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Fabrication technologies for micro-optical elements with arbitrary surfaces

A. Schilling[a], Ph. Nussbaum[a], I. Philipoussis[a], H.P. Herzig[a], L. Stauffer[b], M. Rossi[c], E.-B. Kley[d]

[a]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
[b]Leica Geosystems AG, CH-9435 Heerbrugg, Switzerland
[c]CSEM Centre Suisse d'Electronique et Microtechnique
Badenerstrasse 569, CH-8048 Zürich, Switzerland
[d]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 in photoresist, binary mask lithography in combination with reactive ion etching in fused silica, and High-Energy-Beam-Sensitive (HEBS) glass graytone lithography in photoresist. We analyzed the efficiencies and the deflection angles of different elements in order to quantify the performance of the different technologies. We found that higher efficiencies can be achieved with refractive type elements, while precise deflection angles can be obtained more easily with diffractive elements.

Keywords: Micro-optics, Diffractive optics, Microstructure fabrication, Direct laser writing, HEBS-glass graytone lithography, Photolithography

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. 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 in photoresist. We fabricated two different types of elements. 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 with respect to each other and with respect to the theoretical values. We discuss the different sources of losses, as well as the diffractive/refractive behaviour of the elements.

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 with profile depths of up to 30 μm. 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. The pixel size for the writing procedure was 400 nm. Afterwards, the photoresist is developed resulting in a surface relief structure. The laser writer setup is schematically displayed in Fig.1.

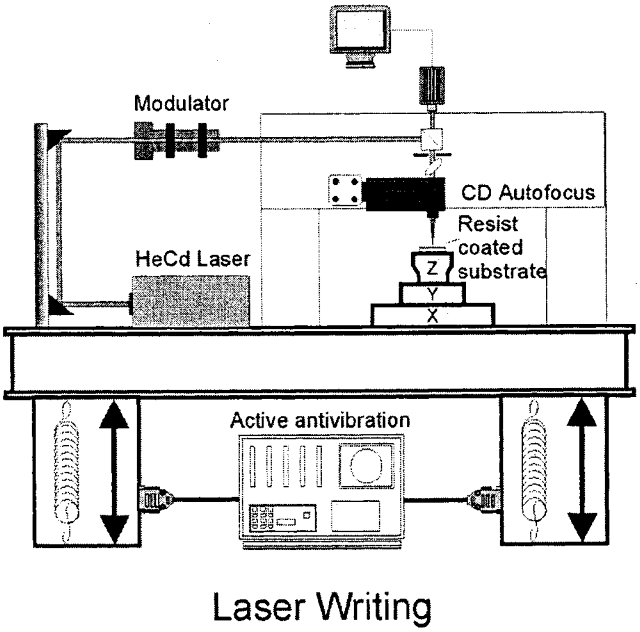

Fig.1: Setup of the laser writer at the CSEM in Zürich.

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] The basic principle of binary mask photolithography combined with subsequent RIE steps is shown in Fig.2.

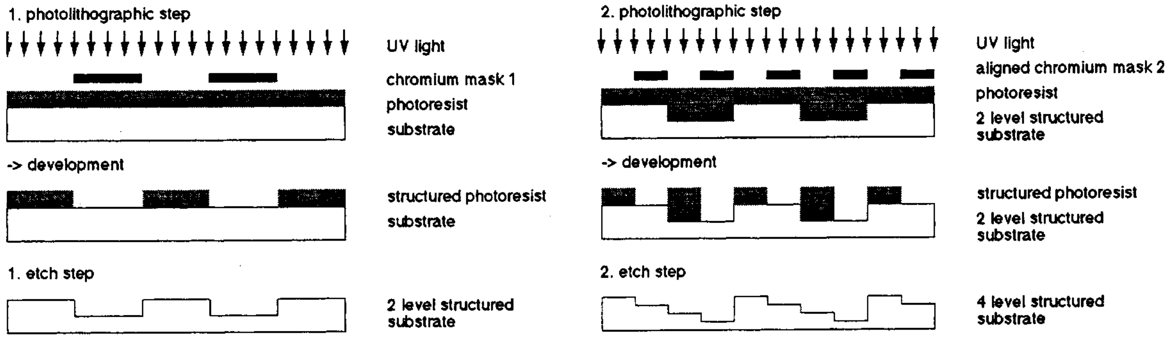

Fig.2: Fabrication of multilevel profiles by binary mask photolithography in combination with reactive ion etching (RIE).

