

Actinic Review of EUV Masks

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ABSTRACT

Management of mask defects is a major challenge for the introduction of EUV for HVM production. Once a defect has been detected, its printing impact needs to be predicted. Potentially the defect requires some repair, the success of which needs to be proven. This defect review has to be done with an actinic inspection system that matches the imaging conditions of an EUV scanner. During recent years, several concepts for such an aerial image metrology system (AIMSTM) have been proposed. However, until now no commercial solution exists for EUV. Today, advances in EUV optics technology allow envisioning a solution that has been discarded before as unrealistic. We present this concept and its technical cornerstones. While the power requirement for the EUV source is less demanding than for HVM lithography tools, radiance, floor space, and stability are the main criteria for source selection. The requirement to emulate several generations of EUV scanners demands a large flexibility for the illumination and imaging systems. New critical specifications to the EUV mirrors in the projection microscope can be satisfied using our expertise from lithographic mirrors. In summary, an EUV AIMSTM meeting production requirements seems to be feasible.

Keywords: photomask metrology; scanner emulation; defect review; EUV optics; EUV mask infrastructure

1. INTRODUCTION

1.1 EUV Mask Infrastructure

The world of lithography continues its path to ever smaller features, and the introduction of EUV lithography will satisfy the requirements of the 22nm hp node and beyond. Carl Zeiss SMS GmbH, a business unit entirely committed to the photomask industry, intends to support this transition by adding EUV capabilities to all relevant parts of its product portfolio. MERIT[®], the system for mask repair, and PROVETM, the system for in-die registration metrology, are currently being extended in their capabilities to fulfil additional and tightened specifications that come with EUV. For AIMSTM, the aerial image metrology system for defect review, a completely new development is required. The Sematech EUV mask infrastructure initiative (EMI) confirmed this tool as the top priority for the high volume EUV mask infrastructure¹. Currently, the financial infrastructure for its development is being organized.

At Carl Zeiss, we have done a study to show the feasibility and to prepare us for the development phase, which will start as soon as the commercial framework is set.

1.2 Defects on EUV masks

In the whole lithographic chain, the most harmful defects are those on the mask. Being accurately replicated with each exposure, they have the potential to render the whole semiconductor product useless. Mask makers and device manufacturers take great care to find defects, to predict their printing impact, and to repair them if necessary.

The required tooling and knowledge to control EUV defects is not a simple extension of 193nm knowhow. In addition to the change of materials and processes, the significant difference is that the EUV mask as a mirror intrinsically is about 4x more sensitive to topological defects compared with VUV masks. On top of this factor, the continuation of feature shrink enabled by EUV to half pitches of 16nm and below gives a perspective of even tighter requirements on mask defects and defect control tooling.

1.3 Will it actually print?

Many simulation and printing studies have been carried out to derive specifications on mask substrates, coated mask blanks, and the structured absorber layer. The first question here is about the smallest size of a defect that may lead to significant change in CD on the wafer. Usually, 10% CD change are considered as the critical level. But these studies also showed that only a small fraction of the potentially harmful defects actually print. Details in the shape of the defect

and its relation to the mask pattern can change this printing behavior in an unpredictable way. Of particular importance for topological or phase defects is the through focus behavior of a defect. It has been shown that in spite of little CD variation in the nominal focus plane, a defect may be significant when the reticle or wafer is slightly defocused².

In spite of continuous improvements, there will still be a significant amount of defects on leading edge EUV masks, which have to be repaired e.g. by e-beam induced chemical etching and deposition, as it is done with MERIT[®]. To reduce the defect repairs to a minimal level, and even more importantly, to ensure successful repairs, a direct verification of the printing behavior of potential defect positions is required.

2. REQUIREMENTS FOR AERIAL IMAGE REVIEW

2.1 Printability

An AIMS[™] essentially targets this question: Will the local CD of a structure created by a given spot on the mask differ from its nominal value by more than allowed, within the targeted dose and focus variations? AIMS[™] does not inspect the whole mask but it relies on a defect map that has to be provided by e.g. a blank inspection tool or a patterned mask inspection tool.

For 22nm half pitch, 10% CD variation effectively correspond to 8.8nm CD change on the mask. To measure this change with sufficient precision, an effective measurement accuracy of 1.3nm on mask level or 0.3nm on wafer level is targeted by the Sematech technical working group on mask infrastructure specifications. A MEEF larger than unity affects the AIMS[™] image in the same way as the aerial image in the scanner, therefore it does not lead to tighter specs. To be extendible to 16nm, the specification will be tightened accordingly.

2.2 Throughput

From the experience with 193nm masks, a reasonable throughput target for AIMS[™] is to review 50 regions of interest within one hour, including load and unload cycles for the mask. For each region of interest, a series of exposures with varying focus is required. Taking into account also calibration steps, we can allow one second exposure time for a single frame of 10x10um. The main impact of the throughput requirement is the source brightness, since it sets the accumulation time for the required number of photons.

