Mask Aligner Process Enhancement by Spatial Filtering

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ABSTRACT

Mask Aligners are used in the Semiconductor Industry to transfer structures with moderate resolution requirements onto substrates. With the casting of the shadow a photochemical reactive resist is exposed. As diffraction appears at the mask structures the exposure wavelength and the proximity gap between mask and wafer influence the quality of the image in the resist. As both parameters are very often not changeable for processes there is a big need to find another way to improve the resist image. In this paper a new approach to enhance the exposure result will be presented. MO Exposure Optics, a novel illumination system for Mask Aligners, uses a combination of two microlens Köhler Integrators. MO Exposure Optics decouples the illumination system in a Mask Aligner from the lamp and ensures a uniform angular spectrum over the whole mask plane. Spatial filtering of the illumination light allows to reduce the diffraction effects at the mask structures and to improve the lithographic process in a Mask Aligner.

Keywords: Photolithography, Mask Aligner, Spatial Filter, MO Exposure Optics, Micro Optics

1. INTRODUTION

A Mask Aligner is a one to one exposure system for the micro structuring within the lithography process. Mask Aligners apeared in micro fabrication since the early 1960s [4]. The main principle of a Mask Aligner is to illuminate a photomask that is in contact or at a small proximity distance from a wafer coated with photoresist. Depending on whether the mask is in direct contact to the wafer or there exist a proximity gap between both, this technique is called contact or proximity printing. In the 1980s scanning and stepping tools took over the structuring for small critical structures in high end lithography. But over the years Mask Aligner were always used wherever the quality of the lithographic performance of a Mask Aligner was sufficient. Projection lithography, as Steppers or Scanners project an image of the mask onto the wafer. By a scaling of this image, the mask resolution can be reduced. Mask Aligners don't need a projection system and can achieve fast exposure times with the one to one exposure. Because of the high throughput and the mature process it is a very cost effective technology and still used for critical structures of typically some microns. The main parameters for the quality of the information transfer from the mask to the wafer are the proximity gap and the properties of the illumination light at the mask plane. Therefor the proximity gap needs to be adjusted very precisely. The illumination wavelength is mostly between 250 nm - 450 nm depending on several requirements such as minimum resolution and resist requirements. The best resolution can be reached if the mask and the wafer are in a very close contact. The resolution limit for vacuum contact is about the dimension of the exposure wavelength. A close contact always increases the risk of damages on the mask or contamination by photoresist. In addition a close contact is very easily destroyed locally by every particle between mask and wafer. To prevent the subsequent decreasing yield or rework, in production a proximity gap is preferred, that ensures a mask and wafer not to

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touch each other. A great effort was invested in projection lithography, and so the front-end, to push the resolution limit and fulfill the roadmap drawn by the Moore's law. Photolithography Enhancement Techniques (PET) where developed over the years such as Source-Mask-Optimization (SMO), Optical Proximity Correction (OPC) and Resolution Enhancement Techniques (RET). The novel illumination system introduced by SUSS MicroOptics allows a transfer of this technologies to Mask Aligner Lithography. It stabilizes the illumination of the exposure field and allows for a well-defined illumination that can be customized to improve the image formation within the photoresist.

2. MASK ALIGNER ILLUMINATION

2.1 Multiple Köhler Integrator

In literature a Köhler integrator is also referred as facetted Köhler illumination or fly's eye condenser. Whereas Abbe illumination only works well with a source that has a uniform irradiance itself, Köhler illumination can be used also for light sources that don't meet this specification, such as light emitting diodes (LEDs) or discharge lamps. Figure 1 shows a schematic drawing of a Köhler integrator. It consists of two identical lens plates that are placed with exactly one focal length distance between each other [3]. 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, which helps to stabilize the flux of the illumination light on the photomask. In Köhler illumination, each point of the target area is illuminated by the entire light source. The uniformity is still limited by intensity variations of the light source. Using an array of micro lenses instead of a single lens, there are almost no variations of the irradiance over each lens. Such lenses can provide a high uniformity and efficiency at the same time, while decoupling the primarily light source from the rest of the optical system.

