Published in Diffractive Optics and Micro-Optics (DOMO), 234-236, 2000
which should be used for any reference to this work

Micro-optical elements with arbitrary surfaces

A. Schilling, Ph. Nussbaum, I. Philipoussis, H.P. Herzig
Institute of Microtechnology, rue A.-L. Breguet 2, CH-2000 Neuchâtel, Switzerland
tel.:+41-32-718-3341, fax: +41-32-718-3201, email: Andreas.Schilling@imt.unine.ch

L. Stauffer
Leica Geosystems AG, CH-9435 Heerbrugg, Switzerland

M. Rossi
Centre Suisse d'Electronique et Microtechnique, Badenerstrasse 569, CH-8048 Zürich, Switzerland

E.-B. Kley
Institut für angewandte Physik, Friedrich-Schiller-Universität Jena, Max-Wien-Platz 1, D-07743 Jena, Germany

Abstract: We present a comparison of three different technologies for the fabrication of micro-optical elements with arbitrary surfaces. We used direct laser writing, binary mask lithography in combination with reactive ion etching, and graytone lithography.

1. Introduction

In recent years micro-optical elements have found their way into applications. Often, these elements have complicated, in the most general case arbitrary, surface profiles, especially when multiple optical functions are implemented in one plane. There exist several possibilities for the fabrication of such micro-optical elements with arbitrary surfaces. We employed three different technologies for the fabrication of elements with an arbitrary surface profile: direct laser writing in photoresist, binary mask lithography in combination with reactive ion etching in fused silica, and High-Energy-Beam-Sensitive (HEBS) glass graytone lithography. One element has an arbitrary surface type profile with three different optical functions, the other element has a linear surface relief profile. We compare the performance of the elements fabricated by the different technologies and discuss the different tolerances and sources of losses, as well as the diffractive/refractive behaviour.

2. Fabrication Methods

Laser direct writing in photoresist [1,2] is one approach to obtain continuous surface relief profiles of diffractive or refractive optical elements. We used the laser writer at CSEM in Zürich which utilizes a focused He-Cd laser beam (λ=442nm) to expose a photoresist coated substrate in a raster scan. Afterwards, the photoresist is developed resulting in a surface relief structure. The direct laser writing technique is a very flexible and fast method to obtain prototypes without the need to generate masks like in photolithographic methods. Another approach for the fabrication of diffractive optical elements with arbitrary surfaces is binary mask lithography in combination with reactive ion etching [3]. Hereby the desired continuous profile is approximated by a multilevel profile. The substrate, fused silica, which is coated with a thin photoresist layer is exposed through a binary chromium mask with a UV lamp. The chromium mask is normally fabricated by laser beam or electron beam writing, depending on the required resolution. After the development step a resist pattern remains which is then transferred into the substrate by the following etch step. The subsequent photolithographic step creates a refined resist pattern which is then again transferred into the substrate resulting in a 4-level surface profile. For 8- or 16-level surface profiles correspondingly more aligned lithography and etch steps are necessary. HEBS glass graytone technology uses a mask which has a continuous variation of transmission (graylevels). This is achieved by using HEBS glass [4] which is fabricated using a silver ion exchange process.[5,6] When exposed to a high energy electron beam, reduction of the silver ions occurs and the optical density of the material changes. The optical density increases with the electron dosage where typical values are 0-2.6 for a wavelength of λ=365nm. A major difficulty compared to binary mask photolithography is that one has to work in the nonlinear regime of the photoresist response. For the graytone technology one needs to establish a characterization curve, resist height as a function of electron dosage by using a set of test structures. This characterization curve is afterwards used to encode the profile of the designed surface

relief structure into electron dose per pixel for the electron beam writing procedure. Once the HEBS glass mask is written the continuous surface relief profiles are fabricated by one single lithography step. This technology is well adapted for the fabrication of deep micro-optical elements.

3. Results and Discussion

We fabricated two different types of elements with the three technologies. The first type, element A, has an arbitrary surface containing several optical functions. The second type, element B, is a linear surface relief element. The element A, fabricated by graytone lithography in photoresist is shown in Fig.1. The same element fabricated by binary mask technology as 8-level diffractive element in fused silica is shown in Fig.2.

