Experimental verification of Sub-Wavelength Holographic Lithography physical concept for single exposure fabrication of complex structures on planar and non-planar surfaces

Michael V. Borisov, Dmitry A. Chelyubeev, Vitaly V. Chernik, Peter A. Miheev,
Vadim I. Rakhovskii, Alexei S. Shamaev
Nanotech SWHL Ltd., Dübendorf, Switzerland

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-wavelength holographic masks (SWHM) have a number of substantial advantages in comparison with the traditional masks, which are used in projection photo-microlithography. The main advantages: there is no one-to-one correspondence between mask and image elements thus the effect of local mask defects almost completely eliminated [1]; holographic mask may consist of single-tipe elements with typical size many times bigger than projection mask elements [2]; technological methods of image quality optimization can be replaced by virtual routines in the process of the holographic mask calculating, that simplifies mask manufacturing and dramatically reduces the mask cost [3]; imaging via holographic mask does not need the projection lens, that significantly simplifies photolithographic tool and reduces ones cost. Our group developed effective methods of holographic mask synthesis and of aerial images modelling and created software package. This methods and calculation results were verified and reported many times [1-3].

Keywords: lithography, holography, non-planar surface, MEMS

1. INTRODUCTION

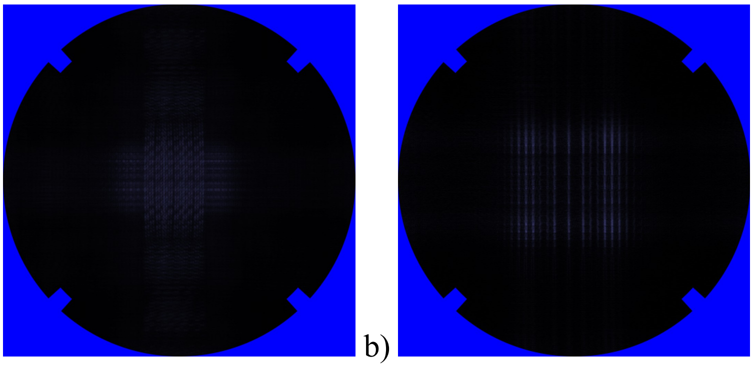
For many modern technologies, we need to deposit complex patterns on non-flat surfaces or produce 3-D patterns. Prevalent MEMS devices, such as pressure sensors, gyroscopes, accelerometers and geomagnetic sensors are nothing but 3-D structures with extremely small critical dimensions and high accuracy of manufacturing. Hybrid lens is another example of non-planar patterns application [4-6]. One of the other major advantages of SWHL compared to projection lithography is the ability to create images of IC and MEMS layers on the photosensitive material deposited on non-planar surface. Thus, using only one exposure you can create images containing sub-wavelength topological elements located on different planes, the distance between which considerably exceeds the depth of focus (DoF) of used optics.

It was necessary to adjust methods of holographic mask synthesis for imaging on non-planar surfaces. Previously used mask synthesis methods for imaging on a plane surface parallel to the mask plane, which based on the calculation of convolutions of matrices using fast Fourier transform, were impossible to use as is for the calculation of the holographic mask that allows you to create images with sub-wave topological elements on non-planar surfaces. However, it has been possible to do this using the method of the image segmentation. The sizes of the segments were chosen so that for any point of the mask each of the segments satisfies the conditions allowing to apply the far zone approximations [7]. In this case, the object field on of the mask surface can be calculated by using of fast Fourier transform for each segment and subsequent summation of fields from all the segments. It was necessary to implement some modifications to the image quality correction methods.

2. EXPERIMENTAL SETUP

2.1 Image topology

For further verification two simple chrome-on-quartz architecture holographic masks (Figure 1) were constructed for 2,5x2,5mm^2 images. The first mask if for flat set of chevrons with decreasing dimensions (Figure 2), the second mask is for image on piecewise flat surface (Figures 3-4)



a) b)

Figure 1. Flat holographic masks transmission distribution: a) for flat image; b) for image on piecewise flat surface. Each mask has simple architecture of perforated opaque chrome layer on quartz substrate. Transmission distribution is implemented by set of transmission zones of square form with varying sizes and with centers in nodes of a uniform rectangular grid. Grid step is 2µm, mask radius is 21.75mm, minimal transmission zone size is 0.75072µm, maximal transmission zone size is 1.9µm.

