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Fabrication of microlens arrays and planar photonic crystals using thermal amplification of resist

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Abstract. Thermal amplification of resist is a possible method of increasing the throughput of e-beam lithography. It is based on chain reaction of resist depolymerization, which takes place during the exposure of positive resist at temperature, higher than its glass transition temperature. Thermal amplification of resist is a bit similar to chemical amplification of resist, but it can be controlled by varying the temperature of specimen. Thermal amplification of resist could significantly simplify the formation of variety optoelectronic and photonic structures. In this research, we discussed possible formation of microlens arrays and planar photonic crystals using thermal amplification of resist. We also discussed primary and secondary electron scattering events influence on the resolution of e-beam lithography with thermal amplification of resist.

1. Introduction

Microlens arrays and planar photonic crystals are widely used in variety of devices [1], such as components of digital optical processors [2], systems of image formation [3], optical communication systems [4], confocal microscopy devices [5], sharp focusing systems [6] and refractive index sensing devices [7]. However, the formation technology of these structures in some cases appears to be sophisticated and poorly controlled. Apparently, the formation technology could be simplified significantly by using e-beam lithography with thermal amplification of resist. This method, based on dry e-beam etching of resist (DEBER), leads to significant increase of the e-beam lithography throughput and allows forming specific well-rounded structures.

2. Dry e-beam etching of resist

Dry e-beam etching of resist (DEBER) is based on e-beam-stimulated chain reaction of depolymerization, which takes places in polymer resist during the exposure at temperature of resist glass transition or higher. Volatile monomers, producing in this reaction leave the etching region.
during the exposure. Various positive resist could be used in this method, such as PMMA, other poly-
methacrylates, poly-α-methylsterene and others.

DEBER allows increasing the sensitivity of PMMA in e-beam lithography process by a factor of
10-300, compared to “wet” e-beam lithography. This also allows formation of spatial 3D-structures
with high vertical resolution (up to 1 nm) and low surface roughness. The specific feature of this
method is well-rounded shape of obtained structures. The disadvantages of this method are poor lateral
resolution (100-150 nm), low image contrast (0.7-1.5). The structures obtained by DEBER are
presented in Fig. 1. There is also more detailed description of DEBER [8].

Figure 1. Continuous structure with rounded relief and nearly sinusoidal profile, obtained by exposure
“in frame” at 125 °С in Camscan S4 electron microscope. Frame size is 2×2.6 mm. Electron initial
energy is 20 keV; Resist initial thickness is 80 nm. Topography and 3D image for average frame dose
is 0.1 μC/cm² (a, b); 3D image and structure cross-section for average dose 0.5 μC/cm² (c, d).

3. Simulation of e-beam etching of resist
For the simulation of electron tracks in PMMA/Si system “direct” Monte Carlo method is applied [9].
In this method, all the dominant processes (elastic scattering, excitation, ionization and secondary
electron generation for E < 20 keV [10]) are simulated separately. Cross sections of elastic events are
obtained from models, based on Dirac equation with Moliere’s screening parameter, and are
interpolated into low energy region (up to 10 eV). Inelastic events cross sections are calculated from
Moller theory and Williams-Weizsacker approximation [11]. Energy loss for inelastic processes is
obtained from Bethe theory modifications [12]. This data is presented in study EPDL97 database of
the Lawrence Livermore National Laboratory [13]. The parameters, mentioned above, also allow
simulation of the tracks of secondary electrons, appearing in ionization processes, based on cross
sections of ionization events at different atom subshells, binding energies and energy and momentum
conservation laws (Fig. 2).

Each interaction between electron and PMMA atoms is determined with the set of random
numbers. The first random number (μ₁) is required for determination of the type of PMMA
((C₃H₂O₈)n) atom, which provides a scattering potential. The second random number (μ₂) allows
specification of the interaction – elastic scattering, ionization or excitation. These two procedures are
based on total cross sections for PMMA atoms and partial cross sections of the processes mentioned
above. We use the third random number (μ₃) to calculate the distance to the next collision point (Δs)
using formula Δs = -λ ln(μ₃), where λ represents the mean free path determined with the total
interaction cross section and density of the material [14]. In case of elastic scattering, two additional
random numbers are generated to determine the azimuth and polar angle of the direction to the new
collision point [13, 14, 15]. In case of ionization, one additional random number is generated to determine secondary electron energy, using spectra of secondary electron from each subshell.

**Figure 2.** (a) Electron track in PMMA, obtained by Direct Monte Carlo algorithm, considering elastic scattering, excitations, ionization events and secondary electron generation; (b) distribution of inelastic interaction between electrons and PMMA atoms, obtained by Direct Monte Carlo algorithm for 20 keV electrons in PMMA/Si structure with PMMA layer width of 900 nm.

4. Planar photonic crystals
Thermal amplification of resist could be used for formation of binary gratings and planar photonic crystals. The structure from Fig. 3 was obtained in PMMA with thermal amplification of resist in e-beam lithography by exposure in series of perpendicular lines. There is asymmetry of structure elements due to difference in line exposure conditions. The well-rounded shape of structure elements could lower the structure efficiency, which is a drawback of the method.

**Figure 3.** (a) 3D reconstruction based on AFM image of the structure, obtained in PMMA with e-beam lithography with thermal amplification of resist by exposure in series of perpendicular lines; (b) the profile of structure element.