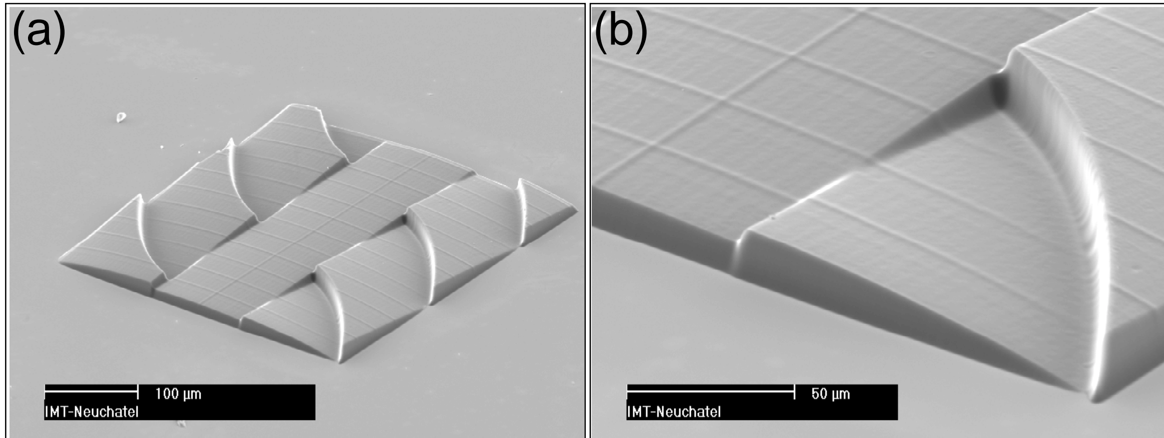

Fig.1. SEM image of element A fabricated by HEBS glass graytone lithography in photoresist. (a) overview, (b) enlarged detail.

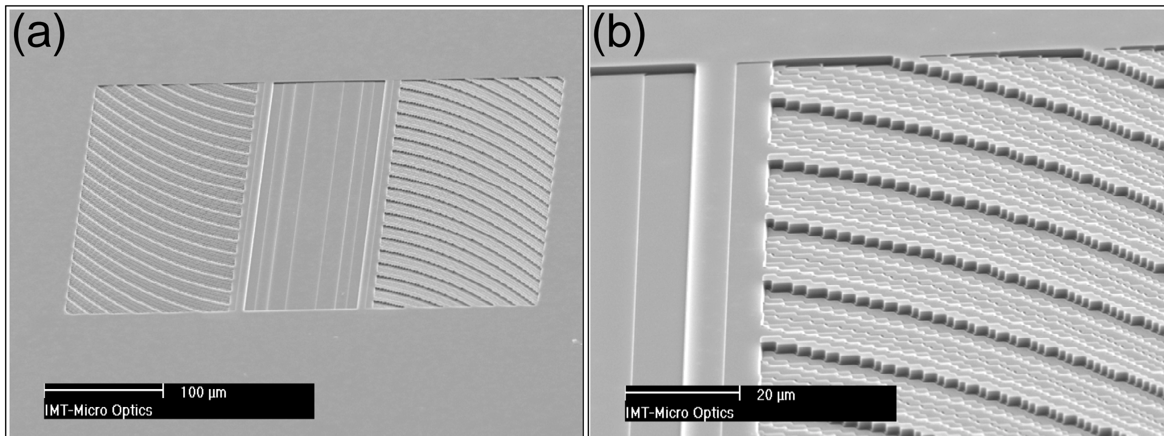

Fig.2. SEM image of element A fabricated by multiple projection lithography in fused silica. (a) overview, (b) enlarged detail.

The element A is symmetric with respect to the center and divided into three parts. The left and right part of the element deflect the light horizontally and vertically while focusing at the same time. The center part has the focusing function only. The element B is divided in the same way where the two outer parts have a linear phase function. The laser written elements are in photoresist, have a continuous diffractive surface relief profile with a depth of 1.4 µm. The HEBS glass graytone elements have a continuous refractive surface profile with a depth of 18 µm. The multilevel, fused silica elements with 8 phase levels have a diffractive surface profile with a depth of 1.65 µm. The small grating periods of element A together with the fixed minimum feature size of 1.25 µm for the multilevel elements caused that the effective number of phase levels was partially smaller than 8.

