Phase-shift at sub-wavelength holographic lithography (SWHL)

Mikhail V. Borisov, Dmitriy A. Chelyubeev, Vitalij V. Chernik, Alexander A. Gavrikov, Dmitriy Yu. Knyazkov, Petr A. Mikheev, Vadim I. Rakhovsky, Alexey S. Shamaev
NANOTECH SWHL, 6-1 Kazarmenny per., Moscow, Russia 109028

ABSTRACT

Authors of the report have been developing sub-wavelength holographic lithography (SWHL) methods of aerial image creation for IC layer topologies for the last several years. Sub-wave holographic masks (SWHM) have a number of substantial advantages in comparison with the traditional masks, which are used in projection photo-microlithography. The main advantage is the tolerance of SWHM to local defects. This tolerance allows considerable reduction of manufacturing environment and post-production verification requirements.

At the report we are also going to consider another important advantage of the SWHL technology. In order to achieve sub-wavelength resolution in this technology it is enough just to alter the number, sizes and positions of transparency areas on the SWHM. There is no need in coating the mask with one- or multi-layer highly-local phase-shifting coat or creating of local phase-shifting structural elements, which is usual for traditional lithography. Introducing of the object wave with the specified phase-shift into the calculation is enough. Our research shows that such approach could be applied to the creation of the test structures as well as to the creation of the real IC layer topologies.

Keywords: sub-wavelength holographic lithography, imaging, phase-shift

1. INTRODUCTION

Masks with phase-shifting domains are used when creating aerial images for IC layers with high spatial resolution. It is possible to achieve $\lambda/2$ resolution on an aerial image when using this technology (here λ is the wavelength of a radiation source). An essential difficulty in the realization of this technology is the necessity to create local areas of phase-shifting coating or phase-shifting structural elements[1] on the mask surface. These areas or structural elements should have sufficiently high spatial resolution, which leads to the use of complex process technologies.

2. SWHL ADVANTAGES AND PECULIARITIES

Authors have been developing SWHL methods of aerial image creation for IC layer topologies for the last several years. Sub-wave holographic masks (SWHM) have a number of substantial advantages in comparison with the traditional masks (PPMM), which are used in projection photo-microlithography. The main advantage is the tolerance of SWHM to local defects. This tolerance allows considerable reduction of manufacturing environment and post-production verification requirements.

High level of tolerance to local defects for sub-wavelength hologram mask could be illustrated by Figure 1. Images reconstructed from a SWHM for a test topology are shown here. Brightness is normalized for the all three images. Without this normalization brightness decreases in proportion to the area which is covered with dust. The test topology consists of 15 strips with $\lambda/2$ width and $\lambda/2$ space between them. These images were obtained with the use of SWHM covered with randomly distributed dust particles with characteristic sizes equal to 1 mkm. At the same time a fraction of total area covered with dust varied from 0% to 98.6% of the area of the whole hologram. Influence of partial darkening of randomly chosen SWHM elementary transmission areas on an image quality was also simulated. As a result, the brightness of reconstructed image decreased in proportion to darkened area, but local defects didn't appear. SWHM construction for such test topology would be discussed late in details.

* rakhvi@gmail.com; phone +7 - 4957552969

28th European Mask and Lithography Conference, edited by Uwe F.W. Behringer, Wilhelm Maurer, Proc. of SPIE Vol. 8352, 83520P · © 2012 SPIE
CCC code: 0277-786X/12/$18 · doi: 10.1117/12.918016

Such high level of image tolerance to local defects apparently allows:

1) to exclude labor-consuming stages of mask control and correction (contemporary technologies of projection mask construction require practically total absence of defects on a mask. Total local defects area S_d on a mask with area S_M is limited by the relation $S_d \leq 10^{-12} S_M$ in according to contemporary requirements. This corresponds to the ratio of a football section area to an area of the State of California. Thus, SWHM appears to be $10^{10} - 10^{11}$ times more tolerable to the local defects influence.

2) to essentially decrease manufacturing environment requirements, substantially decreasing requirements to cleanliness level of rooms serving for SWHM storage and processing.