2.3 Match NA and Illumination

In today's EUV scanners, varying degrees of coherence are used for illumination. Future scanners will provide even more flexibility to adjust the illumination setting for optimal imaging conditions in the race to reduce k1 also for EUV lithography. To accurately predict imaging, AIMS[™] needs to provide the same flexibility for the illumination.

The roadmaps for EUV scanners also predict an increase in the numerical aperture³, which has to be followed by the AIMS[™] emulation. Also the illumination angle, currently set at 6°, will have to be increased. For numerical apertures above 0.35, an angle of 8°-9° will be needed. Therefore an extendible AIMS[™] even needs to provide flexibility in the chief ray angle both for illumination and projection optics.

In addition to these flexibility requirements regarding apertures and shapes of illumination and projection, the ring shape of EUV scanner fields calls for another degree of freedom. The plane of incidence of the chief ray is always normal to the curvature of the field. As the AIMS[™] microscope spot moves from the left side of the mask to the right, the optical system has to follow this curvature, rotating around the optical axis. Figure 1 illustrates how the ray angles have to be followed by illumination and projection optics.

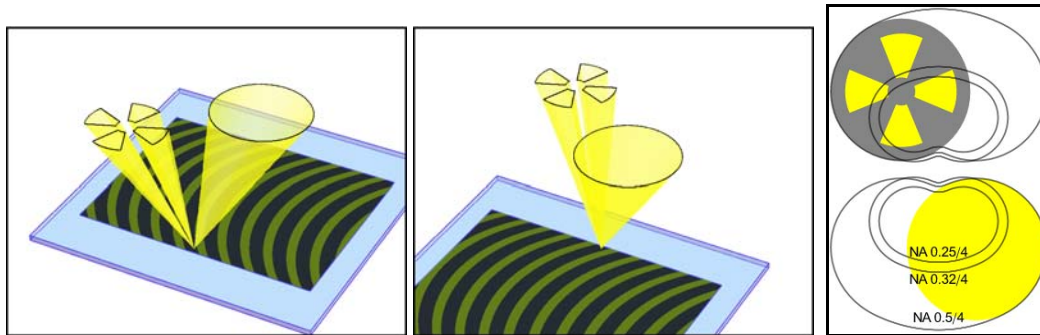


Figure 1 Left and center: As the microscope follows the scanner ring field on the mask, both the light cone for illumination and for projection rotate around the surface normal. For illustration purposes, a quasar illumination was chosen. The circular cone represents the reflected light that is collected by the projection optics. Right: A schematic view of the illumination pupil (top) and projection optics pupil (bottom). During operation, the pupils move inside the kidney-shaped areas, whose size depends on the NA of the scanner.

2.4 Illumination pupil: homogeneous vs. faceted

The fly’s eye illumination system of EUV scanners intrinsically is connected with a faceted pupil, i.e. the fine structure of the pupil consists of a dense grid of bright spots, as illustrated on the left hand side of Figure 2. The exact position of the spots varies between different generations of scanners.

While it is a target for AIMSTTM to match all relevant illumination shapes like e.g. conventional, annular, or quasar shapes, the detailed matching of the spots would lead to a significant decrease in transmission, leading to a further increase in source brightness demands. Moreover, the system effort to provide this enormous flexibility would result in significantly higher cost. Fortunately, the imaging impact of the fine structure of the pupil can be tolerated within the system budget, as Figure 2 illustrates. Our baseline system configuration therefore provides a set of continuously filled pupils, which can be defined through blades defining the illumination aperture.

