Advanced Mask Aligner Lithography (AMALITH)

Reinhard Voelkel[a,i], Uwe Vogler[a], Arianna Bramati[a], Tina Weichelt[a],
Lorenz Stuerzebecher[b], Uwe D. Zeitner[b], Kristian Motzek[c], Andreas Erdmann[c],
Michael Hornung[d], Ralph Zoberbier[d]
[a]SUSS MicroOptics SA, Rue Jaquet-Droz 7, 2000 Neuchatel, Switzerland
[b]Fraunhofer Institut IOF, Albert Einstein Str. 7, D-07745 Jena, Germany
[c]Fraunhofer Institut IISB, Schottkystr. 10, 91058 Erlangen, Germany
[d]SUSS MicroTec Lithography GmbH, Schleissheimerstrasse 90, 85748 Garching, Germany

ABSTRACT

Mask aligners were the dominating lithography tool for the first 20 years of semiconductor industry. In the 1980s industry changed over to projection lithography. However, mask aligners were never sorted out and still today hundreds of new mask aligners are sold each year. This continuing success of mask aligner lithography is due to two basic trends in lithography: (a) Costs for leading-edge lithography tools double approximately every 4.4 years; and (b) the number of lithography steps per wafer was increasing from a few litho layers to more than 35 layers now. This explains why mask aligners, a very cost-effective solution for uncritical litho layers, are still widely used today. In over 50 years of semiconductor industry the mask aligner system has changed tremendously. However, only little effort was undertaken to improve the shadow printing process itself. We now present a new illumination system for mask aligners, the MO Exposure Optics (MOEO), which is based on two microlens-type Köhler integrators located in Fourier-conjugated planes. The optics stabilizes the illumination against misalignment of the lamp-to-ellipsoid position. It provides improved light uniformity, telecentric illumination and allows freely shaping the angular spectrum of the illumination light by spatial filtering. It significantly improves the CD uniformity, the yield in production and opens the door to a new era of Advanced Mask Aligner Lithography (AMALITH), where customized illumination, optical proximity correction (OPC), Talbot-lithography, phase shift masks (AAPSM) and source mask optimization (SMO) are introduced to mask aligner lithography.

Keywords: Mask aligner, proximity lithography, shadow printing, customized illumination, source mask optimization, microlens array, phase shift mask

1. INTRODUCTION

Projection lithography pushed mask aligner lithography out of semiconductor front-end in the early 1980s. However, mask aligner lithography was never phased-out. The installed mask aligners remained in operation for less critical layers. The semiconductor back-end, Advanced Packaging, MEMS, TSV for 3D-IC, and - most recently the very cost-sensitive LED manufacturing - maintained a continuous demand for some hundreds of new mask aligners installed every year in industry. Mature and robust technology, high throughput, ease of operation, low maintenance, moderate capital costs and attractive cost-of-ownership (COO) are the key factors. Since the 1980s, these mask aligner systems have much evolved, from the manual 1" aligner to the fully automatic 300 mm cluster systems of today. Interestingly, the shadow-printing lithography process itself was never improved. Illumination systems of most commercially available mask aligners are still based on technology developed in the 1970s and 1980s. Uniform mask illumination is obtained by optical integrators or fly's eye condensers consisting of some 10 to 20 glass lenses or light rods mounted in a metal frame. A light uniformity of ±3% to ±5% (or worse) and - more important, a significant variation of the angular spectrum of the illumination over the mask field is observed. For shadow printing (proximity lithography) these variations have severe influence on the CD uniformity of the print.

---

[i] voelkel@suss.ch, +41-32-7205103, www.suss.ch, www.suss.com

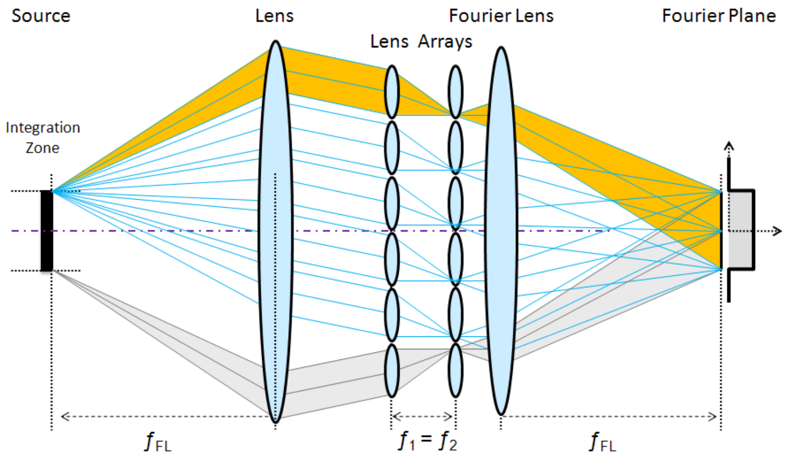
Inspired by the tremendous success that micro-optical beam shaping technology had for DUV wafer stepper/scanner lithography, we have introduced a novel mask aligner illumination system, referred as MO Exposure Optics (MOEO)[1,2]. The MO Exposure Optics system is based on two microlens-type Köhler integrators located in Fourier-conjugated planes. Both Köhler integrators consist of high-quality microlens arrays especially adapted for mask aligner illumination. MO Exposure Optics improves the light uniformity, provides telecentric illumination and fully freedom of shaping the angular spectrum of the illumination light.

Full control of the illumination light allows simulating mask aligner lithography from the light source to the resulting photoresist pattern. Simulation tools like LayoutLab™ from GenIsys[3], Dr.LiTHO[4] from Fraunhofer IISB and VirtualLab™ from LightTrans[5] are used to optimize mask aligner lithography. For shadow printing the focus of optimization procedures is on the reduction of the diffraction effects and on the light propagation in free space after the mask. Targets for lithography optimization are manifold: compensating for errors and irregularities like corner rounding, line width narrowing and edge shortening, elimination of remaining diffraction effects, increasing the gap range of operation (minimum to maximum gap) and a larger free working distance (proximity gap), as well as resolution enhancement.

2. MO EXPOSURE OPTICS (MOEO)

2.1 Köhler integrators: Uniform and telecentric illumination in mask aligner

Illumination systems for mask aligners are based on high-pressure mercury plasma arc discharge lamps emitting ultraviolet light. The light is then collected by an ellipsoid mirror and re-focused in the secondary focal point of the ellipsoid. Microlens-based optical integrators, also referred as fly's eye condensers or Köhler integrators, are used for achieving illumination with good irradiance uniformity[6,7,8].



