Review Article

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Micro-optics and lithography simulation are key enabling technologies for shadow printing lithography in mask aligners

Abstract: Mask aligners are lithographic tools used to transfer a pattern of microstructures by shadow printing lithography onto a planar wafer. Contact lithography allows us to print large mask fields with sub-micron resolution, but requires frequent mask cleaning. Thus, contact lithography is used for small series of wafer production. Proximity lithography, where the mask is located at a distance of typically 30–100 μm above the wafer, provides a resolution of approximately 3–5 μm, limited by diffraction effects. Proximity lithography in mask aligners is a very cost-efficient method widely used in semiconductor, packaging and MEMS manufacturing industry for high-volume production. Micro-optics plays a key role in improving the performance of shadow printing lithography in mask aligners. Refractive or diffractive micro-optics allows us to efficiently collect the light from the light source and to precisely shape the illumination light (customized illumination). Optical proximity correction and phase shift mask technology allow us to influence the diffraction effects in the aerial image and to enhance resolution and critical dimension. The paper describes the status and future trends of shadow printing lithography in mask aligners and the decisive role of micro-optics as key enabling technology.

Keywords: Köhler integrator; lithography simulation; mask aligner; microlens array; micro-optics; proximity lithography; shadow printing lithography.

OCIS codes: 350.3950; 110.2945; 110.5220; 110.3960; 260.1960; 260.5130.

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www.degruyter.com/aot

DOI 10.1515/aot-2014-0065
Received November 28, 2014; accepted January 5, 2015

1 Mask aligners

The optical system of a mask aligner is shown schematically in Figure 1. Light from a light source, typically a mercury plasma lamp, is collected by an ellipsoidal mirror and collimated by a condenser lens. A light integrator, typically a fly's eye condenser or Köhler integrator, is used for homogenizing and light shaping. A field lens, referred to as the front lens, collimates the light. The optical systems provide collimated light with a defined angular spectrum and typically ±3° to ±5° divergence.

Light is diffracted at the photomask pattern and propagates as shown schematically in Figure 2 for four adjacent lines.

The wafer is located at a distance of typically 30–100 μm above the photomask. The aerial image is recorded in a thin layer of photosensitive photoresist on the top surface of the wafer. Alignment marks on a mask and wafer allow a precise alignment of ±0.5 μm at the best. For high-volume production, where mask heating might lead to a significant run-out, the alignment accuracy is typically ±2 μm only.

2 Microlens-based Köhler integrators

For shadow printing lithography, the uniformity of the light irradiance and the uniformity of the angular spectrum of illumination light have to be highly accurate over the full mask field. Light homogenizing in a mask aligner is provided by an optical integrator unit, typically a fly's

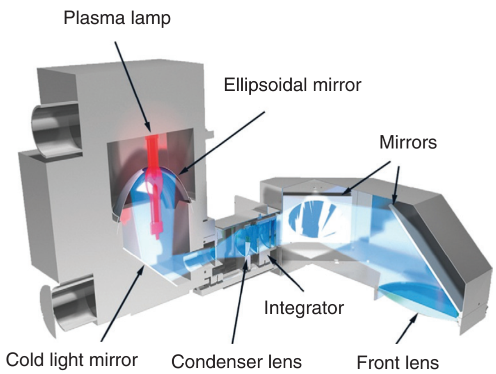

Figure 1 Scheme of the optical system of a mask aligner for proximity lithography. Light is collected by an ellipsoidal mirror and collimated by a condenser lens. An integrator unit provides uniform illumination with a well-defined angular spectrum.

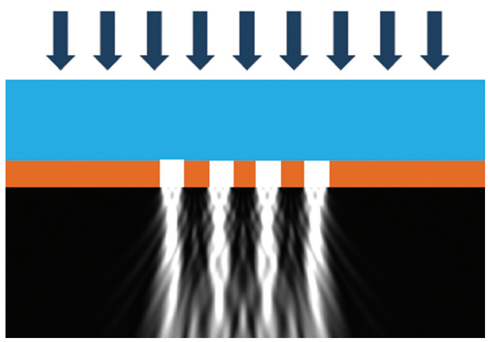

Figure 2 Scheme of the light propagation behind a photomask in a mask aligner (Courtesy of Uwe Zeitner, Fraunhofer IOF, Jena, Germany). The light is diffracted at the photomask pattern and propagates towards the wafer, where it is recorded in a thin layer of photosensitive resist.