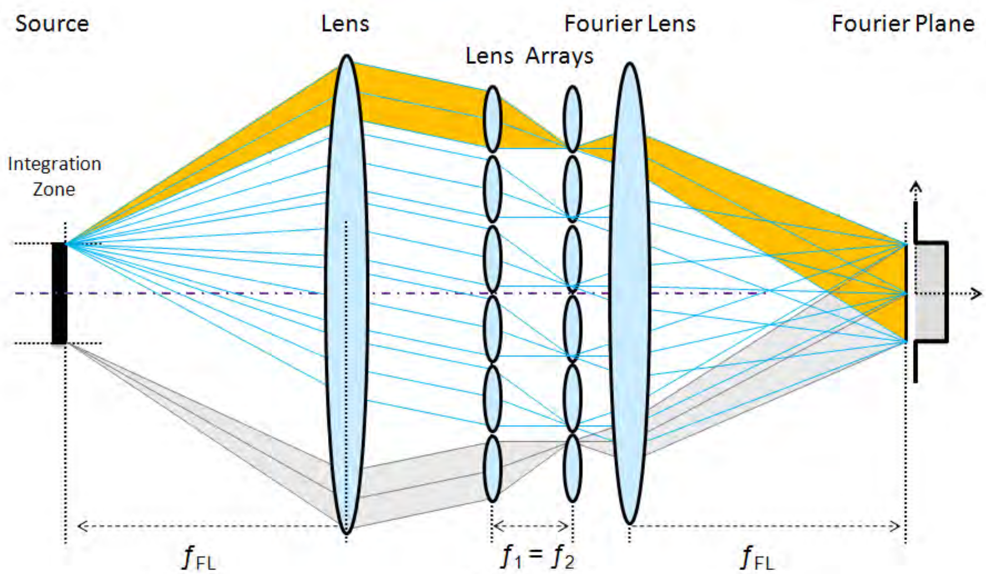

Figure 1. Scheme of a Köhler integrator collecting light from an extended light source within an integration zone and providing uniform irradiance in the Fourier plane of the Fourier lens. Two symmetrical lens arrays located at a focal length distance ($f_1 = f_2$) are used for light mixing. The aperture splitting of the lens array provides a plurality of parallel Köhler illumination systems perfectly decoupling illumination in the Fourier plane from the light source.

2.2 Standard Mask Aligner Optics

A Mask Aligner Illumination System is designed to illuminate the mask plane with a field of uniform irradiance. Figure 2 a) shows a simplified view of the illumination system in a Mask Aligner using two optical integrators. Typically high-pressure plasma arc discharge lamps are used as light source of mask aligners. The arc is placed in the first focal point of an ellipsoid reflector. Ellipsoid reflectors are well-established elements to collect the light from point sources that emit light into a very large angular range. The light is collected in the second focal point of the ellipsoid mirror. To minimize the influence of the arc spread and its actual position there is a diffusing element placed in the secondary focus of the mask aligner. This element will be named Integrator 1 within this paper. As you can see in Figure 2 (a), the Integrator 1 is followed by the so-called Integrator 2. The Integrator 1 has the function to create a radiation field as uniform as possible at the plane of the Integrator 2. A glass plate with pyramids or lenses on one side is used as Integrator 1 within the standard illumination system. The Integrator 2 illuminates the mask plane. To ensure a sufficient uniformity since the 1970s Köhler integrators, as described in Section 2.1, are used as Integrator 2. For example, in Figure 2 (c) a lens plate is shown that is used in Mask Aligners. It consisted of macroscopic lenses with a round outer shape. The single lenses are mounted in a spacific arrangement to create illumination angles at the mask plane, which improve the information transfer for a wide range of application. As the illuminated field of a Köhler integrator can be regarded as the superposition of the particular entry apertures such an integrator illuminates a round field. Light between the lenses is absorbed by the apertures. This standard illumination system is a well suited compromise for the illumination of the majority of applications that use a proximity gap of 20 µm to 100 µm. It is not designed to customize the angular spectrum of the illumination light at the mask plane. The stability of the uniformity is still coupled and influenced by the behavior of the primary light source.