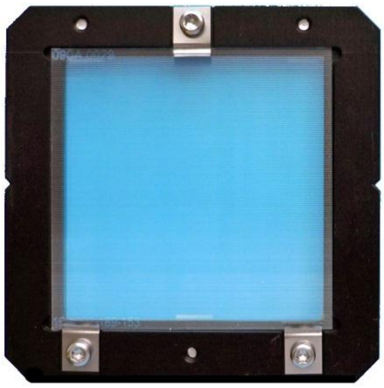


Fig. 1. (left) Scheme of a Köhler integrator collecting light from an extended light source within an integration zone and providing uniform irradiance in the Fourier plane of the Fourier lens. Two symmetrical lens arrays located at a focal length distance (f1 = f2) are used for light mixing. The aperture splitting of the lens array provides a plurality of parallel Köhler illumination systems perfectly decoupling illumination in the Fourier plane from the lamp.(right) Microlens array used as Köhler integrators in mask aligners [SUSS MicroOptics, www.suss.ch].

As shown in Fig. 1, for each channel of a Köhler integrator the entrance pupil of the first lens is imaged by the second lens and the Fourier lens to the Fourier plane. The outer boundary of the uniform illumination area is a superposition of these individual images of the lens array sub-apertures and provides a sharp cut-off, often referred as "flat-top" profile. A Köhler integrator collects the light from the light source, produces a plurality of secondary light sources and modifies the size and geometry of the illuminated target field.

For MO Exposure Optics, two Köhler integrators are used. This first integrator is located in the secondary focal plane of the ellipsoid as shown in Fig. 2. The first integrator is used to decouple the mask illumination light from a misalignment of the lamp within the ellipsoid. The first integrator provides a uniform "flat-top" illumination of the entrance pupil of the second integrator. After passing the second Köhler integrator, in which the light is once again homogenized, a flat-top irradiance profile is generated in the focal plane of the second Fourier lens. In the Fourier plane of the second integrator, a field lens, also referred as "front lens" is located. The front lens provides quasi parallel and telecentric illumination of the mask. Telecentric illumination ensures that the lateral position of the mask pattern is transferred 1:1 to the wafer with no lateral displacement even for large gap proximity lithography.

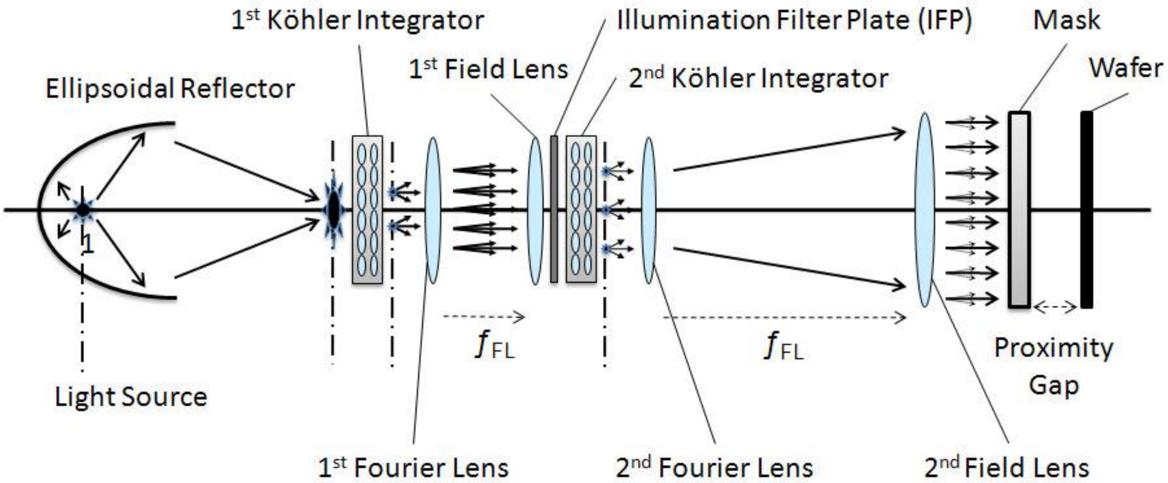


Fig. 2. Simplified view of MO Exposure Optics illumination system for mask aligners comprising two subsequent Köhler integrators. A first Köhler integrator is located near the secondary focal point of the ellipsoidal reflector. A second Köhler integrator is located in the Fourier plane of the first integrator.

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.

2.2 Proximity lithography is limited by diffraction effects at the mask

The performance of mask aligner lithography is determined by two parameters: Resolution also referred to as minimum critical dimension (CD), and overlay. Resolution is defined to be the minimum feature size that can be transferred with high fidelity to a resist layer on a wafer. Overlay is a measure of how accurately patterns on successive masks can be aligned or overlaid with respect to previously defined patterns on the same wafer. The resolution in shadow printing lithography is limited by diffraction effects. Submicron resolution is achieved for vacuum contact, where the air in-between mask and wafer is evacuated. For vacuum contact lithography, very tight requirements regarding flatness and cleanliness apply. Any remaining particle will increase the mask-to-wafer distance and will deteriorate the printing results. In production environment, with the demand for low costs and high throughput, proximity lithography is used. Here wafer and mask are separated by some 30 to 200 microns proximity gap. The achievable resolution decreases with increasing proximity gap due to diffraction[9]. As already proposed by Abbe[10], diffraction effects like side lobes, higher orders and interference effects could be altered by spatial filtering of the illumination light, changing both the angular spectrum and the spatial coherence properties of the illumination light. In projection lithography, a spatial filtering of the illumination light is referred as "customized illumination" and a well-established resolution enhancement technology (RET).

MO Exposure Optics now offers a quick and easy change of the angular spectrum of the illumination light. Using a second Köhler integrator with a large-area microlens array allows placing different obstructions for spatial filtering of the illumination light. Exchangeable illumination filter plates (IFP), in the simplest case a binary mask or metal mask with holes allow altering the angular spectrum and the coherence properties of the mask illuminating light in the mask aligner[11]. The illumination filter plate is preferably located near the second Köhler integrator and defines the light emitting areas of tertiary light sources at the secondary Köhler integrator. Variable or programmable illumination filters using zoom lenses, axicon telescopes, liquid crystal displays (LCD), micro-mirror arrays (DLP), variable membranes (MEMS, MOEMS), spatial light modulators (SLM) and light deflectors, acousto-optical modulators and deflectors, variable diaphragms, and all kind of refractive and diffraction optics and mechanics might also be used.

2.3 MO Exposure Optics (MOEO) provides customized illumination

Fig. 3 shows schematically a simple lithography model for the use of MO Exposure Optics for proximity lithography[12]. The photomask is assumed to have a single square opening similar to a pinhole. Thus, the lithography system is reduced to three planes: The illumination filter plane, defining the angular spectrum, the mask plane and the wafer plane, where the resulting aerial image is recorded in photoresist. In this simple model, the opening of the photomask acts like a pinhole camera and images the illumination filter pattern onto the photoresist. As shown schematically in Fig. 3 (b) the illumination filter plane is assumed to be subdivided in a multitude of coherent areas, where each is considered to be an ideal coherent source, but no coherence between different areas is assumed.

