sources and source metrology

EUV sources

At this time, there are two prominent technologies for the generation of EUV light, both of which depend on the creation of highly ionized Xe plasma. In the first approach, that of gas-discharge-produced plasma (GDPP), a plasma discharge is created and then magnetically self-compressed to generate highly ionized Xe ions. Component lifetimes of electrodes and collectors are the issues for this technology.

The competing technology uses laser-produced plasma (LPP) to generate the EUV emission. Although the overall conversion efficiency for this technology is much less than GDPP, more of the light generated can be collected. LPP systems are much more complex and lifetimes of laser-diodes and collectors are the main challenges for LPP. A key issue for EUV lithography is the achievement of sufficient source power to meet production throughput requirements. Figure 1 shows an EUV source from Xtreme technologies, which is being delivered to ISMT for its EUV microexposure tool. Xtreme is also delivering an EUV source to ASML for its alpha version of an EUV scanner. Description of these and other EUV sources is available online at ISMT's public web site (<http://www.sematech.org/public/index.htm>), under the proceedings of EUV Source workshop, a biannual workshop organized by ISMT to bring together the EUV source community.

Three stepper manufacturers, ASML, Canon and Nikon, have agreed upon the requirements for EUV sources (Table 2). We should note that since 1996, requirements for source power have been increased by a factor of 50, which now stand at 115 W. This has as a result of evolving system requirements, and that this has overshadowed the progress that has been made by the source suppliers. Today, GDPP EUV

TABLE 1. EUV LITHOGRAPHY: CRITICAL ISSUES
Source output
Defect-free ML coated mask blank manufacturing, including inspection
Source and condenser optics reliability
Cost of ownership (CoO) of EUV lithography
Defect-free patterned mask manufacturing/commercial availability
Reticle defect protection (from inspection through exposure)
Effective contamination control of optical path (lifetime)
High NA optics manufacturing
Thermal management of reticle and projection optics at high throughput
Resist – high sensitivity at low power with low LER

(Source: 1st International EUV Symposium, Dallas, TX, USA, October 2002).

sources can generate power in the excess of 60 W while the collector transmits only 5–10 W of that power. In 2000, similar sources were capable of generating approximately 0.1 W after the collector.

Can we achieve the required power from EUV sources? The source power requirements, for a source operating at 6 kHz, are reaching Planck limits for a black body radiating at 60 eV [1]. At present, conversion efficiency (conversion of plasma energy into EUV emission at 13.5 nm) for GDPP is about 0.5% and for LPP is 0.80% for Xe, and there is a push to increase the conversion efficiency. However, it is generally believed that maximum conversion efficiency (CE) for GDPP is about 0.7%, and for LPP it is close to 1.5%. This makes GDPP sources much more efficient because the electrical power does not have to be converted into laser power (which is expected to be at 10% conversion maximum).

There are also efforts by most EUV source suppliers to study other, more efficient emitters, such as Sn, which has more than twice the conversion efficiency of xenon. However, the debris issue will be a bigger challenge with Sn. Despite enormous challenges still ahead, EUV source suppliers are committed to delivering the EUV sources that meet the EUV stepper manufacturer's requirements.

In order to help advance EUV in the pre-competitive mode, ISMT has established programs to address the fundamental data and modeling to understand the Xe and Sn plasma in GDPP and LPP and the investigation of new materials for critical components of EUV sources.



Figure 1. GDPP EUV source from Xtreme technologies. (Photo courtesy of Xtreme technologies).

EUV source metrology

An EUV source assessment program called “Flying Circus” was first conducted by ASML in 2000 to review the status of the EUV sources. Now the Flying Circus II program, under a contract with FOM institute, is being used by ISMT to drive the standardization of source metrology and assess the progress and risk associated with the EUV sources. Additional issues related to metrology requirements of EUV source development and monitoring of EUV sources in production need to be addressed, and a working group has been created to generate an EUV source metrology roadmap. ISMT also has started a program with the National Institute of Standards and Technology (NIST) to address the calibration of EUV source metrology components and to develop more precise EUV metrology.

TABLE 2. EUV SOURCE REQUIREMENTS, PER CONSENSUS OF EUVL STEPPER MANUFACTURERS

Parameter	Value	Unit	Comments
Wavelength	13.5	nm	
EUV power	115	W	At the intermediate focus
Repetition frequency	7–10	kHz	Not agreed upon among suppliers
Integrated energy stability	0.3	%	3 sigma over 50 pulses
Source cleanliness	30 000	h	After the intermediate focus, equal to 7.6 ¥ 10 ¹¹ pulses; definition of cleanliness TBD
Etendue of source output	1–3.3	mm ² -sr	Not agreed upon by the participants
Maximum solid angle to illuminator	0.03–0.2	sr	Depending upon the particular optical scheme; not agreed upon by the participants
Spectral purity			
130–400 nm	<= TBD –7%	%	Depending upon the particular optical scheme; not agreed upon by the participants
> 400 nm	TBD		

(Source: EUV Source Workshop, Santa Clara, CA, February 2003).

