Dry e-beam etching of resist for optics

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Abstract. Method of dry e-beam etching of resist (DEBER) is described. It appears that the method could be extremely useful for formation of wide range of structures for optics and optoelectronics. It is relatively simple to form diffraction or binary gratings, some diffractive optical elements (DOE), 3D structures or planar photonic crystals. Method could be realised in any focused e-beam induced process (FEBIP) system or in e-beam lithographer with minor modifications. DEBER method is significantly more productive than standard or grayscale e-beam lithography. Typical exposure time for 3x3.9 mm^2 area is about 10-100 s. Examples of structures formed by the DEBER method that could be used in optoelectronics are presented.

1. Introduction

Dry electron beam etching of resist (DEBER) proposed by Bruk et. al. [1, 2] could be used for formation of wide range of optical or optoelectronic structures. The method is based on the chain depolymerization reaction, which takes place in the polymer resists during e-beam exposure at the glass-transition or higher temperatures. The volatile reaction products (monomers) are pumped out during exposure.

The method provides quite simple way for formation of well-rounded or 3D structures. In some cases it could be much more flexible than usual methods, in others it could be more productive or convenient.

In this paper we compare DEBER method with usual formation techniques for diffraction or binary gratings, some diffractive optical elements (DOE), 3D structures or planar photonic crystals. Benefits and drawbacks are analyzed.

2. Dry e-beam etching of resist

The DEBER method is based on the chain depolymerization reaction which takes place in the polymer resists during e-beam exposure at the glass-transition or higher temperatures. Volatile reaction products (monomers) are pumped out during exposure (figure 1). Various resists that could be effectively decomposed to monomer under these conditions can be used in the method (poly(methyl methacrylate), poly-α-methylstyrene, polymethyl isopropenyl ketone etc.).

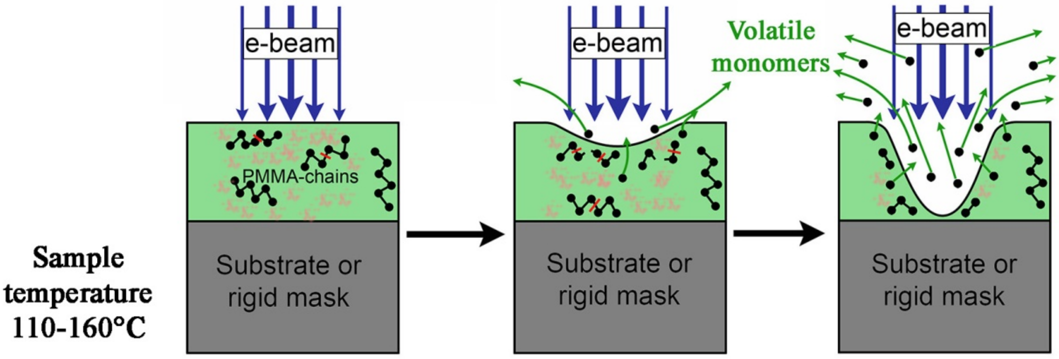

Figure 1. Dry e-beam etching of resist process scheme.

In the DEBER method at a temperature higher than glass-transition temperatures e-beam stimulated chain depolymerization reaction takes place. In this process polymer bonds are broken during e-beam exposure. As a result molecules of terminal macroradicals are formed. These macroradicals at increased temperatures split off monomer molecules one by one with “zipper” mechanism [2, 3]. Lots of monomer molecules are evacuated during exposure. The process is faster at higher temperatures. The relief (trenches or holes) formation is defined by appearance in the exposed region free space due to evacuation of volatile monomers and polymer relaxation as affected by surface tension. Well-rounded shape of the structures is determined by a specific form of the etching kinetic curves of DEBER method [4].

PMMA sensitivity to e-beam in the DEBER method is about 100 times higher than that in the standard “wet” e-beam lithography process. Because of high vertical resolution (about 1 nm) the metod could be used for high-precision 3D structuring. On the other hand DEBER lateral resolution (about 100 nm) and contrast (0.7 – 1.5) are rather low.