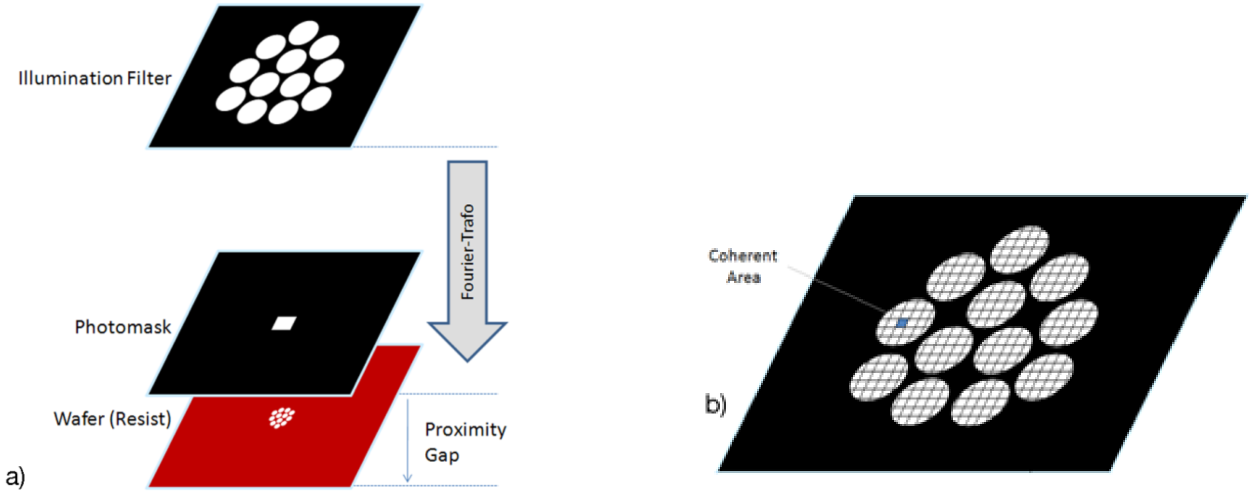


Fig. 3. Simplified lithography model for the use of MO Exposure Optics in proximity lithography. (a) For a single opening in the mask the illumination filter pattern is imaged to the wafer plane. (b) The illumination filter plane is assumed to be subdivided in a multitude of coherent areas, where each is considered to be an ideal coherent source, but no coherence between different areas is assumed. The geometry of the illumination filter plate defines which of the coherent areas are transmitted and can contribute to the mask illumination[12].

The geometry of the illumination filter plate defines which of the coherent areas are transmitted and which areas contribute to the mask illumination. In this simplified model, the optical system performs a Fourier transformation from the illumination filter to the mask. Thus, every coherent area in the illumination filter plane is creating a tilted plane wave while the tilt corresponds to the position of the considered area in the filter plane. Each of these plane waves is coherent, but different waves are incoherent to each other. The mask aligner is considered to be a device which is creating a set of non-interacting plane waves in which the composition of angular components is selected by choice of the illumination filter plate. This simple model is useful to predict the resulting aerial image and to optimize the illumination to improve resolution and fidelity of the resist prints[12].

Fig. 4 shows photographs of (a) of 10 x 10 microns structures on a photomask and (b) to (d) the resulting prints in photoresist (AZ 4110, 1.2 micron thick) exposed at a proximity gap of 100 microns in a mask aligner equipped with the MO Exposure Optics. The corresponding illumination filter configuration is shown schematically in a small window in the upper left corner of the photographs.

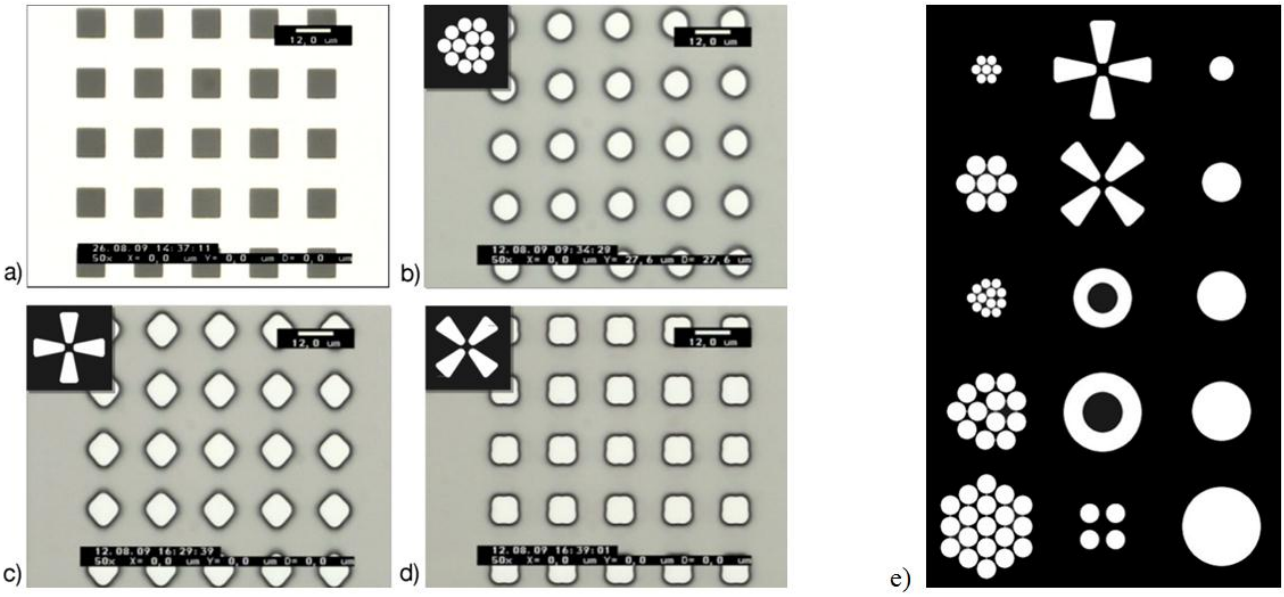


Fig. 4. Experimental results for mask aligner lithography using the MO Exposure Optics and customized illumination. Photographs of (a) of 10 x 10 microns squares holes with 10 microns pitch on a photomask and (b) to (d) the resulting prints in 1.2 micron thick photoresist exposed at a proximity gap of 100 microns behind the photomask using different illumination filters (IFP) shown in more variations in (e).

As shown in Fig. 4 (b), a slightly deformed circle results for an illumination filter similar to standard mask aligner illumination optics (SUSS HR or LGO optics), (c) a cross-shaped illumination filter results in a rhomb pattern and (c) Maltese cross illumination results in structures almost identical to the mask pattern. Fig. 4 (e) shows a variety of illumination filters (IFP) used with MO Exposure Optics, including all standard SUSS optical configurations (HR-, LGO-, D-optics), Quadrupole, Ring, Maltese Cross in the middle row, and different circular illumination settings.

