# Advanced mask aligner lithography: new illumination system

**Reinhard Voelkel, [1,*] Uwe Vogler,[1] Andreas Bich,[1] Pascal Pernet,[1] Kenneth J. Weible,[1] Michael Hornung,[2] Ralph Zoberbier,[2] Elmar Cullmann,[2] Lorenz Stuerzebecher,[3] Torsten Harzendorf,[3] and Uwe D. Zeitner[3]**

[1]*SUSS MicroOptics SA, Jaquet-Droz 7, 2000 Neuchâtel, Switzerland*
[2]*SUSS MicroTec Lithography GmbH, Schleissheimerstrasse 90, 85748 Garching, Germany*
[3]*Fraunhofer Institut für Angewandte Optik und Feinmechanik IOF, Albert-Einstein-Str. 7, D-07745 Jena, Germany*
**voelkel@suss.ch*

**Abstract:** A new illumination system for mask aligner lithography is presented. The illumination system uses two subsequent microlens-based Köhler integrators. The second Köhler integrator is located in the Fourier plane of the first. The new illumination system uncouples the illumination light from the light source and provides excellent uniformity of the light irradiance and the angular spectrum. Spatial filtering allows to freely shape the angular spectrum to minimize diffraction effects in contact and proximity lithography. Telecentric illumination and ability to precisely control the illumination light allows to introduce resolution enhancement technologies (RET) like customized illumination, optical proximity correction (OPC) and source-mask optimization (SMO) in mask aligner lithography.

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## 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, where the mask and the wafer are in close contact or proximity. A mask aligner typically includes an illumination system, a mask stage for aligning the mask and a wafer stage for aligning the wafer. The illumination system illuminates a square or a circle field on the photomask with uniform light irradiance.

Contact lithography offers the highest resolution down to the order of the wavelength of the illumination light, but practical problems such as contamination and resulting damage of mask or wafer make this process difficult to use for mass production. Proximity lithography, where the photomask and the wafer are separated by a proximity gap of typically 30 to 200 microns is well suited for mass production, however, diffraction effects limit the resolution and fidelity of the pattern generated or printed in the photoresist. These diffraction effects are related to the mask pattern and the angular spectrum of the illumination light.

The presented new illumination system [1] provides excellent uniformity of the light irradiance, telecentric illumination and the possibility to freely shape the angular spectrum of the mask illuminating light to minimize diffraction effects in contact and proximity lithography.

## 2. Light source

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, where 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. As shown schematically in Fig. 1 the imaging quality of an ellipsoidal reflector dramatically decreases for extended light sources. For mercury plasma arc lamps with some 2-5mm arc length the cross section of the light in the secondary focal point of the ellipsoid reflector is typically 30 to 40mm and a divergence of ± 15° is found. The geometrical optical flux is proportional to the product of maximum light angle and size of the illuminated field. For such a high geometrical optical flux, emitting from the ellipsoid is quite difficult to collimate and homogenize in subsequent condenser or Köhler integrator system.

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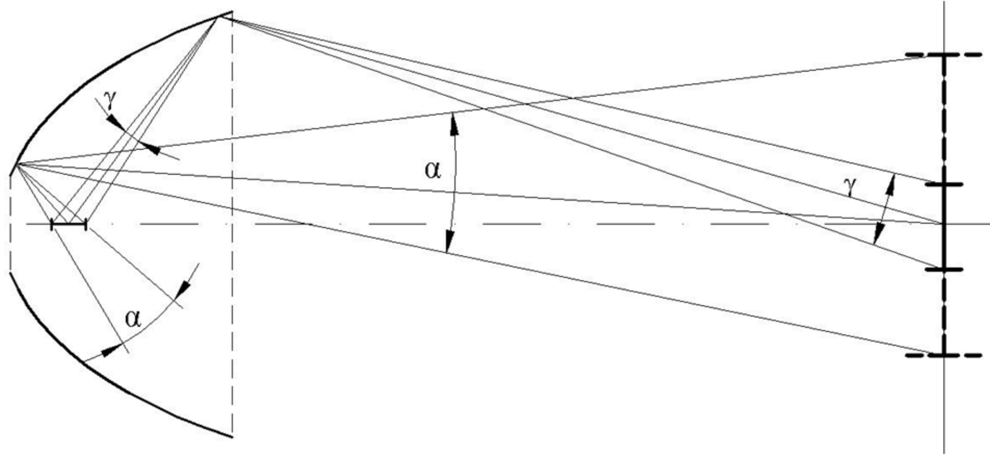


Fig. 1. Scheme of an ellipsoidal reflector as used for Mask aligner illumination.