EUV masks

EUV mask blanks and mask blank metrology

EUV mask blanks are multilayer (ML) coated reflective optics using 40 pairs or more of alternating molybdenum (Mo) and silicon (Si) layers each of 4.1 nm and 2.8 nm thickness respectively on top of a low thermal expansion material (LTEM) substrate. EUV blanks are similar to ML-coated projection optics, however, the blanks take the form of conventional optical lithography blanks (i.e. are flat versus the curved optics) and will have patterned absorber features on top of the ML stack (see Figure 2). Since the mask determines the actual image within the exposure systems, there are several critical performance requirements. Having defects within the ML stack will cause printable defects at the wafer, and thus the reflective ML deposition process must essentially produce defect-free or near defect-free coatings. However, performance is currently between 10× and 100× away from production needs. Peak reflectivity of the ML blanks for production will require 67% or higher centered at the wavelength of the exposure systems where current blanks of 63% have been demonstrated. Reflectivity matching and uniformity across the blank is also essential to maintain dose control where uniformity errors of over 1% can cause CD error impacts. ML defect and reflectivity performance are just two of many EUV mask blank performance requirements that are currently specified in SIA SEMI P38-1102

Specification for Absorbing Film Stacks and Multilayers on Extreme Ultraviolet Mask Blanks.

To verify EUV blanks performance requires the use of many metrology systems to inspect defects, reflectivity performance, and other film-stack properties. Defects are currently being detected through optical techniques (see Section EUV Mask Inspection). However, additional correlation experiments using actinic (i.e., at EUV wavelengths) inspections will help justify and build confidence that all relative defects can be found optically. Reflectivity performance is measured using EUV reflectometers that fall into two categories; synchrotron and stand-alone laser-plasma based. EUV reflectometers measure the full-reflected output spectra of the blanks at multiple sites to verify peak, full width half maximum (FWHM), and uniformity of the reflectivity. To optimize the ML reflective performance and ML process optimization there are several analytical metrology systems that can help provide the ML film thickness control, ML film interactions and impacts of defects on ML films. X-ray diffraction (XRD) systems can provide both ML film thickness control and film delineations. Transmission electron microscopy (TEM) and high-resolution scanning electron microscopes (HRSEM) can provide ML thickness control information but is also very helpful in defect analysis where ML film interactions over or on top of defects can be reviewed.

ISMT is funding several projects to

support EUV blank developments including ion beam sputtering deposition (IBSD) tool/process developments with commercial supplier Veeco, investigating alternative deposition processes through research, and partnering with multiple commercial EUV blank suppliers in procuring increasing quality blanks over time. ISMT and its UAlbany facility (ISMT-North) are providing a state-of-the-art EUV blank development center where specific process module developments along with commercial supplier involvements will foster learning and provide solutions. Additionally, ISMT is funding work at Lawrence Livermore National Labs (LLNL) on the further development of EUV blank defect repair using focused ion beam (FIB) and e-beam repair strategies to help reduce the burden on the defect requirements for multilayer depositions.

Developing commercial EUV mask blanks at acceptable costs will be a major challenge. ISMT is aiding in the technology transfer from the expert knowledge base from both LLNL and Lawrence Berkeley NL to the commercial industry, however, additional innovations will be required on both ultimate performance and cost effectiveness. The improvements in ML deposition processes and the implementation of defect repair technologies may ultimately be required to meet these needs.