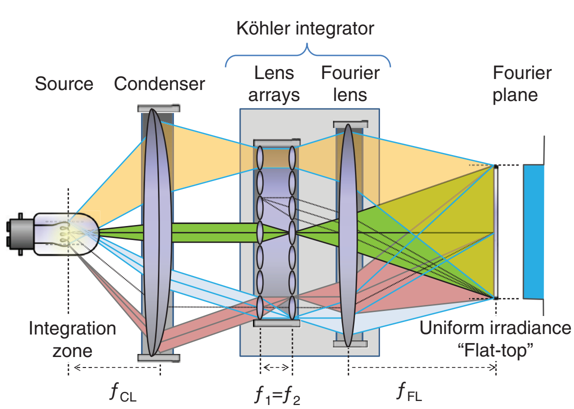

Figure 3 Scheme of a microlens-based Köhler integrator as used for light homogenization in a mask aligner.

eye condenser [1, 2] or a Köhler integrator, as shown schematically in Figure 3.

A Köhler integrator consists of two identical lens arrays, located at a focal length distance and a Fourier lens. The entrance pupils of the first lens array are imaged to infinity by the second lens array. The individual lens channels act as miniaturized Köhler illumination systems. In the Fourier plane, all sub-images of the individual entrance pupils of the first array superimpose. A uniform irradiance distribution, referred to as 'flat-top', is obtained.

In ancient lithography systems, the optical integrators consisted of a small number of individual lenses mounted in a metal frame as shown in Figure 4 (left). The obtainable irradiance uniformity using these optical integrators is typically approximately ±3% to ±5%, limited by lens manufacturing and mounting issues. Another drawback of these optical integrators is the small number of integrating lens channels. Optical integrators comprising only 19 lens channels, as shown in Figure 4 (left), are very sensitive to the alignment of the plasma light source within the light-collecting ellipsoid. A slight displacement of the light source might already result in a severe degradation of the irradiance uniformity.

Modern mask aligner illumination systems are based on optical integrators consisting of a microlens array as shown in Figure 4 (right). Large arrays of plano-convex microlenses with typically 100–500 μm lens diameter are manufactured at wafer level by using melting resist and plasma etching technology [3]. This technology allows us to manufacture aspherical microlens profiles with an accuracy of better than 100 nm (rms) deviation from the ideal profile on planar fused silica wafers. Wafer-based manufacturing technology allows us to obtain a lens-to-lens uniformity of typically 1–2% within the array. Microlenses are manufactured on both sides of the wafer allowing a front-to-backside alignment accuracy of better than 1 μm. Microlens-based optical integrators using approximately 300 000 microlens channels allow us to achieve a light irradiance uniformity of better than ±2% for full field exposure of 200 mm and 300 mm wafers [4].

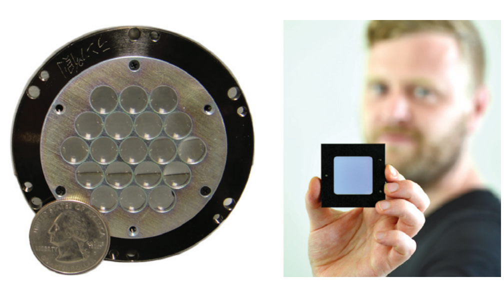

Figure 4 Left: photograph of an optical integrator plate from a Canon 501F mask aligner; right: photograph of a microlens optical integrator plate as used in modern mask aligner illumination systems.

3 Tandem Köhler integrators: MO Exposure Optics®

Microlens-based optical integrators have significantly improved the irradiance uniformity of the exposure light; however, a single-step optical integrator, as shown in Figure 3, is still sensitive to lamp misalignment. A misplacement of the plasma lamp within the ellipsoid directly influences the uniformity of the light irradiance. A misplacement also influences the angular spectrum of the illumination light and the fidelity of the printed resist pattern. These limitations could be overcome by using a tandem integrator configuration [5], shown schematically in Figure 5.

In a tandem Köhler integrator, a second Köhler integrator is placed in the Fourier plane of the first Köhler integrator. The flat-top illumination at the entrance pupil of the second Köhler integrator ensures a uniform angular spectrum of the mask illumination light. The uniformity and the angular spectrum of the mask illumination light are completely decoupled from source variations. The tandem integrator configuration allows us to use all kinds of light sources, e.g., arrays of diode lasers, LEDs or excimer lasers. Any light source that is located in front of the first Köhler integrator and that matches its maximal acceptance angle will deliver similar illumination light.