For efficient collection of the light from a mercury plasma arc lamp, a parabolic reflector providing well-collimated light from extended sources would be the better solution [2]. Unfortunately, the very high thermal energy dissipating from the arc lamp and the small lamp-to-mirror distance leads to severe heating problems for parabolic reflectors. It is also not possible to use hemispherical reflectors to partly reflect the backward emitted light in the forward direction. Further increasing the energy in the plasma would rapidly burn the metal electrodes and significantly shorten the lifetime of the lamp. Ellipsoidal reflectors requiring a very precise lamp alignment and generating a high geometrical flux are the best compromise for mask aligner illumination. A degradation of the electrodes over the lifecycle of an arc lamp results in an increase of the geometrical optical flux from the ellipsoidal reflector and affects irradiance uniformity and exposure time.

### 3. Köhler integrator

For achieving illumination with good irradiance uniformity, most illumination systems contain optical elements that homogenize the light, usually referred to as optical integrators. 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 [3]. Optical integrators are often followed by a lens, referred as condenser or Fourier lens. The lens superposes the light from the different secondary light sources. The irradiance in the superposition plane corresponds to the Fourier transformation of the angular spectrum produced by the optical integrator. Optimum superposition and best irradiance uniformity is achieved in a plane located at a focal length distance behind the lens, referred as Fourier plane.

Köhler illumination [4], proposed by August Köhler for optical microscope illumination, allows to adjust the size and the numerical aperture of the object illumination in a microscope independent from each other. Köhler illumination provides uniform illumination of the object plane independent of shape, extension and angular field of the light source. Each source point can be treated as generating a coherent plane wave of spatial frequency determined by the position of the source point relative to the optical axis. In other words, using Köhler illumination each point at the target area is illuminated by the entire source so that irradiance variations across the source do not affect the target illumination. However, if a single lens element is used to collect the flux of the source, intensity variations of the source limit the achievable uniformity for Köhler illumination. It is preferable to use a plurality of parallel Köhler illumination systems or channels. Typically, the light from the source is collected by an array of lenses as shown in Fig. 2. The combination of an optical integrator and multiple channels Köhler illumination is referred as Köhler integrator [5,6].

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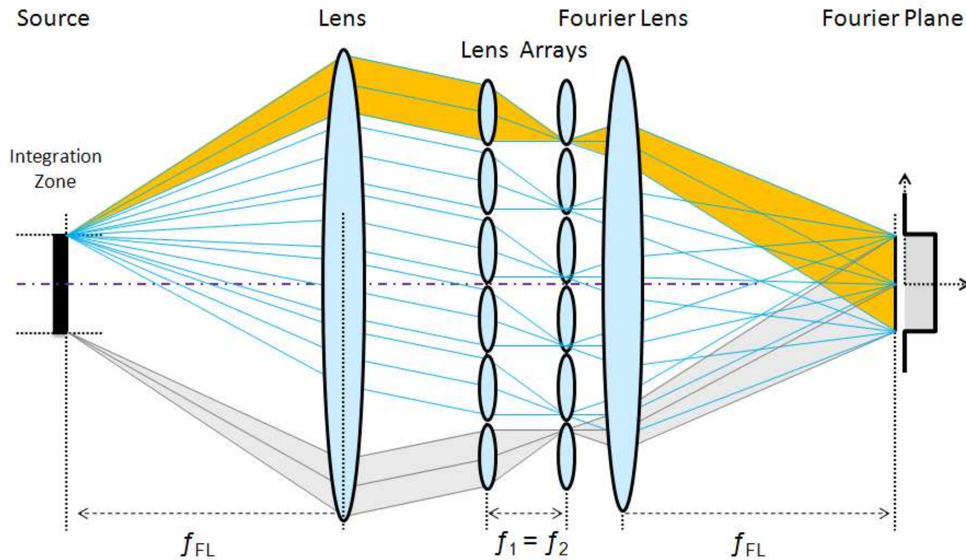


