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Self-Aligned Single-Exposure Deep X-ray Lithography

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Abstract. The method of deep X-ray lithography has been developed, which allows the formation of self-aligned microstructures. Examples of microstructures are presented.

INTRODUCTION

Deep x-ray lithography enables micron-precision formation of 3D microstructures of up to several millimeters in each of the three dimensions [1, 2]. Elements made using the LIGA technology often occur in instruments (spectrophotometer). Since instruments of various types consist as a rule of several interactive elements, they are laid out sequentially using various techniques to ensure the required positioning precision, the so-called combined LIGA technology [1]. However, it is often possible to improve the positioning precision to submicron values or to form several elements of device in one technological step, by means of successive structuring exposures. In so doing, the hidden images created in the resist layer are positioned with a higher precision, and the need for assembly disappears, as demonstrated in the manufacture of the refractive 2D LIGA x-ray lens [3]. The present work reports about the further development of the method to form combined elements.

MASK TRANSMISSION VARIATION

Self-aligned single exposure from planar side

When the deep x-ray lithography is used to produce microstructures with high aspect ratio, the material of the microstructures must be enough mechanically rigid to prevent the microstructures from curving or falling [4] in the course of liquid development and mechanical loading during operation. Such critical design elements include refractive structures of mosaic refractive x-ray lens [5].

This problem can be solved using an increased dose of x- rays deposited during microstructuring since, as shown by the IR spectra of SU-8 (Fig. 1), when the dose grows, so do the number of crosslinks of ether groups and the rigidity of the polymer [6,7]. Therefore, as the simplest implementation of self-aligned patterning, in this section we discuss a local increase in the dose of x-rays during formation of separately standing structures with a high aspect ratio. In this case, the dose of primary radiation in large exposed areas with denser arrangement of microstructures can be, on the contrary, reduced, compensated for by the background of the secondarily and scattered radiation arising in the x-ray resist layer, substrate, and x-ray mask. More exactly, for a mosaic lens, in a distance from the axis of symmetry of the lens, there arise of insoluble resist residuals in the geometrical shadow.

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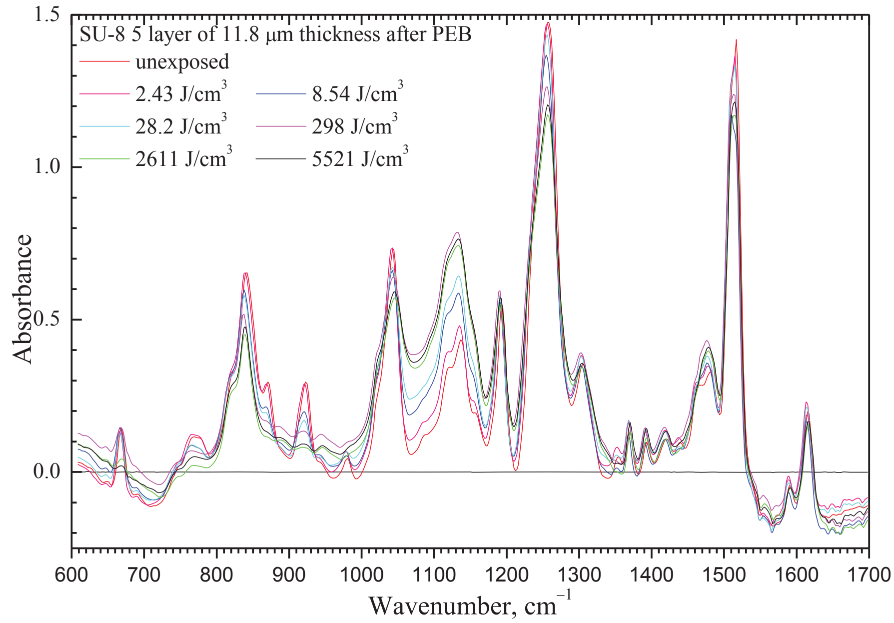

FIGURE 1. Measured absorption spectra of SU-8 for different doses of absorbed radiation.

To meet the above conditions of exposure, we applied a stepped attenuator of x-ray beam, the thickness of which increases with the distance from the optical axis of the x-ray lens. The attenuator, made of polyimide film 100 μm thick, was installed in front of the x-ray mask, as shown in Fig. 2.

