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Actinic metrology platform for defect review and mask qualification: flexibility and performance

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ABSTRACT

The strong effort to push further Moore's law is driving the insertion of EUV pilot production at several captive and merchant semiconductor vendors, which already today puts strong demands on actinic tools metrology capabilities. The EUV mask infrastructure plays a central role for the successful introduction of EUV into high volume manufacturing: to provide the mask shop with actinic review capabilities, ZEISS and the SUNY Poly SEMATECH EUVL Mask Infrastructure consortium developed and launched an actinic metrology platform based on aerial imaging technology. Over the last few years, it was demonstrated how this aerial image metrology platform fulfills the mask shop requirements for actinic defect review and repair verification. In this paper we present the latest performance achievements of the platform together with the discussion on platform based capabilities for possible future actinic metrology extensions, with a special emphasis on the AIMS™ EUV solution for high-NA emulation capabilities.

Keywords: mask metrology, AIMS™, aerial image review, EUV, scanner emulation, defect review, EUV optics

INTRODUCTION

The development of EUV exposure tools has seen unprecedented progress within the last years [1]. The industry drive for further extending the lithography pattern shrinking has propelled the further optimization of the current ASML NXE platforms, as well as the development of the next generation tools with larger 0.55 NA which will experience a major step in complexity. ZEISS already embraced this unique technical challenge not only on the scanner optics side, but also as a main player for semiconductor mask solutions provider. Within the EUV lithographic process, the mask has become an active optical component with larger complexity and potential impact on the wafer aerial image. It is therefore important from a mask shop standpoint to quantify all sources of errors contributing to the final aerial image in order to assign tolerances to the imaging process and therefore to the final wafer printing.
It was demonstrated that for low NA the mask effects are already significant, especially when applications other than defectivity are targeted [e.g. 2]; going towards more aggressive illumination settings and 0.55 NA a full control over the mask performance which goes beyond defectivity review might become necessary in the mask manufacturing process. In this paper, the features of AIMS™ EUV will be described which make it the ideal solution for the qualification of the mask printing performance in the mask shop for the current and future EUV generations. Section 3 reports on the AIMS™ EUV application capabilities which extend beyond defect review, together with showing performance results from recent repeatability measurements. The first of two platform extension options will be presented in Section 4: the AIMS™ EUV can be upgraded for accepting masks both with and without pellicle. The final chapter is devoted to the introduction of ZEISS solution for AIMS™ EUV high-NA. The concept is described and the first images of mask anamorphic structures are shown as imaged in 0.33 NA and 0.55 NA emulation.

AIMS™ EUV PROVIDES THE SAME VIEW OF THE MASK AS ON THE SCANNER

AIMS™ EUV is the mask shop tool which measures and qualifies the mask aerial image before the mask is shipped to the wafer fab for chip manufacturing. Within the exposure tool, the wafer is exposed to the aerial image of the mask, which contains all relevant information from mask and tool side for the formation of the image on the wafer. It is therefore not the physical image of the mask which is important for the wafer exposure, but rather its aerial image. The aerial image is therefore the natural habitat for the qualification of mask defectivity and printing performance.
As such, it is of fundamental importance that the information collected from the mask into the AIMS™ projection optics is the same on the scanner. Figure 1 shows how this system requirement is achieved both in the illumination and in the

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projection part of the tool. The key function of the AIMS™ illuminator is to shape the light to emulate the illumination settings used in the EUV scanner, and to illuminate the mask using the same NA dependent angular space selection of EUV photons distributed around the polar chief ray angle of 6 degrees and mask position dependent azimuthal component. In order to shape the light to emulate the scanner imaging conditions, the AIMS™ EUV system is equipped with several sigma aperture settings, some of which are shown in the left panel of Figure 1 for NXE:3300 emulation (blue) and NXE:3400 emulation (green). The angular space selection within the optical path of the illuminator is achieved by synchronous movement of sigma and NA apertures manipulators. Once the light is reflected and diffracted by the structures present on the mask surface, the diffraction orders are collected into the projection optics: by providing the same NA at mask as the scanner and EUV scanner quality optics, the AIMS™ EUV tool assures the same information in the form of diffraction orders location and relative intensity. The light is collected from the mask and delivered into the projection optics to form the aerial image. The right panel of Figure 1 shows the differences in the projection optics processing of the diffraction orders: the AIMS™ EUV directly records the magnified aerial image onto a CCD camera, whereas the equivalent aerial image on the scanner is shrunk by a factor 4 and then exposed onto the wafer resist for later development. The great advantage of AIMS™ technology is the ability to produce an aerial image of the mask containing all the imaging effects as on scanner up to resist chemistry and development.

