Simulation Tools for Advanced Mask Aligner Lithography

Arianna Bramati[*a], Uwe Vogler[a], Balint Meliorisz[b], Kristian Motzek[c], Michael Hornung[d], Reinhard Voelkel[a]

[a]SUSS MicroOptics SA, Jaquet-Droz 7, CH-2000 Neuchâtel, Switzerland, www.suss.ch
[b]GenISys GmbH, Eschenstrasse 66, D-82024 Taufkirchen, Germany
[c]Fraunhofer IISB, Schottkystrasse 10, 91058 Erlangen
[d]SUSS MicroTec Lithography GmbH, Schleissheimerstrasse 90, 85748 Garching, Germany

ABSTRACT

Contact- and proximity lithography in a Mask Aligner is a very cost effective technique for photolithography, as it provides a high throughput and very stable mature processes for critical dimensions of typically some microns. For shadow lithography, the printing quality depends much on the proximity gap and the properties of the illumination light.

SUSS MicroOptics has recently introduced a novel illumination optics, referred as MO Exposure Optics, for all SUSS MicroTec Mask Aligners. MO Exposure Optics provides excellent uniformity of the illumination light, telecentric illumination and a full freedom to shape the angular spectrum of the mask illuminating light. This allows to simulate and optimize photolithography processes in a Mask Aligner from the light source to the final pattern in photoresist. The commercially available software LayoutLab (GenISys) allows to optimize Mask Aligner Lithography beyond its current limits, by both shaping the illumination light (Customized Illumination) and optimizing the photomask pattern (Optical Proximity Correction, OPC). Dr.LiTHO, a second simulation tool developed by Fraunhofer IISB fro Front-End Lithography, includes rigorous models and algorithms for the simulation, evaluation and optimization of lithographic processes. A new exposure module in the Dr.LiTHO software now allows a more flexible definition of illumination geometries coupled to the standard resist modules for proximity lithography in a Mask Aligner. Results from simulation and experiment will be presented.

Keywords: Lithography Simulation, Optical Lithography, Mask Aligner, Optical Proximity Correction, OPC, MO Exposure Optics, Source-Mask Optimization, Customized Illumination

1. INTRODUCTION

Microlithography in Mask Aligners is widely used for transferring a geometric pattern of microstructures from a photomask to a light-sensitive photoresist coated on a wafer or substrate by exposing both with ultraviolet light, whereas the mask and the wafer are in close contact or proximity. Contact lithography offers the highest resolution down to the order of the wavelength of the illumination light, but practical problems such as contamination and a possible damage of mask or wafer make this process unusable for mass production. Proximity lithography, where the photomask and the wafer are separated by a proximity gap of typically 30 to 100 µm is well suited for production, however, diffraction effects at the mask pattern limit the resolution and fidelity of the resist prints. Diffraction effects like side lobes, higher orders and interference effects could be minimized applying Photolithography Enhancement Technique (PET) such as Optical Proximity Correction (OPC) and “Customized Illumination”. In this context the new illumination optics developed by SUSS MicroOptics enters in.

The so called MO Exposure Optics allows to use front-end concepts like customized illumination and optical proximity correction (OPC) to optimize critical lithography steps and makes it possible to exactly set the angular spectrum. The possibility to have well defined illumination settings is a basic requirement for using lithography simulations [1].

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[*] bramati@suss.ch

The combination of simulation tools, such as LayoutLab of GenISys and Dr.LiTHO of Fraunhofer IISB, with this flexible illumination system can be used to push the conventional limits of Mask Aligner by developing and analyzing new approaches without even touching a wafer.

The first optical lithography modeling began forty years ago, when Rick Dill described the basic steps of the lithography process with mathematical equations. Lithography modeling and simulation became soon indispensable tools for lithographic enhancement. Simulation is widely used for process development and in manufacturing for troubleshooting [2]. For the development of new processes, simulation allows to investigate the influence of process variables like illumination, exposure dose and proximity gap on the resist pattern, described by CD and sidewall angles of resist pattern, before running experiments. Critical processes could be optimized, process windows and yield improved.

2. MO EXPOSURE OPTICS

Illumination systems for contact or proximity lithography in a Mask Aligner are based on high-pressure mercury plasma arc discharge lamps emitting ultraviolet light in a very large angular range. The exposure light is collected by an ellipsoid reflector, whereas the plasma arc is placed in the first focal point of the ellipsoid. Ellipsoidal reflectors are well suited to collect light from a point source emitting light in a very large angular range. Light emitted from the primary focal point is perfectly re-focused in the secondary focal point.

For achieving illumination with good irradiance uniformity, most illumination systems contain optical elements that homogenize the light. Optical elements having this property are generally referred as optical integrator elements. They collect the light from the light source, produce a plurality of secondary light sources and modify the size and geometry of the illuminated target field. Optical integrators are often followed by a lens. This lens is referred as condenser or Fourier lens. The lens superposes the light from the different secondary light sources produced by the optical integrator elements. The irradiance in the superposition plane corresponds to the Fourier transformation of the angular spectrum produced by the optical integrator. The optimum superposition and best irradiance uniformity is achieved in a plane, located at a focal length distance behind this lens, referred as Fourier plane.