EUV substrates and substrate finishing

As described previously EUV mask blanks will use LTEM as the substrate

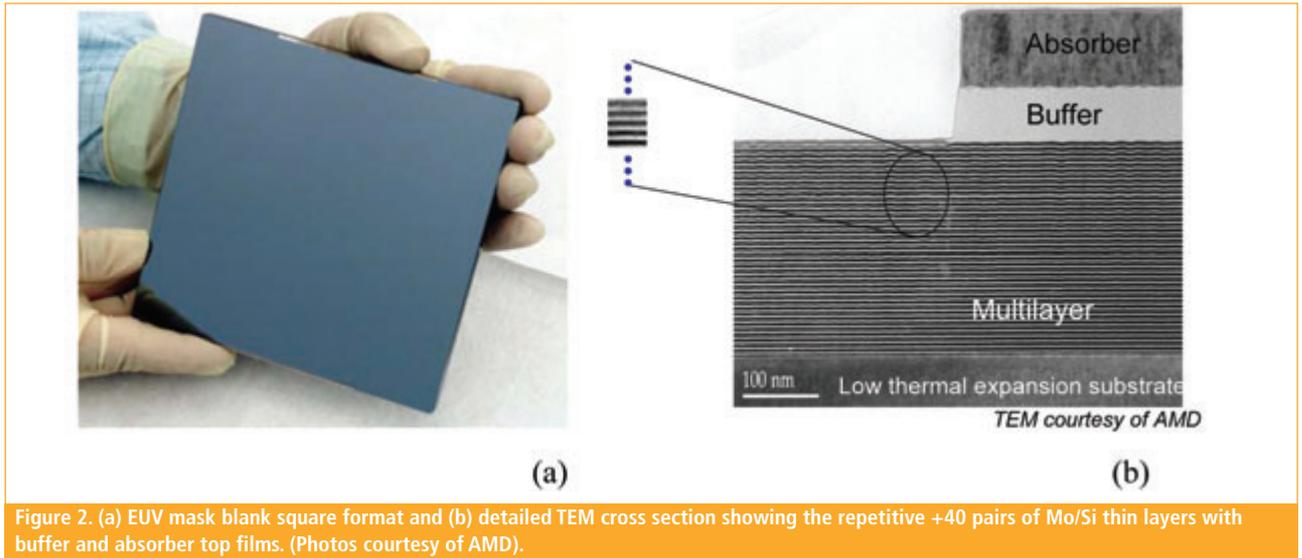


Figure 2. (a) EUV mask blank square format and (b) detailed TEM cross section showing the repetitive +40 pairs of Mo/Si thin layers with buffer and absorber top films. (Photos courtesy of AMD).

material due to the high EUV power at the reticle plane for production systems that are expected to be at least 6 W to support +80 wph exposure tools. The LTEM must have bulk properties of mean coefficient of thermal expansion (mean CTE) on the order of ± 5 ppb/K to limit material expansions that would cause image placement distortions plus possess finishing characteristics suitable for EUV blank use. Even before the ML reflective films are deposited the LTEM substrates must have very stringent performance requirements on flatness, local slope, roughness, and defectivity. The LTEM materials of choice are either a glass based or ceramic system that can be figured and polished using similar optical mask blank and EUV substrate polishing techniques. Such candidates include but not restricted are ULETM manufactured by Corning and ZerodurTM manufactured by Schott Glas. All the required production grade performance needs of EUV substrates are currently specified in SIA SEMI P37-1102 Specification for Extreme Ultraviolet Lithography Mask Substrates.

Currently no one has successfully demonstrated EUV mask substrates that meet all of the top-class performance specifications described by P37-1102. Improvements have been made on each single specification, however, achieving all simultaneously will be challenging. Both frontside and backside flatness requirements of less than 30 nm peak-to-valley (P-V) are needed in order to maintain proper position within the focal plane within the exposure system. Current performance from several commercial blank suppliers has shown frontside flatness averages of 200 nm P-V. A relatively new performance

requirement for lithography blank and mask industry is the “local slope” requirement of $\angle 1.0$ milliradian. Since EUV masks are reflective, any significant local surface perturbation/oscillation can cause absorber features near or on top of such perturbations to cause an image placement (IP) error during exposure. Metrology methodologies to incorporate flatness and roughness errors over a 100 nm down to 400 nm spatial periods will require the integration of potentially three types of metrology tools (i.e. flatness interferometer, phase measuring contrast microscopy (PMM), and atomic force microscopy (AFM)). To date there has been only preliminary “local slope” performance measurement conducted by LLNL that showed a ~ 3.0 milliradian error from commercial substrates. Proper substrate preparation is essential for increased ML reflectivity and defect minimization. Having a very smooth starting surface before the 40 or more ML pairs are deposited is essential. As surfaces become rougher the ML interface contrast degrades as the surface roughness can propagate through the ML stack. Specifications of needing surface roughness of < 0.15 nm RMS are required, however, blank suppliers have been able to demonstrate roughness on the order of 0.20 nm RMS and below. Also if there are defects on the substrate before ML is deposited there have been studies that shows that these “native” defects can cause printable defects in the EUV mask. The native defect density requirements for essentially defect free performance at defect sizes of 50 nm translate to defect density of 0.003 defects/cm² for reasonable yields. Therefore improved substrate

fabrication technologies need to be developed to eliminate/reduce substrate defects. Both EUV substrate figuring/finishing as well as cleaning processes will become required enablers to meeting such stringent performance.

EUVL mask blank multilayer deposition

One of the critical challenges for EUVL is the deposition of the multi-layers for use as mask blanks. The biggest issue with multi-layer deposition is defects in the multi-layers.

Currently, EUVL multi-layers are deposited using the IBSD tool, which uses an accelerated beam of ions to sputter material from a target onto the mask blank substrate. International SEMATECH has decided to pursue this technology and try to determine if it can be used to make EUVL mask blanks at the current target specification of 0.003 defects/cm² at a 35-nm equivalent PSL size. Other technologies that have been looked at and still hold potential for low defects are magnetron sputtering, which is currently used by LLNL for optics coatings, and e-beam evaporation.

