Micro-Optics: Enabling Technology for Illumination Shaping in Optical Lithography

Reinhard Voelkel*
SUSS MicroOptics SA, Rouges-Terres 61, CH-2068 Hauterive, Switzerland

ABSTRACT

Optical lithography has been the engine that has empowered semiconductor industry to continually reduce the half-pitch for over 50 years. In early mask aligners a simple movie lamp was enough to illuminate the photomask. Illumination started to play a more decisive role when proximity mask aligners appeared in the mid-1970s. Off-axis illumination was introduced to reduce diffraction effects. For early projection lithography systems (wafer steppers), the only challenge was to collect the light efficiently to ensure short exposure time. When projection optics reached highest level of perfection, further improvement was achieved by optimizing illumination. Shaping the illumination light, also referred as pupil shaping, allows the optical path from reticle to wafer to be optimized and thus has a major impact on aberrations and diffraction effects. Highly-efficient micro-optical components are perfectly suited for this task. Micro-optics for illumination evolved from simple flat-top (fly's-eye) to annular, dipole, quadrupole, multipole and freeform illumination. Today, programmable micro-mirror arrays allow illumination to be changed on the fly. The impact of refractive, diffractive and reflective micro-optics for photolithography will be discussed.

Keywords: optical lithography, photolithography, pupil shaping, customized illumination, light shaping, micro-optics, microlens arrays, diffractive optical elements, DOE, ROE, micro-mirror array, MEMS mirrors

1. INTRODUCTION

Jay W. Lathrop and James Nall from the Diamond Ordnance Fuze Laboratory (DOFL) are reported to be the first to use the term photolithography[1]. They used a standard microscope to project a pattern from a photographic film onto a slice of germanium. The germanium was painted with a thin layer of Kodak photoresist. Soon after introducing photolithography, Jay W. Lathrop left DOFL to join Texas Instruments (TI). James Nall went to Fairchild Semiconductor. Both took their photolithography approach to the new companies. Fairchild's revolutionary planar process[2], invented by Jean Hoerni in 1957 and transferred to production in 1959, set out a technology path that semiconductor industry still uses today. In Hoerni's planar process, a thin silicon oxide (SiO_2) film was deposited on a silicon wafer. The SiO_2 film was then coated with photoresist and photo-structured by exposure through a photographic film containing the layout of the circuit. Subsequent SiO_2 etching, heat diffusion and metal layer deposition were applied to manufacture the transistors and to connect them electrically. Hoerni's planar process required five successive exposure steps, where the subsequent mask pattern had to be aligned to the previously patterned structures. Hoerni's colleague Robert Noyce added resistors, capacitors and connections to build a planar integrated circuits (IC). At the same time at Texas Instruments, Jack Kilby developed a slightly different approach to integrated circuits. Both companies, TI and Fairchild used photolithography to bring their silicon ICs into mass production. Photolithography became a key enabling technology of the new semiconductor industry in the early 1960s.

Lathrop and Nall, the photolithography pioneers, had projected a demagnified image of the mask pattern onto the wafer. They were able to print very small feature sizes, but the microscope's limited image field size was a severe limitation of their lithography approach. Many exposures steps side-by-side were required to pattern a full 1'' wafer. However, the time was not ripe for a projection stepper lithography. Industry opted for 1:1 full field shadow printing technology, the contact lithography in mask aligners. Contact lithography had already been established in industry for the manufacturing of larger scale printed circuit boards (PCB). The important difference between a PCB mask exposure tool and the mask aligner was

* voelkel@suss.ch, +41-32-5664444, www.suss.ch, www.suss.com

the alignment step. Alignment marks, in the simplest case two dots located at widely different points on a wafer, were superimposed during the alignment procedure.

2. ILLUMINATION SYSTEMS FOR CONTACT MASK ALIGNERS

For the first 20 years of the semiconductor industry, optical lithography was dominated by mask aligner lithography. In early contact mask aligners simple white light movie lamps or photographic spotlights were used. A very popular lamp was the Sylvania Sun Gun shown in Figure 1, a white light lamp designed for 8mm movie cameras and photography. Such lamps were cheap, easy to handle and provided collimated bright white light with a sun light spectrum.

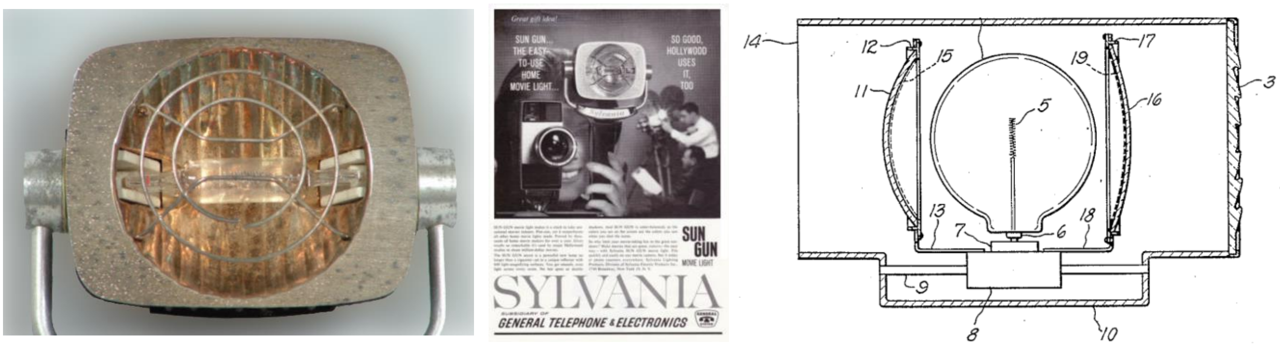


Figure 1. (Left) Sylvania Sun Gun, a light source for 8mm home movies and photography was widely used in first contact mask aligners. (Right) Scheme of a similar photographic spotlight[3] with a light-concentrating reflector (11), a second heat-directing reflector (16) with dichroic film (16) for heat confinement and a Fresnel lens (3) for collimation [US patent 2,798,943].

More elaborate light sources were required, when wafer standards changed from 1" to 2" size in 1969, to 3" in 1972 and to 4" in 1976. A larger wafer area to be illuminated needed a scale up of the illumination system. Filament lamps were replaced by more powerful high-pressure mercury plasma arc discharge lamps. Ellipsoid reflectors for efficient light collection of plasma arc lamps were introduced. In a first approach the light uniformity was improved by using ground glass diffusers placed in or near the secondary focal point of the ellipsoid mirror. When industry standard moved to 6'' wafer size in 1983, light homogenization became even more challenging. Ground glass diffusers were replaced by lenticular arrays as shown in Figure 2.

