# Scanner arc illumination and impact on EUV photomasks and scanner imaging 

Renzo Capelli ${ }^{1}$, Anthony Garetto ${ }^{2}$, Krister Magnusson ${ }^{1}$, Thomas Scherübl ${ }^{2}$<br>${ }^{1}$ Carl Zeiss SMS, Rudolf-Eber-Straße 2, 73447 Oberkochen, Germany<br>${ }^{2}$ Carl Zeiss SMS, Carl-Zeiss-Promenade 10, 07745 Jena, Germany


#### Abstract

The combination of a reflective photomask with the non-telecentric illumination and arc shaped slit of the EUV scanner introduces what are known as shadowing effects. The compensation of these effects requires proper biasing of the photomask to generate the intended image on the wafer. Thus, the physical pattern on the mask ends up being noticeably different from the desired pattern to be written on the wafer. This difference has a strong dependence on both the illumination settings and the features to be printed. In this work, the impact of shadowing effects from line and space patterns with a nominal CD of 16 nm at wafer was investigated with particular focus on the influence of pattern orientation and pitch, illumination pupil shape and fill (coherence) and absorber height. CD, best focus shift and contrast at best focus are utilized in detail in order to study the impact of the shadowing effects. All the simulation cases presented employ a complete scanner arc emulation, i.e. describe the impact of the azimuthal angle component of the illumination arc as in the NXE:3300 scanner and as it can be emulated by the AIMS ${ }^{\text {TM }}$ EUV.


KEYWORDS: EUV photomask, shadowing effect, EUV scanner, illumination slit, compensational repair, EUV absorber, photomask bias, defect inspection, AIMS ${ }^{\text {TM }}$ EUV.

## INTRODUCTION

The technological step required by the introduction of EUV lithography into high volume manufacturing can be considered the most complex within the development of photolithography over the last several decades. Waiting for the whole infrastructure to be available and make EUV a reality, some of the most challenging characteristics can be modelled and studied with the support of simulation platforms in order to achieve the best understanding of the EUV lithographic process and the interplay between the several parameters which describe it. One of the most critical of these aspects is related to the manufacturability of the EUV photomasks, a complex reflective optical component, whose reflectivity is based on the in-phase addition of reflections coming from each boundary of a Molybdenum (Mo) Silicon (Si) multi-layer (ML) structure.

The fact that the EUV photomask is a reflective optical component, as are all optics in an EUV system, requires the illumination of the features printed on the mask to be non-telecentric. In this scheme EUV illumination of the photomask is not normally incident onto the reticle, but has an offset inclination described by a chief ray angle (CRA) of 6 degrees. Depending on the shape of the pupil and upon its coherence, the mask is illuminated with a variety of angles distributed around the CRA. The reason behind this oblique illumination is that the incident ray bundle must be physically decoupled from the one which is reflected from the mask and collected into the projection optics system.

Oblique illumination of three-dimensional mask structures introduces a new aspect with respect to the EUV lithographic process, known as shadowing effects. The overall effect produced by the absorber onto the mask reflective structure and back to the projection optics is a complex combination of angular illumination efficiency and mask reflectivity, meaning that the illumination conditions strongly influence the final printed results. To make the picture even more complex, exposure of EUV photomasks in a high volume manufacturing (HVM)
scanning system (i.e. ASML NXE:3300) is performed through an arc shaped slit which spans a linear size perpendicular to the scanning direction of approximately 100 mm , in which the pupil is kept on axis with the scanning direction throughout the whole illumination field. The three-dimensional direction of an EUV photon can therefore be described by two angles: the CRA $\theta$, which remains constant through the whole illumination domain, and the azimuthal angle $\phi$, which can vary in the range $\pm 18.6$ degrees. Targeting the complete emulation of the scanner imaging process, the AIMS ${ }^{\mathrm{TM}}$ EUV platform matches this sophisticated exposure scheme, although engineered to target a much smaller field ${ }^{1}$.
The arc shaped illumination setup has to be taken into account during mask design. Clear and opaque features are illuminated with different sets of angles depending on their $x$ coordinate on the photomask; as a result, the aerial image of the same structure varies across the $x$ direction. Heavy optical proximity corrections (OPC) must be studied and applied to the mask structures in order to print at target across the whole exposure field; as a consequence, the physical pattern on the mask ends up being noticeably different from the desired pattern to be written on the wafer. This is an application where AIMS ${ }^{\mathrm{TM}}$ EUV will play a leading role as actinic review of EUV photomasks is able to thoroughly determine the overall printing behaviour of biased EUV photomasks.

In this work, the printing process of EUV scanners is discussed with respect to shadowing effects. Special attention is devoted to the impact that the arc shaped illumination has on the shadows produced by the EUV photomask. The structures which have been investigated are lines and spaces with vertical (V), horizontal (H) and 45 degrees inclined orientation, with a 16 nm (at wafer level) minimum half pitch; this can be considered as the 7 nm node, which is also the target for AIMS ${ }^{\mathrm{TM}}$ EUV. The main goal of this work is to highlight the complexity of EUV imaging in terms of mask biasing; more than for DUV lithography, the physical size of the structures on the EUV photomask will differ from a 4x replica of the wafer target. Actinic aerial image inspection will therefore assume a key role within the photomask production line.
The following sections include the study of the shadowing effects and their dependence on structure pitch, pupil shape and coherence and absorber height. In order to best simulate the imaging process, the shift of the best focal position and contrast through focus are taken into account in order to emulate the workflow as employed in AIMS ${ }^{\text {TM }}$ EUV.