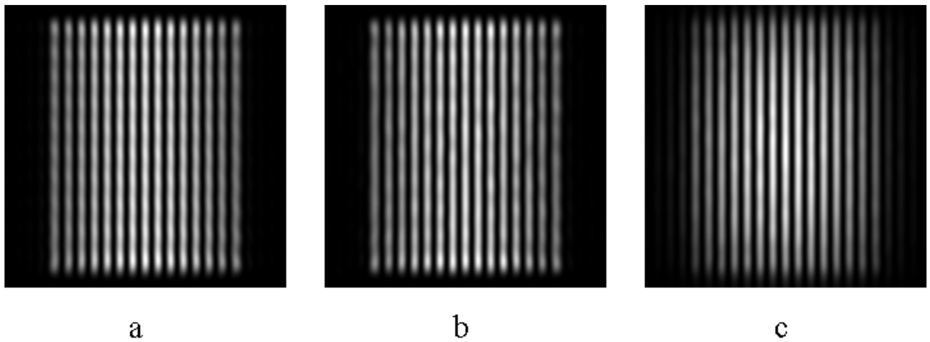

Figure 1. Aerial image reconstructed from SWHM changes as part of SWHM area is covered with random dust. Images a, b and c were reconstructed from SWHM with 0%, 44.8% and 98.6% area dusted correspondingly.

Holographic masks have a number of other advantages. These advantages include practically unlimited service life period and the possibility to illuminate a hologram with a simple optical objective, witch forms an imperfect convergent spherical wave. When calculating hologram transparency function, wavefront aberrations caused by projection system optical elements imperfections could be taken into account by measuring this optical system aberrations and including them into calculation of a pattern of reconstruction wave transparency areas. At the same time it should be mentioned that a SWHM calculation for real IC layer is not simple (but doubtlessly solvable!) mathematic problem, which requires an implication of high-performance computations.

Moreover, one of holographic image creation peculiarities is the presence of so-called zero order diffraction image as well as useful image in the field constructed by a hologram. This zero order diffraction is parasite and doesn't have any information about an aerial image which is being created. A field created by a hologram also contains so-called "conjugate image", which is near to centrally symmetric to useful image when aperture angle is small. Conjugate image brightness doesn't exceed main informative part of an image and moreover its intensity rapidly falls down when moving away from its edge. Thus its intensity is negligibly small at the distance of only several wave lengths from its edge. Therefore it doesn't disturb the informative part of the aerial image, which is being created. However zero order diffraction intensity is several times higher than informative image intensity and so this zero order could substantially disturb useful part of an image in some cases (Figure 2).

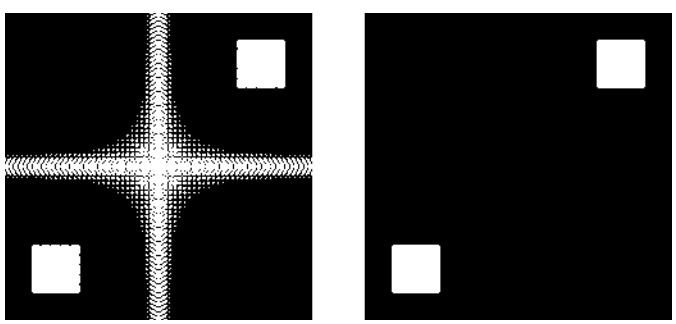

Figure 2. Phase-shifting layer on the hologram suppresses the zero order diffraction.

Authors proposed a method of getting rid of the mentioned parasite image. Exactly, it was determined, that the reconstructed image is practically free from the mentioned above zero diffraction order when transmission function average value for the whole synthesized hologram is equal to zero. However in this case transmission function would be negative at certain hologram domains. In order to manufacture such a hologram this negative values domains should be coated with a phase-shifting layer. This could be technologically realized. Here the domains to be coated have smooth boarders that simplify technological realization of the mentioned above coating.

Moreover, it should be mentioned, that hologram synthesis for real IC layer topology is a complex computational problem demanding the creation of effective algorithms designed for modern computer systems. Authors have developed algorithms for real IC layers holograms synthesis which allow performing the synthesis on the contemporary supercomputer systems in several hours. A SWHM for a topology consisting of 10^{11} simple pixels could be calculated in 3 hours on the MVS-100K JSCC RAS supercomputer. This supercomputer contains 1460 computing nodes.

Hence, the considered approach allows to successfully reduce real technological difficulties of IC manufacturing to computer calculations.

3. PHASE-SHIFT IN THE SWHL

In the current paper, we are going to explore carefully another important advantage of SWHL technology. In order to achieve sub-wavelength resolution in this technology it is enough just to alter the number, sizes and positions of transparency areas on the SWHM. There is no need in coating the mask with one- or multi-layer highly-local phase-shifting coat or creating of local phase-shifting structural elements, which is usual for traditional PPML lithography. Therefore using SWHL allows excluding complex expensive manufacturing processes that are used for creation of local phase-shifting coats or local phase-shifting structural elements on the mask surface in the traditional PPMM technology. The only technology needed for SWHL is the standard electron-beam lithography, which is widely used in traditional PPML at the present time. Thereby using SWHM structure calculation procedure developed by the authors and manufacturing of this structure with the use of the e-beam tool are the only two things needed for creating SWHM that provides phase shift on the aerial image generated at a photoresist.

