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Analysis of an Effect of Perturbations in SWHM and Illuminating Optical Scheme Parameters on an Aerial Image

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***Abstract*— There is considered a new method of sub-wavelength holographic lithography (SWHL) for creation of IC layers aerial images. This approach proposes to use very local defects tolerable holographic patterns and simple optical scheme for photoresist exposure. The paper investigates influence of different perturbations occurring during either mask manufacturing or photoresist exposing on resulting topology image. Simulation showed that practically all perturbations which appear when using modern equipment do not significantly distort the resulting image, while the most problematic phase noise effects could be removed by introducing them into sub-wavelength holographic mask (SWHM) calculation.**

Keywords- sub-wavelength holographic lithography; imaging; sub-wavelength holographic mask

I. INTRODUCTION

During the last several years the authors have been researching a problem of creating IC layer topology light images with the use of sub-wavelength holographic lithography (SWHL) method developed by them [1,2]. A topology of projection photo-microlithographic mask (PPMM) at traditional projection photo-microlithography (PPML) is practically the same (if not considering corrections originated from OPC-technology) as a topology of created IC layer. Using sub-wavelength holographic mask (SWHM) instead of used at the state-of-the-art PPML traditional PPMM has a number of serious advantages as it was shown by our thorough investigation. The main advantage is radically higher rate (more than 10^{10} times) of tolerance of image quality to SWHM local defects for the case of SWHL in comparison with PPML. This estimation originates from comparison of allowed total defects area to mask area rates in DUVL and SWHL. This is caused by very low sensitivity of a reconstructed from SWHM topology image to SWHM local defects, which are related to environment influence as well as to accidental damages in a process of manufacturing and exploitation.

Image quality stability is proved by calculations and local defects (including rather sizable ones) simulations. For example, covering up a considerable part of SWHM area results in minimal changes of image quality (see Fig. 1).

In the case of PPMM a defect having the same size will certainly be reproduced in the image and eliminates corresponding topology objects. Even substantially smaller PPMM local defects lead to absolutely impermissible mergings and breaks in topology elements of created image. It is well known that PPMM quality requirements are very high. In the case of DUV 250 nm technology for this mask topology it is only allowed 0.04 of 300 nm size defects per 1 cm^2 of mask surface, i.e. specific surface defectiveness rate for such a mask should be less than 10^{-11}. When using EUV radiation source (λ=13,5 nm), which provides switching to 22 nm and less technology, this rate should not exceed 10^{-15}. Moreover, EUV mask manufactures are going to develop defectless mask technology by 2015. Therefore, SWHL technology advantages appear to be substantial at the current technology development level and become just overwhelming when moving to NGL-technologies.

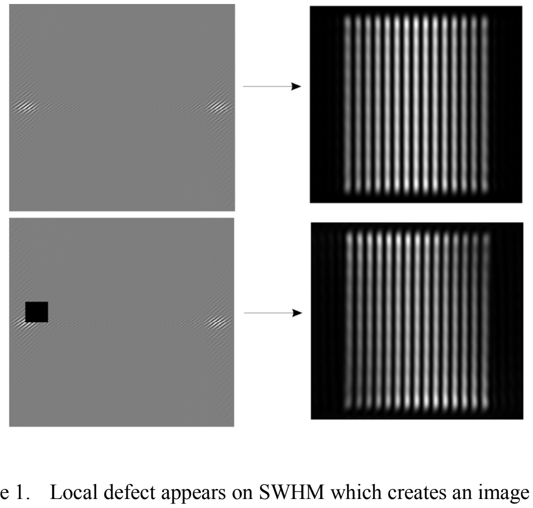

Figure 1. Local defect appears on SWHM which creates an image consisting of 15 strips. The SWHM without local defects and corresponding reconstructed aerial image (upper) and SWHM with local defect and corresponding reconstructed aerial image (below) are represented

Furthermore, an image created by SWHM appears to be rather stable to small perturbations of optical scheme that is used for SWHM illumination, exactly, to mask displacement, aberrations and so on. Furthermore, even when SWHM has many local defects it does not create any local distortions of topology elements in reconstructed aerial image. This was testified by authors' numerical simulations of hologram random dusting (see Fig. 2). The only change is that brightness decreases in proportion to SWHM area covered with these dust defects.