In order to redistribute the light, double-sided monolithic microlens arrays made of Fused Silica are used as first Köhler integrator [3], [4] placed in the secondary focus of the elliptical mirror. This first integrator decouples the light source from the rest of the system, which will be not influenced by small adjustment errors of the source [5]. The second function of the first integrator is to illuminate the area of the second integrator uniformly.

A second Köhler integrator is located at the back focal plane of the first Fourier lens. After passing the second Köhler integrator in which the light is again homogenized, a flat-top irradiance profile is generated in the focal plane of the second Fourier lens. This means that at each location on the Köhler integrator element, light is distributed within a certain range of angles. For the second Köhler integrator this range may extend, for example, from -4° to +4°. Two field lenses are located at the back focal plane of the Fourier lenses. The second field lens is also referred as “front lens” and ensures telecentric illumination of the mask. Transparent areas on the mask transmit the light and illuminate the resist layer on the wafer, thus transferring the minute structures from the mask to the wafer. Telecentric illumination ensures that the lateral position of the mask pattern is transferred 1:1 to the wafer with no lateral displacement.

For the first Köhler integrator a double-sided array with hexagonal densely packed microlenses is used; for the second Köhler integrator two double-sided arrays of cylindrical microlenses are used, whereas the second array is rotated by 90° versus the first array.

The second Köhler integrator slightly increases the geometrical optical flux and modifies the local irradiance distribution in a subsequent Fourier plane. In general, the illuminated area at the entrance pupil of the second optical integrator is equivalent to the area of tertiary light sources at the exit pupil of the optical integrator.

To define the angular spectrum, different obstructions for spatial filtering of the illumination light can be placed before the second integrator. They are referred as Illumination Filter Plates (IFPs) and allow to alter the angular spectrum and the coherence properties of the mask illuminating light in the Mask Aligner. MO Exposure Optics provides full freedom of shaping the light source and an excellent uniformity in irradiance and angle. Since these conditions allow precise modeling of the incoming light, they are suitable for the employment of simulation tools. A scheme of an illumination system for Mask Aligner including MO Exposure Optics is shown in Figure 1.

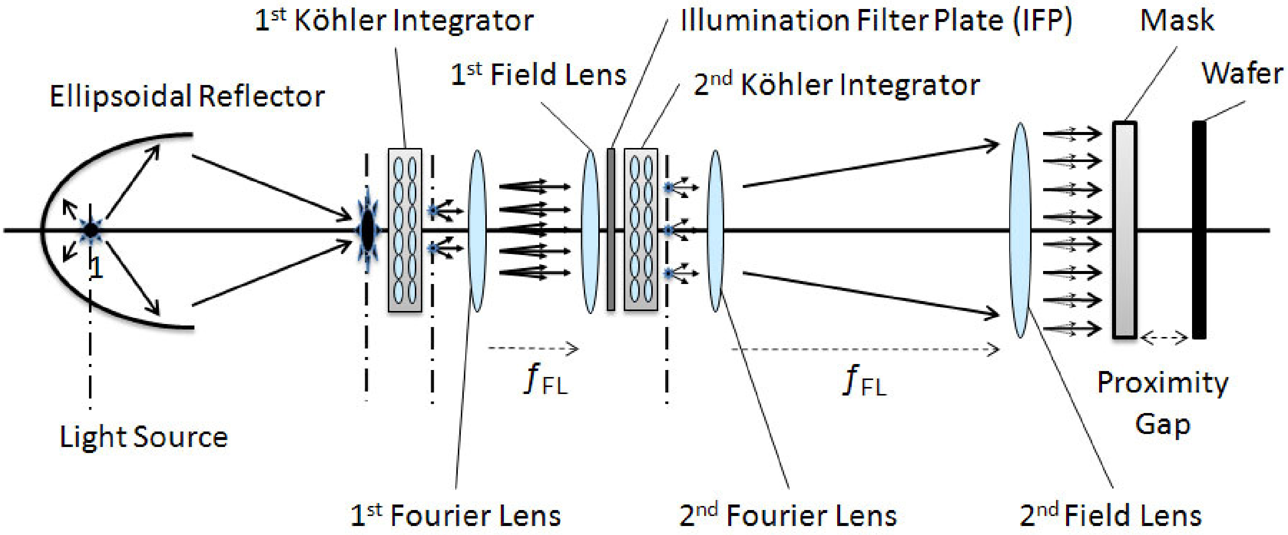


Figure 1: Simplified view of MO Exposure Optics illumination system for Mask Aligners comprising two subsequent Köhler integrators. A first Köhler integrator is located near the secondary focal point of the ellipsoidal reflector. A second Köhler integrator is located in the Fourier plane of the first integrator.