## DESCRIPTION OF SHADOWS

Figure 1 presents a conceptual diagram of the shadowing effects introduced by non-telecentric illumination of EUV photomasks. The reflective portion of the EUV reticle is composed of $\sim 40$ bilayers of $\mathrm{Mo}-\mathrm{Si}$ which provide a peak reflectivity at 13.5 nm wavelength of about $69 \%^{2,3}$.
Each boundary between two subsequent layers contributes only to a small portion ( $\sim 0.1-0.3 \%$ ) of the whole reflectivity of the ML. This means that two EUV photons with the same energy and incidence angle can be reflected at different locations within the ML structure, one being reflected and channelled towards the projection optics, the other being absorbed by the back side of the absorbing structures on its way back out of the mask surface (see Figure 1). This simplified visualization of the reflection process gives a basic idea of the high complexity of the EUV reflectivity process.
Additionally, due to the finite area of the pupil, the mask is illuminated with a distribution of angles centered around the CRA, all of which contribute in shaping the aerial image or the wafer print. EUV ML reflectivity is strongly dependent on the incident angle of the photon, and therefore different regions within the same pupil may give a different contribution to the imaging performance ${ }^{4}$. This short introduction is necessary to justify the use of simulation platforms as the only investigation method of shadowing effects and their effect on scanner imaging performance, before actinic imaging with AIMS $^{\mathrm{TM}} \mathrm{EUV}$ will be available.

In order to give a quantitative description of the difference between a geometric calculation and an actual simulation result, the right panel of Figure 1 presents the formulas for the shadows which are produced on a EUV photomask: this quantity depends on the absorber height, the penetration depth into the ML structure (which together with the absorber height gives the effective height $\mathrm{h}_{\text {eff }}$ to consider for the shadow calculation), the CRA, and the magnification of the projection system. In order to obtain the results shown in the left panel of Figure 2, azimuth angles of $0 \pm 18.6$ degrees are considered for H lines, $90 \pm 18.6$ deg for V lines and $45 \pm 18.6 \mathrm{deg}$ for 45 deg oblique lines.


$$
\begin{aligned}
& C D_{\text {printed space }}=C D_{\text {desien }}-\left(2 h_{e f f} \tan \theta\right) \times M \times \cos \phi \\
& C D_{\text {printed space }}=C D_{\text {desien }}+\left(2 h_{e f f} \tan \theta\right) \times M \times \cos \phi
\end{aligned}
$$

$$
\text { shadow }=2 h_{e f f} \tan \theta \times M \times \cos \phi
$$



Figure 1. Sketch of the structure of a typical EUV photomask (left) together with the geometrical description of shadows created on EUV photomasks during imaging. The green and black printed space widths correspond to different penetration depths of EUV photons. The parameters shown in the formulas (top right) are: the absorber height d, the CRA $\theta$ ( 6 degrees), the effective absorber height $h_{\text {eff }}$ (absorber height $d+$ penetration depth), the magnification $M$, and the azimuthal angle $\phi . A$ simple sketch of the lines and spaces structures considered throughout the whole paper is also shown at the bottom right.

In the processing of an EUV photomask, three different components are required to create a proper bias process:

1. Process bias, known from DUV lithography. The physical mask features are not an exact 4 x replica of the target features on the wafer. This production process driven bias takes into account the steps needed to produce the mask (e-beam writing, etch...) and it will not be considered in this work.
2. Global bias. This bias is needed in order to compensate for the non-telecentric illumination of the photomask, specifically its dependence on the $\theta$ component of the CRA. This bias is process and structure dependent, and it can be thought as the $\Delta C D$ that must be printed on mask in order to print the features at target in the center of the scanner illumination field. In this work, an orientation dependent bias is applied to the every simulation setup so that a line of 16 nm (wafer level) is printed at target in the center of the imaging field $(\phi=0)$, regardless for its orientation or the process used to image it.
3. Azimuthal bias. This bias is also needed to take into account the shadowing effects introduced by the non-telentricity of EUV systems at mask level. However, the local $\Delta C D$ is dependent on the $\phi$ component of the CRA introduced by the arc shape of the illumination field; this bias is also process and structure dependent.

The third component of the photomask bias as described above will be the focus of this work; as a consequence, the $C D$ values measured from the simulations presented in this work at $\phi=0$ will always be the target $C D$ of 16 nm.

## SHADOW DEPENDENCE ON FEATURE ORIENTATION

The resulting CD derived from the geometrical approximation introduced in the last section as a function of its position along the imaging slit (azimuthal $\phi$ angle within $\pm 18.6$ degrees) for lines and spaces with nominal CD of 16 nm (at wafer level) and an absorber height of 50 nm ( $\mathrm{h}_{\text {eff }}=\mathrm{d}$ for the geometrical approximation) is shown in the left panel of Figure 2. The result of a first simulation run of the same setup as described for the geometric case, with a disar 0.6-0.9 as illumination pupil is shown in the right panel of Figure 2. The deviation from the target CD of 16 nm of the plot represents the impact of the azimuthal angle component of the scanner arc imaging, i.e. what in this paper is called azimuthal bias. V lines at the edge of the slit print larger than target CD,
whereas H lines print smaller and the 45 deg oblique lines print larger to smaller across the entire field, and therefore must be subject to the most severe bias (up to 8 nm difference at mask level between structures at $\phi=-$ 18.6 deg and $\phi=18.6 \mathrm{deg}$ ).

