Micro-Optics for Photolithography

Key enabling technology for wafer-based manufacturing technology

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Photolithography is the engine that empowered semiconductor industry to reduce the minimum feature size of the components of a microchip from some 50 microns in the 1960s to below 14 nanometers today. Diffractive and refractive micro-optical components play a decisive role in modern photolithography systems, e.g. for laser line width narrowing, laser beam shaping (customized illumination), as phase-shift masks, for optical proximity correction, and for diffraction-based overlay. Wafer-based manufacturing of high-quality micro-optics and their importance for photolithography will be explained.

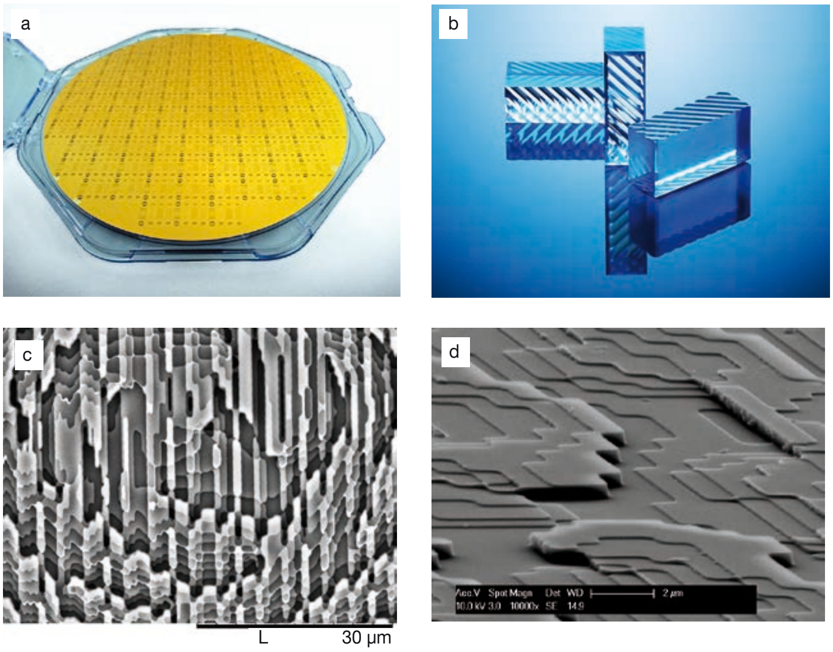


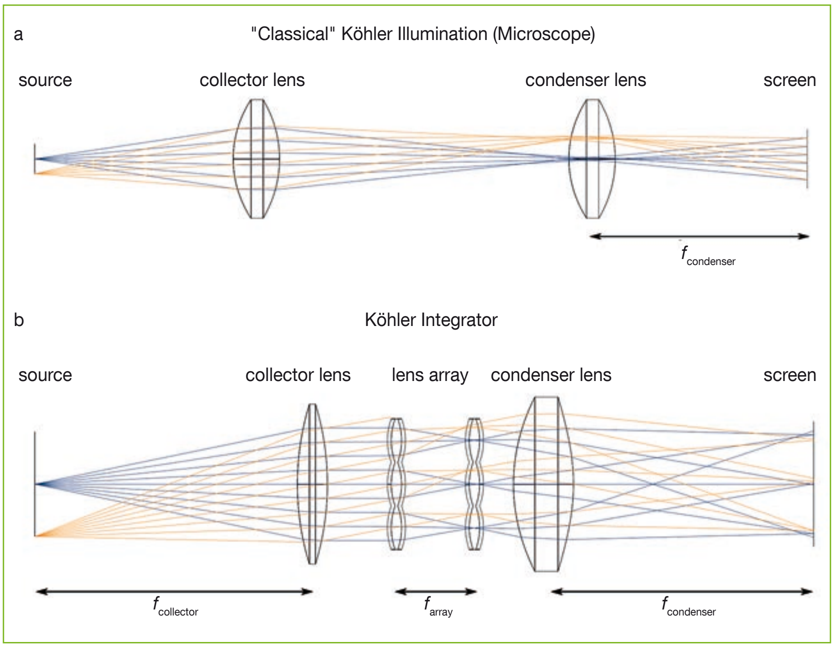
Fig. 1 8 inch wafer populated with diffractive and refractive micro-optical elements (gold mirror coating) (a); double-sided microlens arrays for beam twisting (b); and SEM images of 8-level diffractive optical elements (CGH) designed for laser beam shaping at 193 nm (c) and at 248 nm wavelength (d).