3. SIMULATIONS FOR ADVANCED MASK ALIGNER LITHOGRAPHY

One of the most important parameters to determine the performance of lithographic printing in a Mask Aligner is the resolution, or Critical Dimension (CD). It establishes the minimum feature size transferred with high fidelity to a resist layer on a wafer. The resolution in shadow printing lithography is limited by diffraction effects. The achievable resolution decreases with increasing proximity gap due to diffraction [6]. As already proposed by Ernst Abbe, diffraction effects like side lobes, higher orders and interference effects could be altered by spatial filtering of illumination light, changing both the angular spectrum and the spatial coherence properties of the illumination light.

As stated previously, in practice the angular spectrum of the incoming light in a Mask Aligner can be set by the usage of exchangeable Illumination Filter Plates (IFP). LayoutLab [GenISys] offers the opportunity to set the collimation angle and the shape of the illumination simply by importing gray scale pictures, which correspond perfectly to the intensity given by the different IFPs on the mask plane of SUSS MicroTec Mask Aligners.

LayoutLab is a proximity printing lithography software package, including standard and phase mask simulation, topographical stack treatment and resist process simulation. The use of this software in manufactory environment allows an evaluation of all the intermediate steps of the lithography process. Aerial Image and intensity within the resist are simulated and are easily observable by the user. This makes an evaluation of the depth of focus (DoF) and contrast in function of parameters variations such as tilt, collimation angle, proximity gap and exposure dose possible. Furthermore, the generated resist contours are simulated and the CDs at a defined position and depth in the resist can be measured by a metrology module.

3.1 Source-Mask Optimization (SMO)

In the first experiment, a photomask consisting of 10 x 10 μm^2 periodic quadratic openings, proximity distance of 100 µm and a 1.2 µm thick resist (AZ1518) was analyzed. Two different illumination settings were tested in order to evaluate their influence on both simulated (Figure 2) and experimental (Figure 3) resist pattern. As shown in Figure 2 and 3, the simulated and experimental resist profiles correspond very well. In both of the cases, the actual illumination setting (IFP) defines the resulting resist pattern. The A-IFP illumination shown in Figure 2 (b) and 3 (b) consists of

12 circular openings providing a mixture of annual and multipole illumination. A-IFP corresponds to the standard HR[1] and LGO[2] illumination optics, also referred as "diffraction reduction optics" for previous generations of SUSS Mask Aligners. The resulting prints in both simulation and experiment show a rounding of the edges and a slight deformation of the circle corresponding to the asymmetry of the A-IFP illumination. For Maltese 45° IFP, shown in Figure 2 (c) and 3 (c), the quadrupole characteristics of the Maltese pattern partly compensates the rounding of the edges. This example demonstrates the excellent correlation of simulation and experiment. Customized illumination allows to partly compensate diffraction effects.

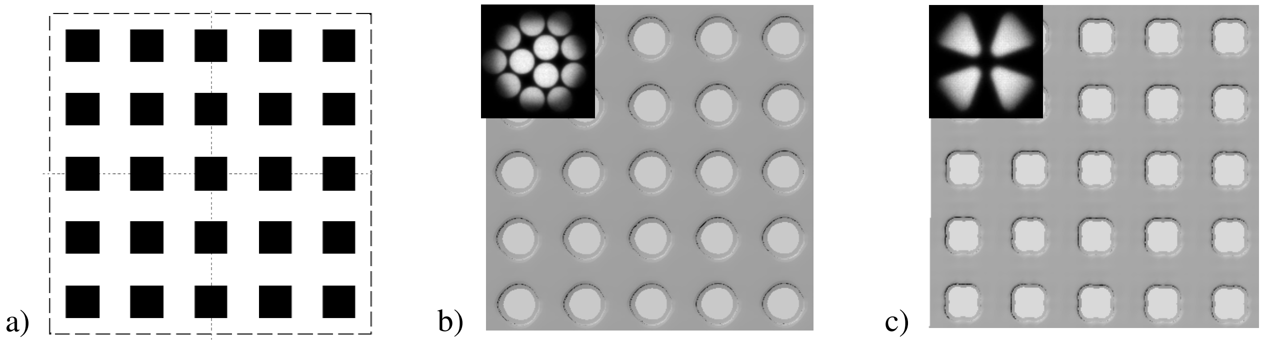


Figure 2: 3D resist profile generated by LayoutLab simulations using different illumination setting. (a) The photomask consisting of 10 x 10 µm^2 large holes with 20 µm pitch. In (b) and (c) the simulated profiles onto 1.2 µm thick photoresist (in this case AZ1518) are shown. The proximity gap was 100 µm. A broad band illumination (g-, h- and i-line) was used with different geometries, corresponding to A-IFP and Maltese-IFP in the Mask Aligner. In the upper left corner of the images the gray scale pictures imported as illumination settings are shown.