The overall behaviour within the same orientation (H-V-45 deg) is similar to that derived through the geometrical calculation, although differences are noticeable through a closer inspection. The shape of the curve representing V lines is rounded and the impact of the azimuthal angle on the printed CD is noticeably reduced, whereas for H lines it is increased while keeping the overall trend unaltered. The behaviour of the CD through azimuthal angle for the 45 deg oriented lines is subject to the largest difference: the CD printed at the edges is larger than for the V lines, with a difference between the two edges of the exposure field of about 2 nm (at wafer level). This graph can also be read from the perspective of the bias to be applied to the mask features in order to print all orientations across the illumination slit at the target CD of 16 nm . Assuming a global bias has already been applied in order to print all three orientations separately at 16 nm in the center of the slit ${ }^{5}$, a second bias in needed in order to compensate for the scanner arc shaped illumination mentioned above. In this context, a negative bias must be applied to V lines across the mask, whereas H lines require a positive bias. 45 deg inclined lines need a negative bias at the $\phi=-18.6$ deg edge, and a positive bias at the $\phi=18.6 \mathrm{deg}$, being the largest in size amongst the three considered orientations.


Figure 2. Left: Calculation of shadows produced for 1:1 V, H and 45 deg oriented lines via the geometric approximation. Right: shadowing effects results for the same structures as given by a $0^{\text {th }}$ order simulation.

This first simulation serves as a reminder of the importance of simulation capabilities in the calculation of the proper bias and OPC structures to be applied to the features printed on a EUV photomask in order to print the desired pattern. Given the importance of bias structures and OPC in EUV lithography, the AIMS ${ }^{\mathrm{TM}}$ EUV platform will become even more indispensable for proper scanner emulation and OPC correction and verification. In the next sections it will be shown that the bias to be applied to all features is a function of several lithographic parameters. The important consequence, and fundamental difference to DUV lithography, is that the manufacturing of the EUV photomask must be done with the preceding knowledge of all the parameters of the lithographic process that will be used to print the mask itself.

## SHADOW DEPENDENCE ON PITCH

A further lithography parameter considered in this work is the pitch of the structures printed on the photomask; dense and isolated lines and spaces will be considered, with pitch values between 32 nm (duty cycle 1:1) and 128 nm (duty cycle 1:7) at wafer level, and the three orientations described in the last section. From current lithography processes it is known that dense and isolated structures have best focal planes which noticeably differ from each other. In order to give a thorough description of the impact of the arc shaped illumination on structures with different pitches, a study of the shift of the best focal plane in response to a pitch variation has first been carried out.

In order to calculate the shift of the best focal plane within the simulations run, contrast versus defocus curves at the center of the slit $(\phi=0)$ have been considered. Assuming that the best focal plane is in the center of the process window and provides the maximum imaging contrast, the shift of this plane can be calculated separately for each simulation setup undertaking the following steps:

1. Fit of the contrast vs. defocus curves with a polynomial function of degree 6 . The degree must be an even number in order to provide symmetry with respect to the best focal position. Six is the first even degree above which no improvement of the fit residuals can be noticed.
2. Analytically find the maximum point of the derivative of this best fit function. The abscissa coordinate of this point is the best focus shift value to employ as input parameter of the defocus corrected simulation setup.


Figure 3. Left: Shift of the best focal plane (nm at reticle level) through pitch for $V$, $H$ and 45 deg lines, measured at $\phi=0$. Right: Aerial image contrast through pitch for the same structures, also measured at $\phi=0$.

The left panel of Figure 3 shows the shift of the best focal plane for lines and spaces as a function of pitch for all three orientations considered in this work. As the pitch of the structure increases, a noticeable shift of the best focus plane towards negative defocus is observed. The values for the best focus shift here reported are to be considered as differential measurement, having full meaning only with respect to one another and not as an absolute measure of the best focal plane. All line orientations are subject to the same general behaviour of the best focus plane shift as a function of the structure pitch: an increasing pitch always translates into a negative shift (away from the mask) of the corresponding best focus position. The largest shift for the simulation cases employed in this work is measured to be 25 nm (mask level) and applies to V lines with 1:1 to 1:7 (denseisolated) duty cycles.
This relationship is particularly relevant to logic designs, where different pitches and orientations are printed on the photomask and, as a consequence, scanning single exposure can not print all the features at best focus on wafer. This case does not however apply to the AIMS ${ }^{\text {TM }}$ EUV platform, where the through focus aerial image stack is by default centered in the best focal plane, although manual operation also allows to emulate the scanner defocus. In the case that multiple different features are contained within the AIMS ${ }^{\mathrm{TM}}$ EUV field of view, the impact of the defocus as it will be on the scanner will be measured, giving a tighter control on the process window parameters. As the depth of focus for the first generation EUV lithography scanner is larger than 100 $\mathrm{nm}^{6}$, the displacement of the best focal plane in response to the change of the structure pitch can be as high as $\sim 25 \%$ of the entire budget. Although within the depth of focus, this is a substantial portion of the budget and the process window may be, as a result, severely reduced.
As a further measure of the influence pitch has on imaging, the right panel of Figure 3 shows the contrast at best focal position for the simulated test cases. As known also from DUV lithography, patterns with increasing pitches are imaged with a lower contrast. This holds for all orientations, with H lines providing in general a
higher contrast with respect to the other orientations considered here. Contrast differences due to pitch and orientation change are however a rather small effect, with a difference between the highest contrast for 45 deg lines with a $1: 1$ duty cycle and the lowest contrast of the V lines at pitch $1: 7$ of about $10 \%$.