Defects have remained as one of the top issues for EUVL multi-layer deposition on mask blanks (ranked #1 in 2001 and #2 in 2002). Only concerns about the source power have shown greater precedence in the rankings. Currently, the EUV-LLC and the Virtual National Laboratory (VNL) have shown they can reach defect levels of approximately 0.1 defects/cm² for 90-nm equivalent PSL size defects. This is a critical issue, and currently ISMT is undertaking root cause and defect analysis at its EUV facility at the University at Albany (UAlbany) to try to improve its IBD to meet the current specification. A

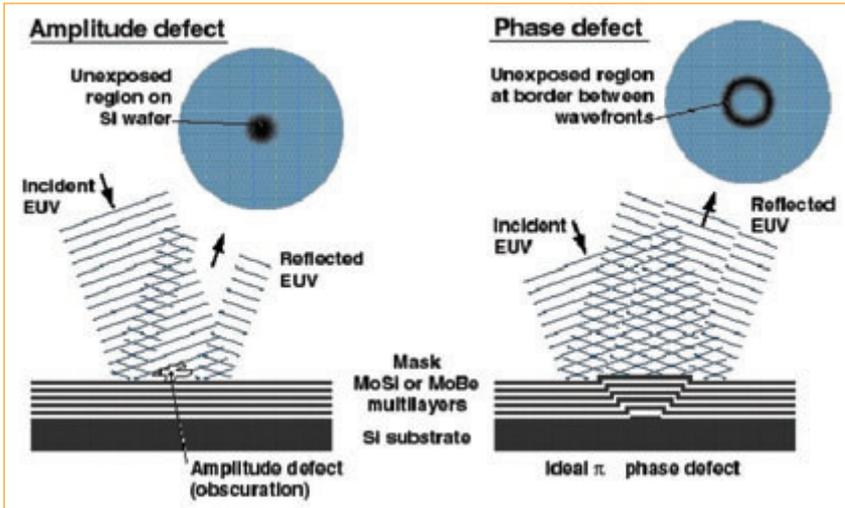


Figure 3. Schematic of phase defects caused by substrate imperfections. Left: amplitude defect due to absorbance on the surface of the multilayers. Right: phase defect caused by substrate surface defect. (Figure courtesy of Lawrence Livermore National Laboratory).

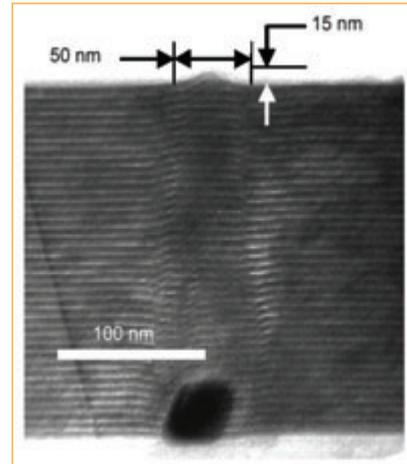


Figure 4. TEM cross section of a multilayer defect grown over an intentionally deposited 60-nm diameter gold particle. (Photo courtesy of Lawrence Livermore National Laboratory).

tool has been installed and we are in the process of transferring the multilayer deposition process from VNL.

EUV mask blank protection and handling

The greatest challenge posed by EUV masks is that, unlike their optical predecessors, they do not have a pellicle. The familiar film-based protective mechanism is not compatible with EUV lithography, as there are no known transmissive materials at EUV wavelengths.

Without the pellicle, the mask is at constant risk of a particle impacting on the patterned surface and inhibiting accurate transference of the image from the mask to the wafer. New methodologies of protecting the mask must be developed. In addition, every stage and process of the finished mask flow must be evaluated for particle exposure risks, using existing optical-mask pathways as a baseline, with anticipated new operations incorporated.

Even the carrier needs to be updated: ISMT is creating a specification for low-particulating, low-outgassing candidate materials that should be useful for EUV-compatible mask carriers. The mask also will be subject to pressure transitions when moving from a non-vacuum carrier to the vacuum exposure chamber. Some turbulence is inevitable, so a passive protection scheme is necessary. This so-called “removable pellicle” will be withdrawn just before the mask is chucked for exposure. ASML has disclosed their approach, using a minimal-contact frame and cover, which uses moderate clamping to inhibit mask movement during transit. Other

supplemental protection schemes, including active methods like thermophoresis, are under consideration.

The actual handling areas on the mask also need definition. Standardized, reserved areas allow for common film deposition layouts, while allowing for innovative contacting solutions. Compatible, low-particulating materials are needed for the mask (cleared substrate surface areas are a possibility but not a certainty) and the gripping end effectors.

EUV mask standards

With the introduction of EUV lithography, new mask standards are needed. Industry experts have identified four areas for urgent development: the mask substrate, the mask blank, electrostatic mask clamping, and the mask carrier. Other opportunities may

arise as EUV evolves toward production capability.

The mask-substrate and mask-blank standards have been published by SEMI as P37 and P38, respectively. Each is expected to undergo periodic revisions as EUV-mask knowledge and capabilities improve, but currently provide solid frameworks on which design decisions can rely. SEMI P37 defines the substrate form factor and material properties. SEMI P38 addresses the films deposited on the substrate, as well as required characteristics of the films.