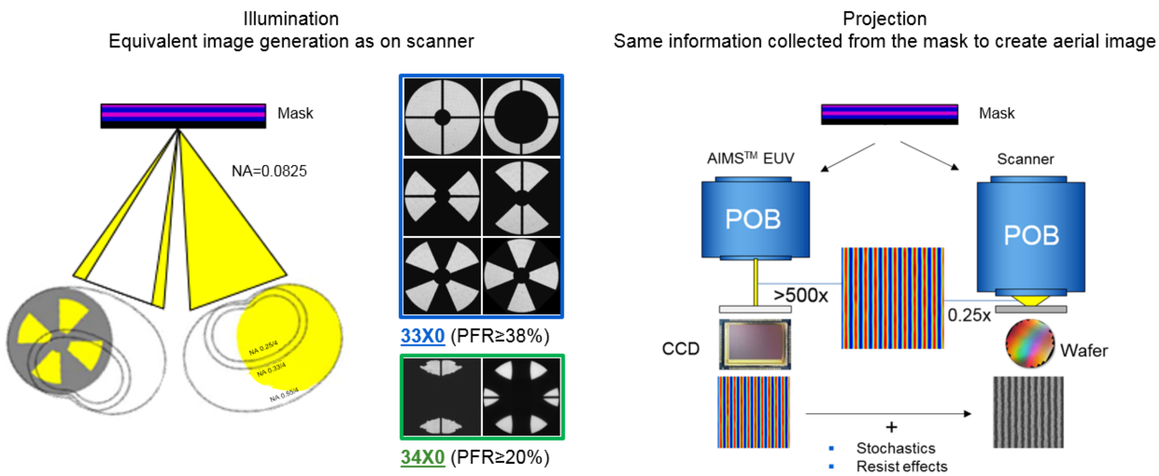

Figure 1. AIMS™ EUV is able to capture all imaging effects contributing to the formation of the aerial image as on the NXE scanners. Left: the illumination system is designed to emulate shape and angular distribution of the EUV photons impinging the mask, providing the same NA at mask level as available on the current NXE scanner systems (0.33 NA). Right: the projection optics provides a large magnification for recording the aerial image on a CCD camera.

Amongst the effects which can be recorded and quantified in the aerial image is the impact of photon stochastics. As reported in [3], the AIMS™ EUV is capable to emulate the dose used in the scanner during imaging: by doing so, a thorough qualification of the photon noise contribution to the mask aerial image in the scanner can be performed, gaining a larger control over the mask printing performance metrics such as CD uniformity, MEEF, line width and line edge roughness.

MEASUREMENT CAPABILITIES AND PERFORMANCE

Over the last few years, the results from several experimental investigations have been reported to the community based on AIMS™ EUV measurements. It has been demonstrated that the system entirely fulfills the industry needs for the defect review application: a significant example was demonstrated in [4], in which the one to one matching between SEM images from wafer prints and AIMS™ EUV printability prediction of programmed multilayer defects was reported, outperforming any competing metrology.