The defocus corrections as displayed in the left panel of Figure 3 were applied to the new simulations setup. The impact of the azimuthal angle of the EUV illumination on the shadowing effects for $\mathrm{V}, \mathrm{H}$ and 45 degrees oriented lines derived applying the defocus correction to all simulations setup is shown in Figure 4 for dense, semi-isolated and isolated patterns, corresponding to pitch values of $32 \mathrm{~nm}(1: 1), 64 \mathrm{~nm}(1: 3)$ and $128 \mathrm{~nm}(1: 7)$.


Figure 4. Dependence of the shadowing effects across the illumination field on the structure pitch. All test cases are biased in order to give a $C D=16 \mathrm{~nm}$ at the center of the scanner exposure field.

Some observations can be drawn on the basis of the set of simulation results presented in Figure 4. First, the overall shape of the CD curves as function of the azimuth angle supports the trend first described in the right panel of Figure 2. The pitch impact can be roughly described as a fine tuning of this general behaviour. Secondly, regardless of the orientation of the pattern, dense pitches need to be printed on the photomask with a larger bias in order to compensate for the arc-shaped illumination of the EUV scanners. Third, the largest variation of the CD measured at the edge of the slit occurs during the transition from dense to semi isolated structures ( $1: 1$ to $1: 3$ duty cycles). The variation from semi isolated to isolated structures ( $1: 3$ to $1: 7$ duty cycles) are significantly smaller. Looking at the dashed red lines in Figure 4 , the shadowing effects on H lines suffer no noticeable variation to a variable pitch (higher than $1: 3$ ) with respect to the azimuthal angle. Fourth, the highest variation within the CD values measured for a single pattern orientation at the edge of the illumination field for different pitches is measured within V lines (STDEV 0.4), whereas the smallest is observed for H lines (STDEV $0.1)$.
In order to quantify the impact of the pitch variation on the shadowing effects measured across the illumination field, a percentage variation can be calculated which considers the CD printed at the edge of the field for dense (1:1) and isolated (1:7) lines. The resulting values for this quantity are $4 \%$ for the V lines, $0.6 \%$ for horizontal and $1,5 \%$ for 45 degree oriented lines: if, for example, $1: 1 \mathrm{~V}$ lines would be biased as for $1: 7 \mathrm{~V}$ lines instead, the CD resulting at the edge of the slit would differ $4 \%$ from the target. Assuming a $5 \%$ specification requirement for the measured CD, all structures at $\phi= \pm 18.6$ deg which were considered here would be printed in specification even with no correct pitch based bias applied to the structure printed on the photomask.

A further issue to be addressed in the context of the characterization of the shadowing effects dependence on the structure pitch is the impact of the pitch driven defocus correction (see left panel of Figure 3) on the measured CD across the field. For this purpose, the CD values at the edge of the slit for V, H and 45 deg oriented lines and spaces with 128 nm pitch (1:7, the value which nominally has the largest focus shift for all three orientations) have been compared before and after correction for the best focal plane shift. The difference between these two values, which quantifies the way the azimuthal angle component impacts the shadowing effects, is measured to be within $0.1 \%$ for all test cases.
Based on the previous results, it can be concluded that the impact of the azimuthal angle of the illumination on the shadowing effects with respect to pitch variation is a minor one.
The results presented in this and following sections are based on simulations which consider only a few of the several parameters which determine the entire lithographic process. They serve as guidelines to achieve understanding of the interplay of the different parameters within the EUV lithographic process, as well as to gain the confidence that shadowing effects can be tightly predicted and controlled with currently available technologies. Other works have addressed the best focus shift dependence on other process parameters; for example, the displacement of the best focal plane through pitch also has a strong dependence on the illumination settings ${ }^{7}$, of which this section considered only one setup configuration.

## SHADOWS DEPENDENCE ON ILLUMINATION PUPIL

The third parameter considered is the pupil shape and its coherence. The pupil used to illuminate the structures on the photomask has an impact on the shadows produced by the lithography process. The way shadows change depending on the azimuthal angle of the EUV illumination is also dependent on the pupil shape and coherence, and must be carefully investigated for the final modelling of the structure across the whole photomask.

In this section, a description of the dependence of the shadows introduced by the arc shaped illumination on the pupil is given. In these simulations of 16 nm line and space patterns with a 32 nm pitch (wafer level), an absorber height of 50 nm has been considered. Annular and disar pupils are employed with a variable coherence, which spans the range 0.2-0.9 in steps of 0.1 while keeping the outer radius of 0.9 constant. Fundamental quantities like best focus shift in response to mask and system parameter change and contrast at best focus are considered as input and control parameters of the simulations.