The chucking standard, recently balloted for ratification, defines the clamping performance requirements needed for consistency between the mask writing tool, the exposure tool, and registration metrology tools. Electrostatic chucking is considered necessary to clamp and flatten a given mask

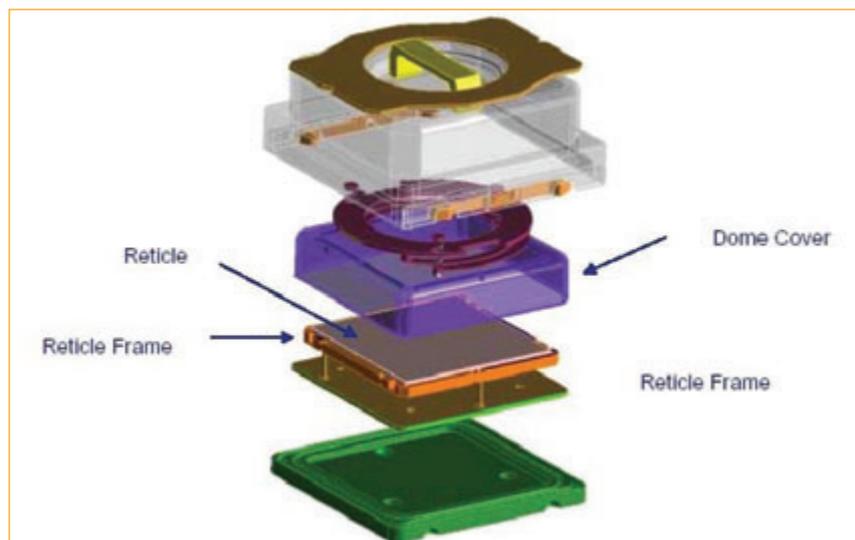


Figure 5. Mask-carrier components. (Figure courtesy of Brian Blum, ASML).

repeatedly, in order to minimize in-plane distortions of the mask pattern and therefore optimize image overlay on the wafer. Model studies conducted by the University of Wisconsin Computational Mechanics Center have indicated that common use of electrostatic chucks at these three critical clamping operations gives smaller, more consistent results than common three-point chucks or a mix-and-match approach. The ITRS projects overlay at the 22 nm node as 9 nm; the models support that electrostatic chucking is the most promising approach for meeting this requirement.

The mask-carrier standard is in development. Industry surveys indicate that the 200-mm standard mechanical interface (SMIF) format has the broadest support, and will be the first form factor addressed; others likely will follow, including 150-mm SMIF and front-opening unified pod (FOUP). The carrier is intended for use from the back of the mask shop through the end of the mask operational flow; this removes carrier-transfer handling and reduces particle-impact risk. Other considerations include the material selections, which ISMT is addressing, and defining mask gripping, carrier-tool interfacing, and supplemental protection accommodations.

Another opportunity for standardization is the mask-identification mark. Whereas optical masks use different barcode formats and mask locations depending on the exposure tool manufacturer, EUV presents the potential for standardizing on a single automated identification format in both symbology and location. ISMT has proposed that the digital data matrix code be adopted, as it has been in many other sectors of the semiconductor industry, such as 300-mm wafers. ISMT plans to conduct a validation experiment in the near future to support adoption. The advantages are two-fold: a standard location simplifies design for mask-support equipment, such as inspection tools, for using the mark, and the data capacity of data matrix is significantly greater than larger barcodes, which would enable greater traceability in the encoded information.

Mask cleans

Contamination control on EUV masks is expected to be a challenging problem. No EUV pellicle is anticipated and consequently numerous cleans will be necessary to remove the contaminants. The issues related to EUV mask cleaning can be summarized as follows:

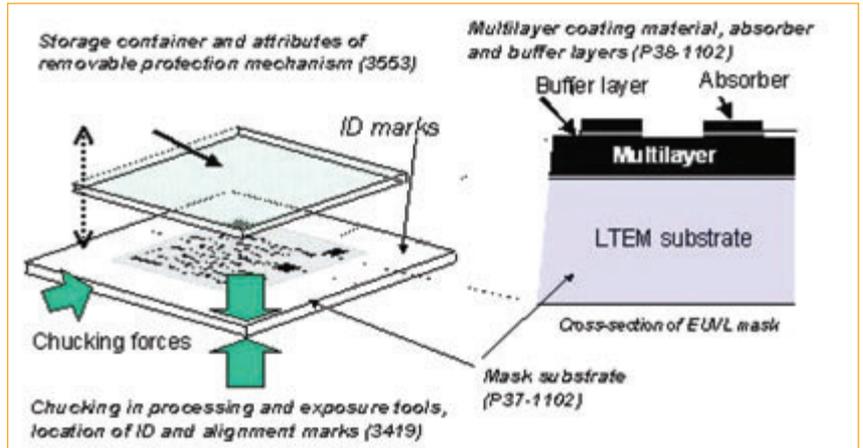


Figure 6. Target areas for mask standards. (Figure courtesy of Scott Hector, Motorola).