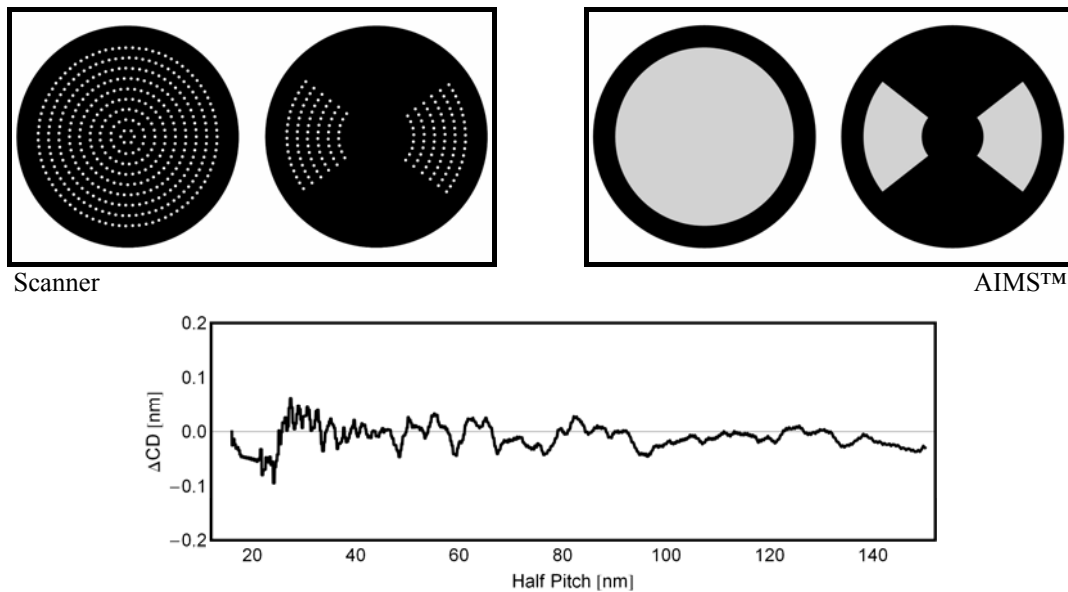


Figure 2 The faceted pupils of EUV scanners (top left) will be emulated by continuous pupil fillings (top right). The graph shows the resulting mismatch in CD prediction, which can be tolerated within the system budget.

2.5 Wavelength matching

The metrology light source in the AIMS™ system will not be the same source as for the scanners. Therefore the required matching between the scanner and the metrology spectrum has to be studied. The light spectrum also is influenced by the number and the characteristics of the multilayer coatings in the system.

The most obvious effect of a wavelength differing from the design wavelength is a drop of reflectivity on the mask level. This however could be compensated with a brighter source or with longer exposure times. Much more difficult for our application is that different reflection orders are damped to a differing degree, so the aerial image does not only change its brightness but also its detailed shape.

We simulated this with a series of dense lines with varying pitches, down to 16nm half pitch, at an NA of 0.5, both in horizontal and in vertical direction. The densest pitch for vertical lines was used for dose calibration.

The most significant effect of the wavelength shift is a H-V difference of about 10nm Δ CD per 1nm $\Delta\lambda$. Second, the pitch dependence for horizontal lines is much stronger than for vertical lines. This is in accordance with our expectations, since the diffraction orders for horizontal lines are in the plane of incidence of the oblique illumination, and the wavelength change roughly corresponds to a change in the angle of incidence. For vertical lines, the effect of the oblique illumination is cancelled due to symmetry.

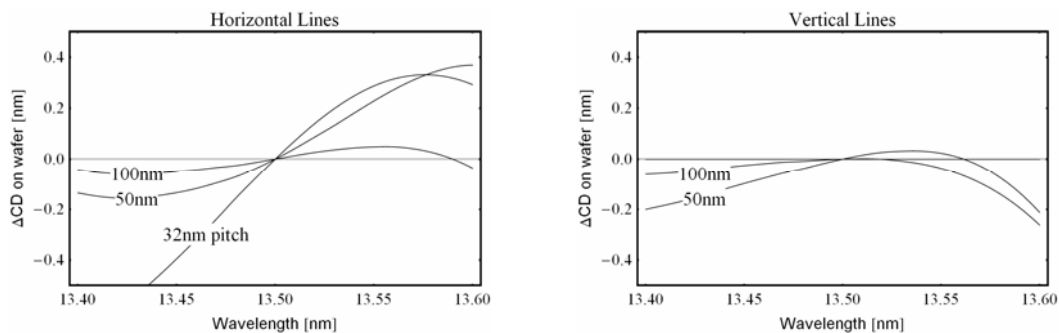


Figure 3 Simulation of the CD effect when the AIMS™ wavelength does not match the scanner wavelength. For each wavelength, the dose was adjusted to print the correct CD for 32nm vertical lines, and the variation was calculated for other pitches and other line orientations.

3. SYSTEM CHOICES

Possible implementations of an aerial image microscope have been investigated several years ago by a Sematech study⁴. The reexamination of these options at the beginning of the feasibility study for our project essentially confirmed the advantages and disadvantages found there. However, progress on technology on the one hand and increased requirements regarding resolution and accuracy on the other hand have changed the weight of these advantages and disadvantages, resulting in a new baseline concept.

3.1 EUV with secondary magnification

Two concepts have been proposed that use a two mirror Schwarzschild EUV optics as first magnification step, enlarging the image by 10-50 times. To allow an electronic recording of this image, a second magnification step is required. Two types of second magnification are possible. The first is a visible microscope, with a scintillator plate converting EUV photons to visible light. The second is an electron microscope, following a photocathode emitting electrons when hit by EUV light. The EUV optics is relatively simple in these cases, and both types of secondary magnifications have already been demonstrated. The main obstacle to implement these concepts is the enormous loss of light due to the second magnification step. For the visible optics concept, the quantum efficiencies of available scintillator materials and the collection efficiency of the optical microscope reduce the effective transmission by more than one order of magnitude. For the electron optics, the efficiency of the photocathode together with the transmission of the electron optical system leads to almost the same total transmission loss.