Values for the best focus shift and contrast at best focus were calculated as in the last section and they are shown in Figure 5, in which the disar and annular pupil cases are respectively shown in the left and right panels. The blue data points in each plot show the shift of the best focal plane (at mask level) as a function of the inner sigma used for the illumination pupil. Ranging from the most to the least coherent illumination settings, the shift of the best focal plane for both pupil shapes can be as high as 50 nm . Once the displacement of the best focal plane is taken into account the imaging performance is also improved; contrast enhancement is measured to be on the order of $14 \%$ for the disar pupil and $7 \%$ for the annular pupil. As already stated for the pitch section, the measurements of the best focus shift have to be considered with respect to one another and not as an absolute estimation of the best focal plane vertical position.


Figure 5. Shift of the best focal plane (nm at reticle level) and aerial image contrast improvement after defocus correction for 1:1 vertical lines and spaces. The pupil symbols on the top corners are only used to distinguish between the disar (left) and annular (right) cases.

Once the defocus correction described in the preceding paragraph and plotted in Figure 3 has been input to the simulation setup, simulations were run in order to describe how the shadowing effects respond to the azimuthal angle component of the scanner illumination slit for different illumination setup. A set of results for V lines and spaces pattern with a $1: 1$ duty cycle (pitch 32 nm ) is presented in Figure 6. In the plot, the CD measured across the arc-shaped slit is plotted against the azimuthal component of the CRA (directly convertible to an X position on the mask). Some observations can be drawn: first, for all simulated cases, the typical "U" shape describing the impact of the azimuthal angle on the shadowing effects for V lines structures has been found. The individual shape is slightly modified by lithographic parameters such as the pupil shape and coherence.


Figure 6. Impact of the scanner arc-shaped illumination on the shadowing effects of $V$ lines with different pupil shape and coherence. In this graph, only $\sigma_{i n}=0.2$ and 0.8 have been plotted for reading ease.

Second, the annular pupil leads to larger shadowing effects than the disar pupil for all coherence settings. Focusing on the extreme values for $\sigma_{\text {in }}\left(\sigma_{\text {in }}=0.2\right.$ and $0.8, \sigma_{\text {out }}$ fixed at 0.9$)$, we measured a $\Delta \mathrm{CD}$ at the edge of the illumination slit between the annular and disar pupils with the same $\sigma_{\text {in }}$ of 0.3 nm and 0.1 nm at wafer level. This translates into a $\Delta \mathrm{CD}$ at mask level of 1.2 and 0.4 nm respectively, which represent the difference in the amount of bias that must be applied to V lines at this nominal position on the mask. The fact that all curves give 16 nm in the center of the field reflects the global bias applied to every simulation setting all features to 16 nm in the center of the field, in order to highlight the impact of the arc shaped illumination alone.
Third, shadowing effects within the annular pupil (red curves in Figure 6) respond differently to a varying coherence only in the outermost half of the field. For the disar pupil, this difference is noticeable across the whole domain, since the dashed and solid blue lines in Figure 6 are never overlapping each other.

Fourth, Coherence has an opposite impact on the shadowing effects for the two pupil shapes employed in this example. A smaller coherence (larger $\sigma_{i n}$ ) produces a larger shadow at the edge of the slit for the disar pupil, whereas for the annular pupil the effect is reversed. Although the shadow is larger for a disar pupil with $\sigma_{\text {in }}=0.8$, the image contrast is the highest registered ( $94 \%$ ).

The dependence of the shadowing effects across the azimuthal angle illumination due to the pupil shape and coherence is a small effect with the largest differences calculated on the order of 1.2 nm at mask level. It is however important to describe the dependence of shadowing effects on the illumination setup in order to correctly bias a photomask across its whole patterned surface, in this way maximizing the process window. The results from this section have also been considered as base to select proper illumination settings for the study of the impact on shadowing effects across the illumination field of quantity such as the structure pitch (previous section) and the absorber height (next section). Disar and annular pupils with a $\sigma=0.6-0.9$ have been selected for this purposes because they provide average shadow effects and good contrast for the $1: 1$ pitch case with 50 nm absorber height.

## SHADOW DEPENDENCE ON ABSORBER HEIGHT

The last parameter that has been considered within this work is the height of the absorber. The goal of this section is to describe the impact of the azimuthal angle component of the CRA on the imaging of L/S structures in relation to its dependence on the absorber height. Two application relevant topics have been considered: the impact of a clear absorber repair (deposition) with an incorrect height and the overlay error introduced by a nonuniform absorber height deposition.

The CD printed at a certain $X$ location (or azimuthal angle $\phi$ ) $\mathrm{CD}_{\phi}$ can be written as the target CD plus a structure and process dependent shadow $\Delta \mathrm{CD}_{\phi}$. In formulas:

$$
C D_{\phi}=C D_{t \arg e t}+\Delta C D_{\phi},
$$

where the $\phi$ index identifies a certain azimuthal angle within the range $\pm 18.6 \mathrm{deg}$, and the factor $\Delta \mathrm{CD}_{\phi}$ represents the shadow produced on the aerial image. This can also be written in an explicit form as