Fig. 2. Scheme of a Köhler integrator collecting light from an extended light source within an integration zone and providing uniform irradiance in the Fourier plane of the Fourier lens. Two symmetrical lens arrays located at a focal length distance ($f_1 = f_2$) are used for light mixing. The aperture splitting of the lens array provides a plurality of parallel Köhler illumination systems perfectly decoupling illumination in the Fourier plane from the light source.

As shown in Fig. 2, 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. If the integration zone is larger than the source, the source can be moved within the integration zone without affecting system performance [7], which helps to stabilize the flux of the illumination light on the photomask. To achieve optimum irradiance uniformity the sub-apertures of the lens array should be sufficiently small to ensure that the incoming light from the source is constant over each sub-aperture. On the other hand, good imaging quality of the individual lens channels is required to ensure aberration-free sub-images of the lens array entrance pupils in the Fourier plane [8]. This imaging quality requirement is a severe limit of both the maximum acceptance angle and the achievable irradiance uniformity of Köhler integrators. If the microlenses are too small then diffraction is the limitation [9]. For lenses with high numerical aperture, the lens aberrations are the limitation. In both cases the image formation is deteriorated, so that the resulting integrated pattern in the Fourier plane becomes fuzzier, less uniform, and less efficient [7,8,10].

## 4. Illumination system for mask aligner lithography

First mask aligners appeared in the early 1960s and were used for the manufacturing of the first integrated circuits [11]. Figure 3 (a) shows a simplified view of an illumination system of a SUSS MicroTec mask aligner. The light from the UV source is redistributed by an array of micro-pyramids, shown in Fig. 3 (b), which is located in the secondary focus of the ellipsoid. The second optical integrator is a Köhler integrator consisting of two concentric rings of 3 and 9 individual lenses of 12 mm lens diameter shown in Fig. 3 (c). The specific arrangement of the lens array was derived in experimental tests providing optimum illumination for both contact and proximity lithography [12]. The mask is illuminated with pseudo annular illumination of typically 0.5° and 2.5° providing a good compromise for contact lithography (large divergence required) and proximity lithography (collimated light required).

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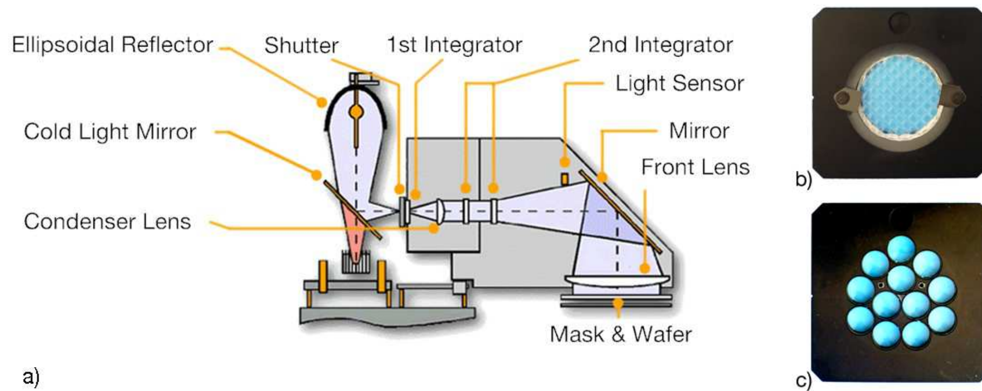


Fig. 3. (a) Schematic view of a standard illumination system for mask aligner lithography comprising an ellipsoidal reflector, 2 optical integrators, a condenser and a front lens. (b) First optical integrator: An array of pyramids used in secondary focus of ellipsoid reflector to redistribute the light. (c) Second optical integrator: Lens array comprising single lenses mounted in multi-aperture metal holder as used for Köhler integration (Fig. 2).