- Minimal etching and roughening is permitted because of sensitivity of film thickness to reflectivity. Simulations and experiments have shown that removal of just a few angstroms of the EUV silicon-capping layer can affect the multilayer reflectivity by up to 2–3%.
- The actual films to be used are still unknown so the cleaning solution must be either flexible or widely applicable.
- The films will be exposed to cleaning processes numerous times during the life of the mask because there is no pellicle to protect them from particles.
- It is imperative that the mask surface be free from any adsorbed contamination, because organic contaminants absorb strongly at 13.4 nm wavelengths.
- There are stringent defect specifications (ITRS 2002 Update) for EUVL:
 - Zero particles above 55 nm in 2006 for 70-nm node final mask; zero particles above 39 nm on quartz substrate.
 - Zero particles above 35 nm in 2010 for 45-nm node final mask; zero particles above 32 nm on quartz substrate.

In order for advanced photomask technologies to be successful, proper cleaning methods must be implemented. Since standard cleaning technologies (sulfuric acid/hydrogen peroxide mixture [SPM], Standard Clean 1 [SC1] and Standard Clean 2 [SC2]) are inadequate, new cleaning methods must be developed to meet these rigorous defect criteria. Ideal future mask quality requires innovative advancements with respect to reticle material components (absorbers and other thin film layers, substrate, and associated structures/materials), processes

(cleaning, etching, etc. and associated residual chemical contamination monolayers), cumulative energy effects, environment (fab, storage, and transport), pattern density, age, etc.

Consequently, ISMT is initiating several tactical and strategic projects focused on advanced photomask cleaning/surface preparation techniques that specify not only the removal of particles, but assure that the selection of both the chemistries and materials used in the cleaning system do not cause reticle contamination or degradation. Emphasis will be placed on assuring that appropriate consideration is given to all possible sources of contamination, and identifying post-process validation techniques to ensure resultant surface cleanliness.

EUV mask inspection

It is currently believed that reflected light inspection at deep ultraviolet (DUV) wavelengths would be sufficient to check the pattern integrity of the finished mask. This inspection, however, lacks the ability to find in the absorber-stack defects that would only show up at EUV wavelength.

It is therefore essential to achieve defect-free EUV mask blanks. Obviously, the capability to detect and locate relevant defects is vital for process development in order to characterize defects as well as for future blank production, which most likely will include some defect mitigation schemes (e.g., repair).

Given the present experience with inspection techniques using optical wavelengths, the current strategy is to use such techniques also for EUV blank inspection. The underlying assumption for this approach to be successful is that any relevant disturbance in the multilayer stack manifests itself at the

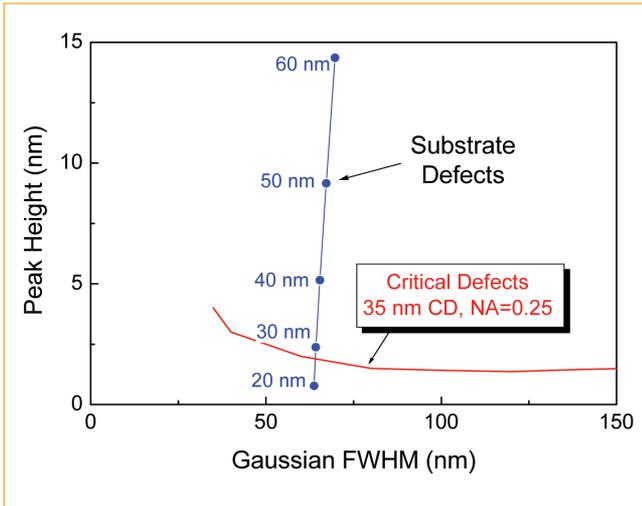


Figure 7. Points show expected size of defects nucleated by a particle at the substrate beneath the multilayer coating, as calculated using a multilayer growth model. Note: The size of a critical defect was determined from the calculated aerial image ($NA = 0.25$, coherence = 0.7, and perfect optics) of a defect near a 35-nm line (140 nm on the mask). A defect is considered printable if it causes a 20% CD change anywhere within a ± 100 -nm depth of focus [2]. (Figure courtesy of Lawrence Berkeley National Laboratory).