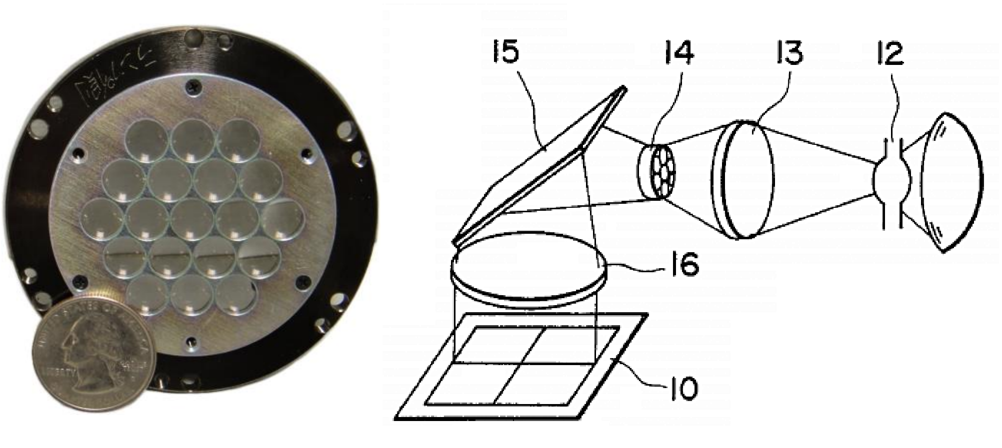
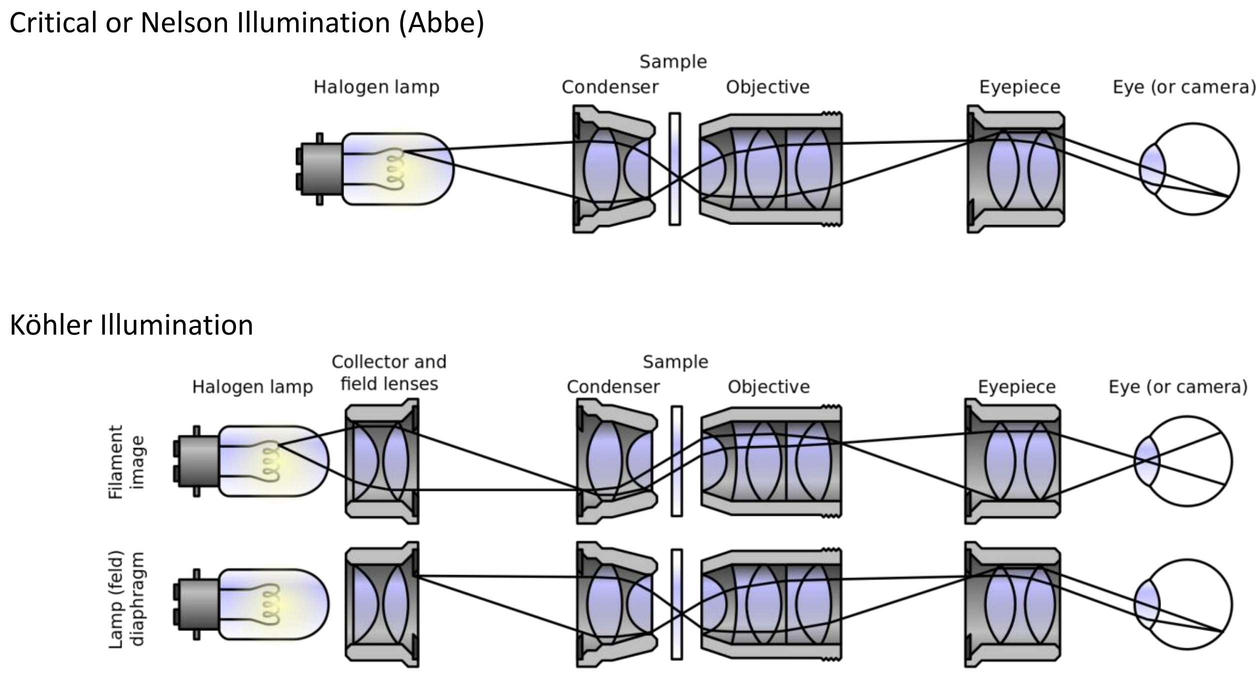


Figure 2. (Left) Photograph of an optical integrator plate from a Canon 501F mask aligner and (right) scheme of an illumination optical system from Canon described in US Patent 4,530,587 comprising a Hg lamp (12), a condenser lens (13), a lens array serving as an optical integrator (14), a reflecting mirror (15) and a collimator lens (16) as used for first Canon projection steppers referred as "step type mask aligner".[4]

The single lens array type optical integrator plate shown in Figure 2 comprises 19 individual lenses mounted in a hexagonal arrangement. Each lens generates an image of the source under a different angle. In the mask plane these images overlap and form a quasi-uniform illumination.

3. ABBE AND KÖHLER ILLUMINATION

In the following chapter we will give a short introduction to the basic principles of illumination. In early microscopes the so-called critical or Nelson illumination, shown in Figure 3, was used. The critical illumination, introduced by Edward Nelson, relies on Ernst Abbe's fundamental work[5] on image formation and resolution published in 1873. Nelson called this illumination "critical" when the illumination aperture fills at least ¾ of the objective pupil ($\sigma > 0.75$). Nelson also discovered, that the aberration level of imaging instruments depends on the illumination[6]. For critical illumination the light source is imaged in the sample plane. Preferably an extended and homogenous light source is used.



Source: Zephyris (Richard Wheeler), http://en.wikipedia.org/wiki/User:Zephyris/Gallery

Figure 3. (Top) Critical or Nelson illumination, later improved by Ernst Abbe; and (bottom) Köhler illumination in a microscope as invented by August Köhler in 1893.

Köhler illumination, proposed by August Köhler[7] in 1893, 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.

A further improvement of Köhler illumination is achieved by using multiple parallel Köhler illumination systems or channels as shown in Figure 4. 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[8], which helps to stabilize the flux of the illumination light on the sample.