Combining the described above SWHL technology with double-patterning and immersion allows reaching about $\lambda/8$ resolution on the image at the photoresist. Meanwhile creation and verification costs for such SWHM significantly decrease in comparison with creation and verification costs for traditional projection mask. The detailed explanation of this approach could be found at references[2,3].

Let's consider an example illustrating SWHM creation. Test image consists of 15 parallel strips witch have $\lambda/2$ width and $\lambda/2$ space between them. Traditional PPMM for this image should have 7 phase-shifting layers. In the case of SWHM a large quantity of reconstruction radiation transparent areas should be created by the e-beam lithographer. These areas are identical circles with diameters equal to about 2λ or circles with different diameters varying from 0.7λ to $40\text{-}50\lambda$. Meanwhile neither phase-shifting layers nor phase-shifting structural elements are created on the mask.

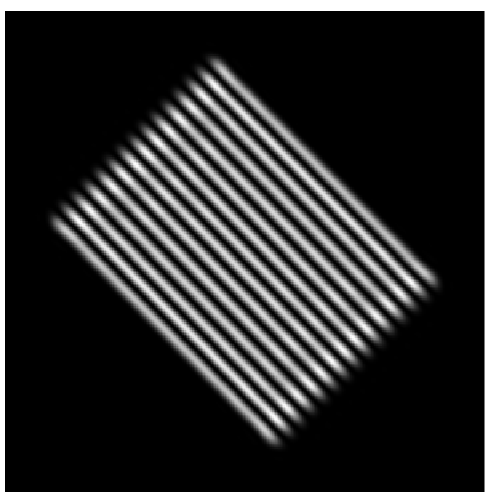

Figure 3. Arial image for 15 strips reconstructed from the SWHM with transparency function shown at Figure 4.

Calculation of positions and sizes of transparency areas is based on the classical Gabor approach with the means of calculation the square of absolute value for the sum of object and reconstruction waves. Let's discuss in more details the specific peculiarities of hologram synthesis of our test image shown at Figure 3.

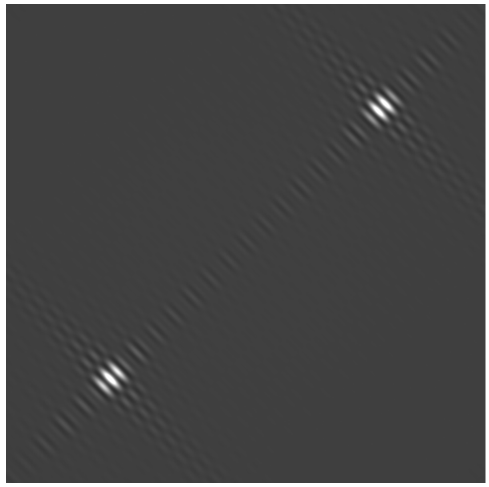

Figure 4. SWHM transparency function for the test image consisting of 15 strips.

It is easy to point out two symmetrical transmission areas on the SWHM (Figure 4). An angle between two segments connecting centers of these hologram transmission areas with an image center is about 60 degrees (Figure 5). If an angular aperture had been substantially less than 30 degrees, these two transmission domains would have not completely appeared on the holographic pattern and the reconstructed image would have been of poor quality.

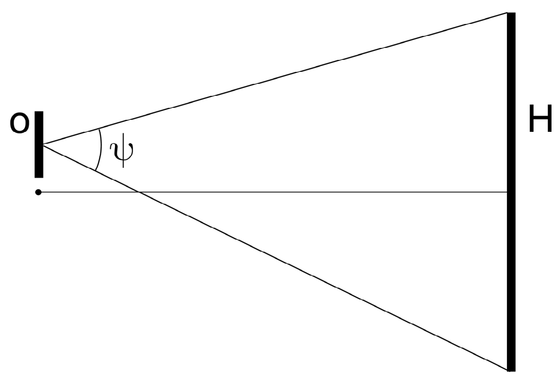

Figure 5. SWHL optical scheme: an object O, hologram H.