II. SIMPLE OPTICAL SCHEME USED AT SWHL TECHNOLOGY

The main function of the optical scheme is to form an aerial image similar to a given one on photoresist surface. An initial image supposes to be a topology of some IC layer or a fragment of such layer. A proximity of created aerial image and initial topology is characterized by possibility to get such a working layer topology in a result of photoresist exposure and further processing, that would correspond to the initial one with errors being smaller than given tolerance.

Optical scheme consists of coherent radiation source, rather simple objective which forms convergent spherical wave, Si-wafer covered with photoresist layers, layer (usually Cr) where SWHM topology is formed and photoresist layer (see Fig. 3).

When illuminating an SWHM synthesized in accordance to described at [1, 2] technology, on photoresist surface there are appear:

a) useful aerial image (+1-st diffraction order), which forms a photoresist image of given IC layer topology with appropriate tolerance;

b) "virtual" aerial image (-1-st diffraction order), which is close to centrosymmetric reflection of the useful one;

c) an area where zero order diffraction radiation concentrates, in our case its form resembles a cross and it is a result of diffraction on hologram edges.

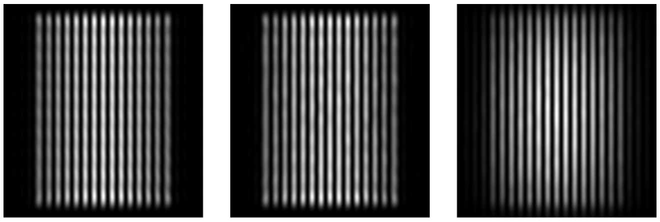
a b c

Figure 2. Aerial image reconstructed from SWHM changes as part of SWHM area is covered with random dust. Images a, b and c were reconstructed from SWHM with 0%, 44.8% and 98.6% area dusted correspondingly

A hologram/SWHM is represented by some function of transmission or darkening defined on holographic plate and possessing the values from 0 to 1. It is assumed that electromagnetic wave intensity decreases by the corresponding value when radiation penetrates through SWHM in a certain point. Physical realization of such a hologram/SWHM could be a quartz plate covered with thin chromium layer with reconstruction radiation transmission areas (TA) having different sizes and specified positions. It is also possible to regulate transmittancy by variating TA density when all TAs are small and uniform. TA positions and sizes appears as a result of calculation when SWHM is decomposed into square cells.

SWHM is the main component of the technology because it contains all information about constructed aerial image. SWHM is also the most active component leading to a risk of distortion of information written on it and therefore to aerial image quality decrease. Tolerance of an image constructed by SWHM to its local defects was mentioned above, but there could appear global disturbances revealing on the whole SWHM surface. Such disturbances may appear in processes of manufacturing of SWHM, positioning it at optical system and photoresist exposure. SWHM is unavoidably affected by surroundings temperature fluctuations, SWHM form deviations appearing as a result of quartz plate deflects caused by its weight, quality of coherent radiation generated by laser. SWHL image quality could be significantly affected when replacing gray hologram with so-called "binarized" hologram, consisting of a large number of small holes. Our purpose is to examine level of influence on the resulting image quality and this impact nature for different disturbances appearing in a process of SWHM manufacturing and illumination.

III. TRANSMISSION FUNCTION OSCILLATION PERIOD AND HOLOGRAM ELEMENT SIZE SELECTION

An important hologram parameter is a size of logical element. Selection of size for this element does play an important role in hologram "binarization". It could be expected that the more logical elements hologram has the better continuous transmission function is reproduced in a process of discretization. But fine partitioning has many drawback. Hologram elements number increase leads to quadratic increase of computation time. Hologram elements size decrease leads to unavoidable decrease of TA average size. Light cancels to penetrate TAs with $\lambda/2$ diameter, where λ is reconstruction radiation wavelength. Small size of holes could also lead to appearing of inaccuracies related to a process of SWHM manufacturing [3,4]. Too big SWHM element size leads to impossibility to reproduce continuous transmission function by TAs. Therefore it appears a problem of determining the maximum size for SWHM element which allows to reproduce continuous transmission function. For evaluation of this parameter it should be considered a question of minimal oscillation period of transmission function. The following estimation could be obtained: $T \approx \lambda D/S$ [5]. Here T is the estimated period, λ is wavelength, D is a distance between hologram and image plane, S is an image size. Computational simulation shows that cell size should be between T/6 and T/4.