The described mask aligner illumination system proved to be a good compromise and is installed in about 2,000 mask aligners. However, if only few relatively large lenses are used to collect the flux of the source, intensity variations of the source limit the achievable uniformity. The required very precise lamp alignment necessitates short service and maintenance cycles. Preferably, a densely packed array of some thousands of identical microlenses is used for light integration [6].

## 5. New illumination system for advanced mask aligner lithography

In the following, a new illumination systems based on two microlens-based Köhler integrators located at a focal length distance of each other is presented [1]. This new illumination optics is shown schematically in Fig. 4.

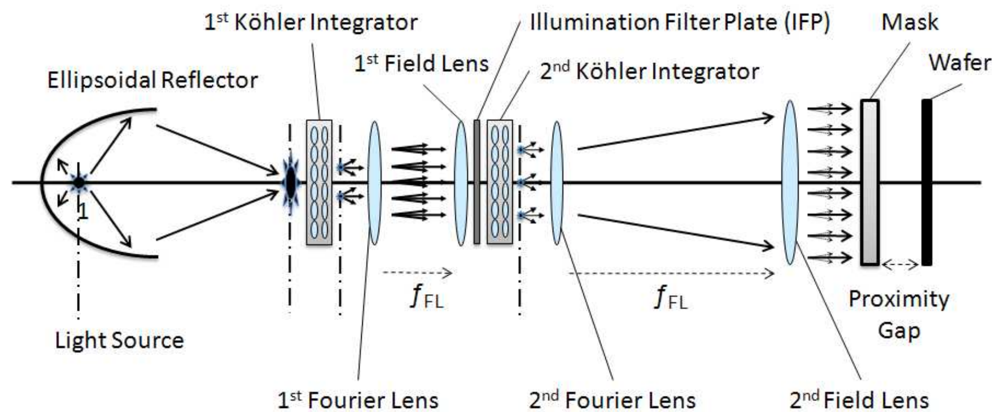


Fig. 4. Simplified view of a mask aligner illumination system comprising two subsequent Köhler integrators. A first Köhler integrator is located near the secondary focal point of the ellipsoidal reflector. A second Köhler integrator is located in the Fourier plane of the first integrator.

The light emitted by the light source is focused by the ellipsoidal reflector to its secondary focal point. After passing a first Köhler integrator in which the light is homogenized, the angular spectrum is transformed to flat-top by a first Fourier lens. A second Köhler integrator is located at the back focal plane of the first Fourier lens. After passing the second Köhler

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integrator in which the light is again homogenized, a flat-top irradiance profile is generated in the focal plane of the second Fourier lens. 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. Opaque 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.

The integration zone of the first Köhler integrator is significantly larger than the secondary focus of the ellipsoidal reflector, thus the illumination system is decoupled from the light source. A displacement error of the arc lamp in the ellipsoidal reflector does not influence the properties of the mask illuminating light. The first Köhler integrator is adapted to the high geometrical optical flux from the ellipsoidal reflector. Double-sided monolithic microlens arrays made of Fused Silica [6] are used as first Köhler integrators. The microlens arrays are manufactured on 8" wafers by using resist melting and reactive ion etching technology [13,14]. Densely packed microlens arrays with aspherical lens profiles are used to provide high transmission and optimum flat-top irradiance profiles. Figure 5 (a) shows the irradiance distribution in the far-field of a microlens array manufactured in Fused Silica by resist melting and reactive ion etching technology measured in a goniometer. Figure 5 (b) shows schematic drawings of the microlens arrays used as Köhler integrator elements. 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, where the second array is rotated by 90° versus the first array.