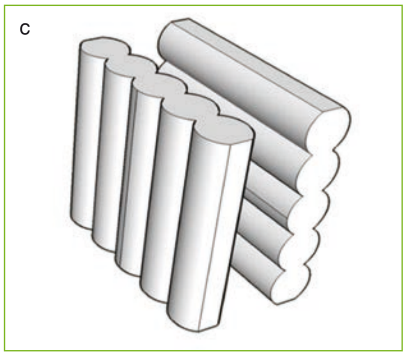
Photolithography

Nowadays, we are used to have tens of Gigabytes of memory in our smart phones. Retail prices for flash memory are around one dollar per Gigabyte. In 1980, the first Gigabyte hard drive ever, the IBM 3380, weighed 250 kg and cost more than $ 80’000. Some ten years ago, a first Gigabyte SD flash memory card was introduced for a retail price of $ 500. The $ 500 will buy today’s leading edge SD cards with 512 GB, 500 times more for the same price. Semiconductor technology is moving forward with an incredible pace since more than fifty years. The driving force behind is “shrinkage”, also referred to as “die shrink”, i.e. the ability of semiconductor industry to reduce the minimum feature size of the components of a microchip from some 50 microns in the early 1960s to below 14 nanometers today. Die shrink allows manufacturing more chips on a wafer, reducing manufacturing costs, minimizing the power consumption and improving the performance in terms of speed, storage capacity and customer convenience. The key enabling technology behind shrinkage is photolithography. In a photolithography process, the layout of a microchip is copied onto a photosensitive layer on the wafer.

In 1960s and 1970s, mask aligners in contact or proximity mode were the dominating photolithographic technology. They were replaced by scanners and projection steppers in the 1980s. In 1995, state-of-the-art projection lithography systems were operating at 248 nm wavelength providing a resolution of 250 nm (half-pitch). Nowadays, modern 193 nm steppers are able to print features below 40 nm (half-pitch, single exposure) – a fifth of the wavelength – and far below Abbe’s diffraction limit. Double patterning, multiple patterning, directed self-assembly (DSA) and other lithography enhancement techniques are used to achieve below 14 nm half-pitch today.

A resolution enhancement from 250 nm resolution (single exposure) in 1995 to below 40 nm today was achieved by further improving the projection optics and by the introduction of immersion lithography, allowing a high numerical aperture of $NA = 1.35$. When lens optimization reached its very limits with surface qualities on the atomic scale, significant improvements could only be achieved by optimizing the mask illumination. Shaping the illumination light, also referred to as pupil shaping, allows the optical path from reticle to wafer to be optimized and has a major impact on aberrations and diffraction effects. Highly-efficient micro-optical components are perfectly suited for





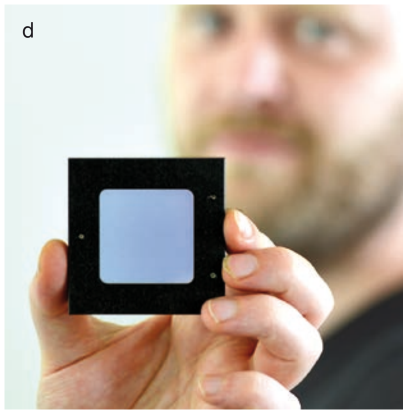


Fig. 2 Scheme of the classical Köhler illumination as proposed by August Köhler in 1893 for microscope illumination (a), lens-array-based Köhler integrator for flat-top illumination (b), scheme of two double-sided cylindrical microlens arrays as used for Köhler integrators (c); and photography of a mounted microlens-based Köhler integrator as used for mask aligner illumination systems (d).