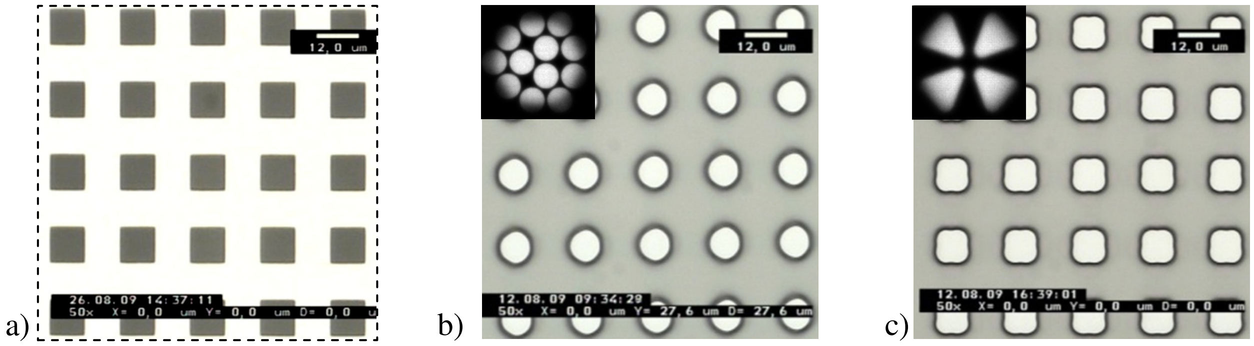


Figure 3: Experimental results for Mask Aligner Lithography using MO Exposure Optics and customized illumination. Photographs represent the photomask consisting of 10 x 10 µm^2 large holes (a) and of resulting prints in 1.2 µm thick photoresist (b) and (c). The photoresist was exposed at a proximity gap of 100 µm using different IFP illumination filter configurations shown in the small window in the upper left corner of the photographs.

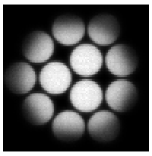
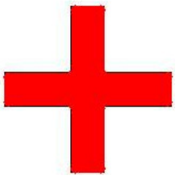
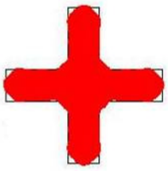
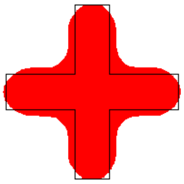
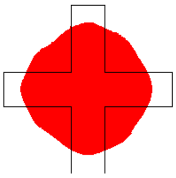
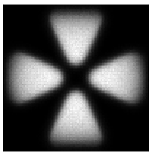
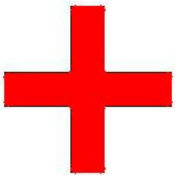
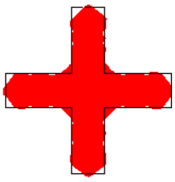
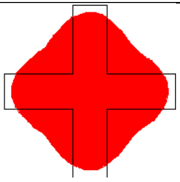
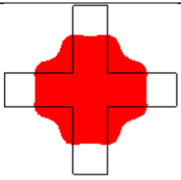
The results shown in Figures 2 and 3 indicate a correlation of the pattern of the Illumination Filter Plates (IFP), in fact a binary object and the resulting resist print. This correlation is very similar to the image generation of a pinhole camera (camera obscura). In the mask aligner, each 10 x 10 µm^2 opening of the photomask acts as a pinhole and "images" the IFP pattern to the resist layer. Similar to a pinhole camera, the size of the resist image scales with the IFP dimensions and the proximity gap. To obtain an optimized resist structure not only the IFP pattern, but also the scaling is important. The larger the gap, the smaller the IFP and the smaller the divergence of the illumination light should be. This very simple model of a pinhole camera is very useful to understand the phenomenon of proximity printing and corresponds well with more sophisticated simulation approaches. Customized illumination allows to optimize the shape of the resulting structures in the photoresist to a certain extent. To further improve the resist prints, additional measures are needed. A classic use for Optical Proximity Correction (OPC) is the situation where a mask contains one critical feature that is

[1] HR: High-Resolution Optics, used for contact and small gap proximity lithography in SUSS Mask Aligners

[2] LGO: Large-Gap Optics, used for large gap proximity lithography in SUSS Mask Aligners

difficult to print, while everything else on the mask is transferred correctly into the resist. In the following example we tried to improve a 25 µm length and 5 µm wide cross onto the resist with exposure gaps up to 200 µm. At the beginning we started evaluating different illumination settings. For small gaps the resist profile for the two different settings are quite similar, but with increasing proximity gap the profiles get different.

Table 1: Generated resist profile using LayoutLAB in contact mode, 20 µm, 50 µm, 100 µm and 200 µm proximity gap. Two different illumination settings were tested: the so-called A and MALT 0° IFP.

Illumination	**Contact**	**20 µm**	**50 µm**	**100 µm**	**200 µm**
					
					

For large gaps, the quality of the resist print is not usable. A further improvement can be achieved by altering the mask layout. Figure 4 shows the mask (black solid line) and the correspondent resist footprint (in red) given at 100 µm gap using quadrupole illumination with and without optimized mask. It can be easily seen that the employing of the optimized mask is successful; the resist footprint has a size and shape much closer to the original mask design.