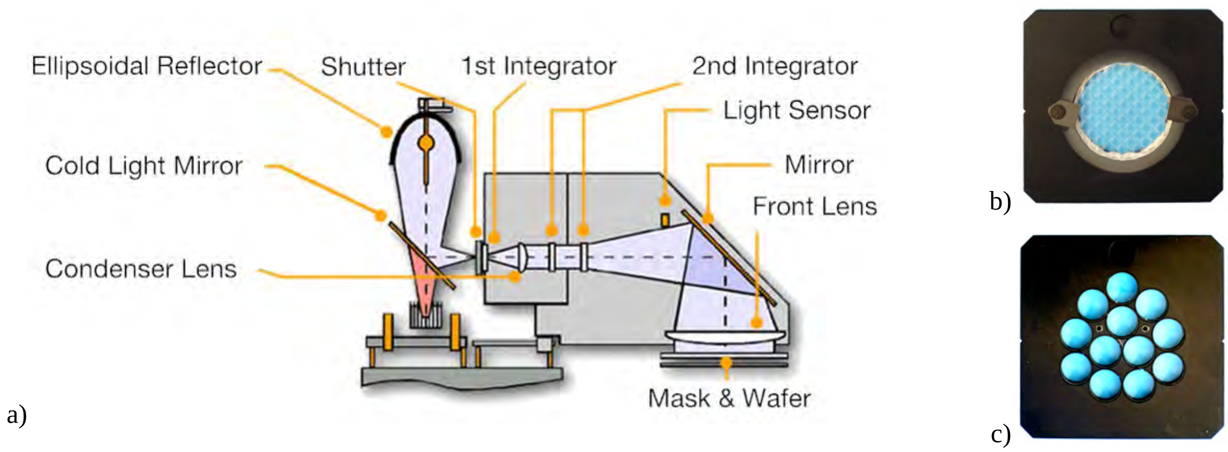

Figure 2 a) Schematic view of a standard illumination system for Mask Aligner comprising an arc lamp, an ellipsoidal reflector, two optical integrators, a condenser and a front lens. b) The first integrator is prismatic plate for light diffusion. c) The second integrator consists of two identical lens plates located at a focal-length distance.

2.3 MO Exposure Optics

As already discussed in Section 2.1 a bigger amount of lenses improves the performance of a Köhler integrator. Therefore in the MO Exposure Optics two microlens arrays are used for the function of the Integrator 1 and the Integrator 2. There are high specifications for a mask aligner illumination system concerning efficiency and long term stability. Therefor high quality fused silica lens plates are used, shown in Figure 2. For the Integrator 1 a monolithic double-sided lens plate with round lenses and a hexagonal arrangement is used. The usage of a micro lens based Integrator 1 decouples the light source completely and creates a uniform and stable field at the Integrator 2. The Integrator 2 consists of two crossed double-sided plates with cylindrical lenses [1]. They are used because of the fill factor of 1 compared to the round lenses with a fill factor at most 0.9. The 10% of the light which passes the lens plates between the lenses through the plane faces without being distributed uniformly over the target area. As crossed cylindrical fly's eye condensers create a uniform radiation in perpendicular directions, a squared uniform field is created at the mask plane.