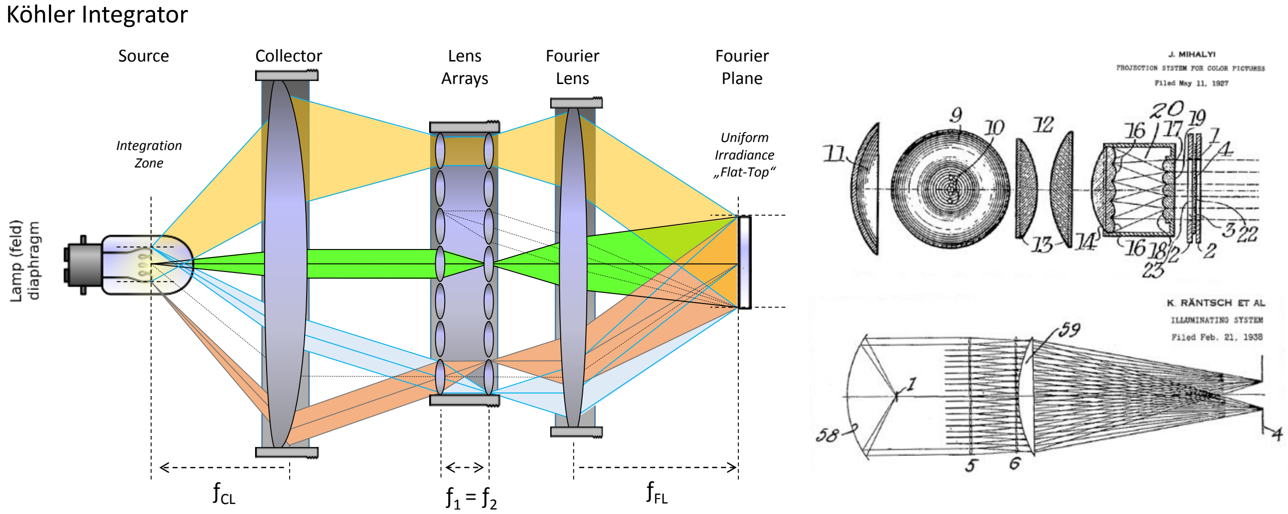


Figure 4. (Left) Scheme of a fly's eye or Köhler integrator comprising a two lens array. (Right) Early patents for fly's eye condensers by Joseph Mihalyi[9] in 1927 and Kurt Räntsch[10] in 1938. A Köhler integrator collects light from an extended light source within an integration zone and providing 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 multiple parallel Köhler illumination systems perfectly decoupling illumination in the Fourier plane from the light source.

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[11]. 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[12]. For lenses with higher numerical aperture, the lens aberrations are the limitation. In both cases the image formation deteriorates, so that the resulting integrated pattern in the Fourier plane becomes fuzzier, less uniform, and less efficient[13]. Although microlens array Köhler integrators were invented in the 1930s, their application for lithography remained impracticable until the 1990s, because high-power UV-light sources required to manufacture microlens arrays in fused silica with high precision. This was not possible until suitable wafer-based manufacturing technology became available.

4. OFF-AXIS ILLUMINATION FOR PROXIMITY MASK ALIGNERS

As discussed, contact lithography in mask aligners was the lithography standard technology for the first decade of semiconductor industry. However, contact lithography is not a valid solution for mass production. Contamination, scratches and resist sticking and other issues required a frequent mask cleaning and inspection. A severe limitation for yield and throughput. A single defect could already make a complete microchip unusable. Mask damage and contamination limited the overall yield to typically less than 20% at that time. In the mid-1970s contact lithography was replaced by proximity lithography. In proximity lithography, the photomask is located some 10 to 50 microns above the wafer. Changing from contact to proximity lithography had significant impact on the requirements for illumination. For contact lithography the angular spectrum of the illumination light is uncritical. For proximity lithography, also referred as shadow printing, the exposure pattern blurs with increasing mask-to-wafer gap due to diffraction. Thus, for proximity lithography well-collimated illumination is mandatory. According to the Van Cittert-Zernike theorem[6], the degree of partial coherence is related to the degree of collimation of the illumination light (etendue of light source). Thus, for better collimated mask illumination light, the diffraction effects get worse. Unwanted secondary orders, also referred as side lobes, become stronger and the structures printed in resist on the wafer are blurred for increasing proximity gaps.

Again, illumination techniques from microscopy, like off-axis illumination[5] and apodization, were applied to enhance the resolution in photolithography. Off-axis illumination turned out to be a very useful strategy to significantly reduce the diffraction effects for proximity lithography. Figure 5 shows the optical system described in US Patent 3,941,475 and filed for the usage in Tamarack Scientific proximity mask aligners[14] in 1974. A Köhler integrator (fly's eye) configured for off-axis (annular) illumination was introduced. Figure 5 (left, top) describes how the resulting aerial image in the near-field of a mask is dominated by secondary diffraction orders, referred as side lobes; (left, bottom) describes how the diffraction effects could be reduced by off-axis illumination (apodization); (right, top) describes a tandem lens array optical integrator, also referred as fly's eye condenser or Köhler integrator; and (right, bottom) describes different kind of optical settings (ring, multiple rings, multipole) for diffraction compensated illumination.

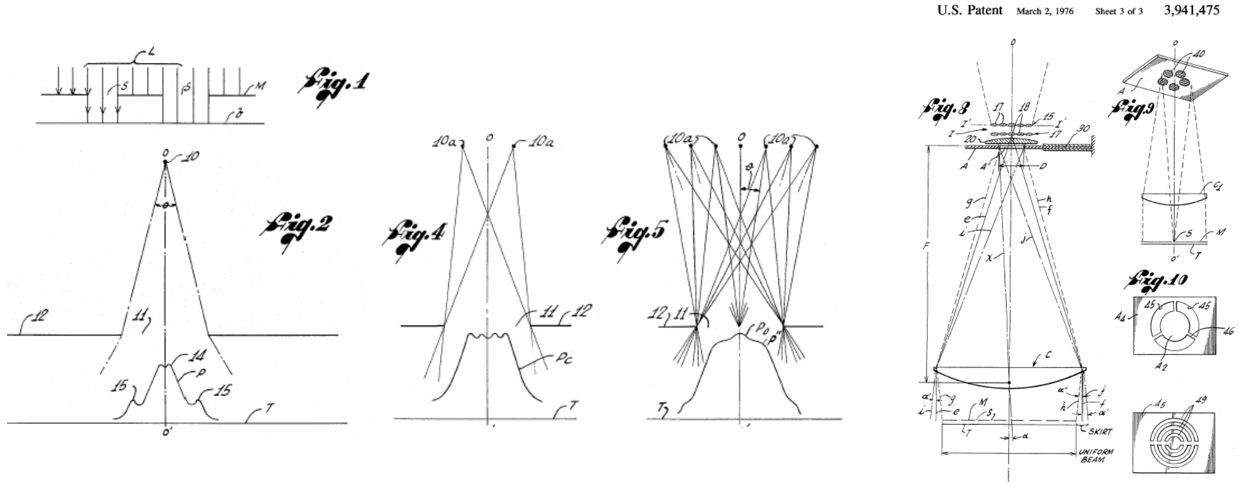


Figure 5. Illumination system for proximity mask aligner lithography[14], comprising a tandem lens array integrator (fly's eye or Köhler integrator) and off-axis ring illumination to reduce diffraction effects shown in US Patent 3,941,475 filed by Tamarack Scientific in 1974.