this task. Micro-optics for illumination evolved from simple flat-top (fly's-eye) to annular, dipole, quadrupole, multipole and freeform illumination over the last twenty years. Lately, programmable micro-mirror arrays allow the illumination settings to be changed on the fly. Diffractive and refractive micro-optical elements and reflective micro-mirror arrays (MEMS) play a decisive role in modern photolithography systems, e.g. for laser line width narrowing, laser beam shaping (customized illumination), as phase-shift masks (PSM), for optical proximity correction (OPC), and for diffraction-based overlay (DBO). Micro-optics is a key enabling technology for photolithography.

The invention of modern "planar" micro-optics

Interestingly, modern micro-optics was much related to semiconductor industry and its wafer-based "planar" technology from the very beginning. Dennis Gabor's invention of holography in 1947 allowed to record complex optical functions in a planar photographic plate. In 1963, at the dawn of Silicon Valley, Adolf W. Lohmann, the later co-inventor of the computer-generated holograms (CGH), started to work at IBM Development Laboratory in San Jose, California, in the heart of the rapidly growing semiconductor industry. At that time, Fairchild Semiconductor, the technology leader of the new semiconductor industry, had grown from the eight illustrious founders in 1957 to more than 3000 employees. Fairchild's revolutionary "planar process", invented by the Swiss Jean Hoerni in 1957, set out a technology path that semiconductor industry still uses today [1]. Fairchild also introduced the photolithography process, i.e. micro-structuring by light, to high volume manufacturing. Photolithography became the key enabling technology of the new semiconductor industry. Both, the planar "wafer-based" process and photolithography also became industry standard for the manufacturing of high-quality diffractive and refractive micro-optics.

The invention of the CGH, the first modern "planar" micro-optical component, was certainly inspired by the success of semiconductor technology. In the middle of the 1960s, Lohmann, who was responsible for IBM's Optical Signal Processing Division located in Silicon Valley, was once approached by Byron Brown, a summer student, who asked for a project that would combine holography and computers. They developed a method to calculate holograms in a computer and to print them with the plotter [2]. Luckily, he had access to both, a computer and a plotter. The black-and-white pattern printed by the plotter was then photographed in a special repro-camera, reducing the plot pattern by a factor of 20:1 to 200:1. The camera image was recorded on high-resolution photographic plates. Similar cameras were used by semiconductor industry to copy Rubylith-based microchip layouts to photomasks for contact printing on 1 or 2 inch wafers. Lohmann's CGHs were binary amplitude holograms with two levels of amplitude transmittance, still suffering from low diffraction effi-

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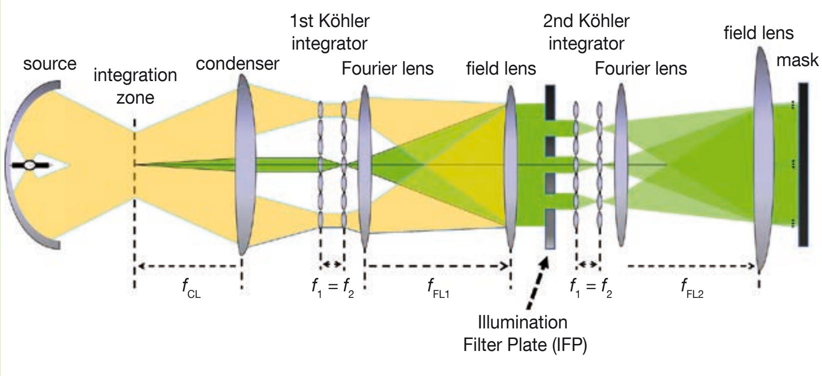

Fig. 3 Scheme of a tandem Köhler integrator configuration referred to as MO Exposure Optics. In a tandem Köhler integrator, a second Köhler integrator is placed in the Fourier plane of the first Köhler integrator.

ciency, parasitic diffraction orders and a high noise level. However, the idea to replace standard optical manufacturing technology, like grinding and polishing, by a highly-parallel wafer-based processes was born and triggered the development of all diffractive and refractive manufacturing technologies we have today.