We analyzed the efficiency and the deflection angles of the different elements. Table 1 shows a comparison of the measured diffraction efficiencies which were achieved with the different technologies for the elements A and B. The

efficiencies were measured with a focused VCSEL laser diode from Honeywell at λ=850nm where the spot size (full width at $1/e^2$ intensity level) at the plane of the element was 50 µm, determined with a knife edge measurement.

Table 1. Measured diffraction efficiencies, normalized with respect to transmitted intensity through unstructured substrate.

	element A left part	element A right part	element B
efficiency multilevel	70%	70%	82%
efficiency laser writer	70%	68%	81%
efficiency graytone	78% (effective) 84% (maximum)	78% (effective) 84% (maximum)	81% (effective) 88% (maximum)

For the graytone elements the effective efficiency includes the losses at the non-ideal edges whereas the maximum efficiency is measured when the beam does not hit an edge. We found that the efficiencies of the element B achieved with the three different technologies were nearly equal, slightly above 80%. For the element A, which has steeper slopes or correspondingly smaller grating periods, the graytone element had a higher efficiency while the laser written elements and the multilevel elements performed nearly equal. The sources of the losses for the different elements are quite different. For the multilevel element the losses are mainly related to the approximation of the ideal structure by the multilevel structure and alignment errors between the different lithographic steps. For the laser written elements the main losses are caused by the finite width of the writing beam and surface roughness. The main losses of the graytone elements originate from surface roughness and the non-ideal edges. Table 2 shows a comparison of the measured and designed deflection angles of the elements A and B which were fabricated by the three technologies.

Table 2. Comparison between measured and designed deflection angles for the element A and B.

	element A deflection angle, vertical	element B deflection angle
design value [degree]	4.01	3.38
multilevel [degree]	3.97	3.36
laser writer [degree]	4.11	3.47
graytone [degree]	4.45	3.67

The multilevel elements reproduced quasi perfectly the designed deflection angles. The laser written elements showed slight deviations from the design values, while the differences were largest for the graytone elements. The reason for this behavior is that for the multilevel elements the directions are determined by the grating periods which are in turn very well defined. For the refractive graytone elements the directions are determined by the surface profile which is more difficult to control and therefore shows larger deviations. Because of the diffractive surface profile of the laser written elements the deflection angles are better defined than for the graytone elements while the deviations from the design values are slightly larger than for the multilevel elements.

4. Conclusions

With the graytone elements we achieved for smaller grating periods the highest efficiencies, while the deviations of the deflection angles from the design values were largest. The multilevel elements reproduced best the designed deflection angles, with moderate efficiencies for small grating periods. The efficiencies of the laser written structures were comparable to the multilevel elements, while the accuracy of the deflection angles was better than for the graytone elements, nearly as good as with the multilevel elements. With the refractive type elements better efficiencies can be achieved for large deflection angles, while with diffractive elements precise deflection angles can be obtained more easily.

5. References

[1] M.T. Gale and M. Rossi, *Diffractive Optics for Industrial and Commercial Applications*, J. Turunen and F. Wyrowsky eds.; Ch.4 Continuous-relief diffractive lenses and microlens arrays, Akademie Verlag Berlin, 1997.

[2] M.T. Gale, Th. Hessler, R.E. Kunz, H. Teichmann, Fabrication of continuous-relief micro-optics: progress in laser writing and replication technology, OSA Technical Digest Series, **5**, 335 (1996).

[3] M.B. Stern, *Micro-Optics: Elements, Systems, and Applications*, H.P. Herzig ed.; Ch. 3 Binary Optics Fabrication, Taylor & Francis (1997).

[4] C. Wu, Method of making high energy beam sensitive glass, U.S. patent 5,078,771 (1992).

[5] W. Däschner, C. Wu, S.H. Lee, General aspheric refractive micro-optics fabricated by optical lithography using a high energy beam sensitive glass gray-level mask, J. Vac. Sci. Technol. B, **14**, 135-138 (1996).

[6] Ch. Gimkiewicz, D. Hagedorn, J. Jahns, E.-B. Kley, F. Thoma, Fabrication of Microprisms for Planar Optical Interconnections by Use of Analog Gray-Scale Lithography with High-Energy-Beam-Sensitive Glass, Appl. Opt., **38**, 2986-2990 (1999).