Half-tone proximity lithography

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ABSTRACT

The half-tone lithography using pixilated chromium masks in a projection stepper is an established technology in micro-optics fabrication. However, the projection lithography tool is comparably expensive and the achievable lateral resolution is typically limited. By using pixel diffraction effects, binary and continuous profile lithography with submicron resolution can be installed on a conventional mask aligner. To achieve this goal the control of both, the angular spectrum of the illumination and the mask features is essential. We used a novel micro-optics based illumination system referred as "MO Exposure Optics System" in a SUSS MicroTec MA6 mask aligner for the dedicated shaping of the angular illumination distribution. In combination with an adapted lithography mask the formation of a desired intensity distribution in the resist layer is possible. A general mathematic model describes the relation between the angular spectrum of the mask illumination, pixel size and pitch in the mask, proximity distance and propagated field, which also includes special cases like Talbot imaging. We show that a wide range of different micro-optical structures can be optimized by controlling the light diffraction in proximity lithography. Parameter settings were found for submicron binary pattern up to continuous profile structures with extensions up to several tens of microns. An additional interesting application of this approach is the combination of binary and continuous profiles in single elements, e.g. micro lenses with diffractive correction or AR structures. Experimental results achieved for blazed gratings with a period of 2 microns are presented.

Keywords: half-tone proximity lithography, micro optics, blazed gratings, mask aligner, source mask optimization, RET

1. INTRODUCTION

Fabrication of grey level micro optical structures can be realized by different technological approaches, most promising by laser direct writing or photo lithography using a grey level mask [1]. Generating a grey level mask is also a wide technological field, but typically the standard technology for photo masks – the electron beam lithography – is used. One technique is the darkening of special glass, the well known the HEBS glass (Canyon materials Inc.), which can be used in contact printing. The other is generating the grey levels by writing pixel arrays in conventional chromium masks, to be used in projection lithography, where the pixel will not be resolved in the micro structure due to the demagnification generated by the projection optics in the stepper.

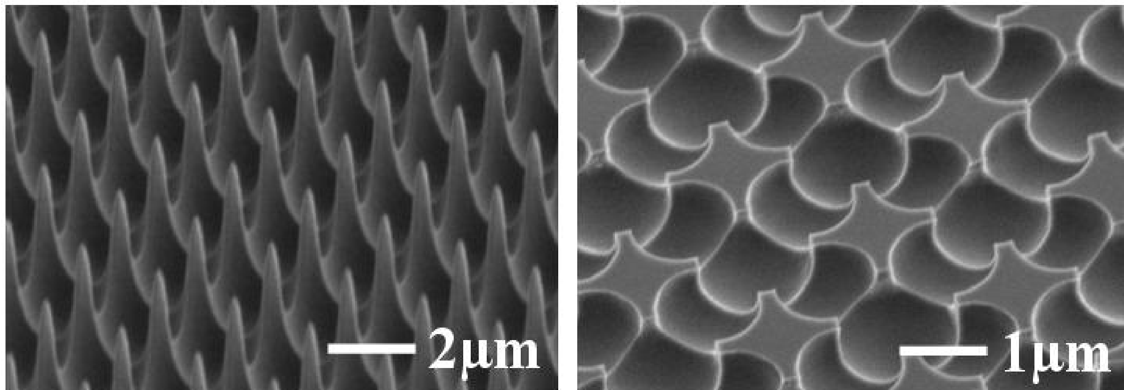

Figure 1. Different realized microstructures: in photo resist (left), etched into silicon (right)

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All technologies require an expensive exposure tool or a costly monopolized mask technology and therefore the pixilated chromium masks technology for the usage in proximity lithography for cost effective micro optics fabrication on a huge number of running mask aligner production tools was investigated.

As it was expected the pixilation of the chromium mask will be transferred by diffraction into the resist structure and the variation of mask parameters and proximity distance influences the diffraction pattern. An approach to reduce disturbing diffraction pattern in the resist is to shrink the pixel size down below the wavelength of the exposure tool. Such small feature sizes have been fabricated on a 50kV electron beam writer VISTEC SB350 OS. Grey tone masks on the base of 5 inch standard chromium reticles with different pixel sizes down to 100nm, different number of grey levels and also different grey level generation methods - pulse width modulation, pulse density modulation and binary quantization methods as used in digital half-toning e.g. Floyd-Steinberg algorithm - were generated and tested for micro optical structures.

The best results with respect to the global shape of the generated components like micro lenses or prisms has been achieved the pulse width modulation, where a regular pattern is formed in the resist which corresponds to the pixel matrix in the mask. The magnitude of the pattern does not scale with the pixel size but scale with the pixel pitch. In order to eliminate the super lattice resist structures created by mask pattern diffraction the mask pitch has to be smaller than the exposure wavelength. That way, even for high resolution electron beam lithography it is getting hard to write a half tone mask with a moderate number of grey levels. Hence, the super lattice pattern can not be avoided but might be controlled by the right choice of the process parameter settings. This results in micro optical structures as shown in figure 1, where the period is in the micrometer range and below – an interesting area for plasmonic and resonance effects. The patterning leads to an optical function that can be used in the photon management of optical components and devices, e.g. gratings and micro lenses, solar cells or micro laser resonators. Spiked 16 level micro lenses are fabricated, where the reflection is reduced by plasmonic resonances and the anti reflection effect scale with the spike height (Figure 2).