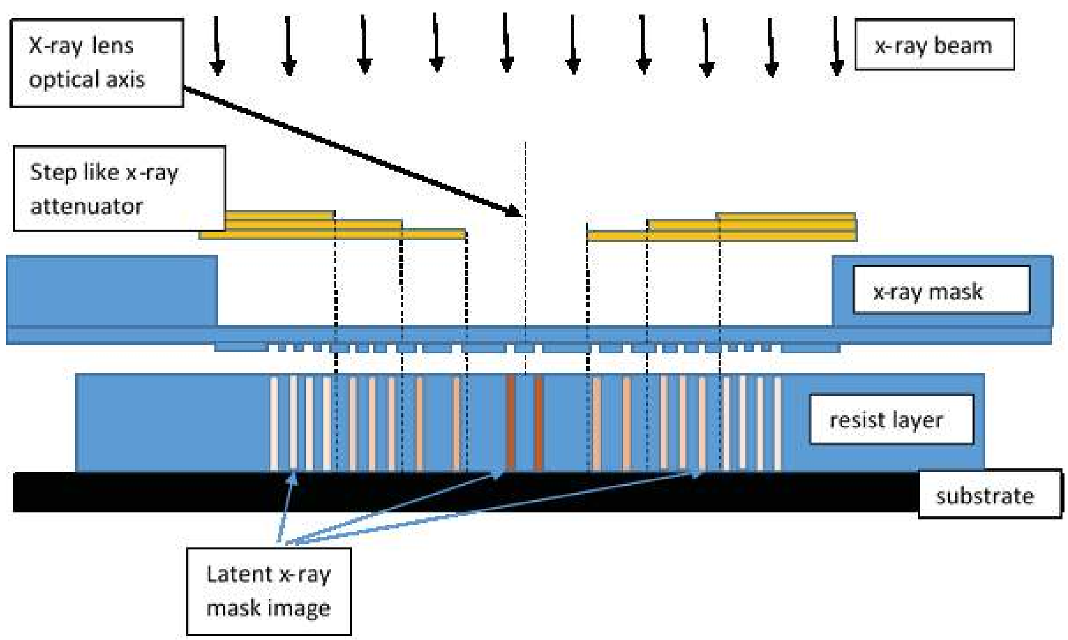

FIGURE 2. Arrangement of distributed absorber.

In this case, there are fixed parameters for scanning across x-ray are used, as well as terms of subsequent liquid development. The completed structures of the x-ray lens are shown in Fig. 3. Individual microstructures stand upright; detailed studies confirm absence of resist residuals between the structures.

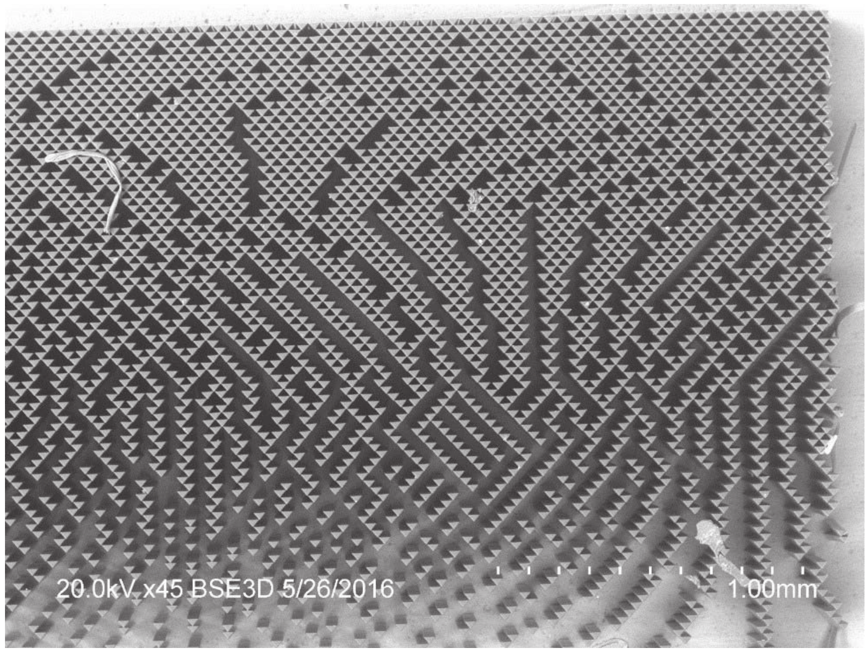

FIGURE 3. REM image of fragment of x-ray mosaic lens. At optical axis, dose is 90 J/cm^3; that at lens periphery is 40 J/cm^3.