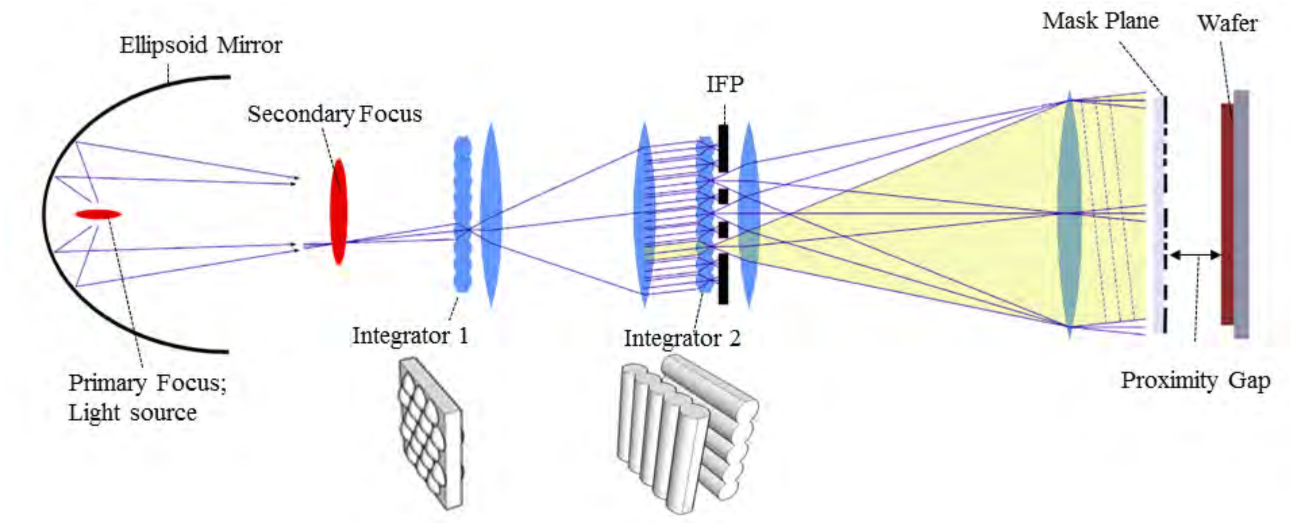

Figure 3 (a) Schematic principle of the MO Exposure Optics. Two Köhler integrators ensure a uniform irradiance and angular spectrum over the entire mask plane. Therefor double-sided lens plate with round lenses is used as Integrator 1. The Integrator 2 consists of two double sided cylindrical lens plates.

3. SPATIAL FILTERING

Mainly two parameters determine the performance of lithographic printing in Mask Aligners: Registration and resolution, also referred to as critical dimension (CD) Registration 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 is defined as the minimum feature size that can be transferred with high fidelity to a resist layer. The transfer is mainly limited by diffraction. As already mentioned, the mask is not illuminated by a plane wave. The illumination can be regarded as an incoherent superposition of plane waves. Their vectors are tilted in respect to each other. Increasing the size of the angular spectrum (i.e. the collimation angle) corresponds to a decrease in the spatial coherence. Reduced spatial coherence supresses diffraction effects. At the same time it smears out the image and reduces the contrast and the slope of the irradiance at the edges. By customizing the angular spectrum it is possible to adjust an ideal trade-off of those effects.

In standard mask aligner illumination system, the angular spectrum of the light in the mask plane is defined by the lateral positions of the individual lenses of the Integrator 2. The change of the spatial illumination of the Integrator 2 leads to a change in the angular spectrum at the mask plane. Many variable concepts might be used, such as variable or programmable illumination filters using zoom lenses, axicon telescopes, liquid crystal displays (LCD), micro-mirror arrays (DLP), variable membranes (MEMS, MOEMS), spatial light modulators (SLM) and light deflectors, acousto-optical modulators and deflectors, variable diaphragms, and all kind of refractive and diffraction optics and mechanics.

The MO Exposure Optics uses exchangeable metallic apertures to define the illumination of the Integrator 2 [2]. The IFPs allow a quick and easy changeover between different illumination settings. Furthermore the IFPs can be produced quickly and very economically. Additionally this concept enables to adjust all illumination geometries that can be mechanically manufactured and so offers a much bigger variability than other approaches. As the irradiance distribution is well known at the plane of the Integrator 2, also grey scale IFPs can be used to produce intermediate levels within the angular spectrum at the mask plane. In Figure 4 a) the integrator 2 and a standard IFP is show. This IFP is customized to produce an angular spectrum at the mask plane that matches with the angular spectrum that is produced by the standard macroscopic Mask Aligner optics which was shown in Figure 2 c).