3.2 Zone plates

The zone plate concept has the most elegant optical configuration – only one optical element is required to image the reticle onto a CCD sensor. The critical aspects have already been denoted by Sematech’s study in 2001.

The quality of the zone plates was not sufficient to provide high aberration quality and low enough flare. Since then, zone plate manufacturing has made great progress. For example, recent results from the AIT⁵ confirm an excellent zone plate quality. Still, a wavefront qualification of the zone plates would be required for an AIMS™ development program. This adds to the development cost, but seems feasible.

Another critical aspect is the strong chromatic aberration inherent to the zone plate concept. The only way to deal with this is to work with very small bandwidth source. The maximum bandwidth is determined by the requirement to predict the EUV scanner CD, which does not suffer from chromatic aberration, within sufficient accuracy. Taking $\Delta CD < 0.125\text{nm}$ on wafer level as a tolerable deviation, we calculated for a zone plate with 0.5 mm focal length a maximum FWHM bandwidth of 0.01nm, i.e. $\lambda/\Delta\lambda > 1350$. We did not find a laboratory scale source that delivers sufficient power and brightness with this spectral purity.

Further, the freedom to correct aberrations of a single zone plate is very restricted. Basic theory of lens design tells us that even a perfect zone plate can be corrected only for one single spot. The aberrations at the edge of a 10 micron large field are around 0.3λ wavefront rms for full numerical aperture, which is one order of magnitude too high. So the usable field size would be severely restricted. A theoretical solution to solve the field aberration problem is to use a curved zone plate, e.g. one that is concentric around the center of the object field. However, such a zone plate would be very hard to manufacture and to handle.

3.3 All EUV

The concept closest to the scanner imaging conditions is an optical system consisting only of EUV mirrors. From the pixel size of available CCD cameras of about 13um, a required magnification of 750x can be calculated. Since the focal length of a two mirror Schwarzschild system can not be made arbitrarily small, a two mirror system with this magnification would have a tracklength of several meters, which is obviously not feasible. Adding a second pair of mirrors allowed us to reduce the tracklength to 1m. Using our current technology of aspherical EUV mirrors for the large first pupil mirror, we were able to stick with spherical shapes for the other three mirrors, adding limited cost to the system. The all EUV optics allows high wavefront quality within the full field of view and supports the same bandwidth as the scanner. Its high transmission allows a relatively modest demand on source brightness.

In addition to the established EUV mirror technology, the most prominent challenge is the manufacturing of mirrors close to the field, which have very tight specifications on micro-roughness and particles. Below, we demonstrate that we are confident to reach these new targets. Figure 4 (right) compares the key challenges of the different concepts. These results, together with our assessment of current source technology, made all EUV our concept of choice.



	Source brightness	Top challenge
EUV + Visible	750	Source brightness
EUV + PEEM	700	
Zone Plates	26	Source bandwidth
All EUV	32	Small sub-apertures

Figure 4 Left: A design example with a magnification of 750, with one aspherical mirror and three small spherical mirrors. Carl Zeiss patent application. Right: Key challenges of the concepts studied.

4. THE PHOTON BUDGET

4.1 Shot noise

A fundamental limit to the fidelity of CD prediction is the number of EUV photons that are used to form the image on the camera. Effectively, they act as a dose error with very high spatial frequency.

In the wafer exposure with EUV light, there is some mitigation of shot noise due to the resist blur⁶. In our system, such a blur is absent. There is a computational equivalent of blurring that we can use without loss of generality in the prediction capabilities. The optical system has a well defined cutoff in transmittable spatial frequencies. Frequencies higher than this cutoff can not originate from the reticle in the object plane but are artifacts from shot noise. A Fourier filter using this cutoff effectively implements an averaging over neighboring pixels just to the point justified by physics. In addition, a deconvolution with the MTF of the camera can also be included in this filter. Figure 5 shows an example how numerical methods are used to obtain the maximum CD fidelity for given shot noise.