DEBER process could be implemented in some scanning electron microscopes (SEM), e-beam lithography or focused e-beam induced process (FEBIP) systems. Most of the systems require minor modifications for it.

It is possible to transfer relief after DEBER process from the resist to the silicon or fused silica substrate or to the metal mask [4].

3. Diffraction gratings

Three main technologies are used for diffraction grating formation: ruling, holographic technology and replication [5]. Master grating for replication could be obtained by ruling, holographic or DEBER method. Ruling is a complex and low-productive process but it provides the grating of the highest efficiency. Moreover very large grating can be obtained by ruling. On the other hand light scattering could be relatively high for ruled gratings.

Holographic gratings have sinusoidal shape. Their efficiency could be high for the radiation of some wavelength range. Holographic gratings may offer advantages to spectroscopic systems in which light scattered from the grating surface is performance-limiting. Holographic method is high-productive. Only some special resists could be used for holographic method.

Simple gratings obtained by DEBER method are quite similar to holographic gratings (figure 2). They also have sinusoidal shape and limited efficiency. Throughput for DEBER method is lower than ruling or holographic method but it is high enough for small gratings production. DEBER exposure time of 3x3.9 mm^2 is about 10-100 s (exposure dose 0.1-1 $\mu C/cm^2$). DEBER method is extremely accurate due to e-beam system exploitation. Moreover the shape of the grating produced by DEBER method could be modified. The shape of the grooves could be skewed, for example. Also complex grating like binary gratings could be produced by DEBER method if e-beam lithography or FEBIP system is used. Large set of positive resists could be used with DEBER method.

4. Diffractive optical elements

Diffraction optical elements (DOE) contain staircase structures. Usually these structures are formed by grayscale e-beam lithography or multiple e-beam lithography (EL) processes followed by plasma etching. The main problems are incorrect depth of the structure and misalignment. These effects lead to the significant decrease of the DOE efficiency. Grayscale e-beam lithography provides low vertical resolution. And for multiple EL processes it is difficult to align them properly. Both processes are extremely low-productive.

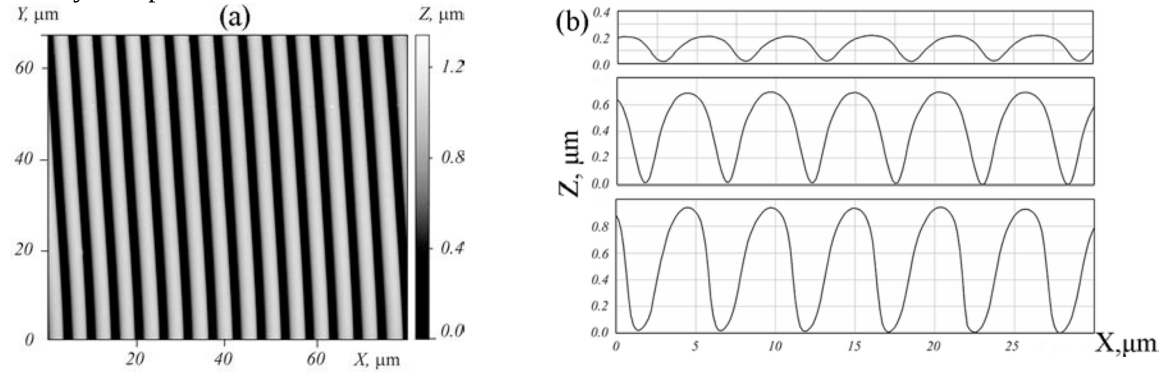

Figure 2. AFM image (a) and profiles (b) of diffraction gratings obtained by DEBER method.

Formation of staircase structures by DEBER process is quite simple (Figure 3). The technique is similar to grayscale e-beam lithography. But due to specific etching mechanism vertical resolution of the DEBER method is 1-2 nm. So incorrect depth is not a problem for the method. DEBER is a one-step process and misalignment also does not take place for the method. The method also is high-productive.