Besides defect review and repair verification applications, the AIMS™ EUV provides the full means for a full EUV mask qualification within the aerial image. An interesting field of application and unique to EUV lithography, the mask 3D effects topic has been gaining a growing interest over the last years. Being inherent to the reflective attribute of EUV imaging, mask 3D effects add complexity both to the imaging process and to the mask design and manufacturing. Research is ongoing in the field of EUV mask materials in order to find an absorber material which allows for a reduction of the impact of 3D effects [e.g. 5]. Progress towards this goal needs support from the mask infrastructure to validate the results that can already be achieved by means of imaging simulation tools. As previously demonstrated, the AIMS™ EUV is the ideal platform to address this challenge as it provides the same illumination scheme and aerial image formation process as available on the exposure tools. Over the last few years ZEISS published a series of experimental results all aiming to demonstrate the capability of the AIMS™ EUV to qualify all sorts of mask 3D effects, allowing the experimental validation of theoretical models and/or simulation results. Figure 2 shows a sequence of the main results achieved with the platform: measurements of CD change through slit position (i.e. shadowing effects) of unbiased mask structures [6], shift of the best focus plane for specific structures going through feature pitch [2], and measurements of the telecentricity effect (i.e. pattern shift through focus) for several structures as function of imaging parameters and their matching simulation results [7].

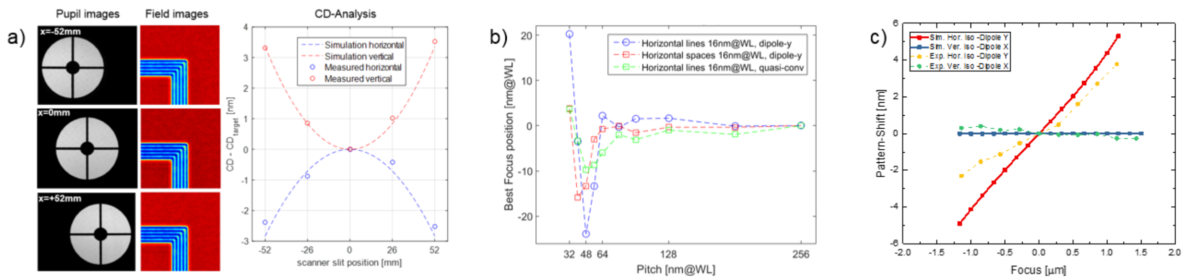

Figure 2: AIMS™ EUV qualification of mask 3D effects published over the last years. a) Measurement of the shadowing effects for a 5 L-bar structure. b) Measurement of the best focus shift through structure pitch of a 64nm (mask level) L/S pattern imaged with different illumination settings. c) Measurement of pattern shift through focus and comparison to simulation results.

The AIMS™ EUV platform is capable to provide a full understanding of the EUV imaging process, supporting validation of theoretical models and contributing to the overall advancement of EUV technology.

As a further confirmation of mask qualification capabilities in a production environment, Figure 3 reports on an exemplary CD reproducibility measurement in which information on both repeatability of the measurements and local mask CD uniformity can be extracted. The left panel shows an AIMS™ EUV image of 64nm (at mask level) lines and spaces pattern, on top of which a matrix of 35 regions of interest (ROI) is plotted to show the areas used for measurements of the CD value. The results are reported on the right, in which the three graphs show the CD measurements for different repetitions as measured at negative defocus (top), best focus (middle) and positive defocus (bottom).

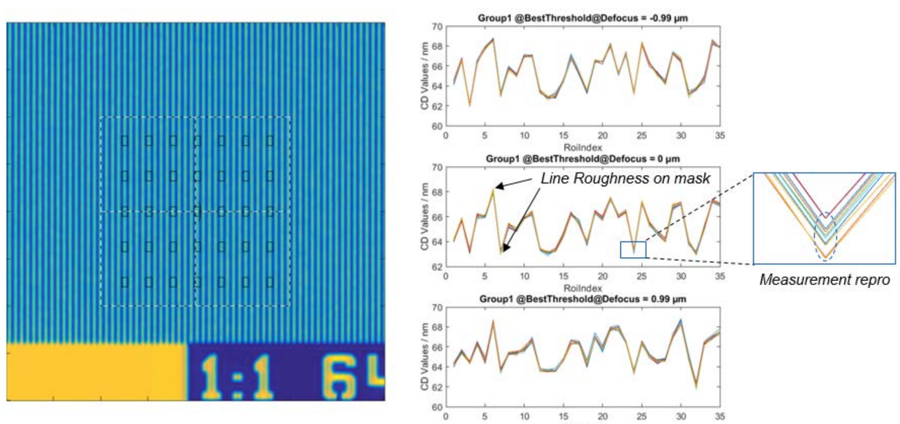

Figure 3. Exemplary CD reproducibility measurement of a 64nm (mask level) L/S pattern for three different defocii values, in which the CD roughness of the structure is also visible in the center graph.