$$
\Delta C D_{\phi}=2 h_{e f f}(\tan \theta) \times M \times \sin \phi,
$$

with $\theta=6 \operatorname{deg}$ CRA and $M=4$ magnification factor. The quantity $h_{\text {eff }}$ can be thought as an effective height which takes into account both the height of the absorber on top of the photomask, and the penetration depth of the EUV photons within the multi-layer reflective structure of the photomask itself. Whereas a linear relation exists between $h_{\text {eff }}$ and the absorber height, the relation between $h_{\text {eff }}$ and the penetration depth cannot be easily put into a geometric formula, due to the complex nature of EUV reflectivity. The dependence of the CD variation in response to an absorber height variation has been investigated in the literature ${ }^{8}$. Rigorous simulations show an increase (decrease) of the measured CD at wafer level for increasing (decreasing) absorber thickness, with embedded oscillations showing a period of about half the exposure wavelength ${ }^{9}$. This effect has also been confirmed experimentally via wafer print studies ${ }^{10}$. As a conclusion, a direct proportionality between CD and absorber thickness variation can be expected, which will affect the overall dependence of the shadowing effects on the absorber height across the scanner illumination field.
The results of simulations run for the two different pupil shapes are shown in Figure 7. As reported in Reference 7, the absorber height also has an impact on the best focal plane: different height values are focused at different vertical planes. This has been taken into account within the simulation setup, with the best focus shift being calculated from the contrast vs. defocus curves as explained in the previous sections. Typical values are within 25 nm at reticle level.


Figure 7. Shadowing effects through the illumination field due to the azimuthal angle component of the CRA for different absorber height values (40 to 70 nm ). Panels in the left (middle, right) column show the V (H, 45 deg ) lines test cases illuminated with a disar (top) and annular (bottom) pupil.

This work considers values for the absorber height between 40 and 70 nm , in 10 nm steps. The simulations presented in this section have been run for all three orientations of $1: 1 \mathrm{~L} / \mathrm{S}$ patterns illuminated by disar and annular pupils with $\sigma=0.6-0.9$. As it is clear from the plots shown in Figure 7, the overall trend of the shadowing effects across the mask illumination field remains the same through the different values of absorber height which have been considered. As expected, the shadows produced at the edge of the slit, i.e. the deviation from the target CD value of 16 nm , are larger for higher absorber height for all orientations. It is interesting to describe in detail the behaviour of the printed CD at the azimuthal angle coordinate $\phi= \pm 18.6 \mathrm{deg}$. For this purpose a cut of the previously presented data on the edge of the illumination field has been performed and the results of this procedure are presented in Figure 8 in order to display the dependence on the absorber height of the shadows produced on the EUV photomask.


Figure 8. CD measured at the edge of the scanner slit for disar and annular illumination pupils for $V$ and $H$ lines (left panel) and 45 degrees oriented lines (right panel). $L$ and $R$ indexes in the right panel refer to the left and right of the slit, i.e. the coordinates $\phi=-18.6 \mathrm{deg}(L)$ and $\phi=18.6(R)$.

As previously discussed, the proportionality between the magnitude of the shadowing effect and the absorber thickness cannot be expected to be perfectly linear, because of inherent oscillations of this dependence typical of the process. However, a global trend can be observed within all test cases which were simulated in this work. Quantitatively, a first order estimation of the variation of the shadow $\Delta \mathrm{CD}_{ \pm 18.6}$ per nm absorber height can be derived by dividing the difference $\mathrm{CD}_{\phi= \pm 18.6}(70 \mathrm{~nm})-\mathrm{CD}_{\phi= \pm 18.6}(40 \mathrm{~nm})$ by 30 nm , which represents the total range of absorber height used in the simulated cases. This indicates values between 0.2 nm (green curve in the right panel of Figure 8 ) and $1 \mathrm{~nm}(45 \mathrm{deg}$ lines at $\phi= \pm 18.6 \mathrm{deg}$ with annular pupil).

A fundamental application within photomask processing which is very sensitive to the height of the absorber is defect repair. The simulations presented in Figure 7 and Figure 8 can be further extended in order to investigate the impact of an absorber defect repair performed with an inaccurate absorber height, and relate it to the capabilities of the MeRiT® repair tool which presently offers processes for EUV absorber defect repair and compensational repair of multi-layer defects ${ }^{11,12}$.

To quantify the impact of an absorber repair with incorrect height, $\mathrm{V}-\mathrm{H}$ and 45 deg lines with a $1: 1$ duty cycle illuminated with a disar 0.6-0.9 pupil have been considered. For each structure, three azimuthal angles have been taken into account and simulated for: the center ( $\phi=0 \mathrm{deg}$ ) and the two edges of the imaging slit ( $\phi= \pm 18.6$ deg). All combinations of structures and positions have been biased in order to print at the target CD of 16 nm at wafer level. The fundamental difference with all simulations reported above is that structures at the edge of the mask have also been subject to azimuthal bias, and therefore fully resemble the on-target features patterned on the final product mask. This is essential in order to quantify the difference in shadows introduced by the absorber height parameter within a repair process, where the features should be biased ahead of time to print at target across the whole field. Figure 9 shows the results of this investigation. Structures biased for 40 nm (top part of the left panel) and 70 nm (bottom part of the left panel) nm height have been simulated to be repaired with 70 (over-deposition) and 40 (under-deposition) nm height, respectively; the error in the absorber deposition process introduced in these simulations is therefore 30 nm . The value of the $\Delta \mathrm{CD}$ introduced by the erroneous repair with respect to the target $\mathrm{CD}, \Delta \mathrm{CD}=\mathrm{CD}-16 \mathrm{~nm}$, is plotted for all test cases in the left panel of Figure 9 . Here, the typical $5 \% \Delta C D$ specification for absorber repair process is plotted as a dashed black line at $\Delta C D= \pm 0.8 \mathrm{~nm}$ for both the over-deposition and under-deposition cases.