IV. SWHM MANUFACTURING INACCURACIES

Inaccuracies appearing in a process of hologram manufacturing could be divided into several groups:

a) Size inaccuracies of holes disposed on "binarized" hologram.

b) Quartz plate nonflatness.

c) Mistakes in TA centers positions.

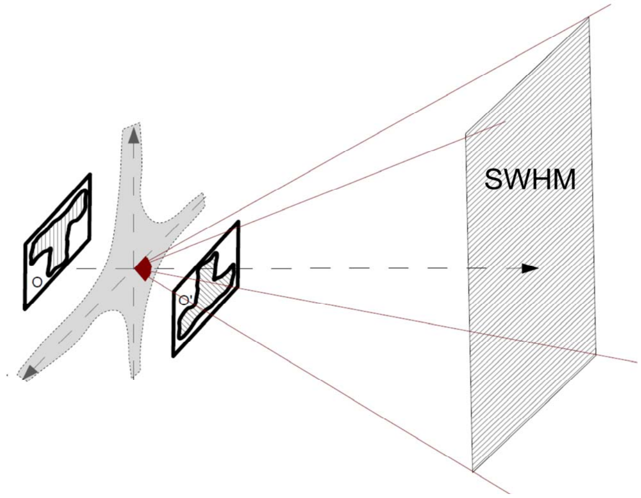

Figure 3. The SWHL optical scheme

Simulations of SWHM illumination showed high level of tolerance to the described above error types. Errors of the first type could be up to 3-4% of maximum allowed TA size when binarizing by different size TAs and choosing SWHM logical element size in accordance to the previous section. The resulting image quality decreases to a little degree. This means that if, for example, hologram logical element size is equal to 1 mkm, than manufacturing errors of hologram holes could be up to 30 nm without affecting image quality. Inaccuracies of TA sizes were simulated by a set of independent normally distributed random variables.

Errors of the second type are caused by the fact that transparent substrate covered with mask layer, e.g. layer of Cr, has nonzero inhomogeneous thickness. This leads to so-called phase noise. Penetrating through hologram wave front form is distorted because a substrate refraction coefficient differs from surroundings refraction coefficient. This results in appearing speckle noise on an aerial image [5,6]. For modeling these errors effects a relief map of some real quartz substrate was acquired. This map was introduced into calculation as corresponding fluctuation of wave front. Image quality significantly changes when quartz plate thickness differences exceed half of radiation wavelength. Otherwise image quality changes inessentially. Substrate thickness changes smoothly as it could be seen on surface relief map. That is thickness variation characteristic period is comparable to SWHM size. If independent random variables are used for modeling holes phase shifts (it corresponds to local nonflatness), then requirements to maximum amplitude of phase deflection toughens to λ/20, what corresponds to up to λ/8 of possible quartz plate thickness variations. It should be mentioned, that knowing plate relief in advance it is possible to introduce certain corrections into calculation that will compensate corresponding wavefront fluctuations and will eliminate speckle noise. Manufacturing of quartz plates with λ/10 – λ/15 flatness is not a big deal when the modern state-of-the-art tools are used, so phase noise will not achieve the level when it could significantly corrupt resulting image.

Errors of TA center positions are equivalent to a combination of errors of the previous types. Really, supposing reconstruction wave having ideal spherical front it could be seen that shift of TA at SWHM plane results in changes of amplitude and phase of coming light wave and in changes of optical paths connecting this TA and image plane points. This is equivalent to certain combination of phase noise and TA size change. Computational simulations performed for different images and optical schemes proved image quality stability for rather big allowed fluctuations of hologram holes positions. In this simulations it was used that modern e-beam lithography systems utilized for SWHM manufacturing provide <20 nm accuracy in TA center positioning.