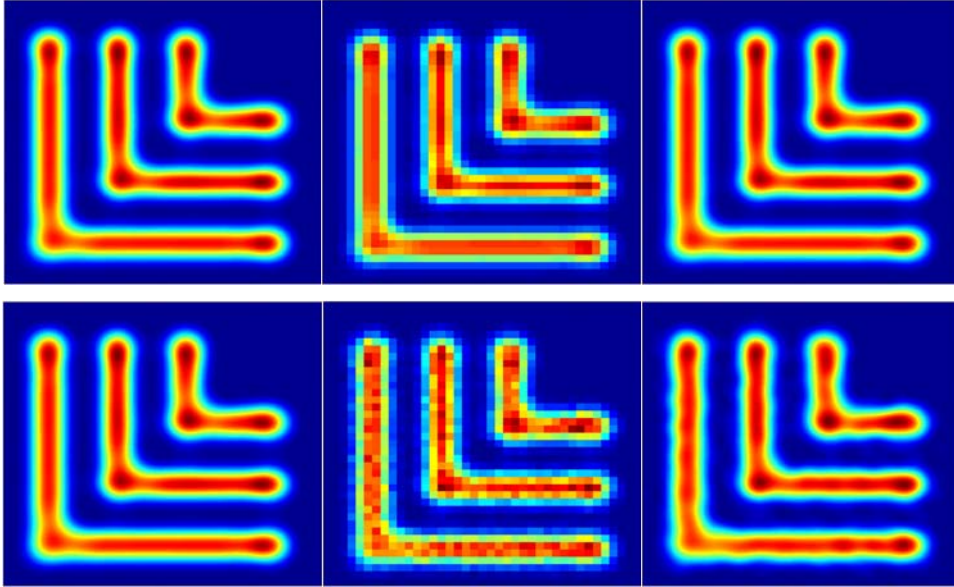


Figure 5 Illustration of the image processing to get optimum CD fidelity in spite of the CCD pixelation and shot noise. Left: Original image, Center: image on the CCD, without (top) and with 5% (bottom) shot noise. Right: reconstructed images. Right top: The pixelation effect can be completely reconstructed by inverting the MTF of the camera. Right bottom: The shot noise effect can be suppressed due to an effective averaging.

We simulated the CD prediction error due to shot noise for several values of NA and different types of features. Figure 6 shows an example. As one might expect intuitively, structures with low NILS are most sensitive also for shot noise errors. The formula for long range dose errors,

$$\frac{\Delta CD}{CD} = \frac{2}{NILS} \frac{\Delta I}{I}$$

gives a good indication of the CD dependence for this effect.

The shot noise of the single pixel follows a Poisson distribution, which is inversely proportional to the square root of the average photon number. Also, for small pixels, the algorithm described above leads to an effective averaging, so that only the amount of light incident per area is relevant for the prediction error:

$$\Delta CD \propto \frac{1}{p\sqrt{N_{ph}}} \text{ (in 2 dimensions)}$$

$$\Delta CD \propto \frac{1}{\sqrt{p \cdot N_{ph}}} \text{ (in 1 dimension)}$$

Here, p is the size of a single pixel, and N_{ph} is the average number of photons incident on a CCD pixel.

The maximal pixel size is given by the Nyquist-Shannon theorem, or equivalently by the resolution limit of Abbe:

$$p_{mask} = \frac{1}{\beta} 0.25 \frac{\lambda}{NA}$$

Here, $\beta=1/4$ is the magnification from reticle to wafer.

As the pixel size approaches this limit, the MTF of the CCD already drops significantly. The image reconstruction algorithm enhances the spatial frequencies affected by this MTF drop, but inevitably it also enhances the shot noise. As a result, the CD error for large pixels exceeds the scaling given above. In Figure 6, this is visible for the 27nm pixels, which are exactly at the Shannon limit for NA 0.5.

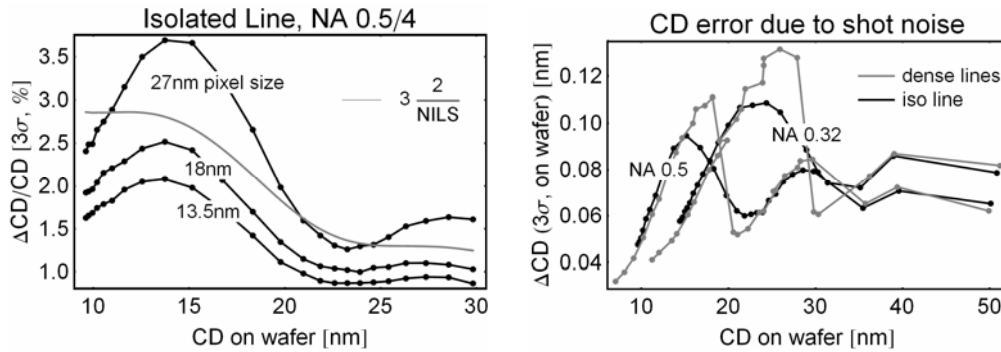


Figure 6 Left: Relative CD error induced by 1% shot noise for different pixel sizes. An isolated line was imaged at a scanner NA of 0.5. The gray line shows the analytic NILS based result for a long range noise with 1% dose variation. Right: CD prediction error as simulated for the AIMSTM error budget. The shot noise contribution is smaller than 0.125 nm on wafer level.