Repair number for over and under deposition
under-deposition

Azimuthal angle across the slit ( $\mathbf{\pm 1 8 . 6}$ deg)
Figure 9. Left: Impact of incorrect absorber height onto the repair process of an absorber defect. Over and under deposition cases are shown in the top and bottom panels respectively. The black dashed line represents a $5 \%$ CD specification common in defect repair. Right: Repair number for the different test cases described in the text.

From the plot it is noticeable that H lines have the highest $\Delta \mathrm{CD}$ at the center, and this quantity diminishes towards the edge of the slit; the impact of a repair with a height deviating from the nominal on H lines is therefore higher in the center of the imaging field than at the edges. This property can be expected, since it has already been shown that H lines need the highest compensation for the azimuthal bias at $\phi=0$ deg. For V lines this effect is the opposite, whereas for the 45 deg lines the impact is variable across the entire field. In order to better quantify the process sensitivity to a non-nominal repair height, the repair number shall be introduced. This is a typical quantity used in the process of defect repair, defined as $C D$ variation per nm absorber height deposited (or etched). For the test cases presented in Figure 9, this number can be derived by dividing the $\Delta \mathrm{CD}$ values by the 30 nm difference in absorber height (for nominal and repair). Throughout the calculations, a linear trend of the $\Delta \mathrm{CD}$ vs absorber height has been assumed; as it has been shown in Figure 8, this assumption can be thought as a valid first order approximation. Repair numbers for the over and under deposition cases described above are reported in the right panel of Figure 9. Interestingly, it is possible to notice that the repair number is different for over and under deposition cases.
The maximum absorber height deviation which would still provide an acceptable repair can be found dividing the $\Delta \mathrm{CD}$ specification of 0.8 nm (at wafer level) by the correspondent repair number shown in the Table. As a result for the 16 nm half-pitch node, V lines at the center of the illumination field can be repaired with a $\leq 20 \mathrm{~nm}$ over-deposition or $\leq 26 \mathrm{~nm}$ under-deposition processes. For H lines the process must be more tightly controlled: a repair with 8 nm over-deposition or 10 nm under-deposition is the limit for printing within the target CD of 16 $\mathrm{nm} \pm 5 \%$.
Some conclusions can be drawn on the basis of the findings described above. First, H lines are the most sensitive to the height of the absorber deposition or etch within a repair process, contributing to higher height control requirements for this orientation. Second, the repair numbers for the over and under deposition cases are different from each other. Third, a height control of $\pm 8 \mathrm{~nm}$, as well as all the other values reported in this work, is well within the MeRiT® capabilities of repairing absorber materials. The absorber height control capabilities by the current MeRiT® platform is within nm precision ${ }^{13,14}$, and therefore the tight control of the repair process is not an issue with respect to shadowing effects and bias.

One more aspect related to the impact of the absorber height onto the imaging performance relates to the overlay or image placement error. With the simulations it is possible to measure the shift of the central coordinate of the aerial image in response to a variation in the height of the absorber. This is shown in Figure 10, where the aerial images of H and 45 deg oriented lines with a $1: 1$ duty cycle and illuminated by a disar pupil with $\sigma=0.6-0.9$ are presented. A first glance at the plots shows that the center of the images, identified as the point of lowest intensity in the different colored curves, is subject to a drift towards X values lower than 16 nm (the center of the simulation domain) as the absorber thickness is increased changed. The behavior of this shift is displayed in the insets within each panel of Figure 10, where the center of the aerial image for H (left panel) and 45 deg (right panel) lines is plotted against the absorber height. V lines are not shown because no shift has been measured for this orientation in response to an absorber height variation.

The shift of the aerial image center has been measured for both H and 45 deg oriented lines towards lower X coordinates. A good linear trend between this shift and the absorber height was found and quantified by $\mathrm{R}^{2}$ values higher than 0.9 for both cases. Between the absorber thickness values of 40 and 70 nm , the largest shift was measured for H lines to be 1.3 nm ; the highest gradient measured within this trend is about 0.5 nm for 10 nm variation in the height of the absorber. According to the 2013 release of the international technology roadmap for semiconductor (ITRS) ${ }^{15}$, overlay specification for production EUV photomasks will be $3 \%$ of the pitch size. Considering the structures which have been simulated in this last section, a 1:1 lines and space pattern with CD of 16 nm is described by a pitch of 64 nm . Therefore, overlay specifications must be within 2 nm . A 0.5 nm overlay error (at wafer level) introduced by a 10 nm absorber height variation from nominal can absorb up to $100 \%$ of the 2 nm (at mask level) overlay specification, i.e. the entire budget for overlay errors. This argument shows the fundamental importance of height control within the EUV photomask production and repair process.


Figure 10. Aerial images of 1:1 H (left panel) and 45 deg (right panel) lines and space patterns with different thickness values of the absorber ( 40 to 70 nm in 10 nm steps). The insets within the two panels show the drift of the aerial image center position as a function of the absorber height.

As shown by the simulation work presented here, the absorber thickness has an influence on imaging parameters such as overlay and repair success. However, all specifications needed in order to reduce overlay errors or to influence the positive outcome of a repair process due to absorber misplacement are well within the MeRiT® capabilities.