Until recently, most illumination systems for mask aligners used similar Köhler integrators, comprising lens plates of some 10 to 20 individual lenses arranged on two or more concentric rings. In 2008, SUSS MicroTec introduced an improved illumination system[15,16] referred as MO Exposure Optics®, and shown schematically in Figure 6.

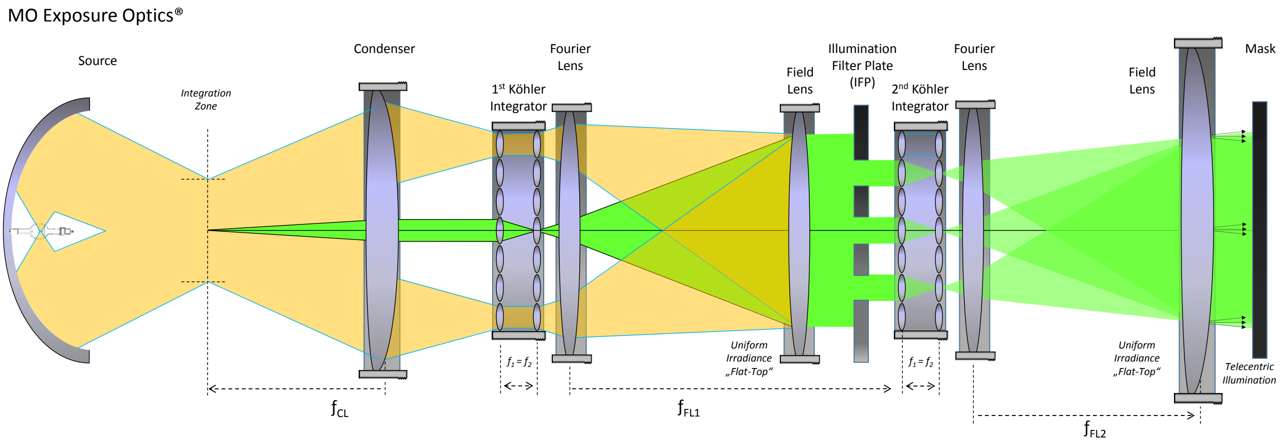


Figure 6. Simplified view of MO Exposure Optics® illumination system for mask aligners, comprising two successive Köhler integrators. A second Köhler integrator is located in the Fourier (or focal) plane of the first integrator. Flat-top illumination from the first integrator illuminates the entrance pupil of the second integrator. The photomask is located in the Fourier plane of the second integrator. A field lens is used to provide telecentric illumination.

Figure 6 shows a simplified scheme of a MO Exposure Optics® illumination system. Two Köhler integrators are placed at a focal length distance. As shown in Figure 4, a Köhler integrator generates a uniform, so-called flat-top illumination in the Fourier plane. The combination of a tandem Köhler integrator performs a "self-calibration" effect. As long as the light from the ellipsoid enters the 1st Köhler integrator, a perfect flat-top illumination is obtained in the entrance plane of the 2nd integrator. Therefore, the mask illumination light remains uniform and telecentric, independent of lamp misalignment. Lamp changes do not require a lamp readjustment. For spatial filtering of the illumination light, also referred as “customized illumination”, an illumination filter plate is placed in the entrance plane of the 2nd integrator. As shown in Figure 6, the illumination filter plate (IFP) defines the angular spectrum of the illumination light by blocking or allowing the light to enter the lens channels of the 2nd integrator. Changing the IFP allows a quick changeover from different illumination settings.

5. OPTICAL INTEGRATORS

Köhler integrators were invented in the 1930s and widely used for applications like film or slide projectors. Their application in photolithography remained difficult. Illumination with light in the ultraviolet (UV), starting from g-line (435nm) and moving over to i-line (365nm), 248nm and 193nm wavelength, required highly transparent glass materials like fused silica (SiO_2) or calcium fluoride (CaF_2). First optical integrators were manufactured by glass molding, i.e. heating and press forming using a metal tooling. Figure 7 a) shows such a diffuser plate with a matrix of pyramids as used for SUSS mask aligners. Whereas glass molding in standard low-T_g glass has long been understood, molding in fused silica is much more difficult, as the glass softening point is 1’600°C. The achievable profile quality of molded array plates in fused silica is quite limited. Thus, in the past, the preferred solution for manufacturing lens plates was mounting of individual lenses or lens slabs in a metal holder, as shown in Figure 7 b) and Figure 2 (left) show optical integrator plates for SUSS and Canon mask aligners. Alternatively sets of cylindrical lenses, as shown in Figure 7 c) and d), can be used.