If the pixel size is chosen too small, the magnification of the optical system becomes unnecessarily large, leading to additional system complexity, additional cost and reduced transmission due to additional mirrors. As a tradeoff, we chose a pixel size of 18nm for the baseline configuration.

Taking the shot noise sensitivities from the calculation above, one can determine the maximum shot noise acceptable under realistic usage conditions. We concluded that 15 000 recorded photons are required per 18nm pixel to guarantee sufficient CD fidelity. Figure 6 (right) confirms a resulting CD prediction error of less than 0.125nm on wafer level.

4.2 Illumination System and Source Requirements

The illumination systems of EUV scanners are usually lossless, i.e. they work without vignetting. In contrast to this our system uses blades to provide the illumination flexibility as described above. Most of the EUV power supplied by the source is therefore vignettted at one of the stops in the system.

This is illustrated in a schematic overview of an illumination system in Figure 7 (left). In order to transfer the required brightness of the source to the mask a critical illumination setup may be considered. Most of the power will already be lost at the field stop, which is placed to select a sufficiently bright and uniform part of the field with dimensions corresponding to the field size of the mask, see Figure 7 (center). The illumination pupil will be formed by selecting a uniform portion of the source far field (Figure 7, right). Within that pupil aperture, another moveable blade needs to be implemented that follows the ring field.

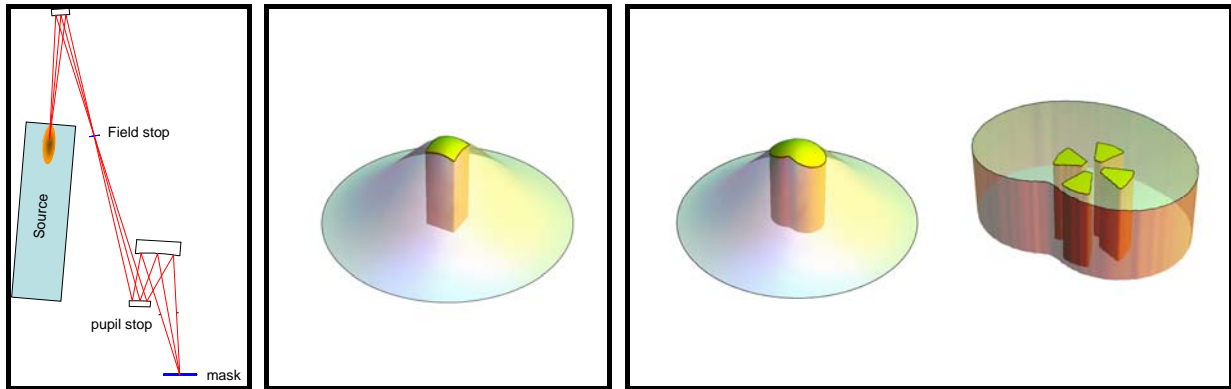


Figure 7 Concept for an illumination system (left). Illumination intensity in the field plane (center) and pupil plane (right). Center: Clipping is used in the field plane to select a sufficiently flat region. Right: Also in the pupil, we first need to select a region with sufficient illumination flatness, then a blade is used to cut the desired illumination setting from this region.

Taking into account these vignetting effects, the source power requirement is 600mW for a directed source with Gaussian profiles in the near and far field. Most sources however are not directed but emit radiation into the whole angular range. In this case, the power emitted in 2π will be several Watts, depending on the source size and on the emission characteristics. It is relevant for imaging that the pupil and field distributions shown above are constant in time, which directly translates to tight specifications on stability of the source emission characteristics.

The most significant challenge for the illumination system, however, is to provide a sufficient photon number into the small area of a pixel of $18 \times 18 \text{ nm}^2$ size, using the angles allowed by the scanner setting. The smallest setting supported has a solid angle of only 0.007 sr.

Using the anticipated transmission of the system, we estimate a minimal brightness of the source of $32 \text{ W/mm}^2/\text{sr}$. This number is calculated for “clean photons”. If there is transmission loss for debris mitigation, vacuum separation or wavelength filtering, the brightness at the source must be increased accordingly. It is physically impossible to increase the brightness in the illumination system. Therefore this specification is the prime number for the source selection.

5. SCANNER OPTICS TECHNOLOGY ENABLES AIMS™

Compared with traditional metrology optics, AIMS™ EUV has to deal with additional challenges: The system has to work in vacuum, refractive lenses can not be used any more, and EUV photons react very sensitive to surface inhomogeneities or contamination.

AIMS™ EUV would not be possible without the expertise gained with EUV optics over the last 15 years, which acts as a starting point for the development of AIMS™ specific EUV technology. Some examples for this technology transfer are given here.