The intensity distribution in the resist layer is strongly influenced by the proximity distance between the mask and resist layer. For periodic mask pattern discrete proximity gaps were interesting, where a self-imaging of the mask pattern due to the Talbot effect occurs. This has been successfully used for copying gratings or for period reduction [2].

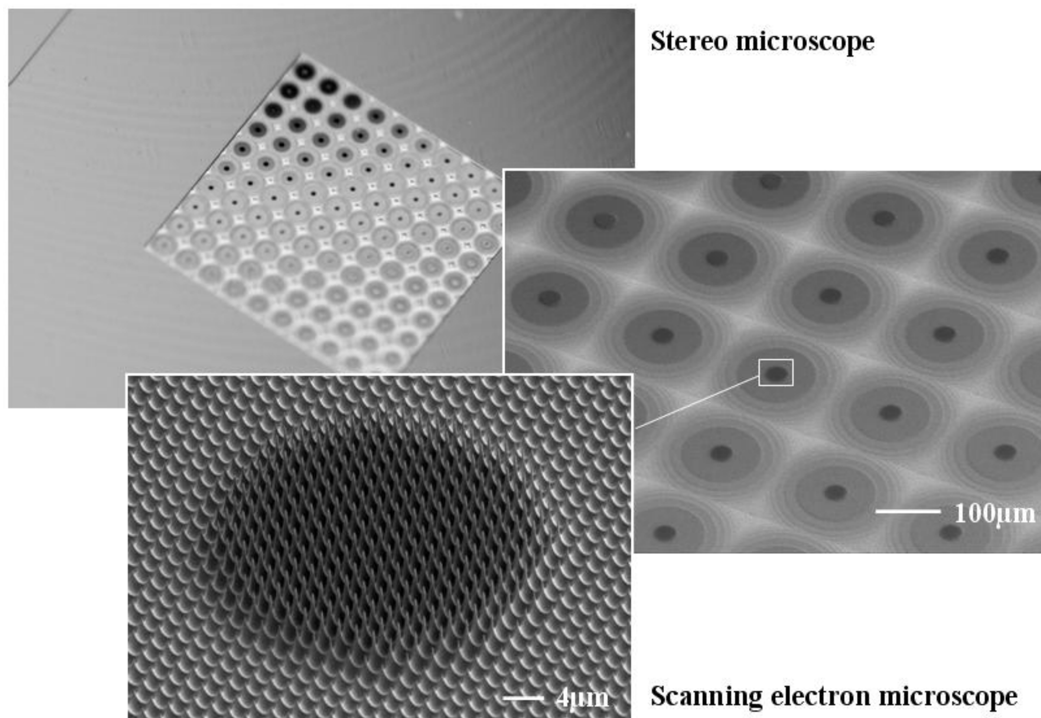

Figure 2. Stereo and SE micrographs of a gold coated micro lens array, fabricated by proximity lithography in photo resist AZ4562 using a pixilated chromium mask, where 16 grey levels are coded. In the stereo micrograph an antireflection effect in the dark lens areas is shown and the SE micrograph displays the effect related pattern.

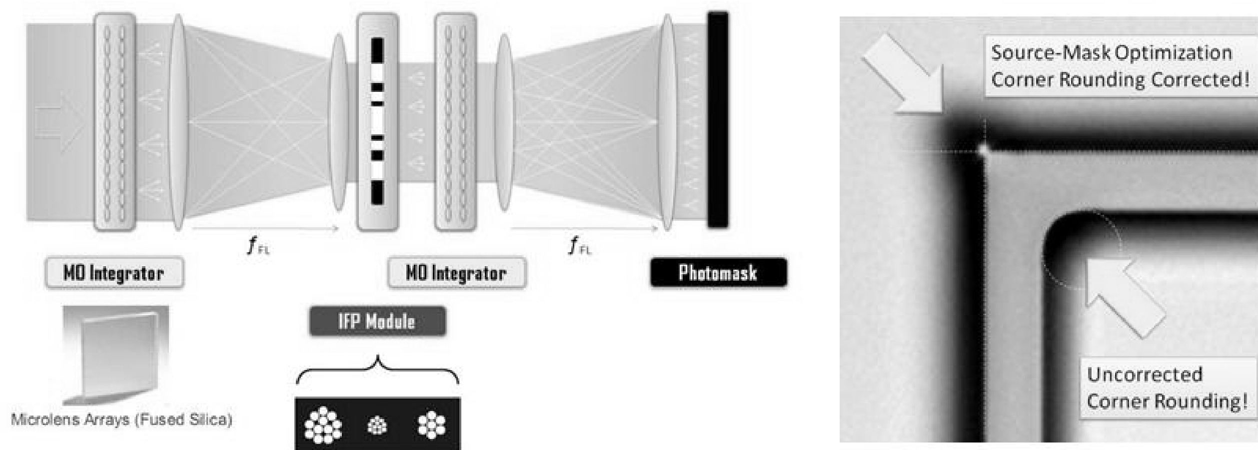

Figure 3. Schematic view of the "MO Exposure Optics System", where 2 micro-optic integrators and an illumination filter plate define the mask illumination settings. This allows introducing the source-mask optimization, a photolithography enhancement technique, into mask aligners to compensate image errors as shown using the example of the correction of corner rounding (5 µm trench in 10 µm thick photo resist AZ9260).