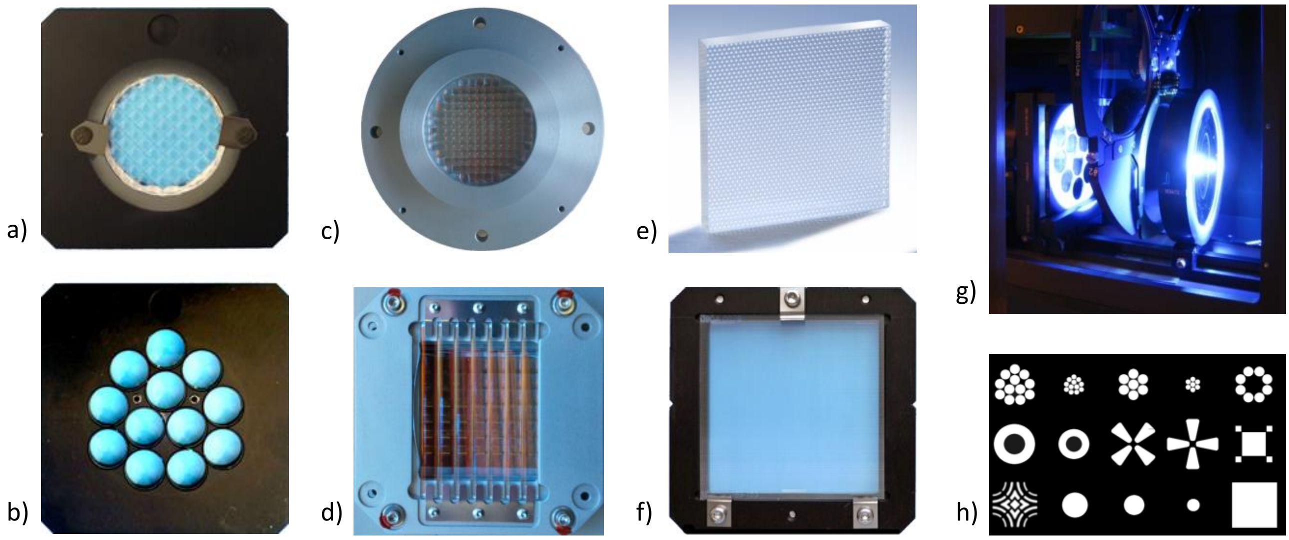


Figure 7. a) Glass molded diffuser plate (array of pyramids); b) lens plate consisting of individual circular lenses mounted in a metal plate; c) and c) optical integrators consisting of individual cylindrical lenses mounted side-by-side; e) microlens array manufactured by wafer-based technology in fused silica; f) microlens optical integrator plate as used for MO Exposure Optics®; illumination system for state-of-the art mask aligner comprising two Köhler integrators and an illumination filter plate (IFP); and h) library of illumination plates as used in mask aligners equipped with MO Exposure Optics®.

The mounting of individual lenses, as shown in Figure 7 b) to d), has three major drawbacks. The individual optical lenses or lens slabs need to be manufactured with very high precision and piece-to-piece repeatability. They need to have identical optical parameters, like focal length, aberrations and outer dimensions. Secondly, they need to be mounted very accurately. Especially for Köhler integrators (Figure 4), the positions of the lenses in the two arrays need to be very precise to ensure perfect overlap in the Fourier plane. Lastly, manufacturing and mounting problems are a severe limitation for the minimum size of the lenses and the overall number of lenses used for a lens plate. Typically, such mounted lens plates comprise only 10 to 20 individual elements. If only a few relatively large lenses are used to collect the flux of a light source, intensity variations of the source limit the achievable light uniformity. Thus, for these Köhler integrators, the uniformity is still sensitive to lamp misplacement necessitating regular service and maintenance cycles for the lithography tools.

6. WAFER-BASED MANUFACTURING TECHNOLOGY FOR HIGH-QUALITY REFRACTIVE AND DIFFRACTIVE MICRO-OPTICS

Wafer-based technology like resist coating, lithography and deep reactive ion etching (RIE) were originally developed in semiconductor industry, but also applied on micro-optics manufacturing[17] since the 1980s. In 1985, Popovic[18] proposed a microlens fabrication technology which is based on micro-structuring of photoresist by photolithography and a subsequent resist melting process, shown in Figure 8 (left). Reactive ion etching (RIE) is used to transfer the resist microlens into wafer bulk material like fused silica, silicon or borofloat glass. The melting resist technology and subsequent RIE transfer for fabrication of refractive microlens arrays has much evolved and is quasi industrial standard. High-quality microlens array in fused silica with aspherical lens profiles of better than < 100nm (rms) deviation from ideal, are manufactured in 8’’ wafer technology today.

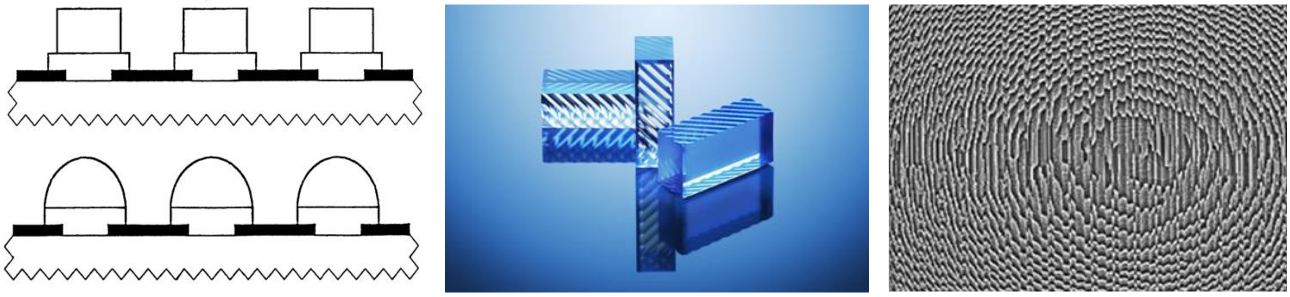


Figure 8. (Left) Scheme of a photoresist melting method to manufacture refractive microlens arrays as proposed by Popovic[18] in 1985, (center) double-sided microlens arrays manufactured by resist melting and reactive ion etching (RIE) silica wafer; and (right) SEM-image of a 8-level diffractive optical element for beam shaping manufactured with i-line wafer stepper and reactive ion etching (RIE) on 8’’ fused silica wafers.

Mike Gale[19] patented and manufactured multi-level diffractive optical elements (DOE) in 1977 by using two successive photolithography and sputter or plasma etching steps. Today, 8- or 16-level diffractive optical elements with < 50nm overlay error and < 5nm step height error provide diffraction efficiencies up to 98% for shaping and splitting monochromatic laser beams.