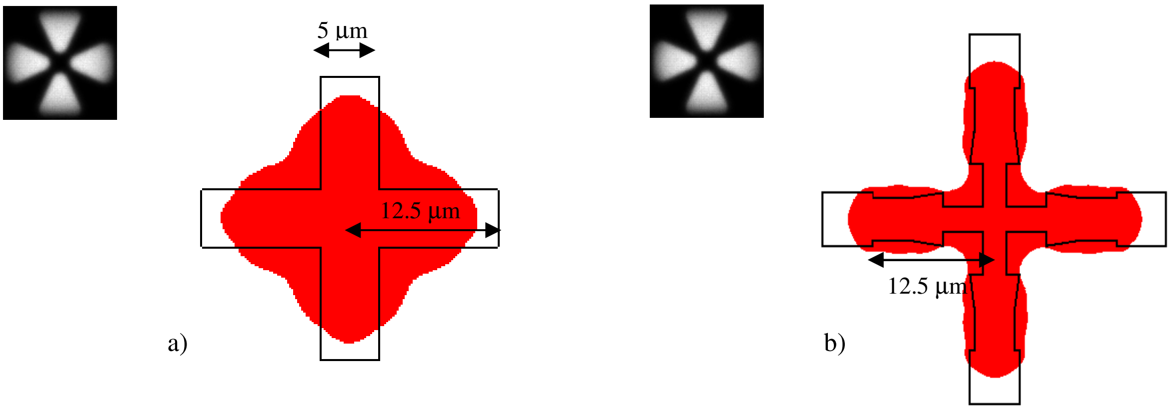


Figure 4: Simulated resist footprint (red) given at 200 µm gap and quadrupole illumination (a)+(b). The conventional mask (a) and the optimized mask (b) are described by the solid black line. Using Fresnel-type OPC mask (c) and small circular illumination geometry the size of the feature in the resist is close to the original mask (wide: 5 µm). Illumination configurations are shown in the upper corner of photographs.

As shown in Figure 4, severe corner rounding effects are still dominant in the resulting resist profiles. For certain applications this might not be acceptable and additional measure for photolithography enhancement are needed. An example of corner fidelity improvement is shown in the following Figure 5. Simulation results obtained by Dr.LITHO software, a simulation tool developed by Fraunhofer IISB, are presented. Dr.LiTHO includes rigorous models and algorithms for the simulation, evaluation and optimization of lithographic processes using optical or EUV image projection. Recently, a new exposure module for Dr.LiTHO has been developed, including a flexible definition of illumination geometries coupled to the standard resist modules for proximity lithography.

Customized illumination and OPC are used to increase the process window for the lithography process. Process window improvement in Mask Aligner Lithography is related to a better tolerance of the process versus gap and exposure dose variations. An example for a 10 µm elbow structure, printed at proximity gaps around 50 µm, is shown in Figure 5. Here the illumination is assumed to have a circular spectrum with a collimation angle of 1.5°, achieved using a circular IFP with 26 mm diameter [7]. The straight sections of the lines are fairly easy to print. However, as shown in Figure 5 (a), the L-shape shows significant rounding at the inner and outer corners.

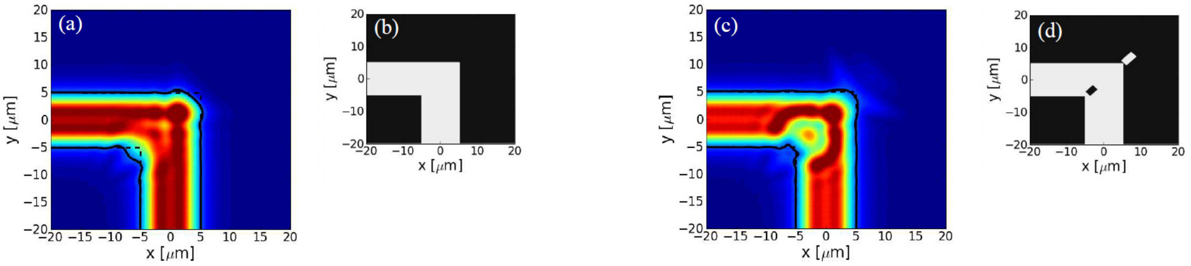


Figure 5: A 90°bend in a 10 µm line printed at a proximity gap of 50µm without (a) and with (c) OPC. The masks are shown respectively in (b) and (d).

In Figure 5, the light intensity distribution in the resist layer is shown. The solid black line shows the footprint of the developed resist. A significant rounding of the corners is observed in Figure 5 (a). To eliminate the rounding two rectangles of variable size and position were added to the mask. We will refer to these squares as ‘OPC rectangles’ in the following. Size and position of the OPC rectangles were optimized to reduce the corner rounding. The result of the optimization is shown in Figure 5 (c). As shown in the drawings, the rounding of both the inner and outer corner is greatly reduced and the level of equal Photoactive Compound (PAC) concentration lies much closer to the ideal profile indicated by the dashed line.