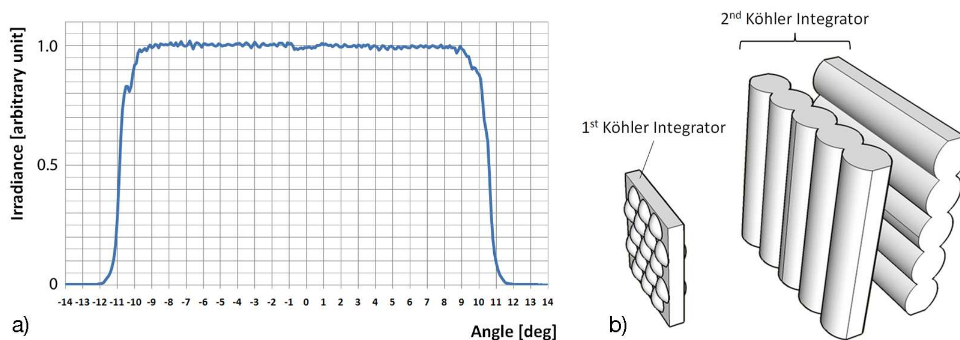


Fig. 5. (a) Flat-top irradiance distribution in the far-field of a microlens array manufactured in Fused Silica by resist melting and reactive ion etching technology measured in a goniometer. (b) Schematic drawings of the microlens arrays used as Köhler integrator elements.

The first Köhler integrator of the new illumination system modifies the local irradiance distribution and provides a uniform irradiance profile in its Fourier plane. Preferably, a field lens located in the focal plane of the first Fourier lens is used to provide telecentric illumination of the subsequent optical system. The second Köhler integrator is located at the Fourier plane of the first Köhler integrator. The second Köhler integrator produces a plurality of tertiary light sources each emitting a light bundle. The second Köhler integrator homogenizes the incident light such that a uniform irradiance in the Fourier plane is introduced. 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°. 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.

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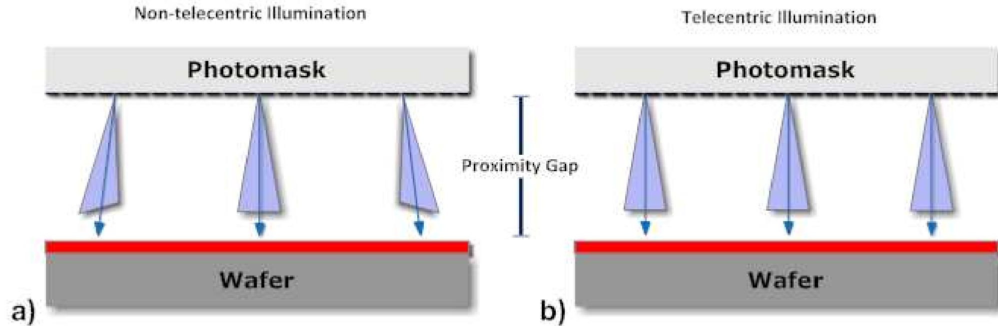


Fig. 6. Illumination of photomask with (a) non-telecentric and (b) telecentric light. Telecentricity error of mask illumination light bundle leads to lateral displacement errors also referred as "run-out errors" of the printing pattern on the wafer for shadow lithography in mask aligner using proximity mode.

A field lens, also referred as front lens, is located at the back focal plane of the second Fourier lens and collimates the illumination light. The field lens ensures telecentric illumination of the mask. Telecentric illumination ensures that the mask is illuminated with light bundles with its central ray entering the mask plane perpendicularly. Transparent areas on the mask transmit the light and illuminate the resist on the wafer, thus transferring the 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 as shown in Fig. 6.

## 6. Angular spectrum of illumination light

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 [15]. 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 a 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 [16]. As already proposed by Abbe [17], 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).

In standard mask aligner illumination systems, as shown in Fig. 3, the angular spectrum was defined by the lateral positions of the individual lenses within lens array and the focal length of the front lens [18]. The new illumination system now offers a quick and easy change of the angular spectrum of the illumination light [1]. Using a second Köhler integrator with a large-area microlens array as shown in Fig. 7 (a), allows to place 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, as shown in Fig. 7 (b), allow to alter the angular spectrum and the coherence properties of the mask illuminating light in the mask aligner [1,19,18]. 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

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modulators and deflectors, variable diaphragms, and all kind of refractive and diffraction optics and mechanics might be used.

