Development of diffractive optical elements with low surface roughness by direct laser writing

S A Fomchenkov\textsuperscript{1,2}, A P Porfīrev\textsuperscript{1,2}

\textsuperscript{1}Department of Engineering Cybernetics, Samara National Research University, Samara 443086, Russia
\textsuperscript{2}Micro- and Nanotechnologies Laboratory, Image Processing Systems Institute of the RAS – Branch of the Federal Scientific Research Centre “Crystallography and Photonics” of RAS, Samara 443001, Russia

Abstract. A novel method of forming the phase diffractive optical elements (DOEs) by direct laser writing in thin films of aluminum was presented. The quality of the writing process in aluminum films were investigated depending on the parameters of magnetron sputtering process. This method of phase diffraction optical elements forming substantially reduces the time, fabrication steps, costs of production and significantly improves the quality of the elements in comparison with traditional methods.

1. Introduction
Diffractive optical elements (DOE) allow many functions such as multiplication and beam formation, optical signal distribution through processing channels, wave front formation [1,2]. One of the traditional methods of the phase diffractive optical elements fabrication is a method based on micro-structure forming inside the substrate [3,4]. But the most problem part of this method is low fabrication accuracy because of plasma etching involving in this process. Typically, this process begins with the deposition of thin metal film such as chromium on the quartz substrate, which acts as a hard mask. Moreover, the patterns are formed on the hard mask with either by photolithography or by laser writing system. Further, the desired patterns are obtained by etching the substrate with the help of plasma-chemical etching. For example, a quartz substrate is physically etched in a gas (SF\textsubscript{6}) through a chromium oxide (Cr\textsubscript{2}O\textsubscript{3}) mask. After the mask is removed by chemical etching in a special solution. All steps of this method shown in figure 1.

2. Fabrication
The main idea of presented method is removing of low controlling plasma etching process which is responsible for the substrate’s top surface roughness and consequently reduces its efficiency. Furthermore, it will allow us to reduce the number of fabrication steps and consequently reduce the time and costs of production.
In details, this process consists of the following steps:
1) Cleaning of a fused silica substrate.
2) Chromium thin film sputtering on the quartz substrate.
3) Hardmask’s direct laser writing in the chromium thin film by circular laser writing station. The chromium thin film exposed by focused laser radiation oxidizes into Cr\textsubscript{2}O\textsubscript{3}.
4) Unexposed chromium is removed using a special solution.
5) Transfer of the DOE’s profile to the silica substrate achieved using a plasma etching system. This step is one of the most non-controlled.

6) The depth of etching is controlled by the profilometer.

7) Removal of the hard mask in a solution. Washing in distilled water. Blowing with compressed air and again the depth of etching is controlling.

**Figure 1.** General scheme of the phase DOE manufacturing steps: typical method and presented method.

The main idea of presented method is removing of a low controlling plasma etching process which is responsible for the negative effects. External view of plasma etching system “Caroline PE15” shown on figure 2.

**Figure 2.** Plasma etching system using for manufacture by typical method.

Aluminum thin films were deposited by magnetron sputtering system “Caroline D12A”. Then direct laser writing process was conducted by circular laser writing system “CLWS-200S”. When aluminum thin film was exposed by focused laser radiation, it oxidized into aluminum oxide. Unexposed aluminum metal was removed with the help of solution. Laser writing parameters were chosen in such a way that the effect was similar to the annealing process at temperature 700 °C [5,6]. The obtained Al₂O₃ film was optically transparent and allows visible radiations. In the visible wavelength spectrum, Al₂O₃ has a refractive index of 1.8 which is higher than the refractive index of quartz 1.5 that provides a significant refractive index contrast. As a result, this fact reduces the requirement of high aspect ratio of the diffractive element structures in the Al₂O₃ film as compared to the structures in quartz [7]. The general scheme of the presented technological manufacturing process is shown also in figure 1.

Total view of element step by step after each manufacture process is shown in figure 3.
3. Advantages of the presented method

The quartz etching is the most non-controlled part, however the etching process provides high level of roughness. Surface of substrate, which is not covered by chromium oxide mask, interacts directly with plasma inside a vacuum chamber. This kind of etching is not homogeneous, so therefore roughness of open surfaces increasing linear with time and power of etching [8,9].

So therefore developed method also better in providing of high quality elements, with smooth surface. To confirm these conclusions, measurements of elements manufactured in different ways were made by profiler. Results of measurements made by profiler are shown on figure 4.

4. Conclusion

We presented a method in order to reduce fabrication time and significantly improve the quality of the elements. This allows obtaining greater efficiency in comparison with similar structures, made on quartz, using plasma etching systems.

Acknowledgments

This work was financially supported by Russian Federation Presidential grants for support of young candidates of sciences (MK-2390.2017.2) and Russian Foundation for Basic Research grant No. 17-42-630008, 18-07-01122, 18-07-01380, 16-47-630677 in part of design and experimental investigation of multilayer diffractive optical elements and by Russian Federation Presidential grant for support of the leading scientific schools (NSh-6307.2018.8) in part of manufacturing of diffractive optical elements.

References

[1] Bykov D A, Dokolovich L L, Diffraction of an optical beam on a Bragg grating with a defect layer, 2014 Computer Optics 38(4), 590–597.
[2] Rubinsztein-Dunlop H, Forbes A, Roadmap on structured light, 2017 J. Opt. 19(1), 1–55.
[3] Fomchenkov S A, Butt M A, Poddilnov V V, Poletaev S D, Skidanov R V and Kazanskiy N L, E-beam lithography exposure conditions for the fabrication of RGB filter based on metal/dielectric subwavelength grating, 2016 J. of Physics: Conf. Ser. 741(1), 012150.
[4] Butt M A, Fomchenkov S A, Ullah A, Habib M, Ali R Z, Modelling of multilayer dielectric filters based on TiO₂/SiO₂ and TiO₂/MgF₂ for fluorescence microscopy imaging, 2016 Computer Optics 40(5), 674–678.
[5] Butt M A, Fomchenkov S A, Thermal effect on the optical and morphological properties of TiO$_2$ thin films obtained by annealing a Ti metal layer, 2017 Journal of the Korean Physical Society 70(2), 169–172.

[6] Butt M A, Fomchenkov S A, Khonina S N, Dielectric-Metal-Dielectric (D-M-D) infrared (IR) heat reflectors, 2017 J. of Physics: Conf. Ser. 917(6), 062007.

[7] Fomchenkov S A, Butt M A, Fabrication of amplitude-phase type diffractive optical elements in aluminium films, 2017 J. of Physics: Conf. Ser. 917(6), 062026.

[8] Juneja S, Poletayev S D, Fomchenkov S A, Khonina S N, Skidanov R V, Kazanskiy N L, Reactive ion etching of indium-tin oxide films by CCl$_4$-based Inductivity Coupled Plasma, 2016 J. of Physics: Conf. Ser. 741(1), 012105.

[9] Glyanko M S, Volkov A V, Fomchenkov S A, Assessment of surface roughness of substrates subjected to plasma-chemical etching, 2014 J. of Physics: Conf. Ser. 541(1), 012100.