In test print series the shape of the resist pattern can be influenced significantly by the mask illumination settings using a SUSS MicroTec MA6 mask aligner equipped with a "MO Exposure Optics System", a novel micro-optics set developed for the source mask optimization in terms of resolution enhancement and improved manufacturability.

MO Exposure Optics comprises two Köhler integrators (fly's eye condenser), whereas the second Köhler integrator is located in the Fourier plane of the first Köhler integrator. The patented concept of two subsequent Köhler Integrators allows homogenizing both the light intensity and the angular spectrum of the illumination light. Exchangeable Illumination Filter Plates (IFP) located at the second Köhler integrator allow for a quick and easy changeover between different angular settings (Figure 3). MO Exposure Optics also provides telecentric illumination for the full exposure field and is mandatory for the described lithography approach.

In discrete proximity gaps a copy of the aperture (IFP) contour was printed into the resist. That means a strongly scaled image formation by a self-imaging technique as it is described in [3]. This effect has been used in continuous profile printing in the field of micro optics. In a basic approach one and two dimensional periodic masks can be used. The period of the fabricated grating or array is given by the mask and the grating profile or the shape of the array unit cell is determined by the aperture shape. A mathematic model is developed to understand the pattern formation and the influence of aperture, mask and exposure parameters and their interdependency. After that, the method was extended to a wide range of microstructures, on one hand to submicron binary pattern with high aspect ratio and on the other hand to arbitrary profiles having hundred of microns sag height.

2. THEORETICAL INVESTIGATION

2.1 Modeling

In order to study the physical effects, it is useful to reduce the exposure setup down to three planes as shown in Figure 4. A "sum of coherent sources" approach is applied to model the properties of the mask aligner light source [4]. It is assumed, that collimated monochromatic (i-line) light is illuminating the aperture plane. The incoherence is included by decomposing the illuminating plane wave into many spatially truncated areas. Each area is assumed to be coherent but there is no coherence between different areas. Passing through the aperture, each area is multiplied by a transmission function $T(x_D y_D)$ which describes the aperture geometry. An individual coherent area in the aperture plane will be called "aperture point" in the following text. Each point is characterized by its coordinates $x_{D;} y_D$ in the aperture plane and the corresponding value of the transmission function. Figure 4 is illustrating the decomposition of the aperture plane into the set of coherent areas. For now, only the evolution of a single aperture point should be considered. After passing through the aperture, the light is propagating perpendicular to the aperture plane and passes the mask aligner Fourier lens. This lens is assumed to be ideal which means that its optical function can be described as a Fourier transform.

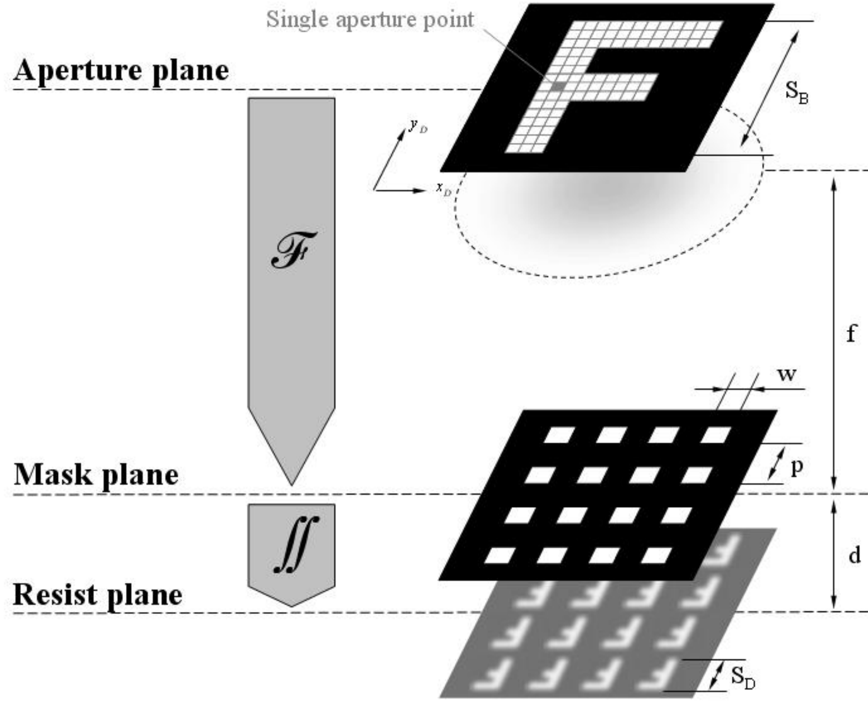

Figure 4. Schematic reduction of the exposure setup to three planes: 1 Aperture plane, where the angular spectrum of the mask illumination will be shaped. The plane is sampled into coherent areas and a single aperture point is highlighted, the corresponding area in the Figure is large in order to illustrate the decomposition but in fact strikes to zero. 2 Mask plane. The mask is assumed as a periodic arrangement of fully transparent openings. 3 Resist plane, where the intensity distribution after the propagation by the proximity distance is formed.