3.2 Fresnel type mask optimization

A Fresnel type OPC mask represents a lithography method that significantly improves the resulting contrast even for very large exposure gaps >200 µm. Simulations and experiments show that MO Exposure Optics and Fresnel-type OPC masks allow to print vias for 3D IC and Through Silicon Via (TSV) at very large proximity gaps, e.g. a square shaped via of 11 x 11 µm at 800 µm gap [8].

In the example shown below a Fresnel Zone Plate (FZP) in combination with a (c) circular and (d) square IFPs is used (Figure 6). As discussed above, each small opening in a photomask pattern acts similar to the pinhole of a camera obscura. From this point of view, the binary Fresnel Zone Plate is just a further enhancement. Certainly, a small pinhole could perform the same imaging task; however, the light efficiency of a pinhole is poor. The binary Fresnel Zone Plate also images the IFP to the resist layer, but provides a much higher efficiency. This method allows to print small vias at very large proximity gaps. In addition, the imaging provides a very large depth of focus (DoF), i.e. the lithography process window is very large.

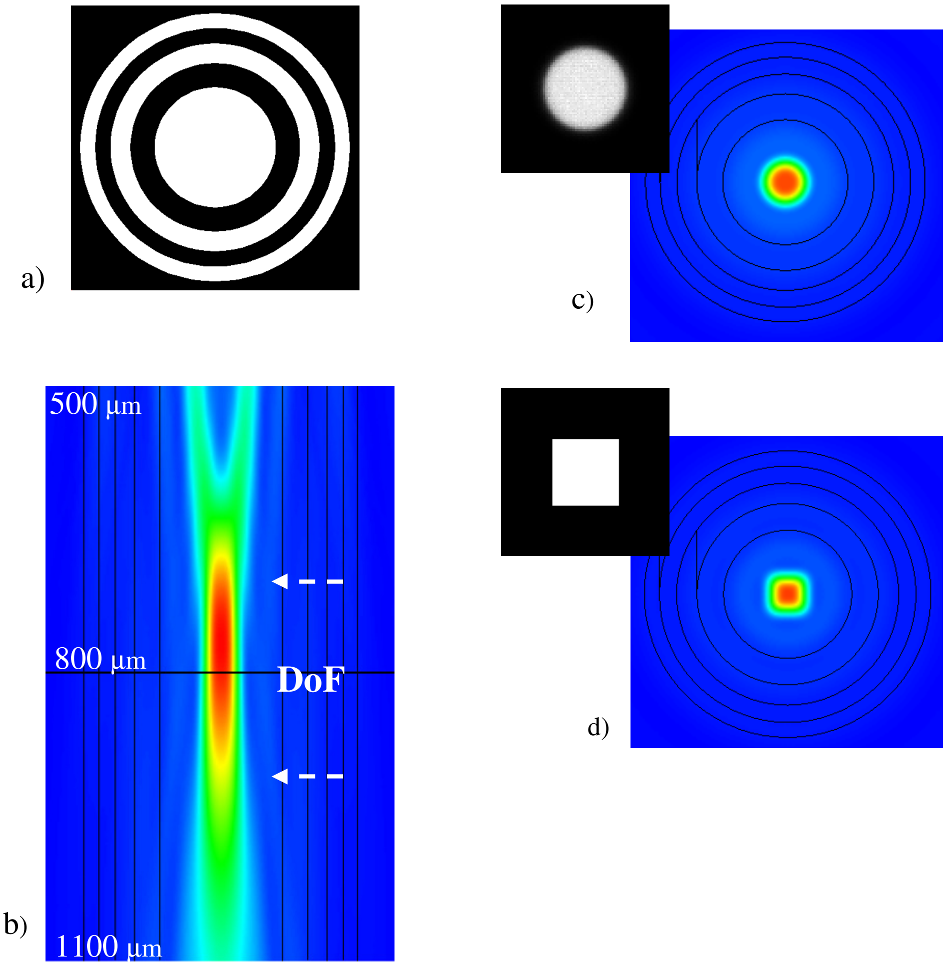


Figure 6: LayoutLAB simulation of aerial image given by a Fresnel type OPC mask exposed to 365 nm light. (a) Mask with a Fresnel zone plate (FZP) of three rings designed for 800 µm gap. (b) Light distribution behind mask. (c) + (d) Aerial Image in 2D view at 800 µm. (c) with circular illumination and (d) square illumination setting.

In the experimental tests a Chrome-on-Glass photomask (Toppan Photomask) with 3 µm minimum features was used. As shown in Figure 7, the experimental results confirm what we expected from simulations once more. The printed feature on the resist presents a square shape with a width of 11 µm and shows that, because of the high contrast, the via has very steep sidewalls. The extended Depth of Focus (DoF) and contrast allows to print small vias on thinned wafer with stable process and high throughput. Advanced Mask Aligner Lithography offers a cost-effective alternative to expensive projection stepper and scanner systems for 3D IC and TSV applications.