High angular aperture is caused by the using of phase contrast. Neighbor strips radiation phases differ by 180º when calculating object field with the use of Gabor method. Therefore, the SWHM calculation (synthesis) seems need to be based on the full system of Maxwell equations instead of prevailing scalar electrodynamic model. Really, in the scalar electrodynamic model, electric and magnetic intensity vectors are assumed to be perpendicular to a direction of light wave propagation. In this case the model is reduced to one scalar wave equation, which specifies a vertical component of electric field intensity. This model is valid only in the case of relatively small aperture angles. Reconstructed image quality was practically the same for SWHM calculated on the basis of scalar model and for SWHM calculated using the full Maxwell equations model while in both cases reconstruction was numerically simulated with the use of complete electrodynamic model. The only difference was image brightness decrease for SWHM created with the use of complete (vector) electrodynamic model.

Simulation of reconstruction based on vector electrodynamic model was carried out on the basis of well-known Stretton-Chu formulae[4]. The other vector model approach was based on ideas of Vladimir N. Seminogov (ILIT RAS, senior researcher). A transmission function for a SWHM calculated by scalar model with the use of Gabor method was closely approximated by very small square domains (holes) which were transparent for reconstruction radiation. Domains density in every small area was equal to the average value of continuous transparency function at this area (Figure 6). Then a reconstruction wave diffraction process was simulated with the use of vector electromagnetic model. A field passed through the every separate hole was calculated on the basis of complete Maxwell equations system. Finally these fields from all the holes were summed up.

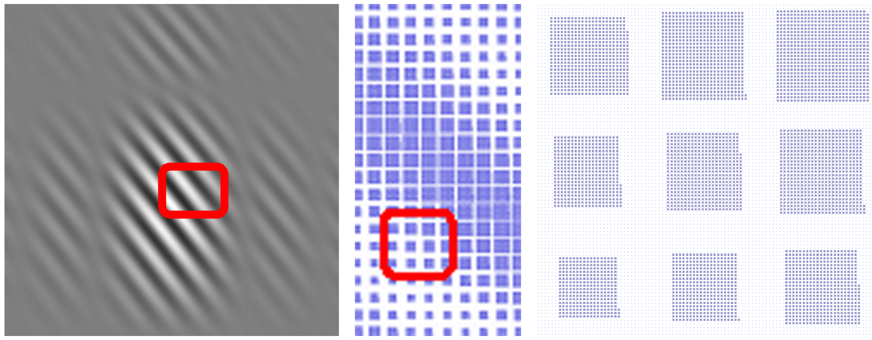

Figure 6. A gray hologram region is binarized by square holes.

Simulation result for reconstruction from the SWHM is shown at Figure 3, while the SWHM itself is shown at Figure 4. Gray color brightness describes the density of transmission domains. In our case an object wave exists only at computations, that is why there is no need to use any technological operations (unlike the case of a traditional PPML) when creating an antiphase illumination from neighbor strips in the process of its modeling.

The last mentioned circumstance becomes of the greatest importance when concerning the problem of SWHM creation for the IC layers topologies having more complex structure than the mentioned above 15 strips test structure.

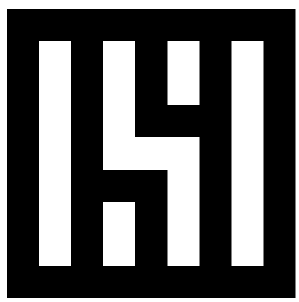

Figure 7. This example of a topology doesn't allow 180 degrees phase shift technology implementation, but allows weak phase-shifting technology, where phase is being shifted by 120 degrees.

Some topology types really don't allow the use of simple 180 degrees phase shift and need the shift of phase for the neighboring elements to be equal to other values, for example, 120 degrees. A simple example of such a topology is shown at Figure 7. Minimal distance between topology elements at Figure 7 is equal to ≈λ/2, where λ is a wavelength of reconstruction radiation. Meanwhile five elements of simple topology shown on Figure 7 could not be painted by two colors in such way that every two elements being at the minimal distance was painted in different colors. Nevertheless it is possible to paint the topology into three colors in such way that every two elements being at the minimal distance was painted in different colors.

Topology elements painted in different colors are assigned with phases 0, 120 and 240 degrees correspondingly, when computing an object field with the use of Gabor method. Then these shifts of phase are used only during SWHM computation. It would be rather difficult to technologically create such phase shifting coatings on a traditional projective mask. In the case of SWHL technology there is no need to create such coatings. It is possible just to use a specific object wave in the computation. This wave should have preliminary specified phaseshifts.

Let's notice that the use of this "weak" phase-shift is not so effective in increasing image quality in comparison with traditional "strong" phase-shift, where shift of phase for the neighbor topology elements is equal to 180 degrees. Nevertheless an application of the discussed above "weak" phase-shift significantly increases an image quality.