The Fourier transform of a shifted single point source is given by a tilted plane wave which is illuminating the whole focal plane. The plane wave tilt corresponds to the aperture points offset from the optical axis of the system. By this tilted plane wave, the periodic mask is illuminated. The mask is assumed to be thin which means that its optical function can be described by multiplication of the plane wave with a periodical transmission function. Two and one dimensional mask patterns can be considered. Every single mask aperture has a rectangular shape. After passing trough the mask, the light is propagating in free space over the proximity distance until it reaches the photo resist. In order to model the free space propagation, the ‘angular spectrum of plane waves’ (SPW) operator is used. Especially in the case of small mask apertures, high diffraction orders carry a significant contribution to the diffraction pattern in the photo resist. Being strongly non-paraxial, Fresnel propagation is not valid for these high diffraction orders. That is the reason, why a rigorous modeling of free space propagation (namely SPW) is required. In this manner, the diffraction pattern created by each aperture point can be obtained. Since different aperture points are not coherent to each other, the same is true for the corresponding diffraction patterns. To take this circumstance into account, the intensities of every diffraction pattern created by a single aperture point are added up, resulting in the overall diffraction pattern.

2.2 Basic results

Analytical calculations and simulations show, that the overall diffraction pattern in the photo resist is approximately given by the highly contracted transmission function of the mask aligner aperture, convolved with a periodical point spread function. In other words, the aperture geometry can be scaled down and is periodically transferred into the photo resist. The point spread function, which describes the replication of the aperture geometry in the diffraction pattern has a minimum period of the mask pitch p and is only localized in some proximity planes behind the mask. Candidates for localization are the well known (fractional) Talbot planes

$$d_{TB} = 2\frac{p^2}{\lambda}\frac{N}{n} \qquad N,n \in \mathrm{N} \qquad \frac{N}{n} \notin \mathrm{N} \text{ for } N,n > 1 \tag{1}$$

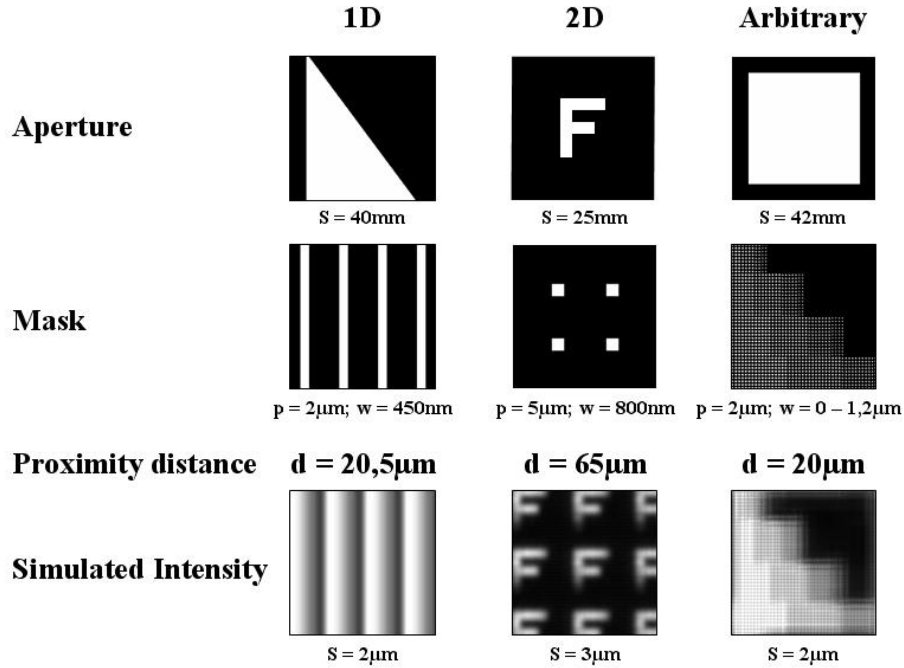

Figure 5. Examples of simulation results for one-, two-dimensional and arbitrary intensity distributions and the used parameter sets

where n give the fraction and N the integer multiple of Talbot distances. The exposure wavelength is denoted by λ . As mentioned above, the geometry of the mask aligner aperture is rapidly scaled down and obeys the relation

$$S_D = \frac{d}{f} S_B \tag{2}$$

where f is given by the focal length of the mask aligner Fourier lens. Typical values for the aperture scaling are in the range between 2000 and 50000. In order to avoid overlapping of aperture images in the diffraction pattern, the relation $S_D \leq p$ should be fulfilled which limits the maximum aperture size in a given configuration. If two dimensional periodic masks are considered, replications of the full aperture geometry can be obtained. In the case of a one dimensional periodic mask, the same is true for the periodic direction, while in the other direction, the intensity of the aperture transmission will be integrated. By arranging the aperture openings in an adequate way, one dimensional grayscale patterns can easily be created. An additional degree of freedom is the manipulation of the size of each mask opening which allows the control of the local intensity of each aperture replication up to a certain extend (Figure 5).