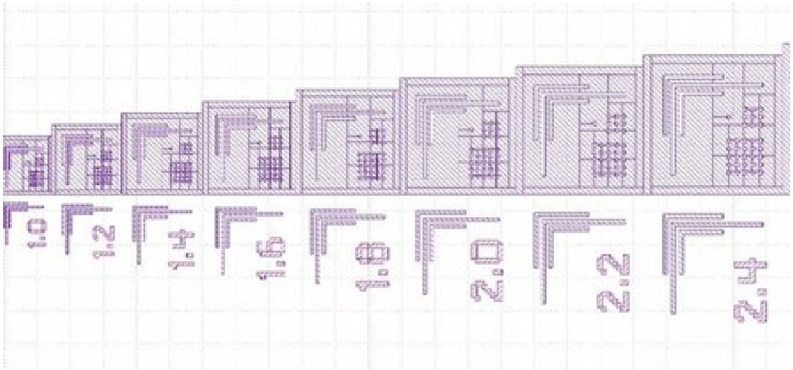


Figure 2. Flat image topology fragment.

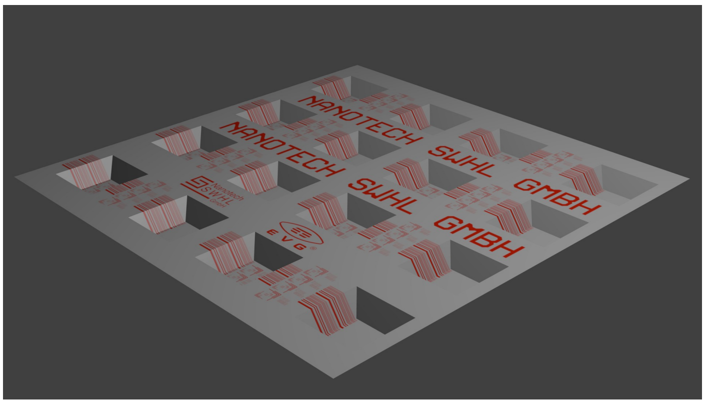


Figure 3. Test topology on piecewise flat surface. The distance between face plane and bottom plane is 100µm, slope angle is 54.74°.

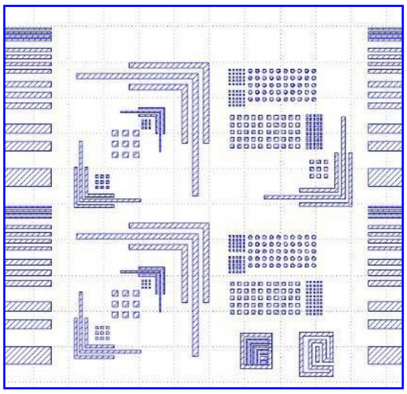


Figure 4. Fragment of test topology on piecewise flat surface. The smallest element size (CD) is 2µm

2.2 Optical setup

He-Cd laser HCL-100V(I) with wavelength of 441,6nm produced by PLASMA JSC were used as light source for masks exposure. The intensity distribution in the beam is essentially uneven with Gaussian distribution, the maximum in the center of the light aperture. The actual intensity at the edge of the mask light aperture is 0.05 from the maximum. This intensity unevenness were taken into account in the mask calculation. The aberration contribution of the plane-parallel mask substrate was also taken into account and neutralized in the process of mask computer synthesis. Zero diffraction order is screened by a field diaphragm located near the image plane. Numerical aperture of optical setup is 0.24.

Control measurements showed that produced masks substrate has a smooth non-parallelism at the level of 0.55λ (on the light aperture of the mask) and a deviation from the calculated thickness by 70µm. Spherical wave front aberration caused by shaping lens in the mask near field is about 0.25λ.

CMOS camera Basler daA2500-14um with 2592x1944 resolution, 2.2x2.2µm^2 pixel size was used for image registration. The image was transferred on the camera through the optical system with an increase of 20x.