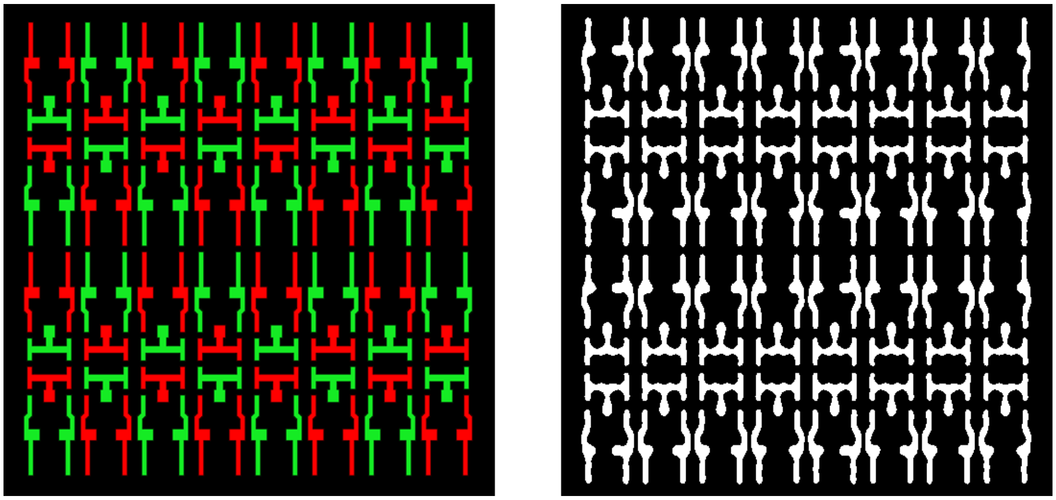

Figure 8. An example of a real IC topology (memory) allows applying “strong” phase-shift technology. Minimal distance between elements is equal to about $\lambda/2$, where λ is a reconstructing radiation wavelength. This topology allows bicoloring in such a way that every two elements having a minimal distance between them are colored with different colors.

An example of a real IC topology of memory elements and its aerial image reconstructed from holographic mask is shown on Figure 8. This example illustrates the case when it is possible to apply the “strong” phase-shift technology.

Here initial topology allows the bicoloring under the conditions mentioned above. Our research shows that such an approach could be applied not only for test structures but also for real IC topology layers manufacturing.

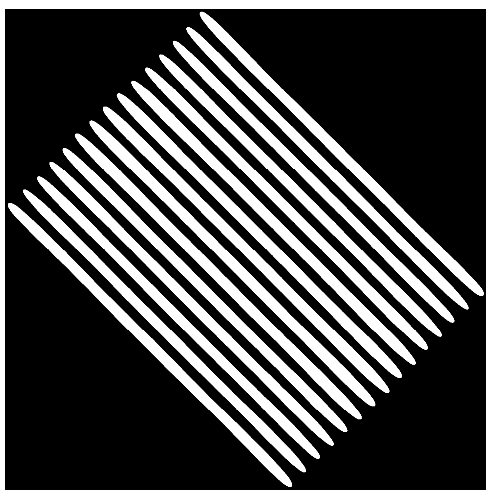

Figure 9. Photoresist free working layer surface domains are marked with white color.

The authors had simulated an influence of created be SWHM electromagnetic field on a photoresist layer with a method and active help of Rodionov I.A. and Gladkih A.A. (SRISA RAS employees). The simulation included a calculation of a standing wave in a photoresist layer, modeling of photoresist chemical structure changing under the influence of this standing wave (the calculation of local concentration of changed by radiation molecules taking into consideration a local radiation intensity), and modeling a process of development of photoresist in alkaline medium. Photoresist free working layer surface domains are show at Figure 9. This is the domains where “exposed” photoresist molecules are being removed during a development.

REFERENCES

[1] Borodovsky, Y., Cheng, W.-H., Schenker, R. and Singh, V. "Pixelated phase mask as novel lithography RET," Proc. SPIE 6924, 0E1-0E14 (2008).
[2] Borisov, M.V., Gavrikov, A.A., Knyazkov D.U., Rakhovskiy, V.I., Chelubeev, D.A. and Shamaev, A.S. "Method of producing holographic images," RF Patent № 2396584 C1 (2009).
[3] Borisov, M.V., Borovikov, V.A., Gavrikov, A.A., Knyazkov, D.Yu., Rakhovskij, V.I., Chelyubeev, D.A. and Shamaev, A.S. "Methods of the development and correction of the quality of holographic images of geometry objects with subwave-size elements," Doklady Physics 55(9), 436-440 (2010).
[4] Stratton, J. A. and Chu, L. J. "Diffraction theory of electromagnetic waves," Phys. Rev. 56, 99-107 (1939).