Self-aligned single exposure from backside

Deep x-ray lithography offers varying not only the lateral dimensions of microstructures but also the third dimension: their height or depths. Variation of the third dimension leads to new benefits of the above-mentioned patterning technique as compared with other lithographic approaches. The height can be varied by means of change in the dose with a distributed absorber. The threshold dose in the characteristic curve of the resist SU-8 corresponds to occurrence of insoluble 3D polymer network in the pre-polymer system and can be reached at a certain distance from the substrate in the layer.

To implement such the technique, the irradiation through an x-ray mask is carried out through the substrate, as shown in Fig. 4.

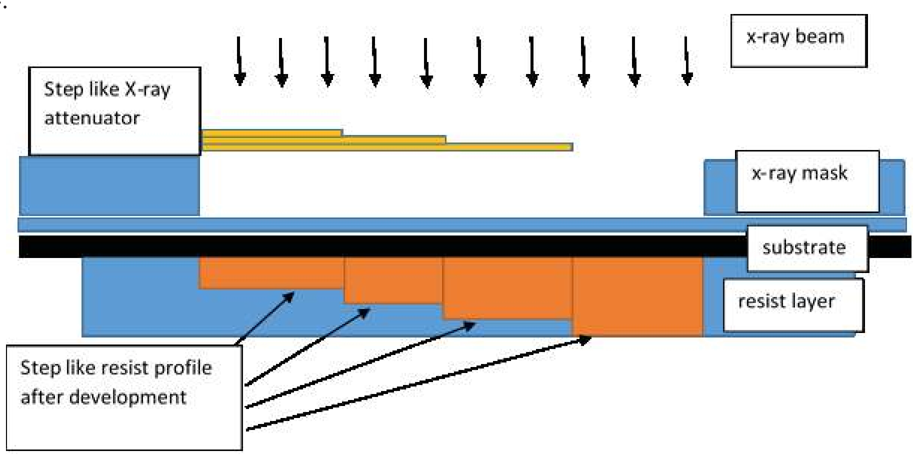

FIGURE 4. Scheme of using stepped absorber at irradiation of SU-8 resist layer through substrate.

Figure 5 represents the result of using a distributed absorber for single-exposure manufacturing of a multilevel refractive x-ray lens developed in [8]. In each of the three levels of the lens, different numbers of refractive microstructures with the same parabolic profile are formed. In accordance with the x-ray refraction law, such a lens focuses in one plane photons with three different energies, which can be generated by a broad-band radiation source.

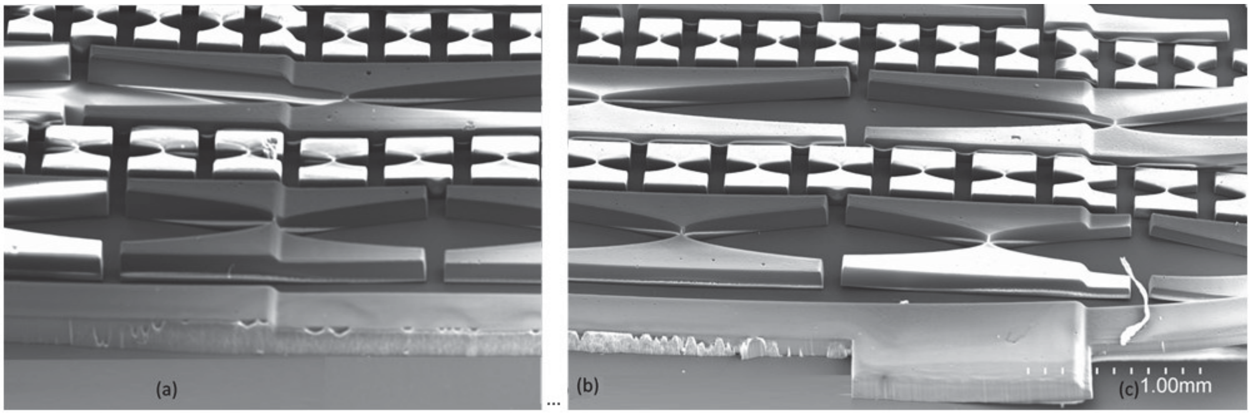

FIGURE 5. REM images of microstructures of refractive x-ray lens with parabolic cylinder profile. Microstructure height: a) 350 um; b) 250 um; c) 150 um.