5. Microlens arrays
In this research, for the first time, thermal amplification of resist is considered to be used for formation of microlenses and microlens arrays. It could be an alternative to common methods of microlens arrays fabrication, such as fabrication by melting photoresist due to several advantages. First, thermal amplification of resist in e-beam lithography provides faster process with fewer stages. There is also theoretically no limitations for focal and aspect ratios for produced microlenses and lower resist transparency reduction due to lower process temperature (125 °C in comparison with 160 °C) [16]. The profile obtained in resist by e-beam lithography with thermal amplification of resist could be also transferred to Si of W in ICP reactor [17]. This technique allows formation of negative molds for further replication.

Microlens arrays were formed in Ultra-55 electron microscope at 128 °C (Fig. 4). The spherical microlens form have been achieved. The exposure process also changes the resist profile around microlenses, which could be explained by monomer redeposition. The etching regimes study is
required for the reduction of this effect. The diameter of obtained microlenses is around 300 nm. Microlenses coalesce together if the distance between them is lower than 750 nm.

![AFM image of trench and microlens array, obtained by e-beam lithography with thermal amplification of resist with different exposure conditions; (b) microlens profile with parabolic approximation.](image)

**Figure 4.** (a) AFM image of trench and microlens array, obtained by e-beam lithography with thermal amplification of resist with different exposure conditions; (b) microlens profile with parabolic approximation.

6. **Primary and secondary electron scattering events influence on the resolution of e-beam lithography with thermal amplification of resist**

Because of the elastic and inelastic scattering, primary and secondary electrons could find the way to the distant regions of the resist layer. As it has been mentioned, there is a high resist sensitivity in the DEBER process and energy of electrons can be as low as 10 eV, so primary and secondary electron scattering could potentially lead to the trench broadening.

In our research, we have applied Direct Monte-Carlo algorithm (section 3) for the simulation of the primary and secondary electron tracks in PMMA/Si structure. This allowed us to estimate the possible trench broadening caused by these processes. At this stage, our calculations are based on three general assumptions:

- The exposure dose is proportional to the exposure time
- The exposure dose is proportional to the number of the interaction events between primary electrons and PMMA molecules
- There is no resist layer thickness reduction during the exposure

The results obtained by the simulation of 80 000 electrons from two beams with different diameters (5 nm and 200 nm, initial energy is 20 keV) were compared with the experimental results obtained using Ultra-55 and Camscan S4 microscopes for the 80 nm PMMA/Si etching at 116 °C (Fig. 5)[17]. Due to the well-rounded trench shape, the edges of etching region were determined as a coordinates corresponding to the minimum detectable etching depth (~2% thickness loss with respect to the maximum etching depth). Determined by this criterion, the width of etching region comprised 500 nm for Ultra-55 and 3000 nm for Camscan S4 microscopes.

In the Fig. 6, there are DEBER kinetic curves for PMMA with 80 nm initial thickness for Ultra-55 and Camscan S4 microscopes measured at 116 °C. For Ultra-55, the 2% thickness loss and maximum measured etching depth correspond to 0.08 s (T2%) and 16 s (Tmax), respectively. For Camscan S4, the 2% thickness loss and maximum measured etching depth correspond to 0.1 μC/cm² (D2%) and 1.3 μC/cm² (Dmax), respectively. Taking into account the assumed proportionality between exposure dose and the exposure time, we determine that the ratio of exposure doses (the ratio of D2% to Dmax, which is equal to the ratio of T2% to Tmax) is 0.005 for Ultra-55 and 0.077 for Camscan S4.

Taking into account our second and third assumptions (the exposure dose is proportional to the number of the interaction events between primary electrons and PMMA atoms; there is no resist layer thickness reduction during the exposure), we can calculate the width of the etching region, which is caused by primary electron scattering. In the Fig. 7, there are spatial distributions of the number of interaction events between primary electrons and PMMA atoms obtained from the simulation for 5 nm
and 200 nm beams, where $N_{\text{norm}}$ correspond to the interaction events number normalized to the maximum interaction events number.

Figure 5. AFM scans of PMMA layer profile (red curves) on Si after etching. The structures were obtained using Ultra-55 (a)) and Camscan S4 (b)) microscopes. The initial thickness of PMMA layer is 80 nm, the blue line corresponds to maximum etching depth. The edges of etching region are shown by green arrows.

Figure 6. DEBER kinetic curves for PMMA: normalized “etching depth vs. exposure dose or exposure time” dependence; initial PMMA thickness is 80 nm; exposure at 116 °C in Ultra-55 (a)) and Camscan S4 (b)).

Figure 7. Spatial distributions of the number of interaction events between primary electrons and PMMA atoms for 5 nm (a)) and 200 nm (b)) beam obtained from the simulation. $N_{\text{norm}}$ correspond to the interaction events number normalized to the maximum interaction events number.

For the estimation of the etching region width, caused by primary electron scattering, we require 0.005 and 0.077 $N_{\text{norm}}$ values for the distributions obtained for 5 nm and 200 nm beams, respectively. The region widths obtained are 15 nm for 5 nm beam and 300 nm for 200 nm beam, which could not be the reason for trench broadening observed in the experiment (500 nm for Ultra-55 and 3000 nm for Camscan S4 microscopes). Therefore, we could hardly explain the trench broadening observed by the primary electron scattering. Other mechanisms that may lead to resolution limitation [18] are expected to have a major impact on trench broadening.

7. Conclusion
In this research, there is presented the microlens arrays and planar photonic crystals obtained by thermal amplification of resist during e-beam exposure of resist. The fabrication of structures with

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certain profile requires the analysis of process parameters influence on monomer redeposition and structure profile. The analysis of primary and secondary electron scattering influence on trench shape and lateral resolution of the method is carried out. The contribution of primary and secondary electron scattering events into trench shape appeared to be quite low, so other processes should be studied – monomer diffusion, chain transfer, resist redistribution and others.

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