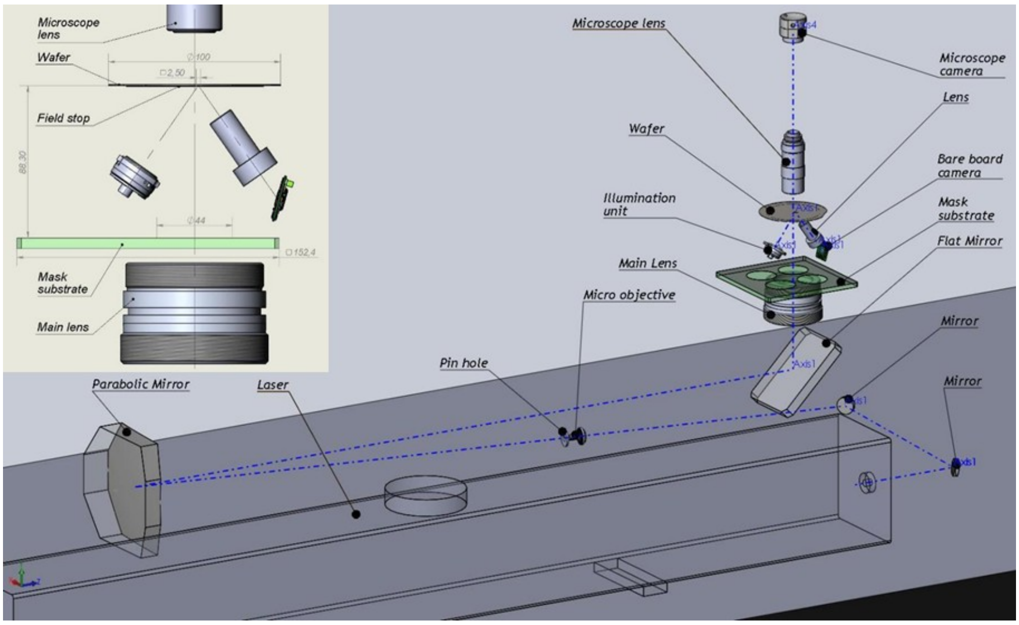


Figure 5. Optical setup.

2.3 Computer simulation

Holograms for described above images and optical setup were synthesized and optimized with software package developed by Nanotech SWHL team. Aerial image and photoresist exposure were modeled before masks were manufactured in order to guarantee the quality of the images. We managed to achieve good image quality with a resolution of near 1µm (Figures 6-7).

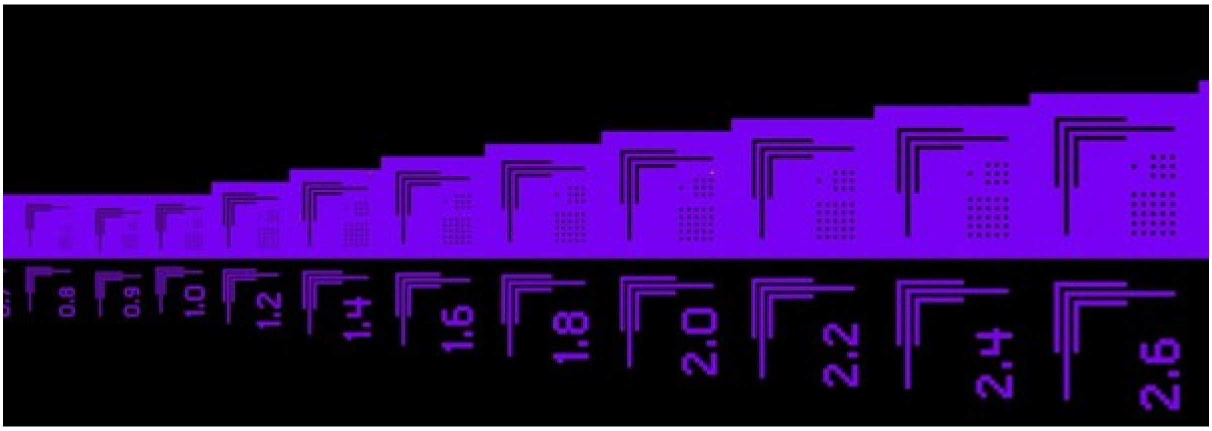


Figure 6. Simulated image of flat set of chevrons with decreasing dimensions.