Two main information can be inferred from the plots: although the nominal CD at mask is 64nm, a significant line width roughness is measured with values spanning between 63 and 68nm at mask level for the 35 ROIs selected. In order to have a visual confirmation of the good measurement reproducibility, a zoom in into a specific ROI is provided by the insert on the right. The reproducibility result is given by the standard deviation of the CD results data points shown as different color curves (bottom peaks): in this specific case, a value of 25% of the total budget was achieved. The data presented in Figure 3 were acquired on the AIMS^{TM} EUV prototype system: for a more complete report over the platform production performance, the reader can refer to the first production values reported on the AIMS^{TM} EUV system in production at Intel mask shop [8].

AIMS^{TM} EUV PELLICLE COMPATIBILITY

Since the beginning of the EUV lithography process development the question on whether a pellicle solution would be feasible and available for the industry has been object of intensive research, with the pellicle being a significant missing piece of the EUV mask infrastructure when compared to 193nm. The two main technical issues to overcome in order to introduce a pellicle for EUV were the scanner limited source power availability and the technical challenge associated with the development of an industrial solution capable of fulfilling EUV lithography requirements. Over the last few years has become more and more clear that a pellicle for EUV masks will be needed by the industry for high volume manufacturing for mature EUV generations, and thanks to the effort of ASML a pellicle industrial solution will be available for EUV high volume manufacturing which fulfills functional, imaging and stability requirements [9]. The same uncertainties on the pellicle feasibility and availability impacted the early AIMS^{TM} EUV system design process, for which the support of a pellicle solution was not foreseen and as such not available on the current systems.
In order to further support the EUV mask infrastructure and provide the mask shop with flexible solutions, ZEISS did a feasibility study for the upgrade of the AIMS^{TM} EUV platform for handling and imaging masks with and without pellicle. This delivered a positive outcome: checked were the static and dynamic volume claims, full sensors functionality and compatibility of the platform infrastructure with the pellicle. Moreover, strategies have been developed for pellicle detection and failure recovery. Figure 4 shows the pellicle volume claims used for the feasibility (right) and a dummy pellicle build on an EUV mask blank used for sensoring calibration at ZEISS (left). As a result of this internal investigation, the AIMS^{TM} EUV customer systems, as well as the prototype platform, can from now on be upgraded in the field to support EUV pellicle. Future new systems will be delivered already pellicle compatible.

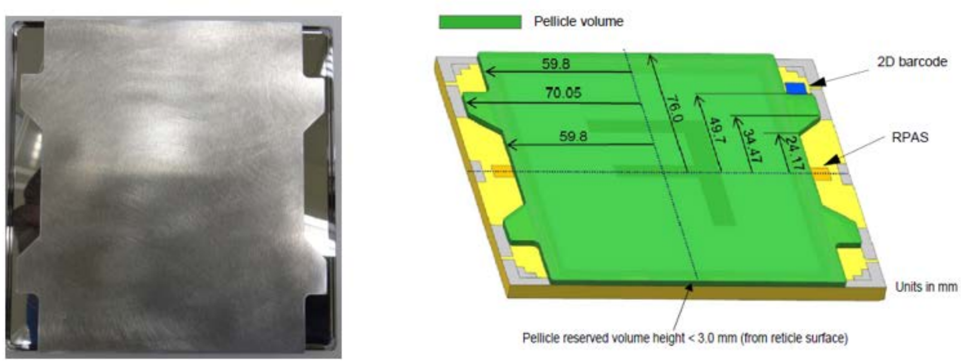

Figure 4. Left: dummy pellicle laid on a mask blank within ZEISS clean room. Right: ASML EUV pellicle volume claims [9].