5.1 Mirror polishing

While EUV mirrors with diameters of 10 inches or more are state of the art, and even aspherical mirrors can be manufactured, a microscope for EUV poses a special problem:

Due to the tiny numerical aperture at the image side, image quality and distortion is very sensitive to small deformations of the last optical surface. For example, microscope optics with NA 0.32/4 and magnification ratio 1:750, with 60cm distance from the last surface to the camera results in a subaperture of 60 μm radius. The challenge is to create a surface that provides lithographic optical quality on this tiny scale. Especially a local tilt of the last mirror surface leads to distortion and a non-uniform sensitivity of single CCD pixels that can not be calibrated. To make sure that the distortion does not exceed 10% of the pixel size, the roughness should be smaller than 35pm RMS within this small subaperture. In a previous study about eight years ago, this was regarded as a significant obstacle, and the concept of an all-EUV microscope was dismissed.

There has been dramatic progress in polishing technology for EUV mirrors, mainly driven by the requirement to reduce stray light in scanner projection optics. Based on recent measurements of current mirror surface quality, we are confident to limit the distortion to an acceptable level. Figure 8 illustrates this development.

In addition to the surface roughness challenges, the small mirrors are much more sensitive to particles or defects, compared to existing EUV optics. Special tooling and dedicated metrology will be needed for particle cleaning, coating, and handling of these mirrors.

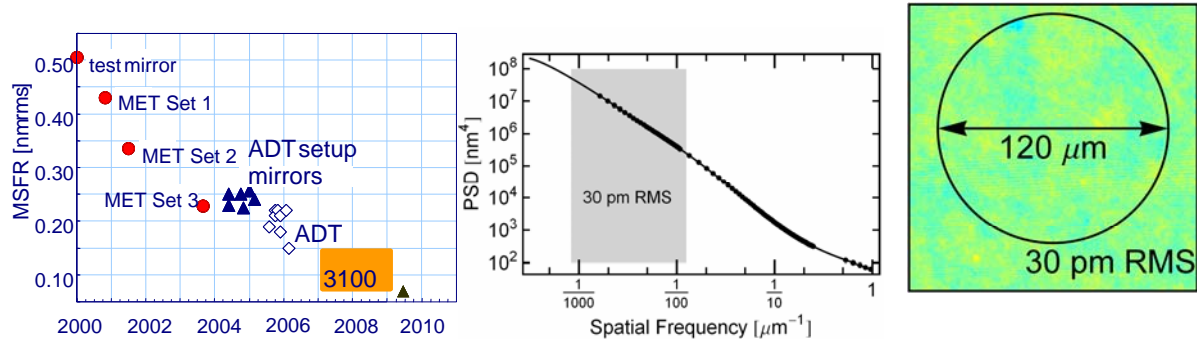


Figure 8 Left: Improvement in MSFR roughness of EUV mirrors. Center: Power spectral density curve of today's residual roughness. The gray inset indicates the frequency range relevant for the small mirrors. Right: Microinterferometric measurement of a champion surface. The circle indicates a typical subaperture. The relevant RMS inside this subaperture is less than 30pm.

5.2 Contamination control

Contamination of the optical surfaces is known to severely deteriorate the imaging capabilities of EUV optics. In a standard HV or UHV vacuum environment, the reflectivity of mirrors drops significantly as soon as the EUV light is turned on. As the major source of concern, hydrocarbons of large molecular weight have been determined.

To enable a sustained operation of EUV, we have developed new methods and processes to create and maintain significantly reduced levels of hydrocarbons within the optical path. Prior to the assembly of the system, we have a cleaning strategy consisting of wet and dry cleaning steps. As an example, Figure 9 shows the residual spectrum of heavy hydrocarbons emitted by a typical vacuum component. Starting from a standard UHV component, further cleaning in our dedicated EUV cleaning facilities suppresses the emission further by two orders of magnitude to reach EUV vacuum quality. These methods reflect the experience from the EUV alpha demo tool and prior small field exposure optics, and are being perfected for the ASML NXE 3100 wafer scanner.

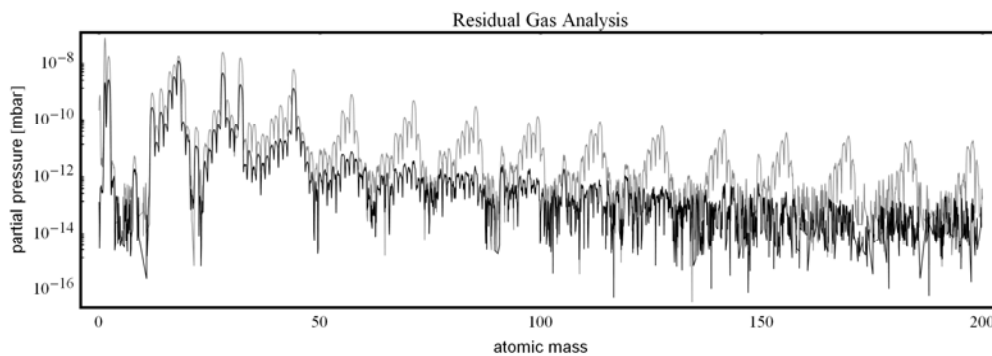


Figure 9 Residual Gas Analysis of a mechatronical component for the 3100 scanner optics. The grey line shows the status before cleaning, the black line gives the residual value after cleaning. For the relevant outgassing of heavy hydrocarbons, a suppression factor of 100 could be achieved.