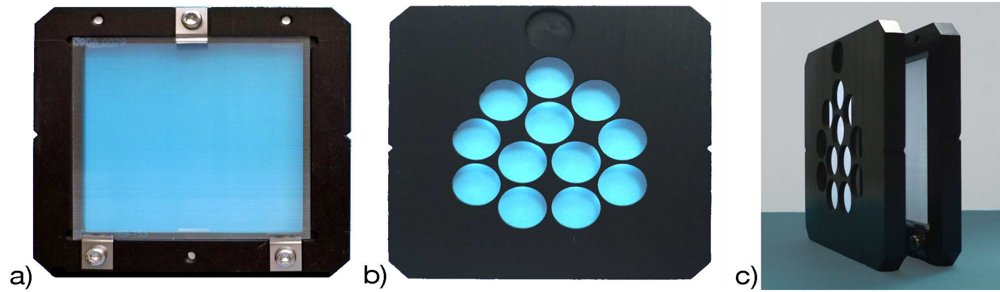


Fig. 7. (a) Köhler integrator with a large-area microlens arrays as used in the new illumination system. (b) Metal mask used as exchangeable illumination filter plate (IFP) providing a similar angular spectrum of mask illuminating light than the standard "A-Optics" mask aligner illumination shown in Fig. 3. (c) The illumination filter plate is placed in front of the first microlens array of the second Köhler integrator.

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.

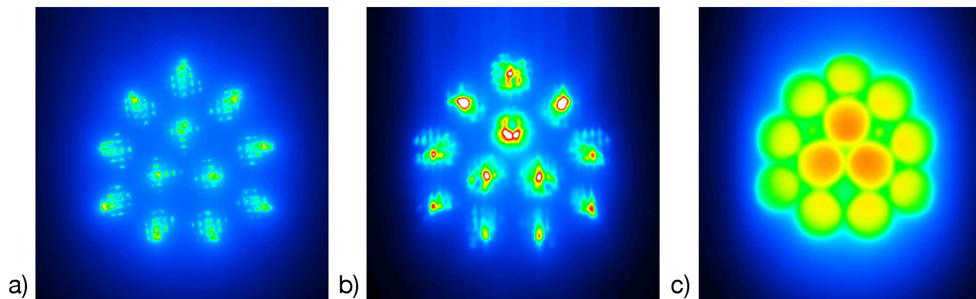


Fig. 8. Angular spectrum of the illumination light impinging the photomask for (a) standard mask aligner illumination system (Fig. 3) in the mask center, (b) at the mask rim. (c) Angular spectrum using the new illumination system (Fig. 4) and an identical spatial filter configuration (Fig. 7), observed at the mask rim. The angular spectrum expressed in color graduation (arbitray units) was measured by recording the Fourier image of a single lens located in the mask plane.

Figure 8 (a) and (b) show a comparison of the angular spectrum obtained in the mask plane of a standard mask aligner as described in section 4. A sub-structuring of the angular spectrum introduced by the pyramid array (first optical integrator) is observed in Fig. 8 (a) and (b). A significant change of the illumination properties is observed for on-axis and off-axis mask areas. In Fig. 8 (b), the angular spectrum of an area at the lower rim of the mask shows a significant asymmetry. Referring to Fig. 6 (a) an oblique illumination might lead to a lateral displacement error (run-out) of the aerial image on the wafer for large proximity gaps. In addition, angular spectrum variations will influence the obtainable CD uniformity. Figure 8 (c) shows the corresponding angular spectrum observed at the rim of the mask plane for the new illumination system. An identical and symmetrical angular spectrum identical to Fig. 8 (c) is found over the full mask area. In contrast to the previous mask aligner illumination system, the photomask is now illuminated with an identical angular spectrum, a major improvement which now allows to precisely model and optimize mask aligner lithography.