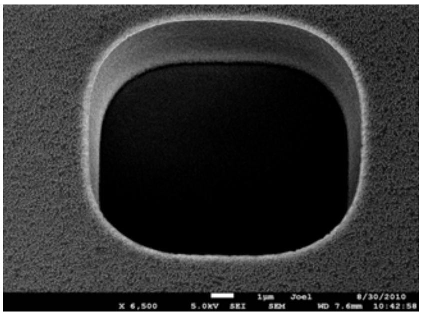


Figure 7: Electron microscope picture of a via printed at 800 µm proximity gap in 5 µm thick AZ1518, using a square IFP. Feature size: 11 µm.

According to the simulation, the feature size printed on the resist decreases at smaller gaps, since the focal spot size decreases. For smaller gaps the size of the FZP decreases too. This is an advantage when the pattern that needs to be transferred into the resist is very closely packed. Simulations allow an evaluation of the minimum distance between FZPs for preventing that overlapping effects get dominant avoiding the focusing function. Figure 8 shows that for two FZPs for a gap of 300 µm with 6 µm distance an overlap is not critical.

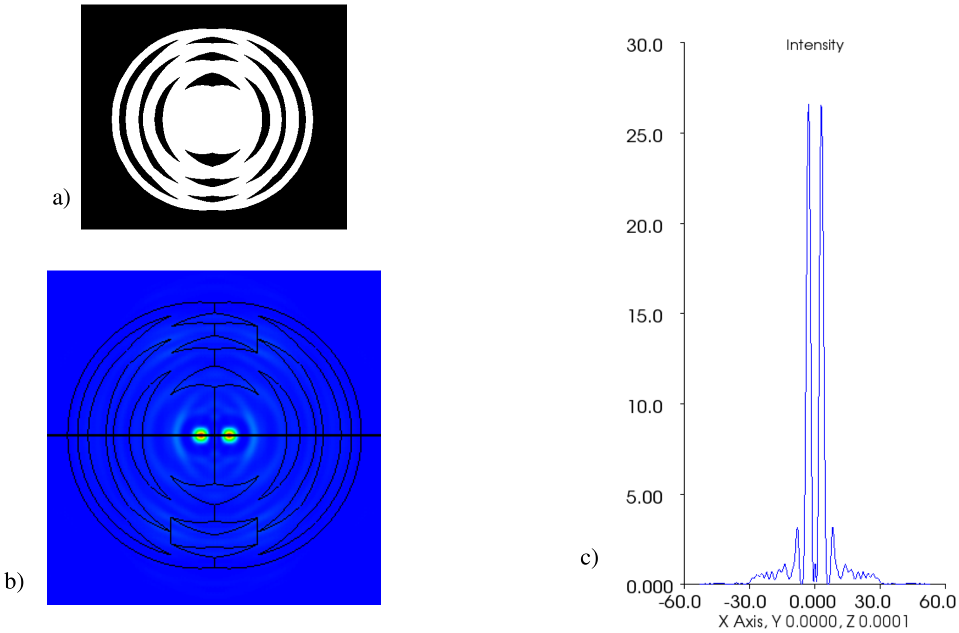


Figure 8: A simulation of an Aerial Image produced by two overlapping FZPs in 300 µm proximity gap. The distance between the centers of the FZPs is 6 µm. The overlap on the mask (a) still produces two spots in the Aerial Image (b). The cross section (c) shows that the contrast is still very high.

3.3 Talbot Lithography

The presented simulation tools for Advanced Mask Aligner Lithography are also well suited for Talbot and Grey-Scale Lithography in a Mask Aligner. These methods allow to obtain sub-micron resolution at large proximity gaps for periodic structures [9]. Talbot effect reproduces the original (or inverted) mask pattern at certain proximity gaps, given by integer or fractional multiples of Talbot length. Hence the optimum exposure gap will depend on illumination wavelength and on mask features pitch.

Following the intensity behaviour for a hexagonal periodic mask at gaps between 0 and 2 times Talbot Length is displayed. For a hexagonal array, of which the unit cell is shown in Figure 9 (a), the Talbot length is 102 µm. It can be seen, in Figure 9 (c) that minimums of light intensity are below chrome hexagon of the mask (between the two vertical lines in the pictures) only at contact regime, at T_L and $2T_L$. In Figure 9 (c) the Aerial Image in 2D is shown for gap interval between T_L-3 µm and T_L+3 µm in order to assess the Depth of Focus (DoF), which results to be about 6 µm. This value will be confirmed by experiments [1]. A good Depth of Focus is needed because it provides a process that is insensitive to gap variations. Gap variations can occur, for example in presence of uneven wafers surfaces. A DoF that is large enough makes Talbot lithography well suitable for manufacturing, e.g., photonic crystals on sapphire wafers as used for LED manufacturing or antireflection texturing of solar cells.