Drawbacks of DEBER method here are edge rounding and low lateral resolution. Edge rounding leads to insignificant efficiency decrease [6]. It appears that if the DEBER method is implemented in the modern e-beam lithography or FEBIP system lateral resolution will be enough for DOE fabrication.

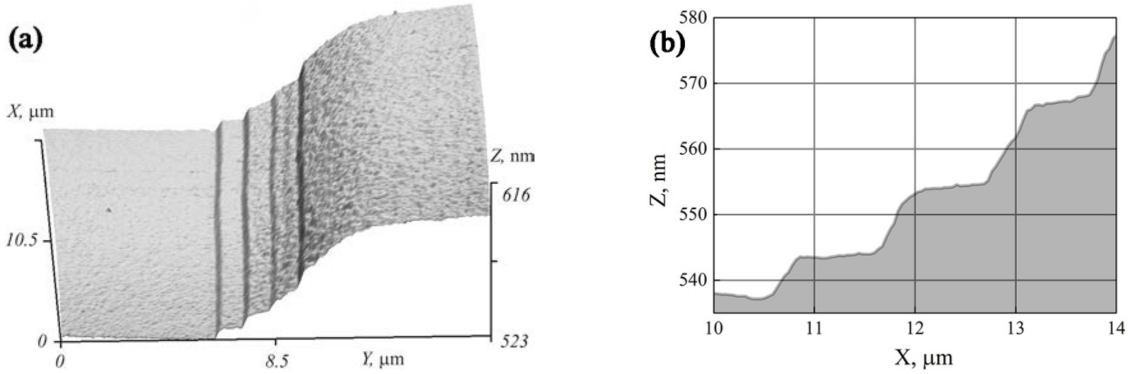

Figure 3. 3D AFM image (a) and profile (b) of staircase structure obtained by DEBER method; the structure was obtained in the Zeiss Ultra-55 SEM by the sequential exposure of overlapped square areas.

5. Other 3D structures

Staircase structures could be also used for angle resolved spectroscopy. DEBER method could be useful for formation of different 3D structures due to high productivity. Microlens arrays, focusators, waveguide couplers, reflecting devices could be fabricated by the DEBER method if it is implemented in e-beam lithography or FEBIP system. The method works here like grayscale e-beam lithography with high vertical resolution, accurate lateral positioning but limited lateral resolution.

6. Binary gratings and planar photonic crystals

DEBER method could be used not just for simple diffraction grating formation but also for formation of complex binary gratings or planar photonic crystals (figure 4). In this case DEBER works like standard e-beam lithography with limited lateral resolution. On the other hand it seems that edge rounding could somewhat decrease efficiency of these structures.

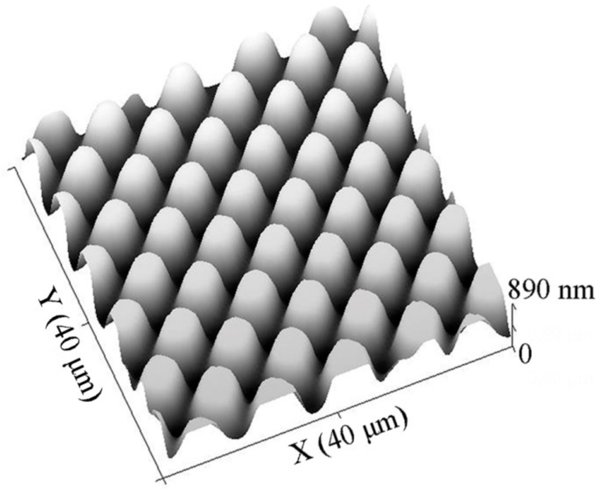

Figure 4. 3D AFM image of structure obtained by DEBER method during exposure of two sets of lines.

7. Conclusion

It seems that DEBER method can be used for formation of wide range of structures and devices for optics and optoelectronics (diffraction and binary gratings, DOE, planar photonic crystals, microlens arrays etc.). If the resist is an appropriate material for application, DEBER method could be used without any additional procedures. In other cases the pattern could be transferred in the substrate material by anisotropic etching. Also the pattern could be used as a model for replication, stamps and matrices.

References

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