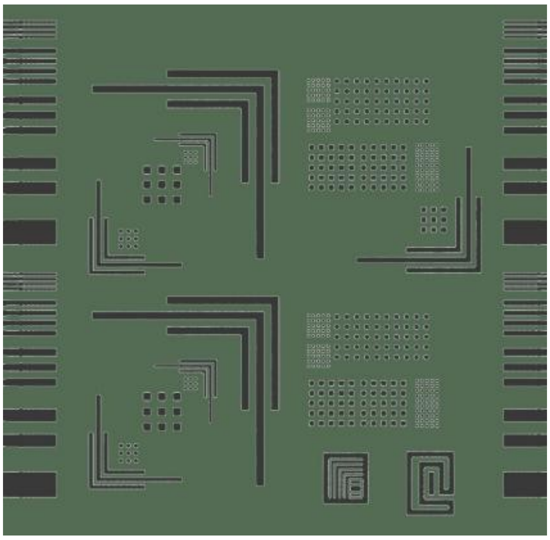
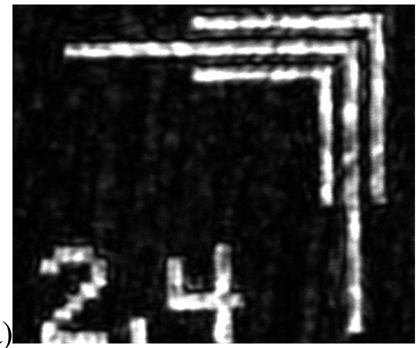


Figure7. Photoresist exposure simulation for fragment of piecewise flat image.

3. RESULTS OF EXPERIMENT

3.1 The first results with noise

Images with regular noise were registered on camera. The noise can be explained by the influence of secondary wave which was reflected from quartz substrate and optical setup elements. The same noise effect was registered on non-flat image (Figure 8). The image quality will be further improved by applying an antireflection coating on quartz substrate.

a) 

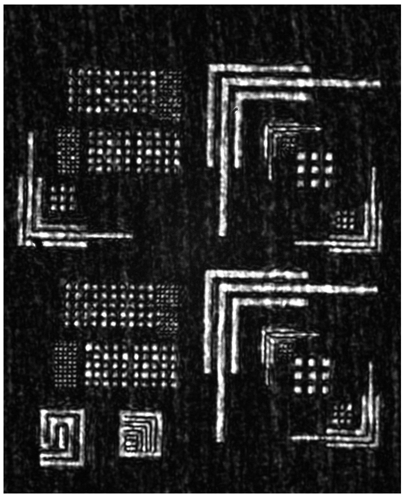
b) 

Figure 8. Fragments of a) flat image (stripes width is 2.4µm); b) piecewise flat image (CD=2 µm) registered on CMOS camera.

3.2 Noise source modeling

One of the supposed sources of noise were secondary reflections from the forming lens. We introduced secondary waves in our simulations and modelled their influence on image quality (Figure 9).

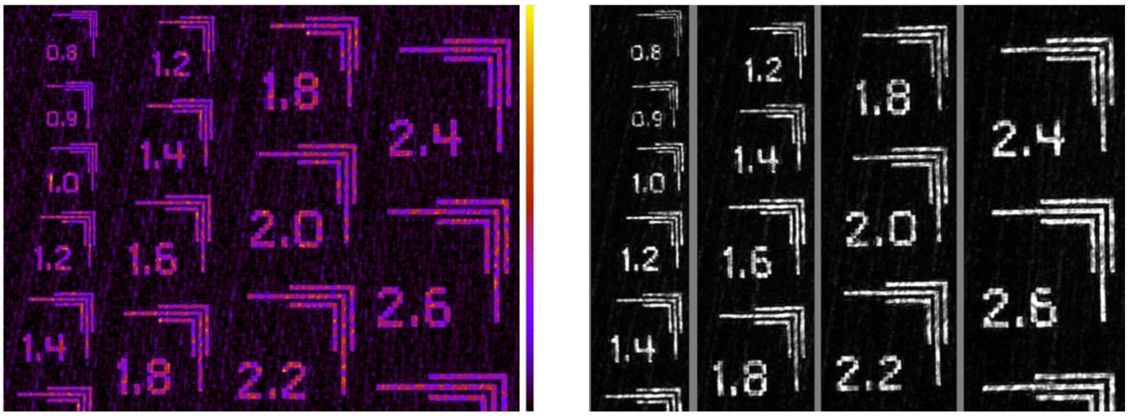


Figure 9. Flat image simulated on computer with secondary wave effect (left) and flat image registered on CMOS camera (right).

3.3 Noise source modeling

To suppress noise from secondary waves we covered all lens from forming system with anti-reflective coating with reflection coefficient value about 0.001% on the wavelength 441.6nm. Forming lens system was returned in optical stand and image quality improved significantly (Figure 10).