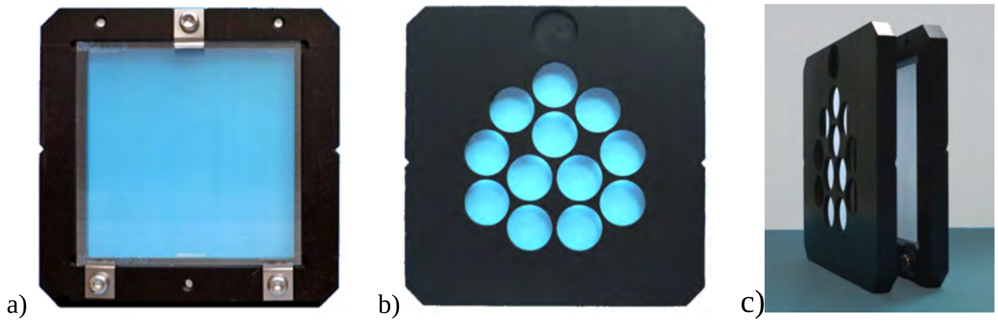

Figure 4. (a) Köhler integrator with a large-area microlens arrays as used for MO Exposure Optics. (b) Metal mask used as exchangeable illumination filter plate (IFP) providing a similar angular spectrum of mask illuminating light than the standard "A-Optics" Mask Aligner illumination shown in Figure 2 (c) The illumination filter plate is placed in front of the first microlens array of the second Köhler integrator.

In Figure 5 a) and b) the measured angular spectrum of the standard Mask Aligner illumination. The angular constant at the center of the mask plane don't matches completely with the angular spectrum at the rim of the mask plane. Caused by the minor number of lenses, such a variation is systematically. It can lead to overlay errors and variations in the information transfer. The angular spectrum of the MO Exposure Optics (Figure 5 c)) is constant over the entire mask plane and the shape ensures equal illumination results compared to the standard illumination optics. So the MO Exposure Optics can be used, even for running processes without having a need to re-optimize the process parameters.

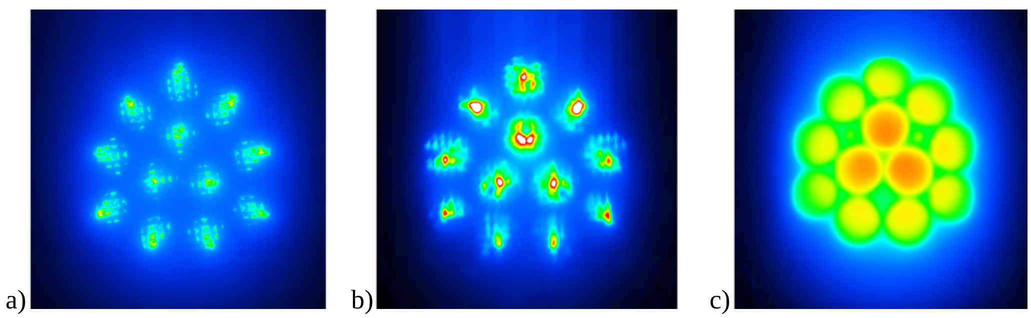

Figure 5. Angular spectrum of the illumination light impinging the photomask for (a) standard Mask Aligner illumination system (Figure 2) in the mask center, (b) at the mask rim. (c) Angular spectrum using MO Exposure Optics (Figure 3) and an identical spatial filter configuration (Figure 4). The angular spectrum expressed in color graduation (arbitray units) was measured by recording the Fourier image of a single lens located in the mask plane.