The focal distance of refractive lens length

$$F = \frac{R}{2N\delta}, \quad (1)$$

where N is the number of microstructures in the refractive lens, R is the radius of curvature of the refractive (parabolic) profile, and $\delta(E)$ is the refractive index decrement, which depends on the photon energy. Thus, for each lens to concentrate photons of a selected energy in a focal plane common to all lenses, it is necessary that $N_1\delta(E_1) = N_2\delta(E_2) = N_3\delta(E_3)$ at the same curvature radius.

Such a lens is of interest for the fluorescence analysis technique with several focused microbeams of x-rays with topical photon energies. Fluxes of x-rays of fixed energies can be generated by an undulator where fluxes of quanta with various energies are separated with a set spacing, which can be taken into account in the manufacture of the refractive microstructures of the x-ray lens.

SELF-ALIGNED SINGLE EXPOSURE BY MEANS OF SPLITTING THE INITIAL X-RAY BEAM

A characteristic feature of deep x-ray lithography is the relatively large thickness of the x-ray absorbing pattern on the x-ray mask. It can be as thick as tens and hundreds of micrometers [1]. This factor can be used to generate during the x-ray exposure a second beam, reflected or refracted by the sidewall relative to the primary beam. In particular, the reflecting properties of sidewall are generally used in photolithography to reduce the interference effects at the edges of mask parts, when their absorption is low [9].

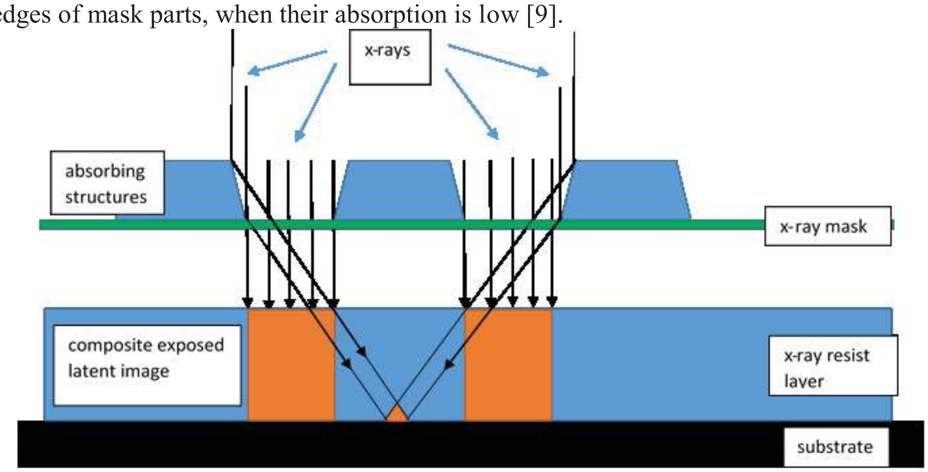

FIGURE 6. Patterning scheme using sidewall reflection. Beams reflected from side walls of various absorbing structures on x-ray mask provide total dose sufficient to reproduce details.

The maximum angle of sidewall inclination in the microstructures of the absorbing pattern at the exposure of resistive material in a wide energy range E can be estimated from the following expression:

$$\vartheta = \frac{\int_0^\infty \sqrt{2\delta(E)} I(E)\mu(E)\exp(-\mu(E)d)R(E)dE}{\int_0^\infty I(E)\mu(E)exp(-\mu(E)d)R(E)dE}, \quad (2)$$

Here I(E) is the x-ray power on the surface of the resistive layer, R(E) is the spectral reflectance of the sidewall, μ is the linear absorption coefficient of the resist, δ is the refractive index decrement of the absorber material on the x-ray mask, and d is the thickness of the resist layer.

A material with a high refractive index decrement, e.g., gold, which is commonly used to transfer the absorber pattern to the x-ray mask, enables creation of a reflective element with high reflectivity at small of grazing angles.

As a result, a pattern with microstructures having a lateral dimension corresponding to the width of the inclined sidewall can be formed.

Since the reflection coefficient is less than one, the dose in the resist is relatively low. To increase the dose, one can use multiple beams reflected from the sidewalls of various structures on the x-ray mask, as shown in Fig. 6: the doses accumulate in one area of the pattern, although the lateral dimension remains small. It should be noted that this method is sensitive to the gap between the x-ray mask and the resist layer, and the maximum dose can be achieved within a narrow range of the gap values. Outside this range, single doses do not cause any noticeable effect.