## 7. Customized illumination

Figure 9 shows schematically a simple lithography model for the use of the new illumination system in proximity lithography [20]. The photomask is assumed to have a single square

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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 photosensitive resist. 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. 9 (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 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 filter plates to improve resolution and fidelity of the resist prints.

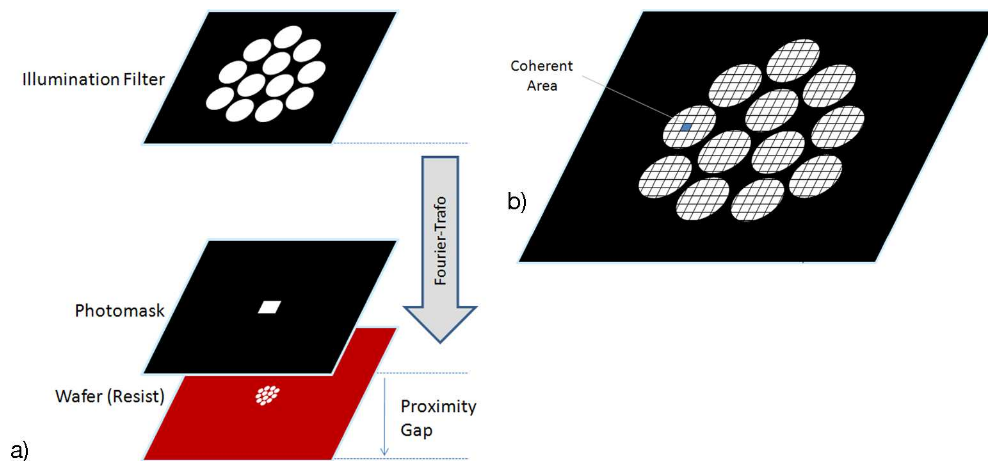


Fig. 9. Simplified lithography model for the use of the new illumination system in proximity lithography. (a) For a single opening in the mask the illumination filter pattern is imaged to the wafer plane. (b) The illumination filter plane is assumed to be subdivided in a multitude of coherent areas, 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.

Figure 10 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 new illumination system. The corresponding illumination filter configuration is shown schematically in a small window in the upper left corner of the photographs.

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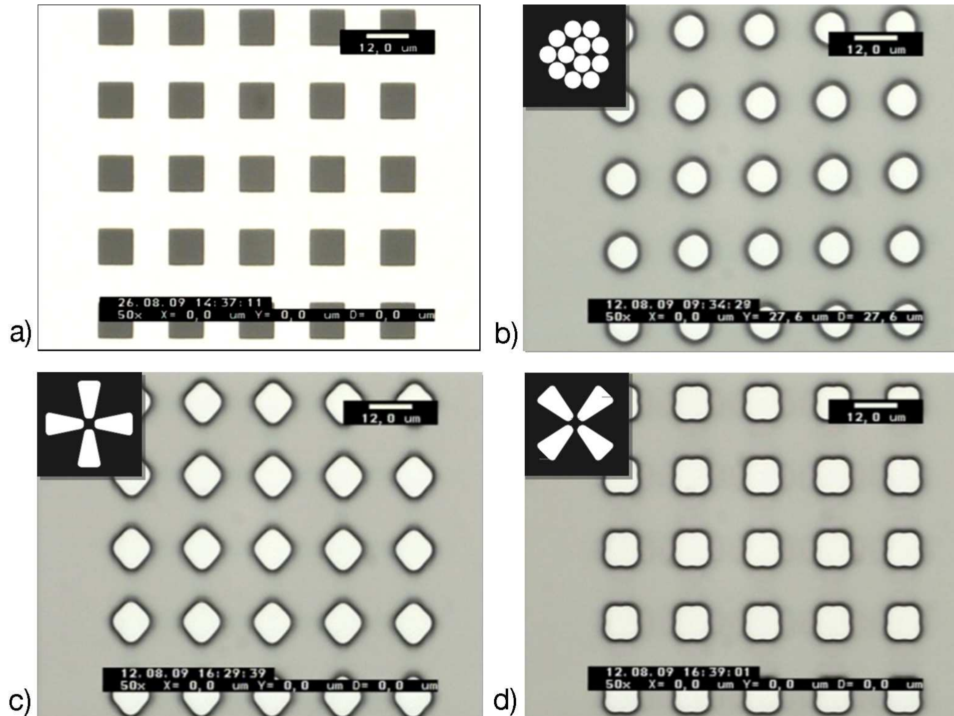