2.3 Replication of aperture geometries in the diffraction pattern

In order to understand the replication of the aperture geometry in particular proximity planes, it is essential to investigate in detail the diffraction pattern corresponding to a single aperture point. As illustrated in Figure 6 a single aperture point is generating a tilted plane wave which is illuminating the mask. That way, the mask is working like a periodical array of identical light sources which are spatially coherent to each other. The interference pattern generated by this array of sources is forming the diffraction pattern of a single aperture point. Figure 7 points out, how this pattern is composed in detail. In every distance behind the mask, the interaction of two diffraction orders is creating a cosine-shaped interference pattern. Assuming that the considered diffraction orders are denoted by μ and $\tilde{\mu}$, the pitch of the generated modulation is given by $p/|\mu-\tilde{\mu}|$. The amplitude of these patterns is varying periodically with the proximity distance d and decreases for rising diffraction orders μ and $\tilde{\mu}$. Since the mask is periodic and widespread, all possible combinations of diffraction orders are superimposed in every p periodic interval behind the mask, adding up to the overall interference pattern. If the amplitudes of the single cosine-shaped patterns are chosen in the right manner, localized diffraction patterns can be created in summation.

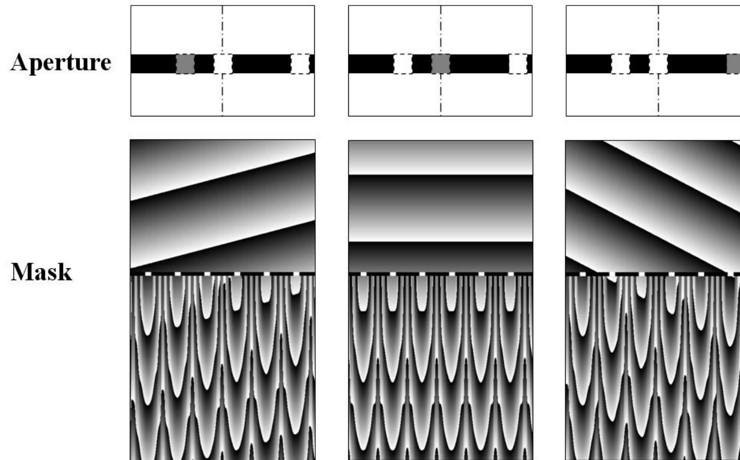

Figure 6. Schematic cross sectional view of the aperture with an exemplary set of aperture points and the related phase distribution in front and behind the mask by the consideration of the respective highlighted aperture point

Figure 7 is illustrating this superposition for the simplified case of equally weighted cosine functions. For the next step of consideration, an appropriate set of parameters (mask pitch p, mask opening w, proximity distance d and exposure wavelength λ) is assumed, which leads to a localized diffraction pattern of a single aperture point. If the location of the regarded aperture point is now shifted in the aperture plane, the tilt of the plane wave illuminating the mask will be changed. This causes a phase shift on all cosine-shaped interference patterns which means a relocation of maxima and minima. Based on the property of the exposure setup that the aperture size S_B is small against the Fourier lens focal width f, the illuminating plane waves are only slightly tilted. Calculations show that in this regime, the phase shift on the cosine-shaped interference patterns will vary linearly with the aperture point location. Further investigations show that this shift will actually be nearly independent from the interacting diffraction orders if the ratio of involved diffraction order to mask pitch will not be too high. This means, that a shift of the considered aperture point will not influence the localized diffraction pattern in its shape but will shift it globally. If now two individual aperture points are considered, two localized diffraction patterns will be formed. They will not interfere, since different aperture points are not coherent to each other. This means, that the corresponding intensity patterns have to be added up.

Figure 8 illustrates the interaction. As stated before, linear shifts in the aperture plane lead to linear shifts in the diffraction pattern. That way, geometries in the aperture plane can be linearly transferred into intensity patterns in the photo resist. The diffraction pattern of a single aperture point acts like a point spread function, describing how points in the aperture plan are transferred down. A highly located PSF will lead to a high resolution of the aperture geometry in the diffraction pattern. Point spread functions with a higher periodicity (e.g. induces by vanishing amplitudes of cosine-shaped interference patterns in fractional Talbot planes) will induce an aperture replication with higher periodicity respectively.

2.4 Theoretical limitations

The lateral resolution of the aperture replication is described by the periodical point spread function in general. Limits for the PSF localization will restrict the maximum resolution. Since the diffraction orders of the mask are getting evanescent above a given number, only a limited quantity of cosine-shaped interference patterns can contribute to the PSF. In addition, only terms with an appropriate weighting factor can improve the resolution. To achieve a good localization, all obtainable interference patterns are important. The overall localization can not be better than the half pitch of the highest contributing cosine-shaped interference pattern. In general, the amplitude of the cosine-shaped interference patterns is falling for higher diffraction orders. By reducing the ratio of mask opening to mask pitch, the reduction rate can be scaled down. It follows that tiny mask apertures in conjunction with the use of high diffraction orders are desirable for a high resolution. Unlike that trend, if the ratio of involved diffraction order to mask pitch is becoming too high, the phase shift which is induced by a shift of the aperture point will derivate form the desired isotropic behavior. That is the reason, why a limit for the highest useful diffraction order exists. The interaction of both trends leads to an optimum mask aperture size w which will maximize the lateral resolution for a given mask pitch and aperture size.