Customized illumination allows influencing and optimizing the shape of the resulting structures in photoresist. A further improvement is achieved if, in addition to customized illumination, also the shapes of the mask structures are modified.

3. ADVANCED MASK ALIGNER LITHOGRAPHY (AMALITH)

In the past, the angular spectrum of the illumination light in a mask aligner varied much over the mask field and could not be change by the user. This was a severe limitation of mask aligner lithography. MO Exposure Optics allows simulating and optimizing photolithography processes. Resolution enhancement techniques (RET) from Front-End Projection Lithography could now be applied to shadow printing lithography.

3.1 Optical Proximity Correction (OPC) and Source Mask Optimization (SMO)

Optical proximity correction (OPC) is a resolution enhancement technology (RET) commonly used to compensate for errors and irregularities like corner rounding, line width narrowing and edge shortening. Optical proximity correction corrects these errors by moving edges or adding extra polygons to the photomask pattern. If both customized illumination and optical proximity correction are used this is referred as source-mask optimization (SMO). Primary goals are enhanced CD control, increased resolution and depth of focus (DoF), improvement of the manufacturability for critical lithography steps and enlargement of the process window.

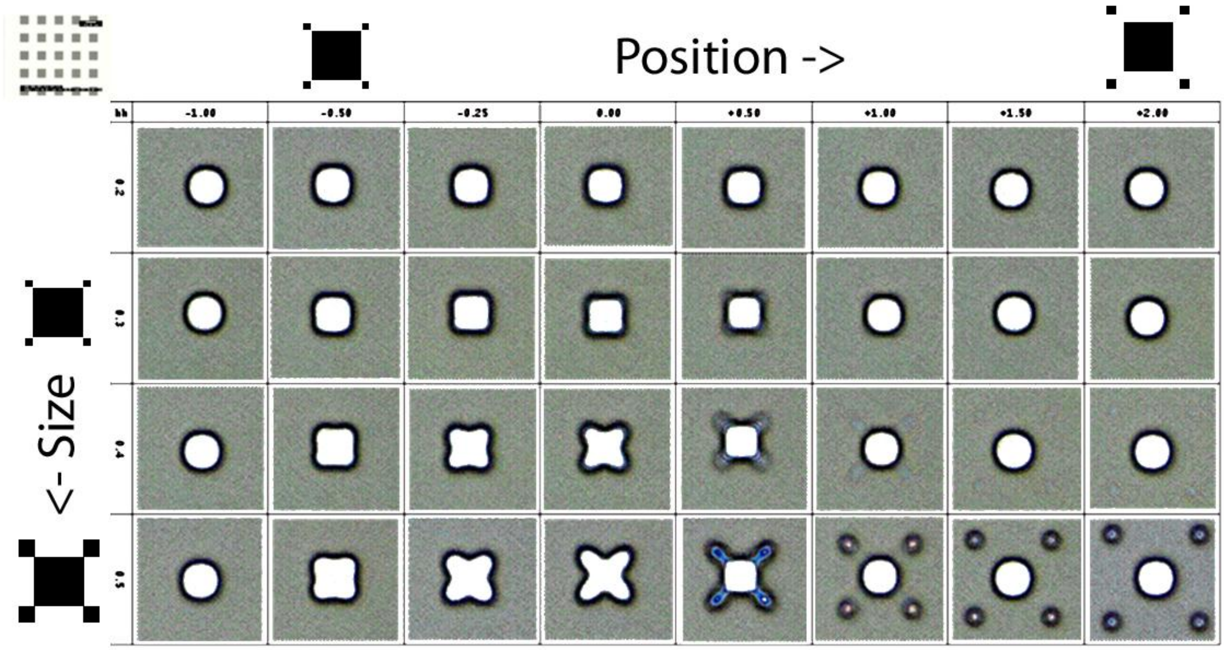


Fig. 5. Experimental results for mask aligner lithography using MO Exposure Optics, customized illumination and optical proximity correction (OPC). Photographs of resist prints (AZ 4110, 1.2 micron thick) obtained for a proximity gap of 50 microns. The resist image in the upper left corner shows the print result for 10 x 10 microns square, similar to Fig. 4 (a), illuminated with a circular illumination filter and no OPC correction. The influence of OPC assist features (serifs) of different sizes (columns) and at different positions (row) are shown in a matrix.

Fig. 5 shows experimental results for mask aligner lithography using MO Exposure Optics, customized illumination and optical proximity correction (OPC). A circular-shaped illumination filter was used to expose a 1.2 micron thick layer of AZ 4110 (AZ Electronic Materials) photoresist with 66 mW/cm2. The resist image in the upper left corner of Fig. 5 shows the print result with no additional OPC assist feature. The circular illumination emphases the rounding of the corners as shown in Fig. 4 (b). OPC assist features (serifs) were added to the square pattern on the photomask. Fig. 5 shows a matrix of resist images for different OPC structures. In horizontal direction the position of the assist features was changed. In vertical direction the size of the assist feature was increased. Source-mask optimization allows pre-compensating print errors due to diffraction and process effects. MO Exposure Optics and source-mask optimization technology have a strong impact on process window enlargement and yield improvement in production environment.

3.2 Simulation tools for Advanced Mask Aligner Lithography (AMALITH)

Three different simulation software tools are available for Advanced Mask Aligner Lithography (AMALITH). The commercially available software LayoutLab™ from GenISys[3] allows optimizing 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[4], a simulation tool developed by Fraunhofer IISB for 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. The third software tool is VirtualLab™, an optical design software developed by LightTrans[5]. VirtualLab™ is based on ray tracing and field tracing. Instead of ray bundles, harmonic fields are traced through the optical system. Field tracing allows simulating diffraction, interference, partial coherence, aberrations, polarization and vectorial effects.