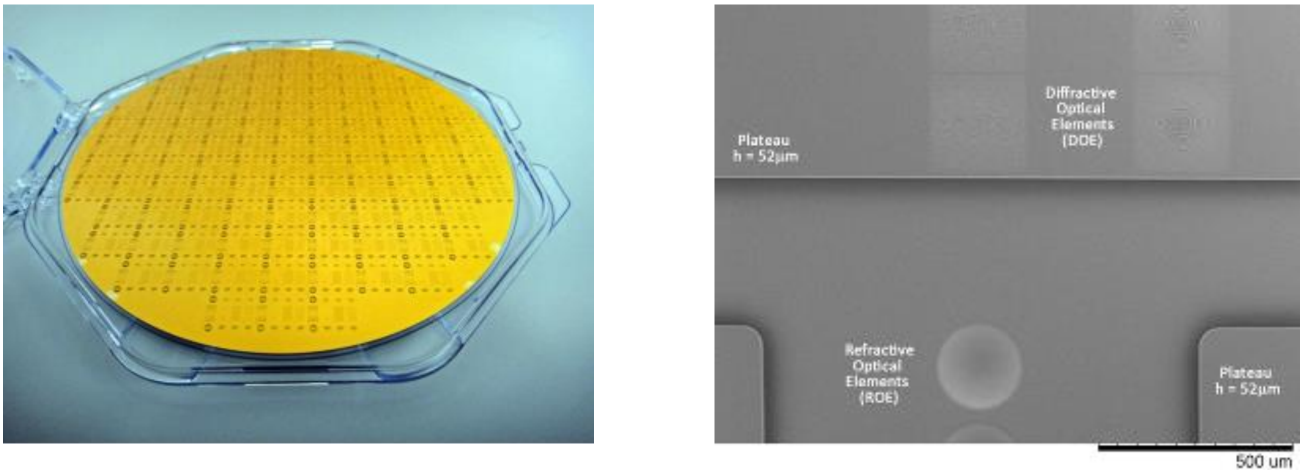


Figure 9. (Left) Photograph of an 8’’ wafer (fused silica) populated with different diffractive and refractive micro-optical elements for focusing and beam splitting. The wafer is coated with a gold mirror layer. (Right) SEM picture of hybrid micro-optics: diffractive optical elements (DOE), refractive microlenses (ROE) and a 52 µm high plateau are manufactured on one wafer side.

Both refractive and diffractive micro-optics, as well as alignment marks, pinholes, posts or other microstructures, microstructures could be combined on one or both sides of a planar wafer, as shown in Figure 9. Wafer-based manufacturing technology is also used to manufacture double-sided refractive microlens arrays, as shown in Figure 7 e) and Figure 8 (center), applied in Köhler integrators for UV and DUV illumination in lithography systems.

Thousands of microlenses are manufactured on wafer-scale with very high precision. Lens-to-lens uniformity is typically better than ±3% on a wafer. Lateral displacement error in the array is typically < 250nm. High-precision microlens arrays now overcome the restrictions of older optical integrator concepts. State-of-the art illumination systems, like MO Exposure Optics®, are based on microlens array lens plates, as shown in Figure 7 f) and g). Although the simplified scheme in Figure 6 indicates that the optical integrators are build from larger individual lenses, they are in practice a microlens array with more than 10000 lens channels. As shown in Figure 6 and Figure 7 h), an illumination filter plate (IFP) is located near the second Köhler integrator and defines the light emitting areas of tertiary light sources at the secondary Köhler integrator. The illumination filter plate (IFP) serves as spatial filter for customized illumination in mask aligners. Refractive microlens array integrator plates made of fused silica and calcium fluoride have also been successfully implemented into illumination systems of state-of-the-art projection lithography systems (wafer steppers).

7. APODIZATION AND PUPIL SHAPING

In the previous chapters we discussed the influence of off-axis illumination on shadow printing lithography. As described by Abbe, off-axis illumination and apodization are suited to improve the resolution in imaging systems. Apodization, from Greek: removal of the feet[20], was first applied in astronomy to suppress the secondary maxima (rings) of the diffraction limited Airy pattern. In astronomy, apodization was established by introducing opaque filter plates in the pupil plane. In projection systems, apodization or pupil shaping is achieved by manipulating the illumination light. The angular settings of the illumination light and the pupil function are conjugated[6]. A more general term for apodization is pupil shaping, describing all kinds of pupil manipulations resulting in a reduction of diffraction effects in the image.

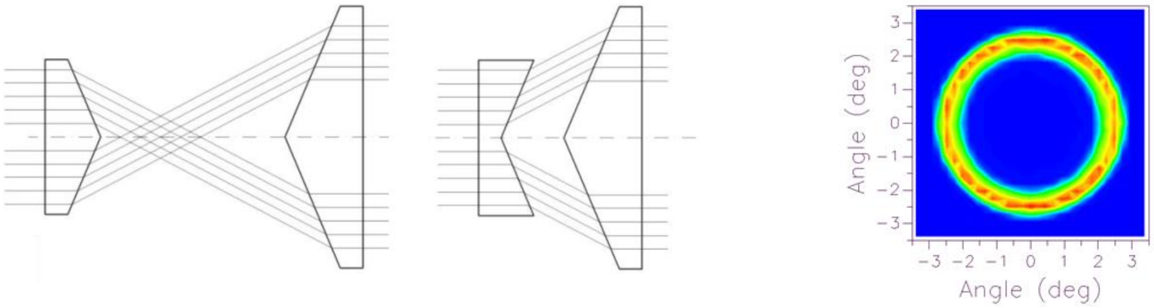


Figure 10. (Left) Axicon telescopes[21] are widely used in illumination systems for projection lithography, as they are telecentric and allow to change the angles of annular illumination without loss. (Right) Angular spectrum for annular illumination, as achieved by using an axicon telescope[22].

A very efficient trick to generate annular illumination without light loss is an axicon telescope as schematically shown Figure 10 (left). Axicon zoom telescopes in combination with a light mixing rod have been introduced for the ASML DUV AERIAL Illuminator by Johannes Wangler[23] in 1993.

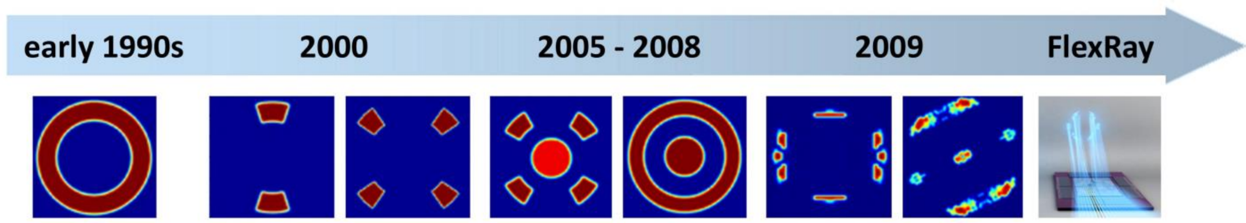


Figure 11. Evolution of customized illumination from axicon telescope annular illumination in the early 1990s to FlexRay micro-mirror-based free programmable illumination today[24].

When lithography changed from i-line to KrF Excimer lasers in the early-1990s, the use of diffractive optical elements (DOE) for beam-shaping became a very valid option. Early work on DOEs for illumination in projection lithography was performed by Wolfgang Singer et al. at the IMT Neuchâtel, Switzerland[25]. Multilevel DOE, as shown in Figure 8 (right), provide freeform beam shaping at high diffraction efficiencies > 95%. Special care is necessary to suppress the 0^{th}, higher spurious orders and straylight. Diffractive beam shaping elements were widely used in combination with an axicon telescope to implement annular, dipole, quadrupole and other simple illumination settings in projection lithography.