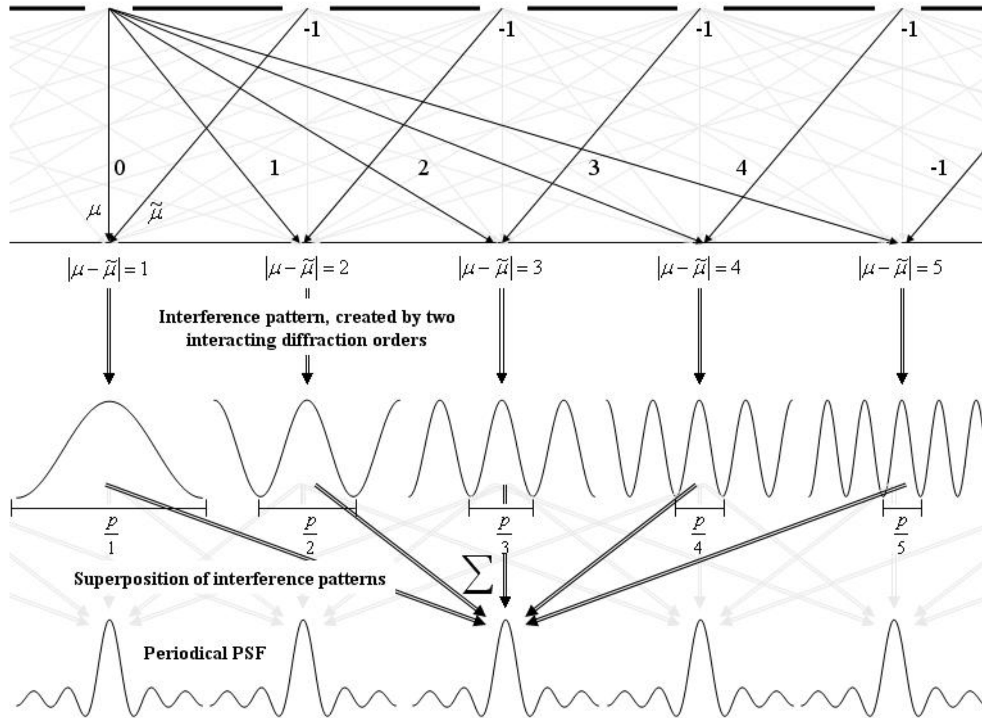

Figure 7. Diffraction pattern, created by a single aperture point: The interaction of two diffraction orders is resulting in a cosine-shaped modulation. The superposition of cosine functions with appropriate weighting can lead to localized patterns. For simplicity, uniform weighting is assumed in this example.

For the case of 2µm mask pitch, the optimum mask aperture will be approximately 450nm. If the mask pitch is enlarged, the optimum mask aperture size will grow slower than linear with the pitch size. Investigations in the PSF show, that the obtainable lateral resolution (full width half maximum) is given by the mask opening w in rough approximation.

$$FWHM_{PSF} \approx w \tag{3}$$

The amplitude of the cosine-shaped interference patterns producing the located PSF is modulated with the proximity distance. That way, the depth of focus (DOF) which can be allocated with the replicated aperture geometry is limited. The modulation frequency is growing for higher diffraction orders, leading to a reduced depth of focus for point spread functions composed by use of high diffraction orders. In reverse, reducing the lateral resolution by increasing the mask aperture size w will lead to enhanced depth of focus. The same is true for a higher mask pitch p, since the modulation frequencies are reduced.

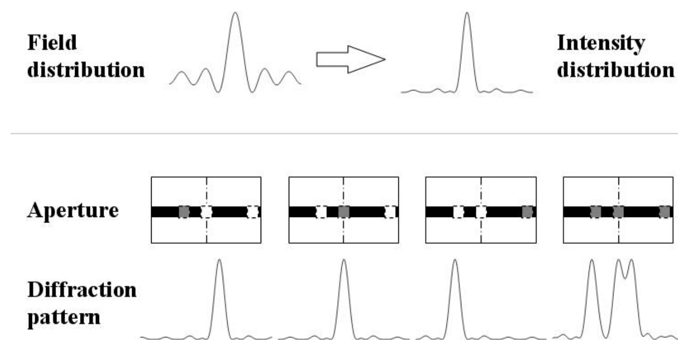

Figure 8. Relation between aperture point position and diffraction pattern location: Linear shifts in the aperture lead to linear shifts in the diffraction pattern; the considered aperture points are highlighted; since the different aperture points are not coherent to each other, the intensity patterns have to be added up