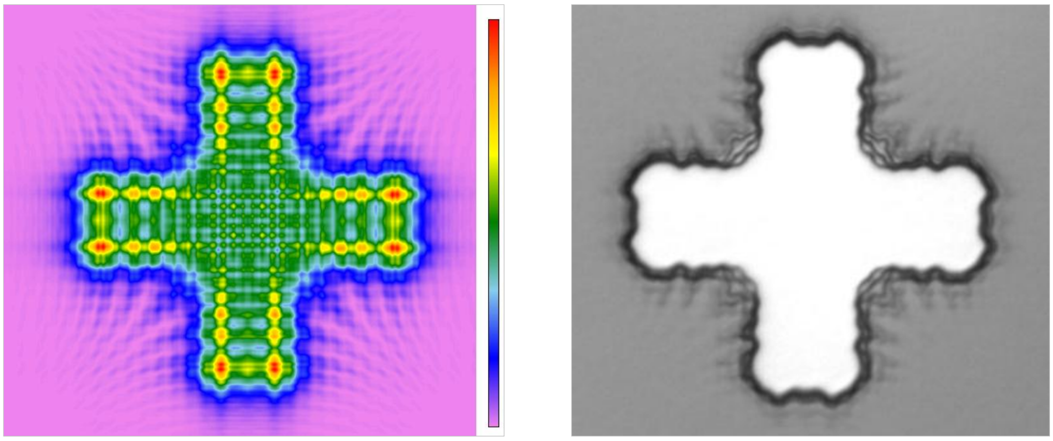


Fig. 6. (left) the calculated intensity distribution of a cross-type mask pattern (10 µm line width) at 30 µm proximity gap; (right) experimental verification (1 µm thick AZ 1518 photoresist on silicon).

Fig. 6 (left) shows the intensity distribution for 30 µm proximity distance of a cross-type mask pattern illuminated with collimated monochromatic light (365 nm). The simulation was done with VirtualLab™ using wave-optical modeling. The corresponding photoresist profile is shown in Fig. 6 (right). Simulation and experiment match well and allow further optimizing of mask aligner lithography.

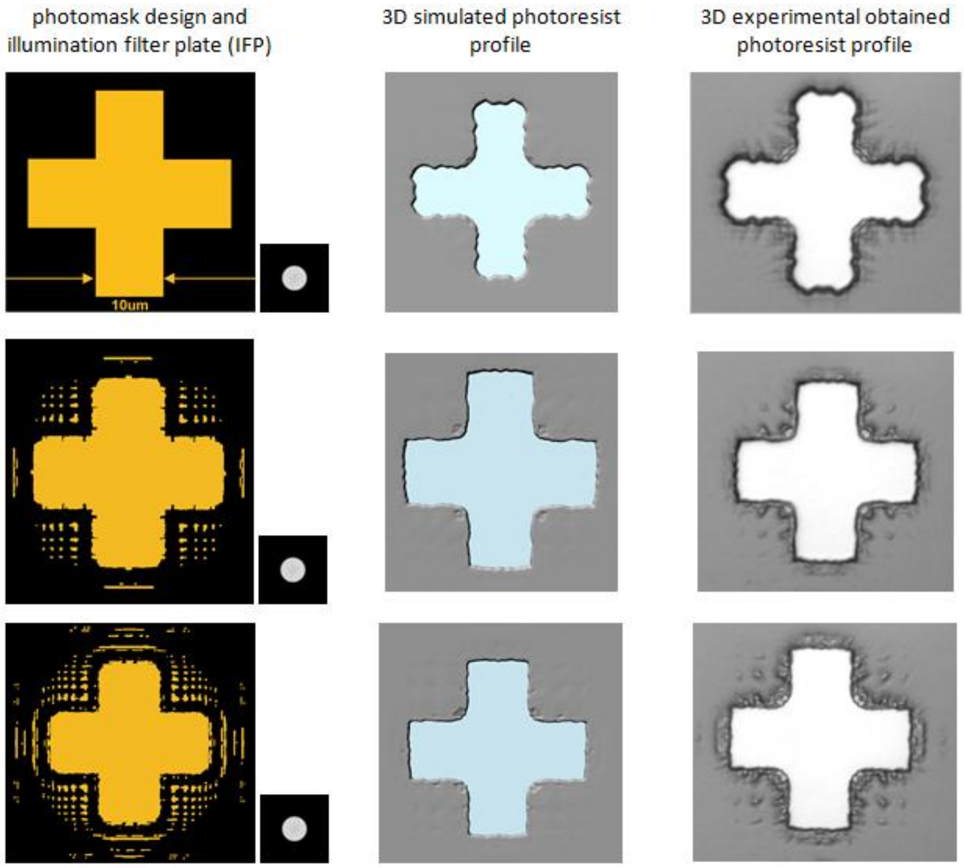


Fig. 7. Simulated and experimentally obtained photoresist profiles using OPC design (left) to compensate diffraction. The line width of the cross was 10 µm, proximity gap 30 µm and a photoresist layer of 1 µm AZ 1518.

Improving proximity lithography is of much interest for all production-related mask aligner processes. For large wafer sizes like 200 mm and 300 mm and high volume production a proximity gap of ≥ 30 µm is needed to avoid any contact of mask and wafer. This proximity gap of 30 µm limits the obtainable resolution to some 3 µm, a severe limitation which has driven mask aligner lithography out of the semiconductor front-end in the early 1980s.

Having gained full control on the illumination light and having reliable tools to simulate and optimize proximity lithography, we can now start to improve the aerial image in the photoresist. In a first step Optical Proximity Correction (OPC) with binary assist features was used to reduce diffraction effects for the example shown in Fig. 6.

Fig. 7 shows that the fidelity of a cross-type mask pattern with 10 µm features could be further improved (compared to Fig. 6) by using binary assist features. OPC design was performed using VirtualLab™. The optimized mask pattern with OPC structures is shown in Fig. 7 (left). The obtained resist image from simulation (center) corresponds well to the experimentally obtained resist structure (right) for exposure in 30 µm proximity gap and 1 µm thick AZ 1518 photoresist. OPC and assist features are a valid technology to improve the fidelity of the edges and contours of a desired mask pattern for proximity lithography in a mask aligner. The degree of lithography enhancement is related to the minimum feature size on the photomask. Smaller feature sizes in the OPC design allow improving the fidelity of the resist print beyond today's limits. However, smaller feature sizes might increase the costs for the photomask, especially if sub-micron features are required.

3.3 Alternating Aperture Phase Shift Masks (AAPSM)

In a next step phase shift masks (PSM) were examined for resolution enhancement. Fig. 8 a) shows a binary photomask, where light is either absorbed by the chromium layer (black) or passes openings (yellow). The shadow pattern at a certain distance behind the mask is affected by diffraction and interference effects. Light also propagates in the dark areas and bright areas are darkened partially.