Wafer-based manufacturing technology

The next step in the development of planar micro-optics was the introduction of dry etching technologies to manufacture binary phase holograms. For this process, the high-resolution plates were used as photomasks and contact-copied onto glass wafer using mask aligner lithography. The micro-structured resist layer was transferred by sputtering or dry etching into the bulk material. In 1977, Mike Gale et al. manufactured multi-level diffractive optical elements serving as color filters on wafer-level [3]. In 1985, Popovic et al. proposed a microlens fabrication technology, which is based on micro-structuring of photoresist by photolithography and a subsequent resist melting and reflow process [4]. Reactive ion etching (RIE) is used to transfer the resist microlens into wafer bulk material like fused silica, silicon, or borofloat glass.

Today, these wafer-based technologies are industry standard for the manufacturing of planar micro-optics and both, manufacturing and testing has been developed to less than 200 nm feature size (half-pitch) and better than 50 nm overlay accuracy [5].

Microlens-based Köhler integrators for photolithography systems

Köhler integrators, also referred to as fly's eye condensers, were introduced for the mask illumination of lithography systems in the 1970s, replacing simpler one-element diffusers and integrators. Lens-array-based Köhler integrators, as shown in Fig. 2, consist of multiple Köhler illumination channels and are used for light homogenization in photolithography systems since the 1990s. The Köhler illumination is realized by using two identical lens arrays, located at a focal length's distance of each other. A large Fourier lens is used for light integration. 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 subapertures and provides a sharp cut-off, often referred to as "flat-top" profile.

Tandem Köhler integrators for mask aligner lithography

A major problem for mask aligner systems which are based on high pressure mercury lamps and ellipsoidal mirrors, are the tight tolerance for the lamp alignment within the ellipsoidal mirror. A misplacement of the plasma lamp might influence the uniformity and the angular spectrum of the illumination light, and thus directly affect the photolithographic process. These limitations could be overcome by using a tandem integrator configuration, shown schematically in Fig. 3.

A tandem Köhler integrator system, also referred to as MO Exposure Optics, was introduced in 2009 for Suss MicroTec mask aligners. In a tandem Köhler integrator, a second Köhler integrator is placed in the Fourier plane of the first Köhler integrator, as shown schematically in Fig. 2b. The flat-top illumination at the entrance pupil of the second Köhler integrator ensures a uniform angular spectrum of the mask illumination light. For tandem Köhler integrators, the light uniformity and angular spectrum of the mask illumination light is completely decoupled from the light source [6]. In addition, a tandem Köhler integrator allows to spatially filter the illumination light by placing an illumination filter plate (IFP) in-between the two integrators. Customized illumination was introduced for mask aligner lithography.

Micro-optics for pupil filling in projection lithography systems

Illumination techniques developed for microscopy, like off-axis illumination and apodization, were also applied to

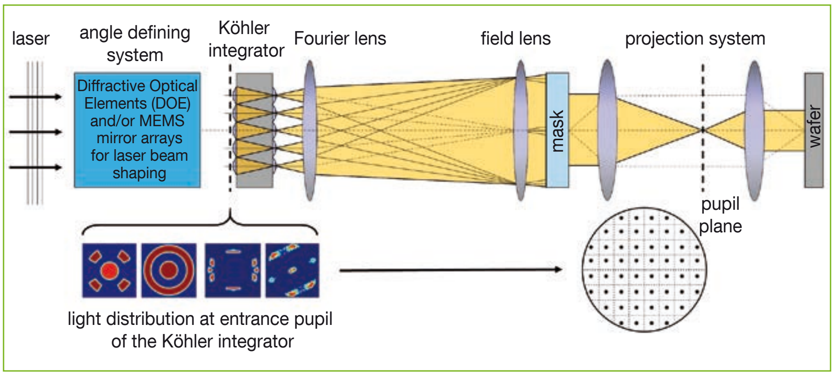

Fig. 4 Scheme of the illumination of a state-of-the-art projection lithography stepper, comprising an angle defining system, a Köhler integrator, and a projection system. The angle defining system reshapes the incident light.