The advance of variable illumination geometries enlarges of course the degrees of freedom for the whole lithography process. As the testing of new approaches is a very time consuming process based on trial and error, it is not sufficient for the development of customized IFPs. During the last years some progresses where made in the field of mask aligner simulation. With the MO Exposure Optics the illumination parameters are the first time in history reliably predictable. Now the first program is already commercially available. With LayoutLab from GeniSys it is possible to simulate the entire lithography process up to the resist image. A version of Layout Lab that includes standard mask aligner illumination geometries and the possibility to integrate any free form illumination by grayscale images is under development at the moment.

4. EXPERIMENTAL RESULS

As already described, the influence of the angular spectrum always depends on the shape of the mask structures and the proximity gap. The following experiment illustrates the impact of customized illumination for special applications. The original mask design, shown Figure 6 a), consists of squares with the dimensions of 10 x10 µm and a pitch of 20 µm. All tests were made under the same conditions. Just the IFP was changed each time. The design of the IFPs is shown in the upper left corner of the micrographs. Using the standard illumination it is not possible to create squares in the resist. The actual squared shapes were printed as circles into the resist. A cross shaped IFP and so a cross shaped angular spectrum created rectangles tilted about 45°. By tilting the IFP by 45° the right orientation of the resist images could be achieved.

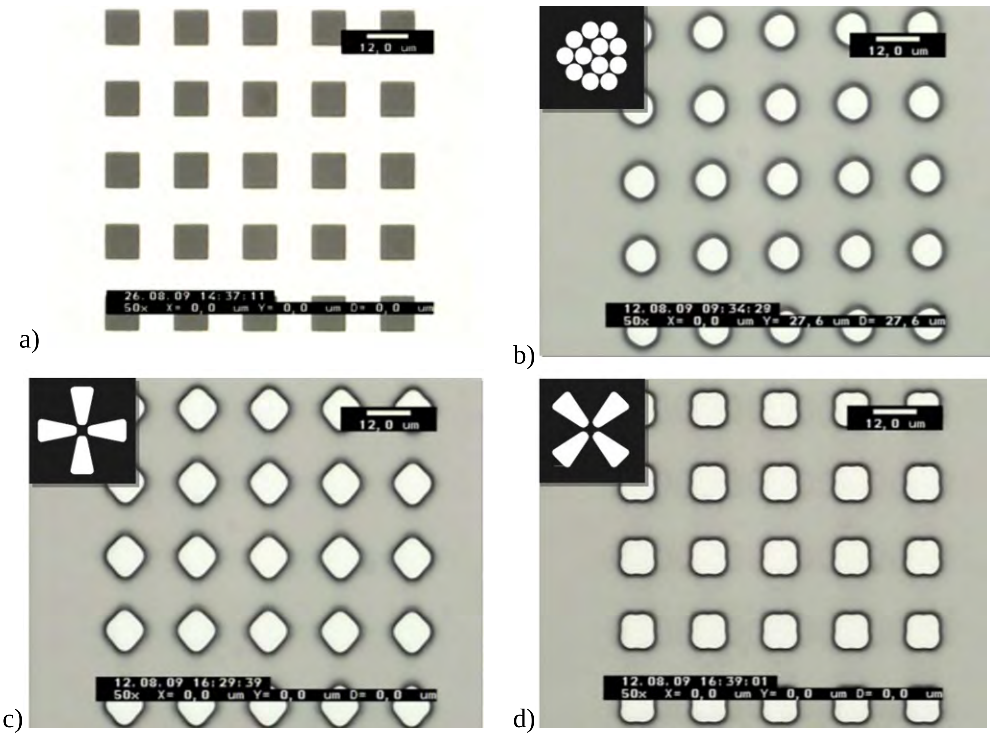

Figure 6. Experimental results for Mask Aligner Lithography using MO Exposure Optics and illumination filtering. Photographs of (a) photomask consisting of 10 x 10 µm large holes and (b) to (d) the resulting prints in 1.2 µm thick photoresist exposed at a proximity gap of 100 µm behind the photomask (a) using different illumination filter configurations shown in the small windows in the upper left corner of the photographs.