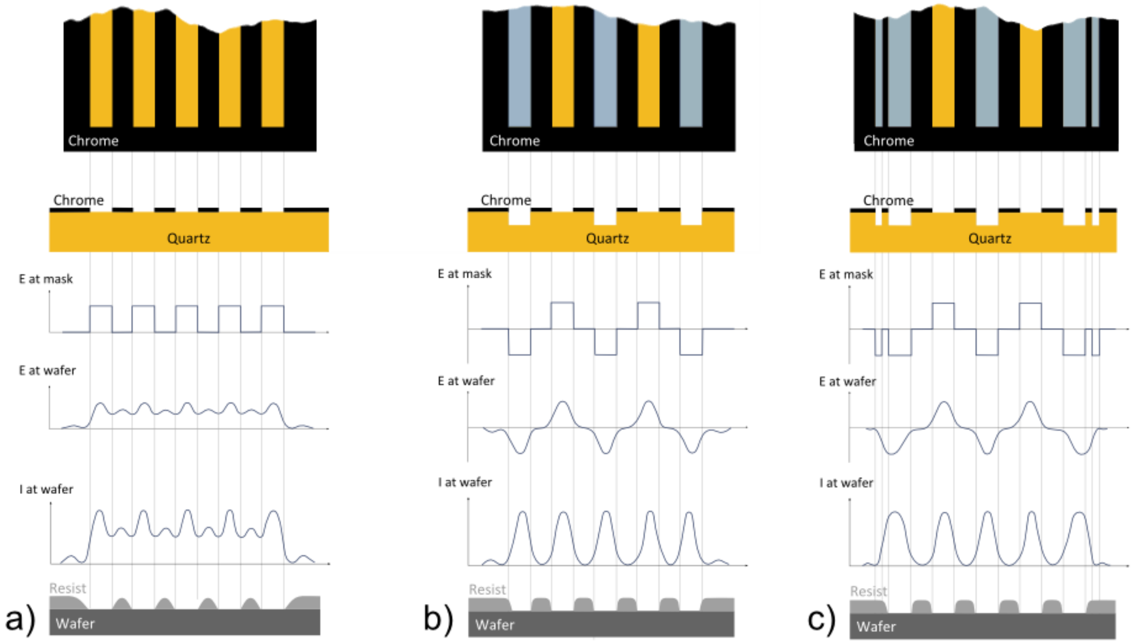


Fig. 8. Three different types of photomasks: a) binary photomask, b) alternating aperture phase-shift mask (blue: additional phase step), and c) alternating aperture phase-shift mask (AAPSM) with additional OPC scattering bar.

For alternating aperture phase shift masks (AAPSM), shown in Fig. 8 b) and c), a phase step (blue) is added to the binary mask structure. Light passing the glass and phase step openings are shifted in phase by 180° versus each other. As shown in Fig. 8 b), this phase shift improves the contrast for proximity lithography significantly. Phase shift masks for resolution enhancement were already investigated for mask aligners[13]. It was demonstrated that 3 µm resolution of is possible for 50 µm proximity gap. However, due to the lack of an appropriate illumination system the obtained structures were distorted and unusable for mask aligner lithography at that time. Fig. 8 c) shows an alternating aperture phase-shift mask (AAPSM) with additional OPC scattering bars. The additional OPC scattering bar corrects the intensity, width and position of the outer lines. OPC correction of line-end shortening is also possible, but was not applied for this evaluation.

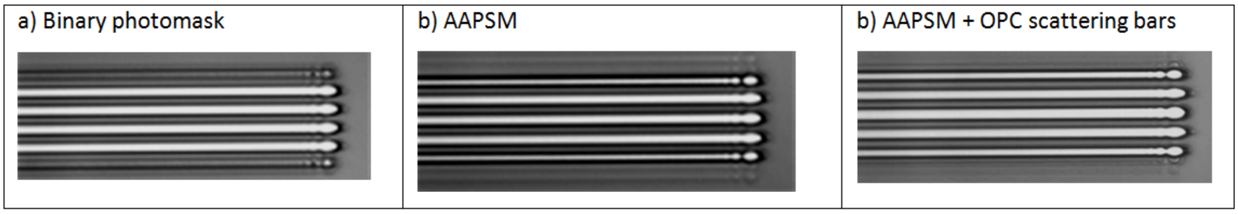


Fig. 9. Prints in photoresist (AZ1512 for 2 µm lines & space at 30 µm proximity gap using three different types of photomasks as shown in Fig. 8. The additional OPC scattering bars in c) correct the intensity, width and position of the outer lines. No correction of line-end shortening had been applied.

Photoresist prints in a mask aligner (30 µm proximity gap, 1 µm thick AZ1512 resist, 365nm) were done for verification of the simulation results. Fig. 9, a) - c) show a similar 2 µm lines & space pattern printed at 30 µm proximity distance. For a) using a standard binary photomasks, only 4 instead of 5 lines are observed (reversal of image contrast), the pattern is not resolved. For the AAPSM shown in Fig. 9 b) the pattern is resolved, however, the outer lines are not exposed with a similar dose and remain smaller. This remaining error is solved by adding OPC scattering bars shown in Fig. 9 c).