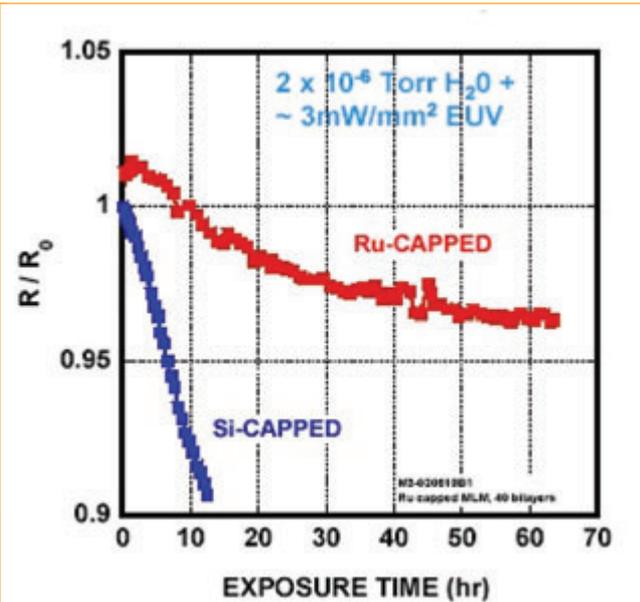


Figure 8. Change in EUV reflectance of ruthenium- and silicon-capped multilayer coatings with time, during EUV exposure in an oxidative environment [4].

surface of the multilayer stack as a small surface anomaly (e.g., a bump). Simulations of the multilayer growth can provide some estimate about the respective sizes. As shown in Figure 7, a 30-nm defect on the substrate would yield a critical disturbance of the aerial image, as well as surface bump of about 2 nm height and 60 nm Gaussian full-width half-maximum (FWHM).

There are basically two questions pertaining to EUV blank inspection strategy:

- What are the relevant (“printing”) defects (sizes and types) in the multilayer stack?
- Can these defects be detected with techniques at optical wavelength, or will actinic inspection be required?

ISMT has set up a number of projects to address these questions:

- A confocal inspection technique at 488 nm wavelength developed by Lasertec Corporation, Japan, has demonstrated a sufficient sensitivity on approximately 12-nm high multilayer surface bumps. In a joint development project with Lasertec, ISMT tries to extend this technique to approximately half the wavelength, in order to increase the sensitivity.
- Another project targets the development of an aerial image measurement tool. This tool would be required to qualify defects (and defect repairs) with respect to their impact on the aerial image, thus addressing

the first question above.

- In a separate project with the VNL, ISMT tries to address whether there are critical defects that are not detectable by optical inspection techniques.

EUV optics contamination

The lifetime of the reflective optics in an EUVL exposure tool remains critical for the commercialization of EUV lithography. Radiation-induced contamination and erosion of the Mo/Si multi-layer coated projection and condenser optics, respectively, are to blame for the current poor lifetime values. For condenser optics for LPP in the engineering test stand at VNL, it is observed that ~ 1 Mo/Si bilayer is removed per 15 M shots of EUV radiation and the bilayer removal on the first condenser optic results in the loss of reflectivity [3]. Some source suppliers have reported higher lifetime data (see Section EUV sources and source metrology). The EUVL stepper manufacturer requirements for collector are 100 B shots.

The condenser-erosion was placed at the top of a list of critical issues at the ISMT EUV Optics Lifetime/Contamination Workshop in February 2003. For condenser optics (particularly those that are plasma facing) the risks are from the following:

- Deposition of debris from source hardware;
- Radiation-induced oxidation and carbonization;

- Erosion (physical removal) of the coating by the plasma.

For Si-terminated Mo/Si-coated projection optics, the primary risk is oxidation. When such a coating is exposed to EUV radiation, the large number of low-energy secondary electrons generated near the surface can dissociate adsorbed water molecules, creating reactive oxygen that can oxidize Si to SiO_2 . To prevent oxidation of the coating, a protective (capping) layer that is oxidation resistant (e.g., ruthenium) must be applied (see Figure 8).

Accordingly, the EUV Optics Lifetime/Contamination Project at International SEMATECH is following a dual approach. First, the goal is to leverage the newly established EUV optics-testing pipeline (illustrated in Figure 9) to establish the legitimacy of accelerated life testing.

The testing pipeline consists of a suite of initial screening tests at Lawrence Livermore and long-term environmental tests at Sandia NIST, where the goal is to study the parametric dependences of variables contributing to projection-optics contamination. The second aspect of our approach is to address the critical condenser erosion problem through a thorough characterization of the source plasma and the study of plasma-surface erosion mechanisms. Once the physical mechanisms that lead to erosion are better understood, it may be possible to develop condenser coatings that resist erosion.

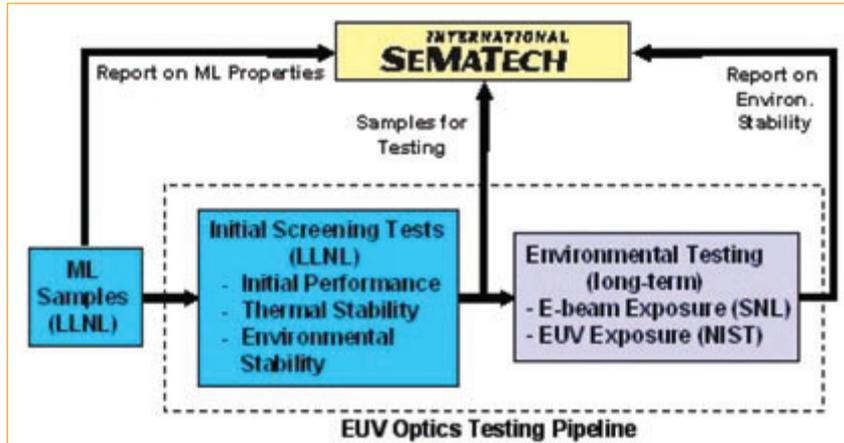


Figure 9. Block diagram of an EUV Optics Life-Testing Project at LLNL, SNL and NIST, funded by International SEMATECH.