AIMS^{TM} EUV HIGH-NA PROOF OF CONCEPT

While the 0.33 NA exposure tools are empowering the industry to bring EUV into high volume manufacturing, over the last two years it has become evident that the future of EUV lithography is high-NA. ASML and ZEISS are committed to design and commercialize the next generation EUV scanner with a 0.55 NA and 8 nm resolution, which will allow to extend pattern shrinking throughout the next decade [10]. The EXE:5000 EUV system will be available early in the first half of the next decade.
With the continuously progressing shrink of the lithography pattern, the mask infrastructure has to keep the pace to provide the industry with the necessary infrastructure solutions. Benefits associated to high-NA imaging have been already reported [11], however these qualitative investigations are until now only available in simulation without an industry standard experimental validation.

As a fundamental component of the mask shop infrastructure, the ZEISS AIMS EUV platform will be ready to support the industry with a 0.55 NA ready system to target the native defectivity applications as well as providing full printing performance qualification of high-NA masks. As already demonstrated for 0.33 NA, the AIMS™ EUV platform will be able to support the development and full understanding of high-NA imaging process while the full infrastructure for high-NA will be setup by the industry: topics such as mask 3D effects and qualification of alternative absorbers can already be investigated on the current platform, currently in 0.33 NA and in the future with 0.55 NA.
Within the last year, ZEISS defined a concept for the extension of the AIMS™ EUV actinic platform to emulation of the 0.55 NA scanner systems EXE:5000. The left panel in Figure 5 shows the conceptual changes of the scanner and AIMS™ platform in going from 0.33 NA to 0.55 NA: as evident from the graphics, and previously reported by ASML [12], the EXE:5000 scanner will be a completely different platform from the currently available 0.33 NA NXE systems. On the other hand, the AIMS™ EUV will be able to provide emulation of the EXE:5000 system by employing changes at the component level on the current platform: this means that the tool footprint will remain the same and the systems currently in the field can be upgraded to support simultaneously the emulation of NXE and EXE scanner systems.
To give the reader a sense of the technical challenge which the AIMS™ EUV faced in order to provide a solution capable of emulating NXE and EXE systems on the same platform, the right panel of Figure 5 shows the geometrical shape of the projection optics entrance and exit pupils as setup in 0.33 NA and 0.55 NA scanner systems. The NXE 3XX0 scanners employ isomorphic optics, i.e. the reduction factor for the mask structure is the standard 4 both for X and Y direction. On the other hand, the EXE:5000 scanner will employ anamorphic optics, i.e. the reduction factor in X and Y will be different: as a consequence the NA at mask will be different for the two directions, which causes the entrance pupil shape being elliptical, holding the desired circular shape for the exit pupil. Focusing on the AIMS™ EUV side, the changes will not impact the projection optics design, i.e. the projection optics will remain isomorphic because of the requirement for parallel support of 0.33 NA and 0.55 NA imaging. To achieve this fundamental requirement, a solution was found to provide the industry with anamorphic imaging using an isomorphic optical system: the solution does not only apply to single focal plane imaging, but extends to cover wafer defocus emulation which oppositely to isomorphic imaging, cannot be emulated by a simple 16x mask defocus. With this solution, ZEISS is able to provide an industry standard defect review and mask qualification platform to extend into the next decades of mask manufacturing for EUV lithography.