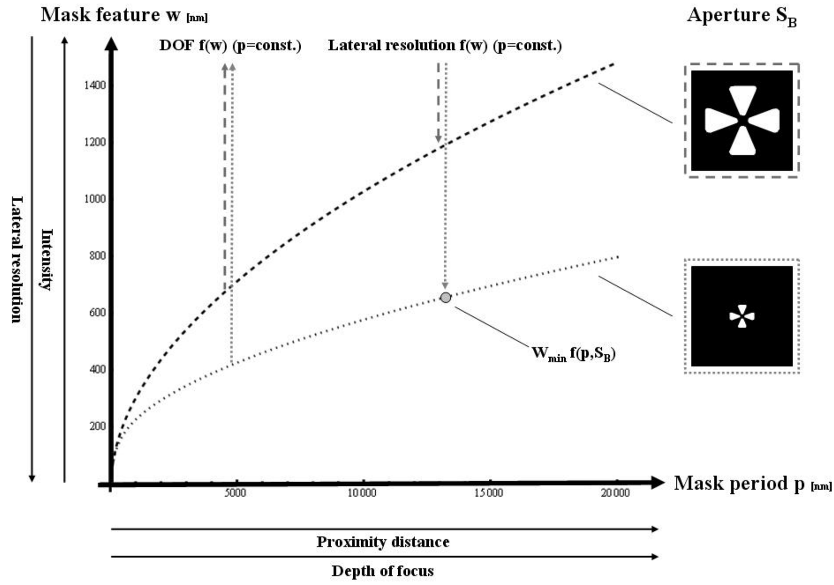

Figure 9. Optimum mask aperture size which maximizes the lateral resolution, smaller mask openings are not reasonable, arrows are illustrating the tradeoff between lateral resolution, depth of focus and intensity in the diffraction pattern

Based on estimations, the depth of focus (full width half maximum) for a given mask pitch p is in the range

$$p \leq FWHM_{DOF} \leq \frac{p^2}{2\lambda}. \tag{4}$$

The minimum corresponds to the maximum in lateral resolution achieved for the optimum mask aperture size w. Nevertheless, sufficient intensity in the diffraction pattern is important in praxis. The intensity scales with the ratio of mask opening to mask pitch w/p for one dimensional masks and its square in the case of two dimensional masks respectively. The given results are summed up in Figure 9.

3. EXPERIMENTAL RESULTS

3.1 Scaled replication of aperture geometries

In order to verify the theoretical results, different aperture geometries, where some are made for resolution enhancement tests by special illumination settings, have been transferred into photo resist (Figure 10) after the "MO Exposure Optics System" was installed on the SUSS MicroTec mask aligner. The shape of the used aperture is clearly recognizable, so the match between the experimental results and the simulations is obvious. A spiral shaped aperture is demonstrating the high obtainable resolution.

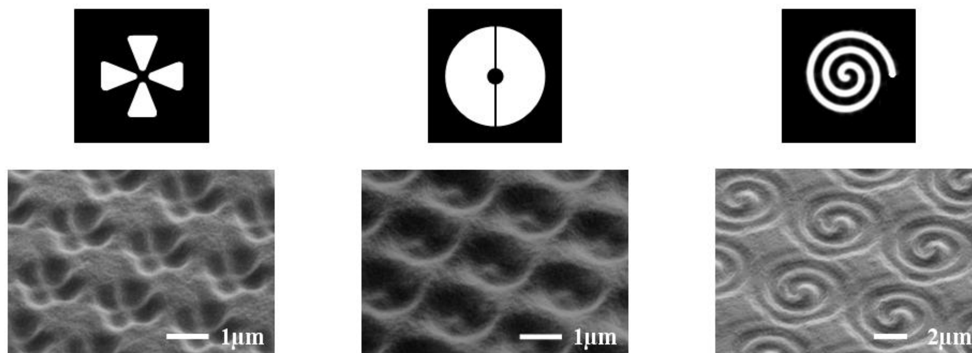

Figure 10. Different aperture shapes and the respective realized pattern in photo resist AZ4562 and AZ1505

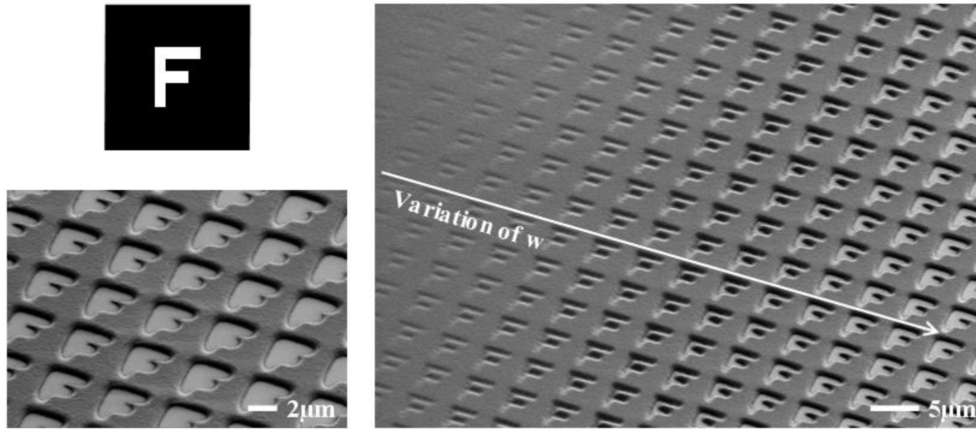

Figure 11. SE micrographs of an “F” shaped aperture in thin binary photo resist AZ1505. The dependency of lateral resolution and intensity on the size of the mask feature size w is shown

Using the fundamental or the half Talbot distance the period of the scaled aperture images is equal to the mask period. The actual proximity gap depends from the mask aligner accuracy. It is essential to pay attention to the limited depth of focus of the diffraction pattern. That way, process conditions like wedge errors, resist inhomogeneity and proximity distance positioning have to be well controlled. The simulated intensity distribution leads to a relief of the aperture using a low contrast resist AZ4562 and a profile height of about 500 nanometers reached in the experiment. Switching to high contrast resists a binary image of the aperture contour could be printed into the resist (Figure 11). This offers a wide range of periodical submicron optical components like micro lens arrays or photonic crystals, where the unit cell of the array is determined by the used aperture. By switching the aperture, a low-cost machine shop fabricated metal plate, a new array can be printed with the same photo mask. A significant cost reduction for mask fabrication and process optimization e.g. for wafer scale stacking optics might be possible that way.