Placing a filter plate in between both the integrators allows us to shape the angular spectrum of the illumination light (spatial filtering). Mask aligner illumination systems using a tandem Köhler integrator were introduced in 2009 and are referred to as MO Exposure Optics® [5, 6].

A stabilized light source, excellent light uniformity, identical angular spectrum over the full mask field, telecentric illumination and the possibility of freely shaping the illumination light (customized illumination) are essential for simulation and optimization of shadow printing lithography. The introduction of tandem Köhler integrators was the decisive move towards advanced mask aligner lithography.

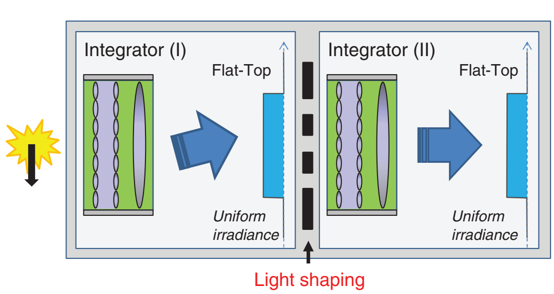

Figure 5 Scheme of a tandem configuration consisting of two subsequent Köhler integrators.

4 Simulation of shadow printing lithography

Shadow printing lithography [7] is described by near-field (Fresnel-Kirchhoff) diffraction. In general, near-field diffraction is investigated by using rigorous numerical methods solving the Maxwell equations. For mask feature sizes significantly larger than the wavelength of the illuminating light and for sufficiently large proximity gaps, approximate methods such as scalar diffraction theory are used. The achievable resolution for proximity printing, noted as lines and spaces (half-pitch), is deduced from the Fresnel integral formula and given by the expression

$$\text{line width (half-pitch)} = \frac{3}{2}\sqrt{\lambda\left(g+\frac{d}{2}\right)} \sim \sqrt{\lambda g} \qquad (1)$$

where λ is the wavelength, g the proximity gap and d the resist thickness [8]. The resolution degrades with the square root of the proximity gap.

Commercially available lithography simulation software such as, e.g., LAB from GenISys GmbH (Taufkirchen, Germany) [9], provides full 3D simulation of shadow printing lithography in mask aligners for multiple wavelengths and different illumination settings. The aerial image calculation is based on Kirchhoff scalar diffraction theory solving the Rayleigh-Sommerfeld integral. Propagation in the resist is simulated by the transfer matrix model (thin film algorithm) including bleaching effects [8]. The light-induced modification and the development of the photoresist material are described by the Dill parameters (extinction in the unbleached/bleached state and photosensitivity of resist) and by the Mack 4 (development rate) parameters. The bulk image intensities are transferred into inhibitor concentrations which define the dissolution rate and the resulting resist profile after development. Lithography simulation software such as Dr.LiTHO from Fraunhofer IISB (Erlangen, Germany) [10] also includes the simulation of chemically amplified photoresists.

5 Process window optimization for shadow printing lithography

Excellent uniformity of the illumination light and the ability to fully simulate the lithography process from the source to the resist process now allow us to optimize the process parameters of shadow printing lithography without performing time-consuming and costly experiments. Recently, a process window methodology has been introduced for shadow printing lithography in mask aligners [7].

The lithographic process window is defined as the set of values for proximity gap and exposure dose to control critical dimension (CD) and the sidewall angle of resist structures. The maximal inscribed rectangle or ellipses in the plot then represent the process window. The overall process window for a specific lithography task is obtained from the intersection or overlap of process windows for all different layout patterns existing in a mask design.

Figure 6 shows the process window for 5 µm CD for proximity gaps ranging from contact to 100 µm. Interestingly the process window is very narrow for a proximity gap of 30 µm. This effect is related to diffraction effects at the edges of the mask opening and explained in much detail in the related publication [7].

In practice, the process window 'A' shown in Figure 6 is related to hard- or soft-contact lithography, where a direct contact of the mask and the wafer is not an issue. The process windows 'B' and 'C' represent proximity lithography. For wafers with excellent flatness and a mask aligner providing a gap setting accuracy of better than ±5 µm, the process window 'B' is the preferred choice. Practical applications for the process window 'B' shown in Figure 6 are very light-sensitive photoresists with a very short exposure time not easy to be controlled precisely. In production, where wafers are not perfectly flat or even slightly bended due to preprocessing, the process window 'C' is the better choice.