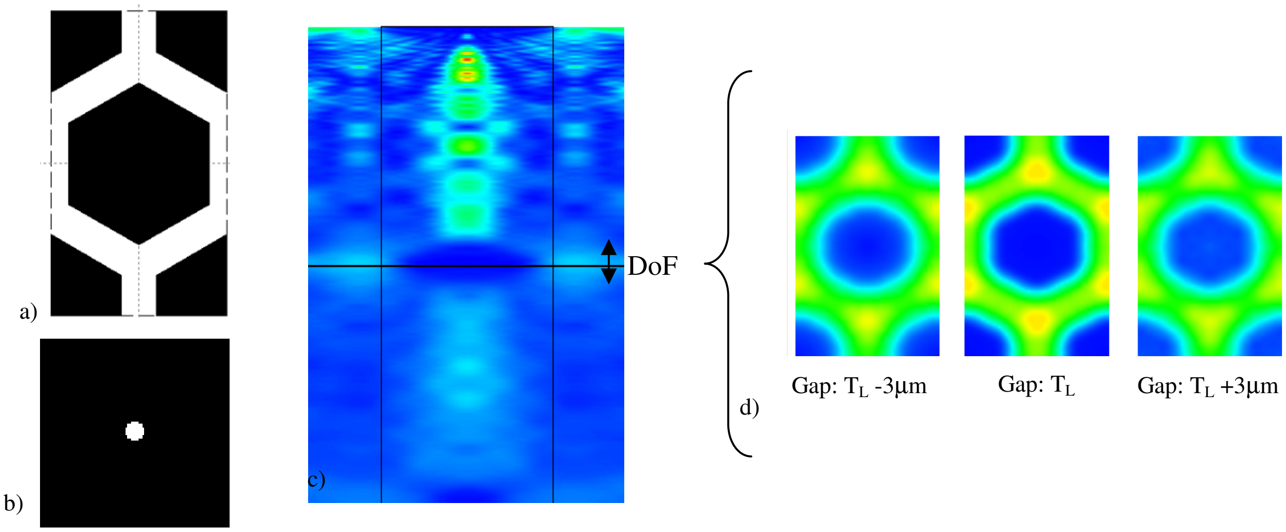


Figure 9: (a) Unit cell of hexagonal array mask. Hexagon size: 4 µm; pitch: 5 µm. (b) Illumination geometry (circular with small collimation angle). (c) Aerial Image cross section between 0 µm and 204 µm. Depth of Focus around the Talbot Length (102 µm) is large about 6 µm. (d) Aerial Image in 2D view for gaps smaller and bigger than Talbot Length (T_L).

A comparison between the simulated three-dimensional (3D) resist profile of hexagonal structure using LayoutLAB and the experimental results using a periodic mask pattern with 5 µm pitch exposed in 102 µm gap is shown in Figure 10. The results from simulation and experiment correspond again very well.

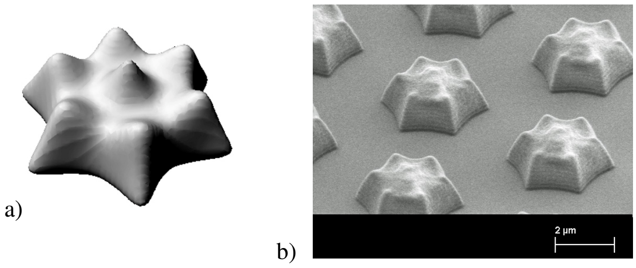


Figure 10: (a) Simulated 3D resist profile and (b) scanning electron microscopy image of a periodical hexagonal structure in photoresist.

4. CONCLUSION

In this paper we presented two simulation tools, LayoutLab [GenISys] and Dr.LITHO [Fraunhofer IISB], for Advanced Mask Aligner Lithography. Advanced Mask Aligner Lithography is based on MO Exposure Optics, a novel illumination optics for SUSS Mask Aligners. MO Exposure Optics provides excellent uniformity of the illumination light, telecentric illumination and for the first time the full freedom to shape the angular spectrum of the mask illuminating light. Now simulation and optimization of all process parameters, from the light source to the final pattern in photoresist, is possible in Mask Aligner Lithography. It was demonstrated that LayoutLab and Dr.LITHO allow to optimize Mask Aligner Lithography beyond its current limits, by both shaping the illumination light (Customized Illumination) and optimizing the photomask pattern (Optical Proximity Correction, OPC). The results from simulation and experiment were corresponding well. Simulation and photolithography enhancement now allows to further improve Mask Aligner Lithography beyond its current limits. Regarding the more than 3’000 Mask Aligners (estimation) installed in cleanrooms worldwide, the presented simulation tools might also have a major impact on semiconductor, LED and MEMS industry.

5. OUTLOOK

The simulation experiments shown in this paper were based on the optimization of the aerial image, in order to avoid resist specific effects and inaccuracy caused by imprecise resist modeling.

The intensity distribution of irradiance in the aerial image gives us fundamental information concerning contrast, Normalized Image Log Slope (NILS) and Depth of Focus (DoF). Evaluating these factors, it’s possible to predict how the resist profile will look and if a process will be successful. At the present time, a model for resist standardization is missing and resist parameters were found on experimental bases. More accurate physical description at the molecular level is needed to allow a rigorous and improved photoresist modeling.

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