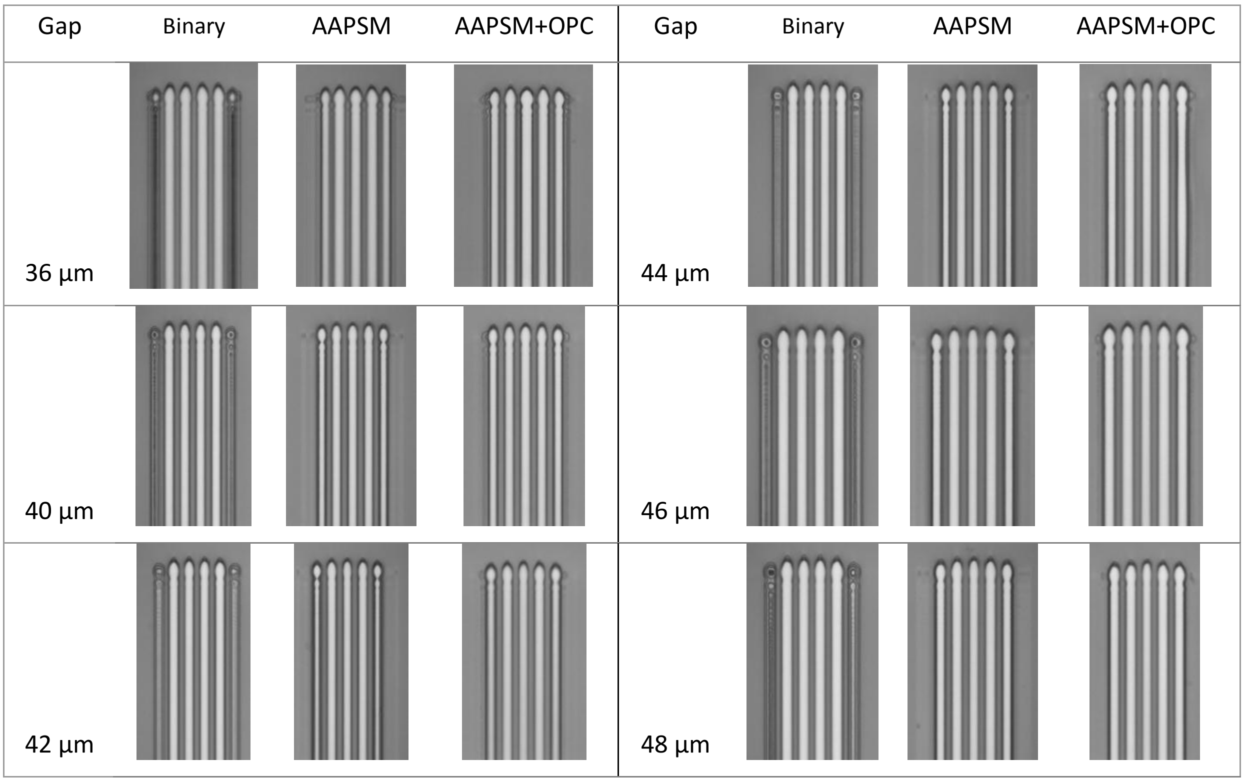


Fig. 10. Prints in photoresist for 2 µm openings (lines & space pattern) similar to Fig. 9, but at different proximity gaps. The prints from the alternating aperture phase shift mask (AAPSM) with OPC scattering bars demonstrates a resolution of 2 µm for a proximity range of operation from 30 µm (see Fig. 9f) to 48 µm.

Fig. 10 shows photoresist prints (1 µm thick AZ1512 resist, 365 nm) for the three different photomask (similar to Fig. 8 and Fig. 9), but at different proximity distances behind the mask. The prints from the alternating aperture phase shift mask (AAPSM) with OPC scattering bars show a resolution of 2 µm (l&s) for a proximity distance from 30 µm (see Fig.

9f) up to 48 µm. The illumination settings for the experiments shown in Fig. 9 and Fig. 10 was a Maltese-Cross (45°) type illumination filter plate (IFP) similar to Fig. 4 (center). Simulation and experiment proofed that AAPSM and OPC allow enhancing the resolution at proximity lithography. In practice, special care has to be taken in OPC algorithms for mask aligners to generate layouts with manageable manufacturing and inspection costs.

3.4 Talbot and Pinhole-Talbot Lithography for printing periodic pattern at large proximity distance

The possibility to freely shape the illumination light and the excellent uniformity in intensity and angular spectrum also allows implementing new lithographic techniques in a mask aligner. Especially for periodic structures, like gratings, photonic crystals, absorbers and patterned sapphire surface (PSS), the Talbot and Pinhole-Talbot lithography are very attractive[12,14]. These techniques allow printing sub-micron features at very large proximity distances on full wafer size in a mask aligner.

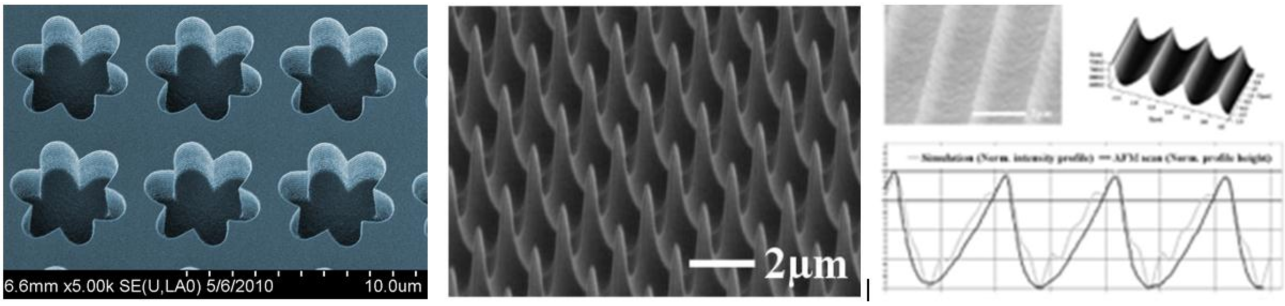


Fig. 11. (left) SEM image of a periodical pattern of 5µm stars printed in 98 µm proximity distance; (center) an array of fine needles printed with half-tone proximity lithography; and (right) SEM and AFM images of a blazed grating structure of 2µm pitch and 0.58 µm height printed in AZ4562 using mask with periodic slits as "pinholes" and Talbot imaging[14].

Fig. 11 shows some examples printed in SUSS MicroTec MA6 mask aligner: (left) the SEM image of a periodical pattern of 5 µm stars printed in 98 µm proximity distance using a pinhole array with 6 µm pitch and 800 nm width square features for MO Pinhole Talbot Lithography. The pattern was printed in AZ1518 resist and then transferred into silicon by reactive ion etching (Bosch process). Fig. 11 (center) shows an array of fine needles with 2 µm pitch printed with half-tone proximity lithography at 10 µm proximity distance. Fig. 11 (right) shows SEM and AFM images of a blazed grating structure of 2 µm pitch and 0.58 µm height printed in AZ4562 using a slit mask and Talbot imaging.

4. COSTS PER LITHOGRAPHY LAYER

Although semiconductor industry changed over from mask aligners to projection steppers/scanners in the early 1980s, mask aligners were never sorted out. Still today some hundreds of new mask aligners are sold each year. This continuing success of mask aligner lithography is due to two basic trends in lithography: (a) Costs for leading-edge lithography tools double approximately every 4.4 years; and (b) the number of lithography steps per wafer was increasing from a few litho layers to more than 35 layers now[15]. This explains why the mask aligner, a mature, very cost-effective and robust solution for uncritical litho layers, is still widely used today.

As shown schematically in Fig. 12, the costs for mask aligner lithography for uncritical layers (> 5 µm resolution) are typically 3x lower than in a low-cost stepper and about 5x lower than in a wafer stepper from front-end. Mask aligner lithography achieves high yield in production, similar to a front-end lithography processes and typically CD uniformity is not even monitored for cost reasons. In practice, the situation is often less favorite. Scientists and engineers always test the limits. The constant demand for higher resolution for a next generation of a device forces process engineers to constantly improve resolution and overlay. As shown schematically in Fig. 12 already a resolution of 4 µm is related to higher costs, usually due to a lower yield. For 200 mm or 300 mm wafers in a production environment it is not trivial to maintain a constant and accurate gap over the full wafer and a gap mismatch is getting more critical if the structures are close to the resolution limit of 3 µm at 30 µm proximity gap. If mask aligners can't handle it anymore, a very painful and cost intensive switch to higher-resolution projection lithography is required. High investment costs, new process development, and higher costs per litho layer are the price. Often a switch to projection lithography is not possible. Especially for very thick resist layers the limited depth-of-focus (DoF) of a projection system is not sufficient. As a consequence, the process engineers try to optimize mask aligner lithography to the very limit. The process window is narrowing and the lithography steps become critical and relevant for the overall yield.