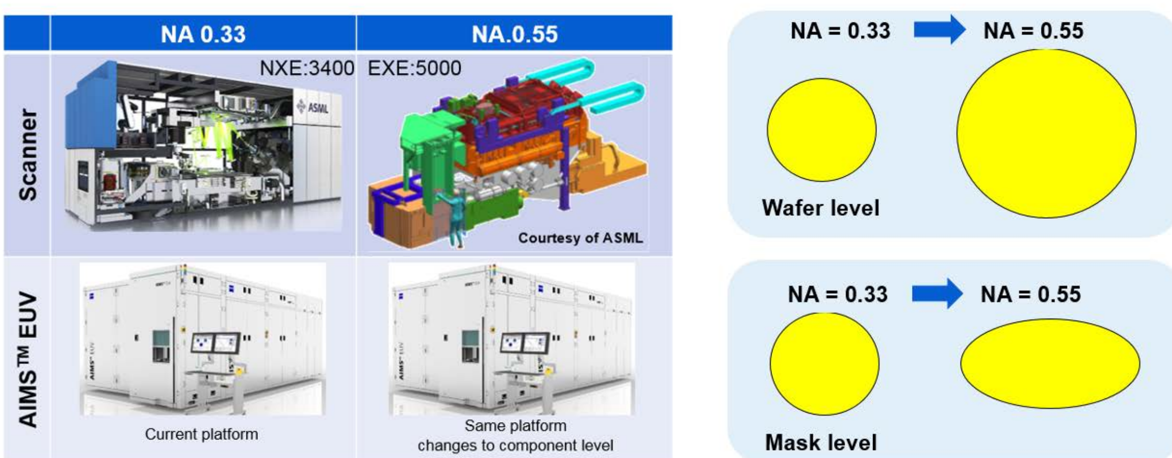

Figure 5. Left: matrix graphically showing the changes in tool concept and footprint associated to the NA increase between current 0.33 NA to 0.55 NA for ASML EUV scanners and ZEISS AIMS EUV. Right: EUV scanner projection optics entrance (mask level) and exit (wafer level) pupil shape and their change between 0.33 NA and 0.55 NA.

The concept described above has been tested on the prototype system at ZEISS Headquarter. A EUV mask used for system adjustment and calibration is equipped with simple anamorphic structures, in which the vertical size is double the horizontal: no mask bias is applied, but rather a simple geometrical ratio. This will also represent a further challenge for high-NA imaging: the mask features and relative bias will look completely different from the desired design at wafer level. Figure 6 shows exemplary structures available on the test mask selected for the high-NA proof of concept experiment with AIMS™ EUV, contact holes and five L bars, both anamorphic and isomorphic: the aerial images, respectively of contacts and L bars at 0.55 NA and 0.33 NA are expected to nominally be the same. However, it is clear how in order to print the same feature design, a 0.55 NA mask must be physically different from its 0.33 NA counterpart.

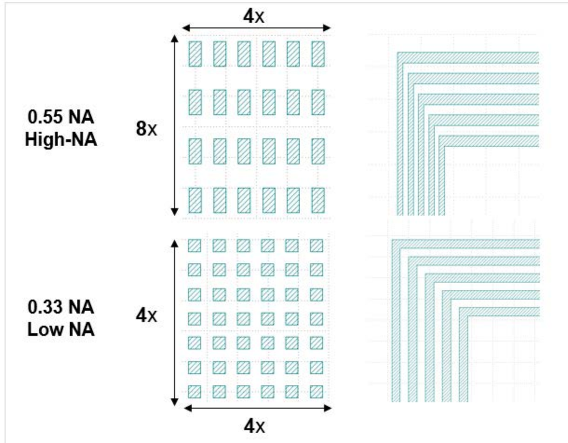

Figure 6. Exemplary anamorphic structures available on the ZEISS AIMS EUV calibration mask. The difference in size between the horizontal and vertical direction is purely geometrical, i.e. no mask bias applied.

The available test mask was loaded into the machine and imaging tests have been performed on the anamorphic structures only (top row in Figure 6) in order to experimentally validate ZEISS concept for an AIMS™ EUV platform supporting high-NA emulation, the results are shown in Figure 7 and Figure 8, respectively for 5 L bars and contact holes.
The nominal CD values of the L bars is reported in the left panel of Figure 7, with the CD in the vertical direction being double the CD in the horizontal direction. By imaging this specific feature in 0.33 NA standard AIMS™ mode, the resulting aerial image captures this difference in horizontal-vertical feature size: the aerial image in the middle panel of Figure 7 nicely shows a much larger intensity for the horizontal spaces if compared with the vertical ones. This geometrical design factor can also be seen in the dark area between bright features: the distance between the bright horizontal spaces is much larger than for the vertical spaces. The right panel of Figure 7 shows the aerial image of the same mask structure imaged in high-NA emulation mode: as it can be observed, the feature size in the two directions is now the same at the net of shadowing effects typical of EUV imaging process. Also qualitatively, high-NA imaging with the AIMS™ EUV platform guarantees the same image quality provided by current systems at 0.33 NA. The same imaging sequence has been acquired for the anamorphic contact holes case: the nominal CD values at mask are shown in the left panel of Figure 8, with the 0.33 NA aerial image resulting in elliptical shaped holes as shown in the middle panel of the same Figure, in which also the factor two structure pitch is also well reproduced. When imaging the same anamorphic contacts in high-NA emulation mode, the resulting aerial image shows rounded contacts in which the CD and pitch in the vertical and horizontal directions are the same.