It is fairly obvious, that the shape of the angular spectrum is somehow printed at the position of every single mask aperture. In this special case the rectangular openings in the resist act like a "camera obscura". The information of the angular spectrum is thereby Fourier-transformed and so projected into the resist, as shown in Figure 7.

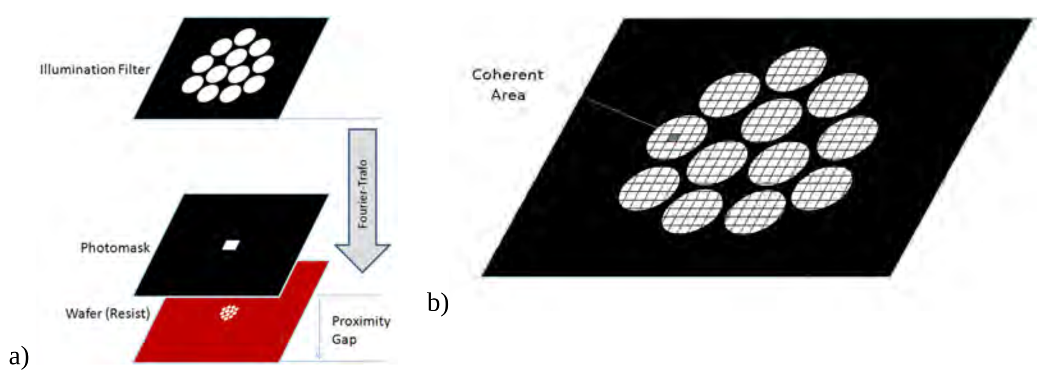

Figure 7. Simplified lithography model for MO Exposure Optics illumination in Mask Aligner. (a) For a single opening in the mask the illumination filter pattern is imaged to the wafer plane. (b) The illumination filter plane is assumed to be subdivided in a multitude of coherent areas, where each is 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.

Beside the actual shape of structures, also the side walls can show an influence. Especially when using hick resist or relatively big proximity gaps the illumination should be optimized for an optimum performance.

5. ADVANCED MASK ALIGNER LITHOGRAPHY

Next to the optimization of the lithography process the novel illumination concept of the MO Exposure Optics also represents a key to completely new approaches for Mask Aligners. It allows implementing a wide field of other lithography techniques in a Mask Aligner, like e.g. Grey-Level Lithography, Lau or Talbot Array Illuminator Lithography (TAILL), Pinhole Talbot Lithography, Mask Aligner Holography using laser light and others. All those methods require a variable and adjustable angular spectrum of the illumination light. The Talbot effect for example can be used to print periodical structures with proximity lithography that are already hard to fabricate in contact lithography [6]. The self-imaging effect is used to create structures that have the same shape as the structures on the mask. The mask must be illuminated with a very small spatial coherence to achieve a sufficient result. An expanded angular spectrum very fast smeared out image with a low contrast, which prevent a transfer into the resist. In Figure 8 an experimental result is shown, where the same mask (a) is used with a small IFP (b) and with a customized IFP (c) and (d).