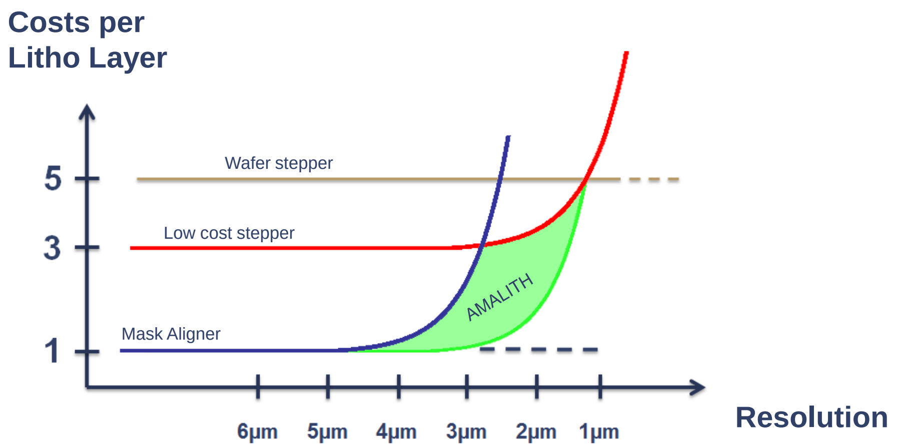


Fig. 12. Scheme for the costs per lithography layer for mask aligners (proximity lithography), low-cost steppers and high-resolution wafer steppers related to the required resolution. Costs per layer increase if the technology is reaching its resolution limits due to yield problems. Advanced Mask Aligner Lithography (AMALITH) allows to push the resolution limits, to increase yield of established but critical processes and to compete with low-costs wafer steppers.

Astonishingly, this unfortunate situation is tolerated, at least as long as the costs for a technology switch are higher than the costs introduced by a lower yield. MO Exposure Optics (MOEO) and Advanced Mask Aligner Lithography (AMALITH) now offer a unique chance to significantly improve resolution and yield for established but critical processes in production. After 30 years of standstill with no roadmap for resolution and quality improvement, it is possible to push mask aligner lithography beyond today's limits. MO Exposure Optics is available for all generations of SUSS MicroTec mask aligners.

5. CONCLUSION AND OUTLOOK

The shadow printing lithography process in a mask aligner was not improved since mask aligners were kicked out of front-end lithography in the early 1980s. Still today, contact-less proximity lithography in a mask aligner is limited to some 3 µm resolution for 30 µm proximity gap. Recently, a novel illumination system for mask aligners, referred as MO Exposure Optics (MOEO), has been introduced. The MO Exposure Optics consists of two microlens based Köhler integrators, providing excellent uniformity of both intensity and angular spectrum of the illumination light. MO Exposure Optics uncouples the light from misalignment and lateral instabilities of the lamp. MO Exposure Optics allows implementing resolution enhancement technology (RET) known from Front-End Projection Lithography like, customized illumination, optical proximity correction (OPC) and source-mask optimization (SMO) in mask aligner lithography. Different software tools for simulation and optimization of the shadow printing lithography process were introduced. Novel mask aligner lithography techniques like halftone-proximity and pinhole-Talbot-lithography for printing periodic sub-micron structures at large proximity gaps were presented. Resolution enhancement by using AAPSM and OPC scattering bars was demonstrated. The results show the high potential to improve mask aligner lithography beyond today's limits. The presented approach for lithography and resolution enhancement in mask aligners will have much impact on yield and costs in production. This new era of mask aligner lithography is referred as Advanced Mask Aligner Lithography (AMALITH).

6. REFERENCES

[1] R. Voelkel, U. Vogler, A. Bich, K. J. Weible, M. Eisner, M. Hornung, P. Kaiser, R. Zoberbier, E. Cullmann, „Illumination system for a microlithographic contact and proximity exposure apparatus“, EP 09169158.4, (2009).
[2] Voelkel, R., Vogler, U., Bich, A., Pernet, P., Weible, K. J., Hornung, M., Zoberbier, R., Cullmann, E., Stuerzebecher, L., Harzendorf, T. and Zeitner, U. D., "Advanced mask aligner lithography: New illumination system", Optics Express 18, 20968-20978 (2010).
[3] LayoutLAB™ V3, 3D Proximity Lithography Simulation, www.genisys-gmbh.de.
[4] Dr.LiTHO Software, Fraunhofer IISB Erlangen, www.drlitho.com.
[5] VirtualLab™, Lighttrans, www.lighttrans.com.
[6] K. Raentsch, L. Bertele, H. Sauer, A. Merz, “Illumination systems”, US Patent 2.186.123, (1938).
[7] Minano J. C., Hernandez, M., Benitez, P., Blen, J., Dross, O., Mohedano, R., and Santamaria, A., "Free-form integrator array optics", Proc. SPIE 5942, (2005).
[8] Voelkel, K. J. Weible, “Laser beam homogenizing: limitations and constraints”, Proc. SPIE 7102, (2008)
[9] R. Voelkel, H. P. Herzig, Ph. Nussbaum, P. Blattner, R. Dändliker, E. Cullmann, and W. B. Hugle, “Microlens lithography and smart masks,” in Micro-Nano-Engineering 96, Microelectronic Engineering, Elsevier, Amsterdam, (1997).
[10] E. Abbe. Beiträge zur Theorie des Mikroskops und der Mikroskopischen Wahrnehmung. Archiv für Mikroskopische Anatomie, IX, 413-68 (1873).
[11] K. Motzek, A. Bich, A. Erdmann, M. Hornung, M. Hennemeyer, B. Meliorisz, U. Hofmann, N. Unal, R. Voelkel, S. Partel, P. Hudek, “Optimization of illumination pupils and mask structures for proximity printing”, Microelectronic Engineering, Volume 87, Issues 5-8, The 35th International Conference on Micro- and Nano-Engineering (MNE), May-August 2010, Pages 1164-1167, ISSN 0167-9317 (2010).
[12] L. Stuerzebecher, T. Harzendorf, U. Vogler, U. Zeitner, and R. Voelkel, "Advanced mask aligner lithography: fabrication of periodic patterns using pinhole array mask and Talbot effect," Opt. Express 18, 19485-19494 (2010).
[13] S. Buehling, F. Wyrowski, E.-B. Kley, A J M Nellissen, L. Wang, M. Dirkzwager, “Resolution enhanced proximity printing by phase and amplitude modulating masks”, J. Micromech. Microeng. 11(2001) 603-611 (2001).
[14] Torsten Harzendorf, Lorenz Stuerzebecher, Uwe Vogler, Uwe D. Zeitner and Reinhard Voelkel, "Half-tone proximity lithography", Proc. SPIE 7716, 77160Y (2010), http://dx.doi.org/10.1117/12.854307, (2010)
[15] Ed Muzio, "Optical Lithography Cost of Ownership (COO) - Final Report for LITG501"', International SEMATECH, Technology Transfer \00104014A-TR, (2000).