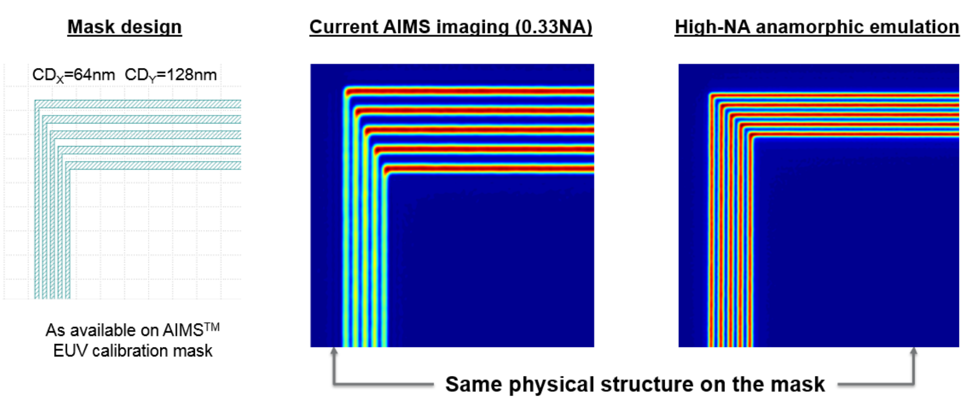

Figure 7. AIMS™ EUV 0.33 NA and high-NA imaging of 5 L-bars structure. Left: structure on the mask taken from the design file. Center: field image acquired with AIMS™ EUV in 0.33 NA imaging emulation. Right: same structure on the mask imaged in 0.55 NA emulation, in which anamorphic structures on the mask are imaged isomorphic in the image plane.

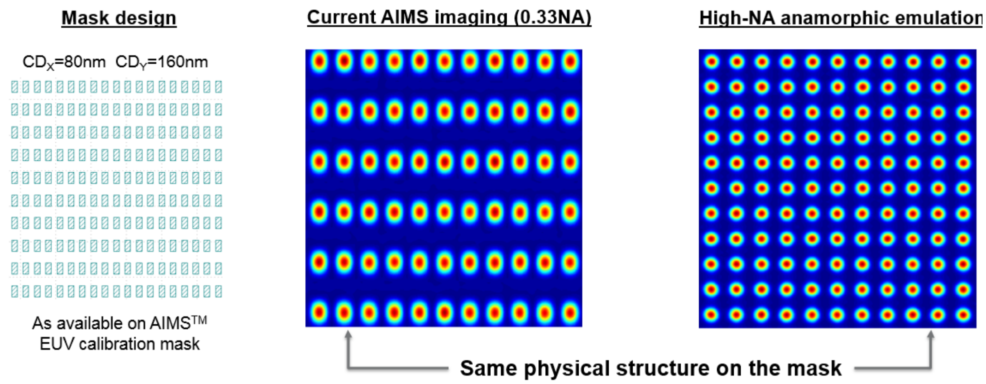

Figure 8. AIMS™ EUV 0.33 NA and high-NA imaging of contact holes array. Left: structure on the mask taken from the design file. Center: field image acquired with AIMS™ EUV in 0.33 NA imaging emulation. Right: same structure on the mask imaged in 0.55 NA emulation, in which anamorphic structures on the mask are imaged isomorphic in the image plane.

The aerial images of anamorphic structures shown here above demonstrate the validity of the ZEISS concept for an AIMS™ EUV platform capable of parallel emulation of 0.33 NA NXE and 0.55 NA EXE:5000 scanner systems. These images were acquired on the AIMS™ EUV prototype tool, however commercial systems can also be upgraded to support high-NA scanner emulation. This proof of concept experiment and the readiness of AIMS™ EUV for high-NA emulation demonstrates ZEISS commitment into supporting the lithography roadmap both on the litho scanner optics but also on the mask side, providing the semiconductor industry with flexible solutions to support further the evolution of EUV lithography.

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