V. HOLOGRAM POSITIONING INACCURACIES

When placing SWHM into the optical scheme it appears a problem to accurate position its plane relatively to the optical axis. All SWHM displacements results in image distortion. Such shifts could be divided into three types when analyzing possible influence of SWHM shifts on image quality (see Fig. 4):

a) Parallel to calculation plane shifts and rotations around the optical axis

b) Shift along the optical axis, which is perpendicular to calculation plane

c) Rotations around axes which are perpendicular to the optical one.

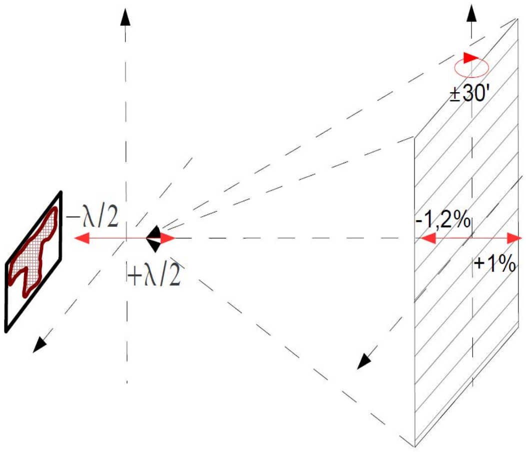

Figure 4. The SWHM positioning errors

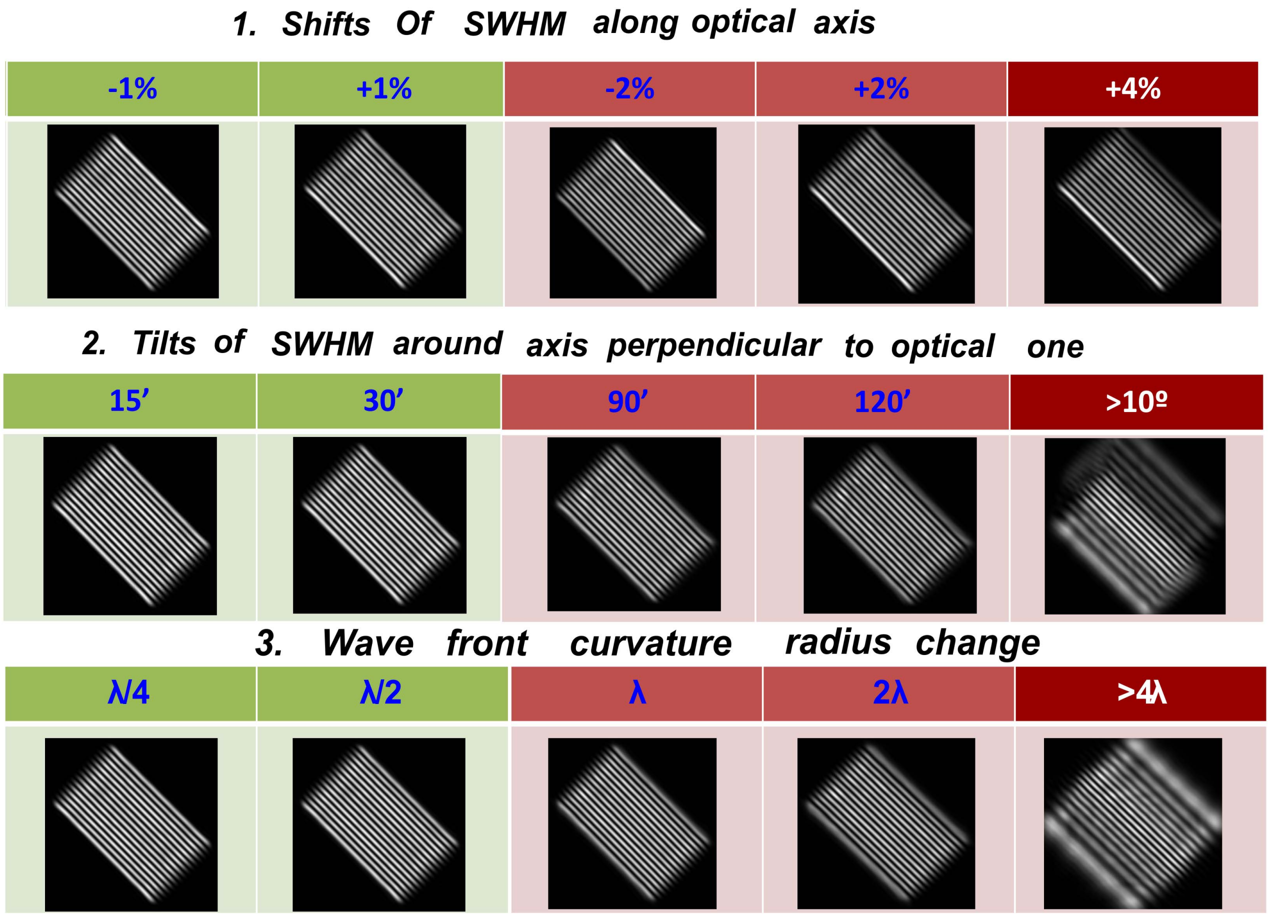

Figure 5. The SWHM positioning errors. Reconstructed aerial images

Minor SWHM shifts inside calculation plane lead to multiplying the function describing the object field by phase factor which always has modulus equal to unity. As far as image intensity is equal to squared modulus of reaching photoresist complex field, such transform does not significantly change image quality. Rotations around the optical axis result in corresponding rotations of image without image quality decrease.

It could be assumed that the 2-nd and the 3-rd type displacements result in distortions that are similar to described above phase and amplitude noises. TAs shift from one reconstruction radiation spherical front to another, forcing optical paths to change. However, it could be noticed that amplitude noise is near proportional to relation of shift value to the distance from image to hologram. In accordance to hologram amplitude noise simulations, which are similar to TA size inaccuracies simulation, the allowable relations of shifts to the calculated distance are up to several percents. It could be shown that phase shifts appearing as a result of such hologram shift are proportional to the value of the hologram shift to the calculated distance ratio. Simulation results confirm these preliminary considerations (Fig. 5). Therefore 1% shifts relatively to the calculated distance are allowable. Image quality remains acceptable in a result of such shifts. Up to 30' rotations around axes perpendicular to the optical axis are also allowable.

Decreasing or increasing distance from hologram to an image results not only in noise but also in image diminishing or magnification. The homothetic transformation center is placed at image plane in a point of reconstruction radiation spherical wave convergence. This effect should be taken into account when matching different IC layers in a process of manufacturing.