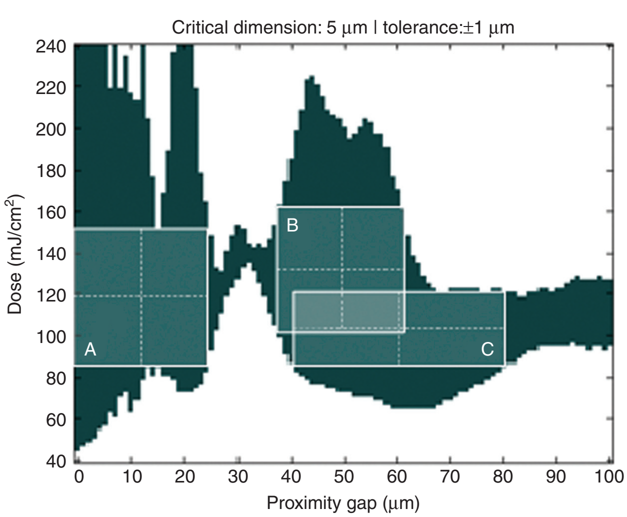

Figure 6 Process windows for critical dimension, 5 µm CD, for an illumination with SUSS LGO optics at 365 nm wavelength. The dark areas show combinations of proximity gaps and dose values, which produce CD values in the range of 5±1 µm. The exposure latitude is indicated by rectangles fitted into the process window.

6 Source-mask optimization

In the previous sections, we discussed the impact of controlling and shaping the illumination light to reduce unwanted diffraction effects and to improve the fidelity of the printed resist structures. Further improvement could be achieved by optimizing the mask pattern. Full control of the lithography process allows us to pre-compensate diffraction effects through the introduction of sub-resolution assist features. This method is referred to as optical proximity correction (OPC) and has been well established in projection lithography for many years [11]. The holistic approach to optimize the light source and the mask pattern is referred to as source-mask optimization (SMO) and turns out to be a very powerful method to enhance shadow printing lithography in mask aligners [12].

A further improvement is achieved by using alternating aperture phase-shift masks as shown schematically in Figure 7. Figure 7 also shows plots for the resulting light field and resist profiles (positive tone resist). For a mask pattern with multiple structures, the waves from adjacent mask apertures interfere. These interference effects typically reduce the obtainable spatial resolution and CD uniformity. Introducing a phase shift between adjacent apertures, as shown in Figure 7B, and additional OPC structures (scattering bars), as shown in Figure 7C, allows us to correct intensity, width and position errors [12, 13].

7 Future of shadow printing lithography in mask aligners

In the past few years, shadow printing lithography in mask aligners has made significant progress. Full control of the illumination light, simulation tools for the complete lithography process chain and the implementation of well-known photolithography enhancement techniques, adopted from projection lithography, now allow us to significantly improve the performance and the yield of established lithography processes. Novel and innovative approaches or techniques are referred to as 'advanced mask aligner lithography' [4, 14].

Talbot lithography, in combination with a pinhole mask (pinhole Talbot lithography), multiple Talbot exposures at different proximity gap positions (displacement Talbot lithography) or flexible mask illumination for Talbot lithography allows us to print periodic structures such as gratings or dot arrays with sub-micron resolution on the full wafer scale [14–18]. Half-tone or gray-level mask lithography allows us to print 3D structures in resist layers