After wavelength shrinkage to 193nm and optimizing projection lenses to the highest level, more sophisticated pupil shaping was required to further reduce half-pitch in optical lithography. Shaping the light source, in combination with phase-shift masks[26] and optical proximity correction (OPC) is referred as source-mask optimization (SMO), and allows the lithographic engineer to increase the process window and to stabilize critical lithography steps. As shown in Figure 11, pupil shaping moved over from annular and multipole illumination to freeform illumination.

The constant demand for further shrinkage of the minimum feature sizes required even more sophisticated pupil shaping. The next measure was to design DOEs explicitly for individual mask layers to obtain a robust process for the most critical structures. These DOEs were manufactured on demand and then used solely for this specific mask layer. In 2009 ASML introduced FlexRay[27], a pupil shaping system based on some thousands of individually addressable MEMS micro-mirrors shown schematically in Figure 11 (at right). For the latest generation of projection lithography steppers it is even possible to manipulate the phase function in the pupil plane. FlexWave[28], introduced by ASML in 2011, provides programmable wavefronts shaping. In combination with FlexRay the light source can be freely shaped now.

8. SUCCESS STORY: MICRO-OPTICS IN PROJECTION LITHOGRAPHY

Micro-Optics comprises all kind of refractive and diffractive miniaturized "planar" optics, like microlens arrays, diffractive optical elements (DOEs), MEMS mirror arrays, phase masks, gratings, synthetic holograms and random diffusers.

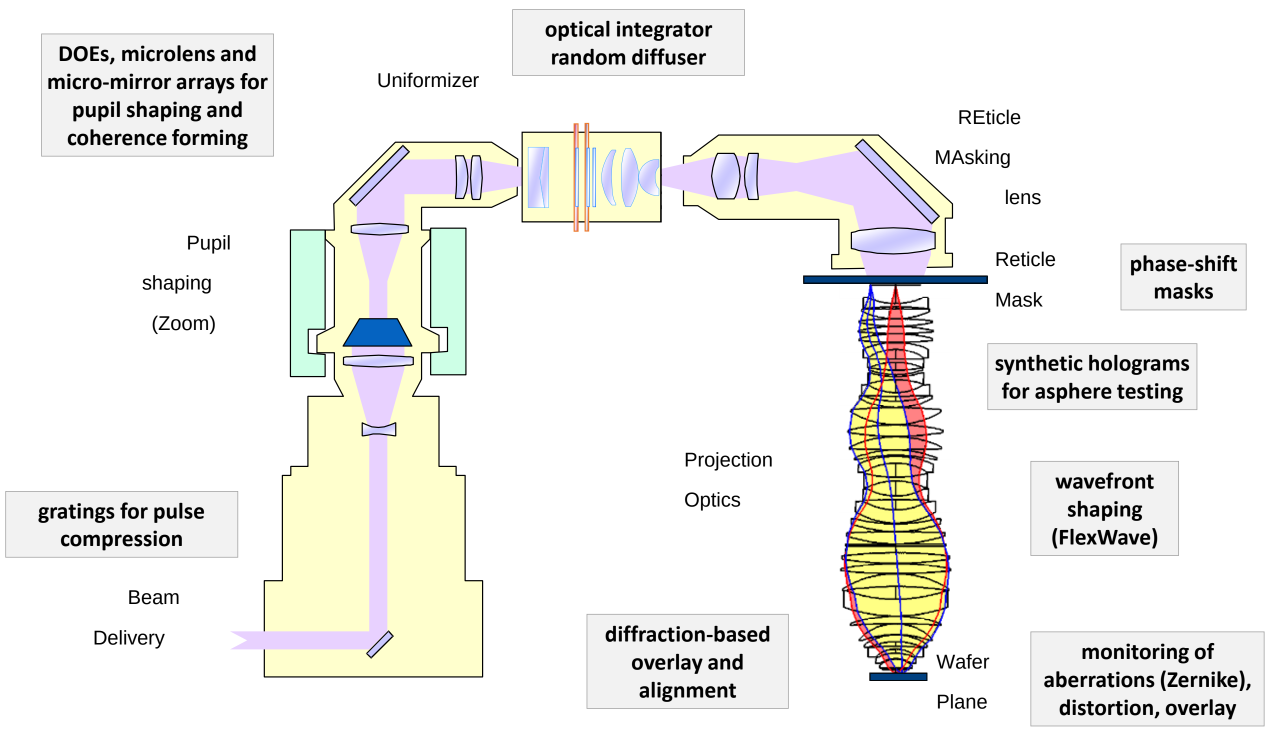


Figure 12. Fields of applications for micro-optics in state-of-the-art projection lithography system[29].

Micro-Optics is a key enabling technology for modern photolithography and has enabled industry to push lithography beyond all limits. Blazed gratings are used in excimer laser light sources for line narrowing without wavefront distortion. As the remaining material dispersion is a very critical parameter for the lens design, achieving ultra-narrow bandwidth and high wavelength stability[30] allows the optical designer to eliminate residual chromatic aberrations. Lens manufacturing for projection lithography systems has achieved highest level with aspheric lens of atomic-scale profile accuracy. For testing of aspheres at this precision, special interferometers using synthetic holograms, as proposed by Johannes Schwider in 1976 are used[31]. The synthetic holograms, a master pieces of micro-optics, are manufactured by e-beam writing at the fabrication limits. For ultrafast and ultraprecise alignment and overlay control in a state-of-the-art projection stepper a multitude of micro-optical elements are used on wafers, reticles, wafer-stages and reticle-stages. These elements allow to precisely align reticle to wafer on the single digit nanometer level. MEMS mirror arrays will also play a decisive role in future EUV lithography for illumination light shaping.

9. CONCLUSION AND OUTLOOK

After wavelength shrinkage to 193nm and optimizing projection lenses to the highest level, shaping the illumination light, also referred as pupil shaping, was the next powerful measure to further reduce half-pitch in optical lithography. Starting from simple annular (ring) and off-axis illumination, the optical designers soon realized that a more sophisticated light source shaping is required to minimize residual aberrations and diffraction effects. Shaping the light source allows the optical path from reticle to wafer to be optimized, reducing or balancing aberrations and diffraction effects. Shaping the light source also allow the process window and to stabilize critical lithography steps to be increased.