3.2 1D – Blazed grating

Important micro optical elements are blazed gratings with periods of 2 to 3 times the illumination wavelength, where the grating works highly efficient in the resonance domain. This period range is often hardly accessible for laser writing and demanding for projection lithography.

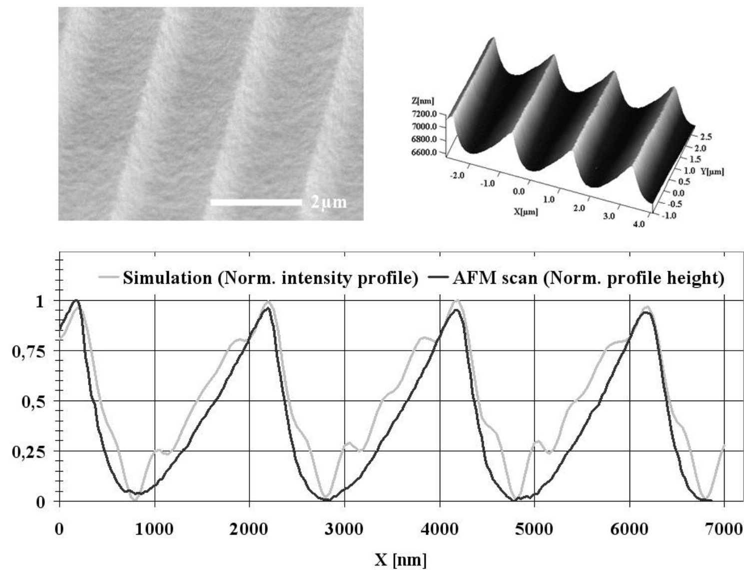

Figure 12. SE micrograph and atomic force microscope scan of a realized blazed grating structure in photo resist AZ4562. The normalized profile scan of the resist structure (height: 580nm) and the normalized intensity profile are shown together

In the grey tone lithography with projection systems the profile is approximate by a small number of grey levels or multiple exposure technology is used. In most cases the very expensive multilevel electron beam writing is applied.

A photo mask with period of 2 microns and a line width of 450 nanometers was generated to print a 2 micron period blazed grating by use of proximity lithography. Corresponding simulations are shown in Figure 5. The triangle shaped aperture, which is needed, will be replicated in the periodic direction only. In direction of the grating lines the intensity will be integrated and results in a triangle shaped intensity distribution within one grating period. A print with the described mask and the triangle shaped aperture was performed in AZ4562. A blazed grating profile with a height of 580 nanometers could be realized as shown in Figure 12. The deviation between the achieved and the simulated profile scan, caused by the resist response, might be transferred in a modification of the aperture geometry optimizing the print result with the adapted aperture in an iterative run. Maybe the correction of the shape results in assisted aperture features, which will not be resolved, similar to the optical proximity correction of photo masks.

4. CONCLUSIONS

A new approach of lithography for micro optics fabrication is presented which offers a wide range of feasible structures by extending the conventional proximity lithography with a photo mask trough shaping its illumination by a new illumination concept. The big advantage of the MO Exposure Optics is that the desired illumination settings can be easily applied by a simple aperture. A model describes the effect of replication of the aperture into the photo resist for discrete proximity distances.

Nevertheless the model is more general and the formed intensity distribution in any proximity distance could be calculated. Theoretical limitations are given to estimate the capabilities of this method. For a high lateral resolution the depth of focus becomes very demanding and the exposure time increases considerable due to reduced intensity using small mask and aperture features. The model helps to estimate the mask parameters, the illumination setting given by the aperture and the lithographic process parameters. Realized microstructures show the potential of proximity lithography if the illumination will be adapted to the mask, especially the replication of the aperture is used for periodic micro-optical components.

5. OUTLOOK

Since blazed gratings have been successfully printed 2D periodical microstructures will be realized in the next step. Also simulations on arbitrary structures for large continuous profiles will be continued. It seems that one parameter more has to be taken into account – the mask phase. The half-tone proximity lithography might have even more possibilities using phase shifting or phase masks. Also adding phase shifting structures to the backside of the mask by a double-sided electron beam lithography process is an auspicious way to improve the illumination of the mask features [5].

The theoretical investigations should be extended to a more general description. That way, non periodic mask features might be considered to optimize the print results for other application fields of mask aligners which are equipped with "MO Exposure Optics System" like micro electronics, micro mechanics or micro fluidics. The proximity distance accuracy will remain a critical point due to the limitations of the depth of focus for high lateral resolution. Besides finding the theoretical optimum for the depth of focus the improvement of the proximity distance accuracy is mandatory. Possible solutions are the use of spacer technologies or solid immersion layers on top of the wafer or on the bottom of the mask.

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