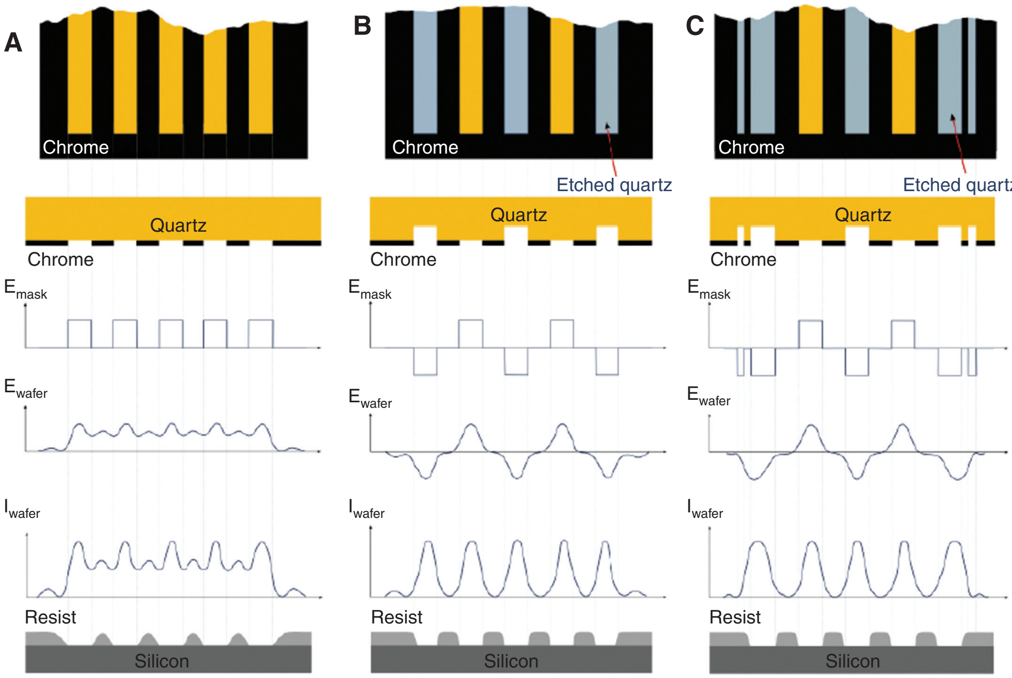

Figure 7 Different types of photomask suitable for shadow printing lithography: (A) binary amplitude photomask, (B) alternating aperture phase-shift mask (AAPSM) and (C) AAPSM with additional optical proximity correction (OPC).

[19]. In a more general approach, a multi-level diffractive optical element (DOE), a computer generated hologram or other types of micro- or nano-optical microstructures or array optics could be used to generate any type of arbitrary two- or three-dimensional structures on a wafer [20, 21].

Table 1 references different tools and techniques already available or in development for shadow printing lithography in mask aligners.

Microlens-based tandem Köhler integrators (MO Exposure Optics®) provide uniform and telecentric illumination light independent from the optical properties of the light source. Thus, a variety of light sources, ranging from mercury plasma lamps to any kind of lasers or light-emitting diodes, could be used for shadow printing lithography in mask aligners.

Recent development of hybrid ArF Excimer lasers, based on a solid-state laser for seeding injection, allows us to tailor the laser beam properties and will be a very attractive high-power DUV light source for shadow printing lithography [22]. High-power ultraviolet MOPA laser diodes allow us to freely program the wavelength spectrum of mask aligner illumination [24]. This is an exciting option for Talbot lithography, because the location of the Talbot plane is a function of the wavelength. Using well-collimated laser light sources allows us to use DOEs, MEMS mirror arrays or axicon telescopes for flexible light shaping in the illumination system [25]. However, using laser light sources for shadow printing lithography in mask aligners is not trivial. Special care has to be taken to manage or suppress coherence effects and speckles [2, 25].

Table 1 Overview of different tools and techniques applied to shadow printing lithography in mask aligners.

Light source	Integrator	Photomask	Photoresist	Enhancement method
– Mercury plasma lamp (254 nm, 365 nm, 405 nm, 436 nm) – Excimer laser [22, 23] (193 nm, 248 nm, 308 nm) – Diode laser [24] (VUV to VIS) – LED array (DUV to VIS)	– Köhler integrator – Tandem Köhler integrator [5] (MO Exposure Optics®) – Axicon telescope for flexible annular illumination [25] – MEMS mirror light shaping [5] – Freeform optical element [26] (Etendue squeezing)	– Binary photomask – Phase shift mask – Alternating aperture phase shift mask [12] – Fresnel zone masks for TSV [27] – Microlens-based 1:1 projection system [28]	– DNQ-novolac resist – DUV resist – Chemical amplified resist – SU-8 epoxy resist	– Customized illumination – Optical proximity correction – Source-mask optimization – Process window optimization – Talbot lithography – 3D simulation software

8 Conclusion

A stabilized light source, excellent light uniformity, identical angular spectrum over the full mask field, telecentric illumination and the possibility of freely shaping the illumination light (customized illumination) are key enabling technology for shadow printing lithography.

Lithography enhancement techniques such as customized illumination, OPC and SMO allow us to optimize shadow printing lithography in mask aligners beyond previous limits. Process window optimization helps to improve the yield in production by giving a qualitative representation of the processes stability.

Shadow printing lithography in mask aligners, considered for a long time as being only an antique production method from the last century's semiconductor industry, has now made the move back to innovation. Research teams at universities and in industries develop new and innovative shadow printing methods. Micro-optics components and light simulation tools are key to a holistic approach for shadow printing lithography in mask aligners.

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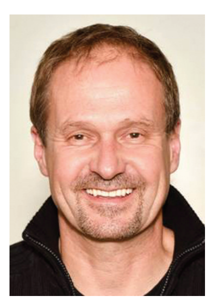

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