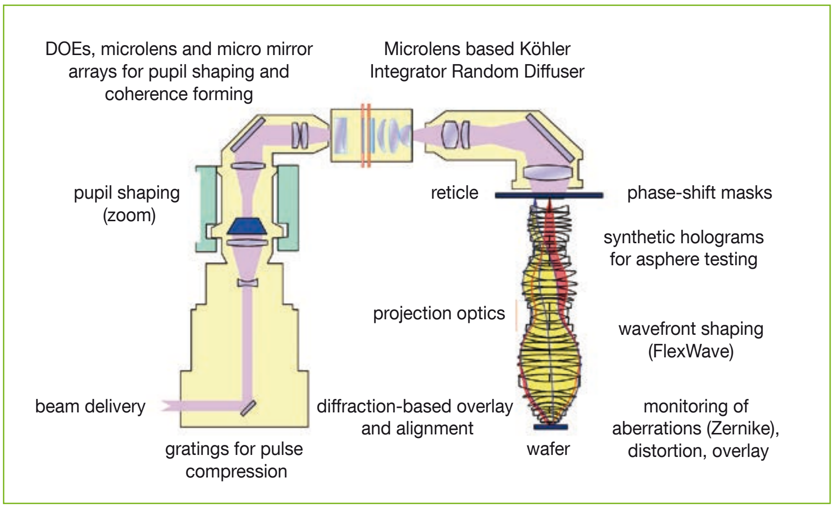

Fig. 5 Fields of applications for micro-optics in state-of-the-art projection lithography system (Courtesy of Robert Brunner, formerly at Carl Zeiss AG, Germany).

suppress the side lobes in the diffraction pattern. Off-axis illumination turned out to be a very useful strategy to enhance resolution for both shadow printing lithography in a mask aligner and in projection lithography. In the simplest case, off-axis illumination or apodization is obtained by using annual or ring illumination of the photomask. Axicon zoom telescopes in combination with a light mixing rod have been introduced for projection lithography systems in the mid-1990s. When industry changed from mercury plasma lamps to well-collimated and mono-chromatic KrF excimer lasers, the use of diffractive optical elements (DOEs) became industry standard. High-quality 8-level or 16-level diffractive optical elements, manufactured on wafer-level in fused silica, allow almost loss-less free-form beam shaping. Microlens-based Köhler integrators replaced the previously used light mixing rods in projection lithography tools in the mid-2000s. In combination with diffractive optical elements (DOEs) or MEMS mirror arrays as "angle defining system", they allow a very precise shaping of the illumination light.

Fig. 4 shows a scheme of the illumination system as used for state-of-the-art projection lithography, comprising an angle defining system, a Köhler integrator, and a projection system. The angle defining system is based on diffractive optical elements or MEMS mirror arrays. Typical light distributions are annual, dipole, quadrupole or more sophisticated free-form distributions as shown in Fig. 4 (left). This light distribution at the entrance pupil of the Köhler integrator defines which individual lens channels of the Köhler integrator are illuminated. For projection systems, the angular spectrum of the illumination light and the pupil function are conjugated. Shaping the illumination light of a projection system is also referred to as "pupil shaping". The pattern shown for the pupil plane in Fig. 4 (right) corresponds to a plane wave illumination of the lens array generating a matrix of discrete spots in the pupil plane. Köhler integrators with a large number of small microlenses allows obtaining a very fine grid pattern in the pupil plane.

Micro-optics in state-of-the-art projection lithography systems

Beside the illumination tasks, micro-optical components and technology is also used for other tasks in a modern projection stepper, as shown schematically in Fig. 5. Blazed gratings are used in the 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 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 [7]. The synthetic holograms, a masterpiece 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 aligning reticle to wafer on the single digit nanometer level.

Conclusions

Micro-optics has proven to be decisive key enabling technology for optical lithography over the last twenty years. Diffractive and refractive optical elements manufactured by wafer-based technology are widely used in all photolithographic systems like mask aligner and projection steppers.

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