Fig. 10. Experimental results for mask aligner lithography using the new illumination system and customized illumination. Photographs of (a) of 10 x 10 microns squares holes with 10 microns pitch on a photomask and (b) to (d) the resulting prints in 1.2 micron thick photoresist exposed at a proximity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

As shown in (b), using an illumination filter similar to Fig. 7 (b) results in a slightly deformed circle, (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. Customized illumination allows to influence and optimize the shape of the resulting structures in photoresist to a certain extent. A further improvement is achieved if, in addition to customized illumination, also the shapes of the mask structures are modified. This will be discussed in more details in the following section.

## 8. 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.

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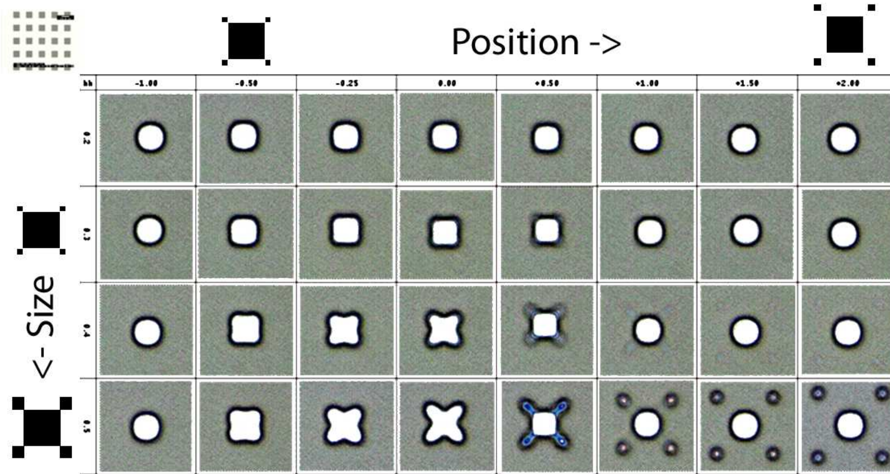


Fig. 11. Experimental results for mask aligner lithography using the new illumination system, customized illumination and optical proximity correction (OPC). Photographs of resist prints (AZ 4110, 1.2 micron thick) obtained for a proximity gap of 50 microns. The resist image in the upper left corner shows the print result for a 10 x 10 microns square, similar to Fig. 10 (a), illuminated with a circular illumination filter and no OPC correction. The influence of OPC assist features (serifs) of different size (columns) and at a different position (row) are shown in a matrix.

Figure 11 shows experimental results for mask aligner lithography using the new illumination system, 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/cm$^2$. The resist image in the upper left corner of Fig. 11 shows the print result with no additional OPC assist feature. The circular illumination emphases the rounding of the corners as shown in Fig. 10 (b). OPC assist features (serifs) were added to the square pattern on the photomask. Figure 11 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 to precompensate print errors due to diffraction and process effects. The new illumination system and source-mask optimization technology will have a strong impact on process window enlargement and yield improvement in production environment.

## 9. Conclusion

The presented work describes a new illumination system for mask aligner lithography. The illumination system consists of two micro-lens based Köhler integrators providing excellent uniformity of both intensity and angular spectrum of the illumination light. The new illumination system uncouples the light from misalignment and lateral instabilities of the lamp. The key enabling elements are the microlens arrays optimized for light homogenizing in the ultraviolet wavelength range. The new illumination system allows to implement resolution enhancement technology (RET) known from projection lithography like customized illumination, optical proximity correction (OPC) and source-mask optimization (SMO) in mask aligner lithography.

## 10. Acknowledgments

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