After metallization, the resulting array of needle like microstructures, as shown in Fig. 7, can be used for auto-electron emission, of which narrow angular distribution of the electron beam is typical.

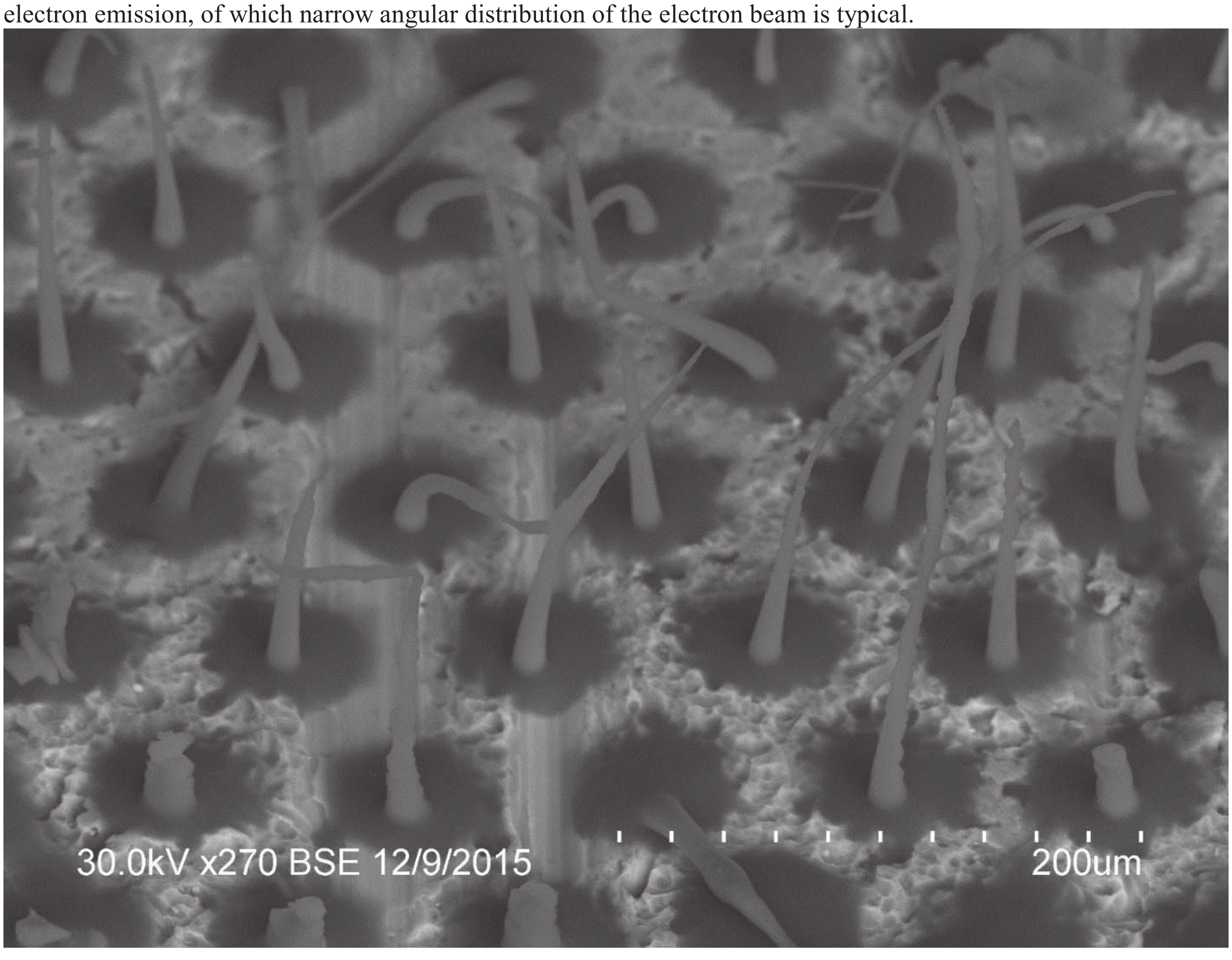

FIGURE 7. Needle like microstructures on bottom of the resist layer, produced by the intersection of splitted X-rays

This is a specific method of forming structures, applied only in x-ray lithography.

CONCLUSIONS

The paper presents the further development of the deep x-ray lithography method in relation to formation of combined microstructures with a high aspect ratio. Dose variation through the use of attenuators of different thicknesses and splitting of the structuring x-ray beam make it possible to impart new properties to the resulting microstructures.

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