4. CONCLUSIONS

Our research shows that SWHL approach could be applied to the creation of the test structures as well as to the creation of the real IC layer topologies. Sub-Wavelength Holographic Lithography technology has the ability to become cheap and simple alternative to DUV lithography in MEMS fabrication. The main factor making SWHL application more advantageous is the possibility to write 3-D object information on a flat holographic mask. Therefore, there is no need in multiple exposures since it is possible to obtain high quality light image on a complex surface. Moreover, there is no restriction on NA value because aerial image does not necessarily belong to the focal plane neighborhood. High NA optics applicability not only makes SWHL technology cheaper but also allows to improve image quality and to decrease pattern critical dimension without wavelength changes. Other SWHL technology advantages are virtual phase-shift, extremely high tolerance to local mask defects, simple optical scheme. The group of authors have developed mathematical models and fast calculation algorithms for flat hologram masks generation and aerial image simulation for complex planar and 3-D patterns of considerable size. Numerical and nature experiments were carried out for technology verification.

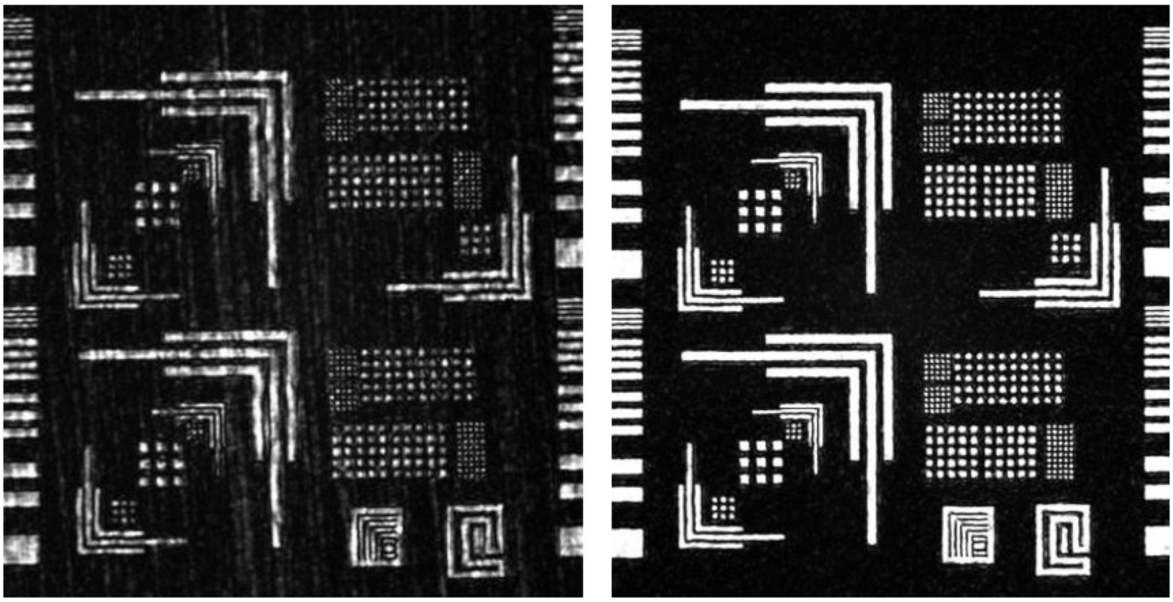


Figure 10. . Fragments of piecewise flat image registered on CMOS camera without AR coating (left) and with it (right).

One of further areas of research is the implementation of holographic methods in optical scheme with dynamically controlled spatial light modulator (SLM) used as holographic mask. In case of successful research it will be possible to use one liquid crystal display (LCD) or set of displays instead of manufacturing expensive mask or set of masks. It must be said that pixel size in modern LCD is relatively large. The use of displays with such elements in case of projection lithography will require reducing lens system with much higher reduction factor, than used before, and we do not know about cases of dynamic mask usage in projection lithography of images with sub-wavelength resolution. Our preliminary calculations showed that it is possible to use LCD with pixel size of about 10μm to produce holographic images with sub-wavelength resolution. Moreover, because of insensitivity of holographic image quality to local mask defects, auxiliary elements of LCD, such as frames and connectors, will not affect image quality.

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