Micro exposure tool (MET)

International SEMATECH plans to provide EUV lithography processing infrastructure to worldwide researchers. Two ISMT facilities are being prepared. Exposure capability is under construction at the Advanced Light Source (ALS) facility at Lawrence Berkeley National Laboratory. This tool will be connected to the synchrotron light source. ISMT is working with Exitech Ltd, of Oxford, England, to build a micro-exposure tool, which will be installed in a cleanroom at UAlbany. This tool uses a stand-alone gas-discharge plasma source made by Xtreme technologies. The projection optics for the two tools are the same design, a two-mirror Schwarzschild lens design resulting from a previous ISMT project. The lens has 5× reduction magnification and a relatively high 0.3 NA. The tools are designed to print 35-nm resist lines at 70 nm pitch and 23-nm isolated resist lines. The infrastructural investment by ISMT in establishing these two facilities targets resist development and EUV learning. The facility at LBNL will be available for researcher use in the third quarter of 2003, and is available for ISMT-

sponsored work 100 shifts per year through the end of 2004. The facility at UAlbany will be available for researcher use in the fourth quarter of 2004, and is planned to run three shifts per day, five days per week through the end of 2007. ISMT member companies, resist suppliers, and resist researchers will have access to the facilities.

EUV resist

The development of EUV resists has started with chemically amplified, 248-nm resist platforms (copolymers of acrylates and hydroxystyrene). Since the primary interactions between EUV wavelengths and the resist are at the atomic level, the optical density becomes less sensitive to molecular structure [5]. Therefore, the choice of polymers is not as important for optical density as with longer wavelengths. The primary challenges for EUV resist development are line edge roughness (LER), photospeed, and resolution. The goals for LER are < 3 nm (3 sigma), photospeed < 4 mJ/cm², and resolution 32 nm for dense features [6]. The current performance of resists is limited by the low NA of the exposure tools, typically about 0.1. Good results from these tools are 80-nm resolution, 5-nm

LER (3 sigma), and 3 mJ/cm². After high NA systems become available (NA = 0.3), the resolution should improve. The ultimate resolution of chemically amplified resists is not known, although there are results from EUV interferometric systems that show indication of 37-nm half-pitch resolution [7]. After resist suppliers have access to high numerical aperture tools, we will learn if there are fundamental limits with chemically amplified resists. The ultimate objective with the high NA tools is to develop resists to meet the EUVL goals for the 32-nm node.

Global co-operation

Development of EUVL lithography will require enormous resources. With these objectives in mind, ISMT has had fruitful discussions with other global EUV consortia, and several cooperative projects have been identified. It is desirable for us to minimize the unnecessary duplication of technology and infrastructure effort to reduce the total cost of EUVL introduction. Collaboration arrangements can be made in the form of complementary projects, data and sample sharing and co-funding of key projects. With these objectives in mind, ISMT has had fruitful discussions with MEDEA+ and plans cooperative projects with other international consortia.

Summary and conclusion

A sustained study on the development of industry infrastructure for EUVL is underway at International SEMATECH. Although significant challenges remain, progress is being made on various technical fronts.

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Figure 10. Imaging station for ALS facility. (Figure courtesy of Exitech).

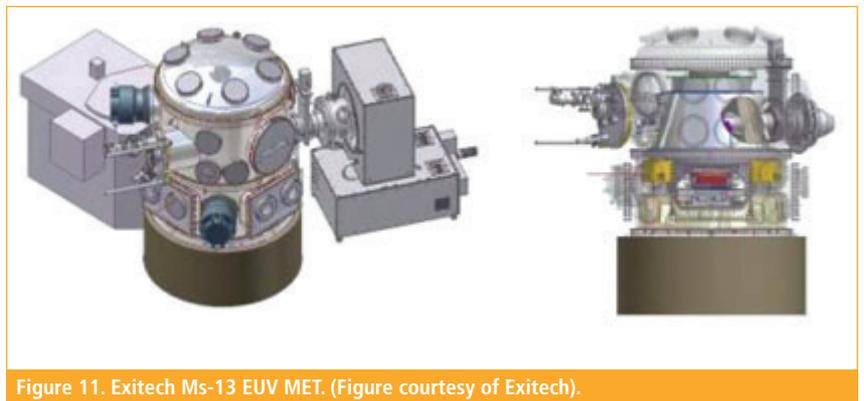


Figure 11. Exitech Ms-13 EUV MET. (Figure courtesy of Exitech).

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