## CONCLUSIONS

Shadowing effects are an inherent characteristic of EUV lithography, arising from the combination of nontelecentric illumination of the mask, finite absorber height and the reflective nature of the EUV optics. The production process of EUV photomasks is made more complicated by the need of properly biasing the features on the photomask in order to print at target across the whole field. This work has shown that shadowing effects, which are directly connected to the bias needed on the reticle, depend on a great variety of lithographic parameters, i.e. are process dependent. The dependency of shadowing effects across the illumination arc on structure orientation, pitch, absorber height and illumination conditions have been investigated. Although small, these effects must be tightly controlled in order to maximize process window and meet CD requirements and uniformity targets.
The AIMS ${ }^{\text {TM }}$ EUV platform, in addition to a production tool for photomask defect review, is an efficient and cost-effective way to fully emulate the scanner imaging conditions and experimentally validate whether the applied mask bias calculated previously meets all target specifications. As demonstrated in the last section, the thickness of the absorber must also be tightly controlled in order to reduce errors in CD measurements and uniformity, and overlay errors. With the ability to control the deposition or etch of absorber material on EUV photomasks within the nm regime, the Carl Zeiss MeRiT® platform for photomask repair is already on track for the development of EUV lithography and able to successfully address all the afore mentioned issues related to the height of the absorber.

## REFERENCES

${ }^{1}$ Hellweg, D., Ruoff, J., Herkommer, A., Stühler, J., Ihl, T., Feldmann, H., Ringel, M., Strößner, U., Perlitz, S., Harnisch, W., "AIMS ${ }^{\text {TM }}$ EUV - the actinic aerial image review platform for EUVmasks", Proc. SPIE 7969, 79690H (2011).
${ }^{2}$ Folta, J. A., Bajt, S., Barbee, T. W., Grabner, R. F., Mirkarimi, P. B., Nguyen, T., Schmidt, M. A., Spiller, E., Walton, C. C., Wedowski, M., Montcalm, C., "Advances in multilayer reflective coatings for extreme ultraviolet lithography", Proc. SPIE 3676, 702 (1999).
${ }^{3}$ Braun, S., Mai, H., Moss, M., Scholz, R., Leson, A. "Mo/Si Multilayers with Different Barrier Layers for Applications as Extreme Ultraviolet Mirrors", Jpn. J. Appl. Phys. 41 (2002) 4074B.
${ }^{4}$ Neumann, J.T., Gräupner, P., Kaiser, W., Garreis, R., Geh, B., "Mask effects for high-NA EUV: impact of NA, chief-ray-angle, and reduction ratio", Proc. SPIE 8679, 867915-1 (2013).
${ }^{5}$ Garetto, A., Capelli, R., Blumrich, F., Magnusson, K., Waiblinger, M., Scherübl, T., Peters, J.H., Goldstein, M. " Defect Mitigation Considerations for EUV Photomasks ", submitted to Journal of Micro/Nanolithography, MEMS, and MOEMS (2014).
${ }^{6}$ Peters, R. et al., "ASML’s NXE platform performance and volume introduction", Proc. SPIE 8679, 8679-50 (2013).
${ }^{7}$ Davydova, N., de Kruif, R., van Setten, E., Lammers, A., Oorschot, D., Schiffelers, G., van Dijk, J., Connolly, B., Fukugami, N., Kodera, Y., Morimoto, H., Sakata, Y., Kotani, J., Kondo, S., Imoto, T., Rolff, H., Ullrich, A., "Achievements and challenges of EUV mask imaging", PMJ (2014).
${ }^{8}$ Yan, P.Y., "The impact of EUVL Mask Buffer and Absorber Material Properties on Mask Quality and Performance", Emerging Lithographiy Technologies,VI, Proc. SPIE 4688 (2002).
${ }^{9}$ van Setten, E., Man, C.-W., Murillo, R., Lok, S., van Ingen Schenau, K., Feenstra, K., Wagner, C., "Impact of mask absorber on EUV imaging performance ", Proc. SPIE 7545, 754503 (2010).
${ }^{10}$ van Setten, E., Oorschot, D., Man, C.-W., Dusa, M., de Kruif, R., Davydova, N., Feenstra, K., Wagner, C., Spies, P., Wiese, N., Waiblinger, M.," EUV mask stack optimization for enhanced imaging performance ", Proc. SPIE 7823, 78231O-1 (2010).
${ }^{11}$ Edinger, K. et al., "A novel electron-beam-based photomask repair tool", Proc. SPIE 5256, 1222 (2003).
${ }^{12}$ Waiblinger, M., Kornilov, K., Hoffman, T., Edinger, K., "e-beam induced EUV photomask repair: a perfect match", Proc. SPIE 7823, 782304 (2010).
${ }^{13}$ Waiblinger, M., Bret, T., Jonckheere, R. and Van den Heuvel, D., "Ebeam based mask repair as door opener for defect free EUV masks", Proc. SPIE 8522, 85221M (2012).
${ }^{14}$ Bret, T., Jonckheere, R. and Van den Heuvel, D., Baur, C., Waiblinger, M., Baralia, G., "Closing the gap for EUV mask repair", Proc. SPIE 8322, 83220C-1 (2012).
${ }^{15}$ The International Technology Roadmap for Semiconductors 2013, http://www.itrs.net/Links/2013ITRS/ 2013Chapters/2013Litho.pdf.