After cleaning, we have to continuously monitor the cleanliness during manufacturing and assembly. To avoid further contamination, the environment in the class 100 clean room and the tooling is built with a restricted material selection.

To prevent contamination during the use of the optics, we have to use further restriction in the materials used inside the vacuum chamber. Straylight induced outgassing or degradation of components is prevented by using dedicated design rules for the components. The built-up of contaminants on the EUV multilayers is further reduced by a vacuum compartment separating possible contamination emitters from the optical surfaces. As a final means of ensuring the optics lifetime over many years, we implemented means to actively clean contaminants from the mirror surfaces.

The success of all these measures is demonstrated in Figure 10, which shows that contamination induced degradation of the optical quality poses no problem today.

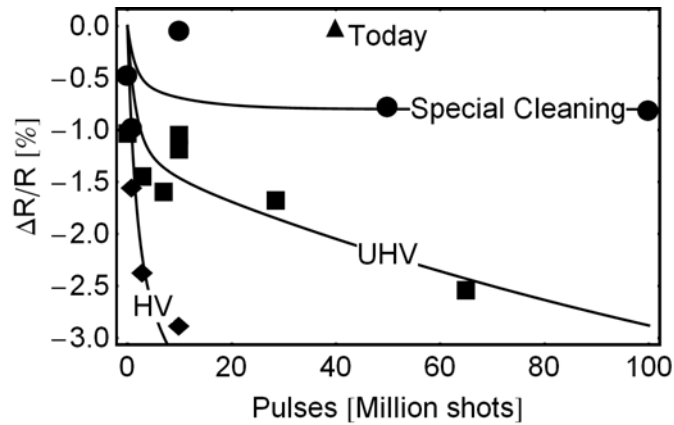


Figure 10 The graph shows the reflection loss of a multilayer in a test chamber under conditions comparable to the projection optics⁷. Starting first with high vacuum cleanliness standards, later upgrading to UHV standards, we observed a significant reflection loss that posed a serious difficulty to multi mirror optical systems. Developing special cleaning strategies as described in the text, we arrived at an acceptable level of reflection loss. Today, after further improvement of our cleaning strategie, a drop of reflection can not be measured any more.

For the optical system of AIMS™, we can select from a broad spectrum of contamination avoidance methods. And we can use the contamination modeling developed for scanners to determine which methods are required and what can be skipped due to the lower power levels in this system.

5.3 EUV Metrology experience

AIMS™ EUV is different from a VUV AIMS™ not only in wavelength, but in many engineering aspects. Therefore it was very important already from the beginning to transfer system know how from the in house metrology systems built to qualify ADT and 3100 scanner optics.

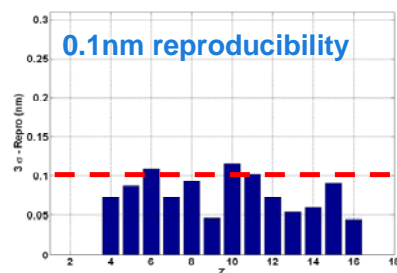


Figure 11 System wavefront interferometer at EUV wavelength. The vacuum vessel can be opened completely to allow to insert six mirror scanner optical systems. On the right hand side, the reproducibility of the wavefront measurements is shown.

From the actinic system metrology tool shown in Figure 11, we can transfer system design know how and several detailed solution. We gained experience in the EUV metrology source, built a small field illumination system, and a

metrology stage meeting EUV vacuum requirements. For the blades, we can use some of the experience with mechatronics inside EUV vacuum. Finally, experience from image sensors in EUV vacuum can be transferred.

6. SUMMARY

For aerial image review, the transition from VUV to EUV involves significant development efforts on almost all components of the system. Our assessment of the feasibility of such a system identified that many of these developments can be done based on EUV scanner technology. The new technology required for a development of AIMS™ EUV includes small field mirrors, a EUV vacuum compatible stage with large flexibility, together with some mechatronics development, and finally bright and stable enough light source. Each of these technologies poses some risk to the project, but overall we are confident that we can build an AIMS™ EUV to meet the industry's needs.

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