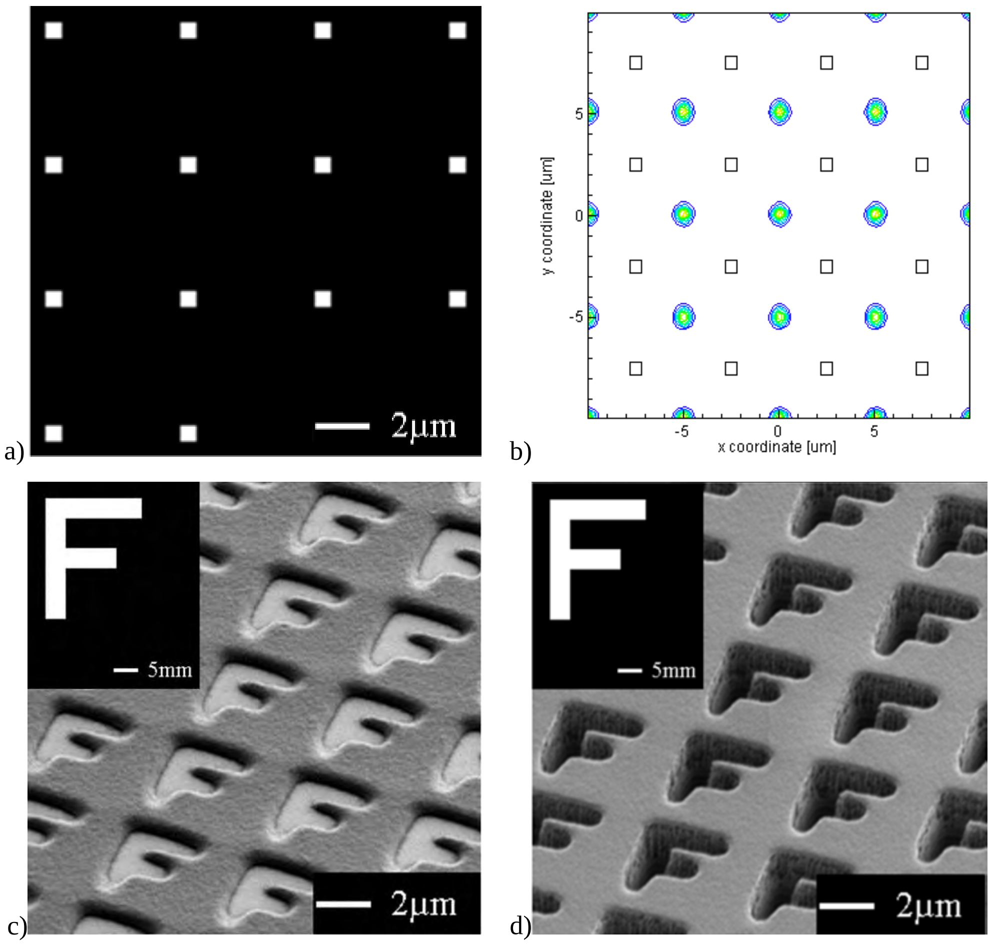

Figure 8. Experimental result utilizing the Talbot effect: a) The same photomask was used for all the following tests. It consists of a pinhole array with 5 µm pitch and 0.6 µm width squares. The proximity gap always was 66 µm b) The simulation of the self-imaging effect. The Spots have the same pitch and size as the mask, but as the half Talbot length was used, they are shifted about half a period compared to the rectangular mask apertures. c) The scanning micrograph shows the pattern that was transferred into AZ1505 with the thickness of 0.5 µm. By using the same mask and a macroscopic F-formed IFP the shape of the IFP is transferred to the resist. d) The scanning electron micrograph shows a print after reactive ion etching.

It was also shown, that is possible to create blazed gratings with the combination of the Talbot effect and customized IFPs [5]. Next to the big proximity gaps, another advantage of using the Talbot effect is that the shape of the resist can be changed by replacing macroscopic IFPs without having the need to design and fabricate a new mask.

6. CONCLUSION

The presented work describes a new illumination system for Mask Aligner Lithography referred as MO Exposure Optics [1]. The utilization of two micro-lens based Köhler integrators provides an excellent uniformity of both intensity and angular spectrum. Simulation tools can be used much more precisely and help to save laboratory time by predicting and optimizing lithography processes virtually. This novel illumination concept allows the implementation photolithography enhancement technologies (PET) from projection lithography. Microlens based fuced silica lens plates used as Köhler integrators in combination with IFPs enable the user to adjust the illumination properties by spatial filtering to his special requirements. Customized Illumination, Optical Proximity Correction (OPC), Source Mask Optimization (SMO) and Resolution Enhancement Technologies (RET) now can be used to improve critical parameters. Resolution and registration accuracy as well as side-wall shapes may be improved.

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