First attempts to use micro-optics for illumination light shaping in projection lithography started in the early 1990s. Wafer-based technology became available for manufacturing of planar micro-optics in UV-transparent Fused Silica. The development of micro-optical components had been promoted in the 1990s by government funded research projects in Germany, Switzerland, the US and Japan. Optical designers from lithography companies then integrated both, refractive and diffractive micro-optical components in their illumination systems to further improve projection lithography.

Diffractive optical elements were the first choice to combine a high degree of freedom in light shaping and a high diffraction efficiency. Refractive microlens arrays were the first choice to provide uniform flat-top illumination for light mixing of divergent light. Micro-optical elements for pupil shaping soon evolved from a simple flat-top illumination to annular, dipole, quadrupole, multipole and very sophisticated freeform illumination settings. Micro-optical illumination became standard in optical lithography. However, their usage in projection lithography had its practical limits. Dedicated diffractive optical elements had to be manufactured on demand for each different mask set. The next major step forward was to combine refractive and diffractive optical elements with a programmable micro-mirror array, referred as FlexRay (ASML). The programmable micro-mirror array allows to change illumination settings on the fly. Similar micro-mirror concepts are now realized in EUV lithography systems. Micro-optics has proven to be decisive key enabling technology for optical lithography over the last 20 years. Future micro-optical elements will incorporate polarization properties, allowing polarization to be shaped.

REFERENCES

[1] Jay W. Lathrop, "The Diamond Ordnance Fuze Laboratory's Photolithographic Approach to Microcircuits," IEEE Annals of the History of Computing, vol. 35, no. 1, pp. 48-55, Jan.-March 2013, doi:10.1109/MAHC.2011.83
[2] Hoerni, J. A.: Method of Manufacturing Semiconductor Devices. US Patent #3,025,589 (1959)
[3] Donald W. Prideaux, “Spotlight Apparatus”, US Patent 2,798,943 (1957).
[4] Kazuo Iizuka, Tadashi Konuki, Masao Kosugi, “Step type mask aligner”, US Patent 4,530,587 (1985).
[5] Ernst Abbe, “Beiträge zur Theorie des Mikroskops und der mikroskopischen Wahrnehmung”, M. Schultze’s Archiv für mikroskopische Anatomie, Vol. IX, 413-468 (1873).
[6] Wolfgang Singer, Michael Totzeck, Herbert Gross, “Handbook of Optical Systems, Volume 2: Physical Image Formation”, Edited by Herbert Gross, Wiley-VCH Verlag (2005).
[7] August Köhler, Zeitschrift für wissenschaftliche Mikroskopie, Band X, Seite 433-440, (1893)
[8] O. Dross, R. Mohedano, M. Hernández, A. Cvetkovic, P. Benítez, J. Carlos Miñano, “Illumination optics: Köhler integration optics improve illumination homogeneity”, Laser Focus World 45, (2009).
[9] Joseph Mihalyi, US Patent 1762932 (1927).
[10] K. Räntsch, L. Bertele, H. Sauer, A. Merz, “Illumination systems”, US Patent 2.186.123, (1938).
[11] F. M. Dickey and S. C. Holswade, “Laser Beam Shaping: Theory and Techniques”, Publisher: Marcel Dekker, (2000).
[12] Voelkel, R. ; Singer, W. ; Herzig, H. P., Dändliker, R., “Imaging properties of microlens array systems”, MOC'95 Hiroshima, 1995, p. 156-159, The Japan Society of Applied Physics, Tokyo (1995).
[13] O. Dross, R. Mohedano, M. Hernández, A. Cvetkovic, P. Benítez, J. Carlos Miñano, “Illumination optics: Köhler integration optics improve illumination homogeneity”, Laser Focus World 45, (2009).
[14] Roland E. Sheets, “Optical microcircuit printing system”, US Patent 3,941,475 (1976).
[15] 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“, European Patent Application, EP 2253997 A2 (2009).
[16] 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", Opt. Exp. 18, 20968-78 (2010).
[17] R. Voelkel, “Wafer-scale micro-optics fabrication”, Advanced Optical Technology (AOT) 1, 135-150 (2012).
[18] US Patent 4689291, Z. D. Popovic, R. A. Sprague, G. A. Neville Connell (1985).
[19] US Patent 4155627, M. T. Gale, H. W. Lehmann, R. W. Widmer (1977).
[20] Handbook of Optical Systems: Vol. 2. Physcial Image Formation. Editor H. Gross, Wiley-VCH, ISBN: 3-527-40378-7 (2005).
[21] John H. McLeod, “The Axicon, A New Type of Optical Element”, JOSA Vol. 44, No. 8, August 1954
[22] U. Vogler, “Optimierung des Beleuchtungssystems für Proximitylithographie in Mask Alignern”, Diploma Thesis, Technische Universität Ilmenau, (2009)
[23] Johannes Wangler: "Illumination device for an optical system with a reticle masking system”, EP 0658810 B1, December 13, 1993]
[24] Carl Zeiss GmbH SMT, www.zeiss.com/smt
[25] Singer, Herzig, Kuittinen, Piper, Wangler: "Diffractive beamshaping elements at the fabrication limit", Optical Engineering, Vol. 35, No. 10, October 1996]
[26] Levenson, Simpson: "Improving Resolution in Photolitho-graphy with a Phase-Shifting Mask", IEEE Transactions on Electr. Dev., Vol. ED-29(12), pp. 1828-36. Dec. 1982]
[27] Bert Koek, SVP Litho Applications, "ASML Holistic Lithography", Semicon West 2009; July 14, 2009, URL: www.asml.com/doclib/productandservices/semicon_west_2009_FINAL.pdf
[28] Mulkens, et.al., "Holistic optimization architecture enabling sub-14-nm projection lithography", Journ. of Micro/Nanolith., MEMS, and MOEMs, Vol. 13 (1) Jan-Mar 2014]
[29] Courtesy of Robert Brunner, Ernst Abbe Fachhochschule Jena, Germany (originally by Carl Zeiss SMT GmbH, Germany)
[30] Takashi Saito et. al., Gigaphoton Inc, “Ultra-narrow bandwidth 4-kHz ArF excimer laser for 193-nm lithography”, SPIE Vol. 4346, Optical Microlithography XIV (2001)
[31] J. Schwider, R. Burow, "Testing of Aspherics by Means of Rotational-Symmetric Synthetic Hologramss", Optica Applicata (Wroclaw), VI, 83(1976)