VI. ERRORS OF ILLUMINATOR POSITIONING AND MAINTENANCE

Illuminator is the least subjected to fluctuations part of the optical scheme because it is installed once and there is no need to remount it in a process of exposing different photoresist layers. Inaccuracies of reconstruction wave front were simulated by changing convergence point coordinates. Various focus shifts in photoresist plane resulted in the corresponding image shifts. Insignificant topology distortions were observed when distance between the focus and photoresist plane was less than λ/2. Bigger shifts are not allowable. These rather strict requirements appear because focus displacement, which is equivalent to reconstruction radiation source shift, results in inhomogeneous phase shifts of field incoming to SWHM.

These shifts are not compensated in any way, although they change smoothly on the hologram plane. That is, there is change of phase for a wave coming to certain SWHM point. Meanwhile, assuming SWHM is precisely installed at the calculated place, optical paths of diffracted wave rays are not changing. When considering SWHM shifts and rotations simultaneously there are appear phase changes of incoming wave and optical path length changes which to a great extent mutually compensate each other.

VII. CONCLUSION

Computational simulation of distortions of aerial image reconstructed from SWHM shows that image quality is in a great extent tolerant to typical optical scheme perturbations. It turned out that typical fluctuation tolerable limits depend on reconstruction radiation wave length with some coefficient which is proportional to relation of SWHM size to image size. Therefore, large-scale fluctuations of hologram from calculate position and binarized grayness function distortions are allowed. Errors of the modern systems for SWHM manufacturing and positioning are considerably less than the disturbances values critical for image quality. The only exception is phase noise appearing as a result of substrate flatness local deviations. Such SWHM phase part fluctuations are not compensated but they are rather small if such deviations change rather smooth on SWHM surface, what is true for every polished surface. Moreover, such deviations effect could be totally removed if wafer flatness profile is measured and is taken into account in a process of hologram transmission function calculation.

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