Hereby the desired continuous profile is approximated by a multilevel profile. In order to achieve high diffraction efficiencies above 90%, at least 8 phase levels per 2π phase difference have to be used, since the first-order scalar diffraction efficiency η depends on the number of phase levels N as [4]

$$\eta(N) = |\operatorname{sinc}(1/N)|^2 \qquad (1)$$

The fused silica substrate, 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. The fabrication process was carried out at CSEM in Neuchâtel.

The third method, HEBS-glass graytone technology, as schematically shown in Fig.3, uses a mask which has a continuous variation of transmission (graylevels).

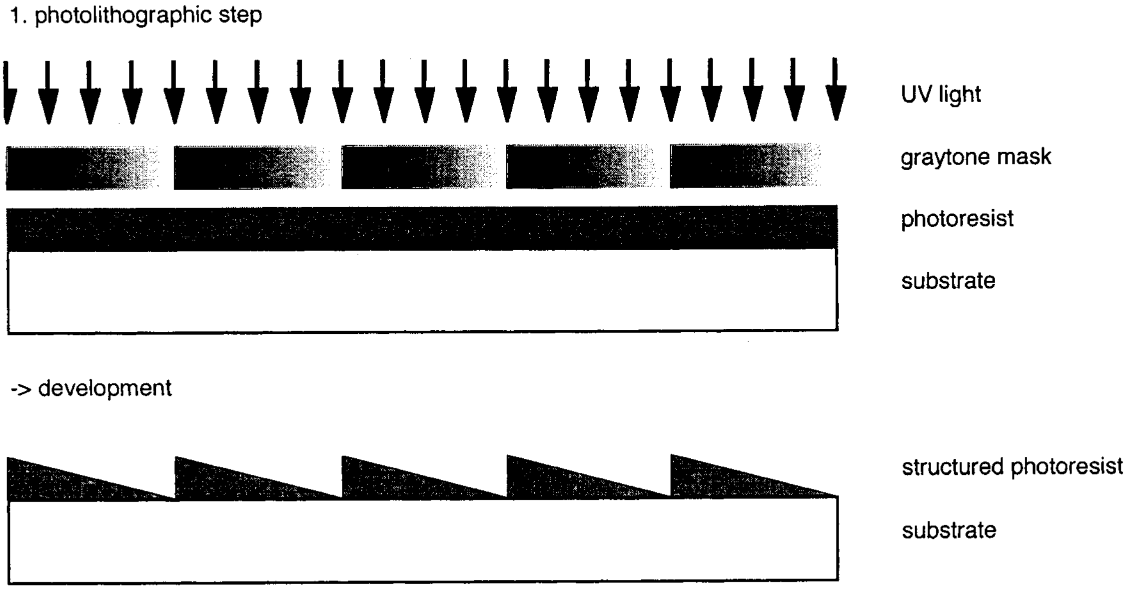

Fig. 3: Sinle-step photolithography with a graylevel HEBS-glass mask to obtain continuous-relief surface profiles in photoresist.

This is achieved by using a HEBS-glass mask,[5] which is fabricated using a silver ion exchange process.[6,7] 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 ρ increases with the electron dosage, where typical values are ρ=0-2.6 for a wavelength of λ=365nm. A major difficulty, compared to binary mask photolithography, is the accurate control of the nonlinear photoresist response. For the graytone technology one needs to establish a calibration curve, resist height as a function of electron dosage, by using a set of test structures. The calibration curve is shown in Fig.4. It 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 a single photolithography step. This technology is well adapted for the fabrication of deep micro-optical elements.[8,9]

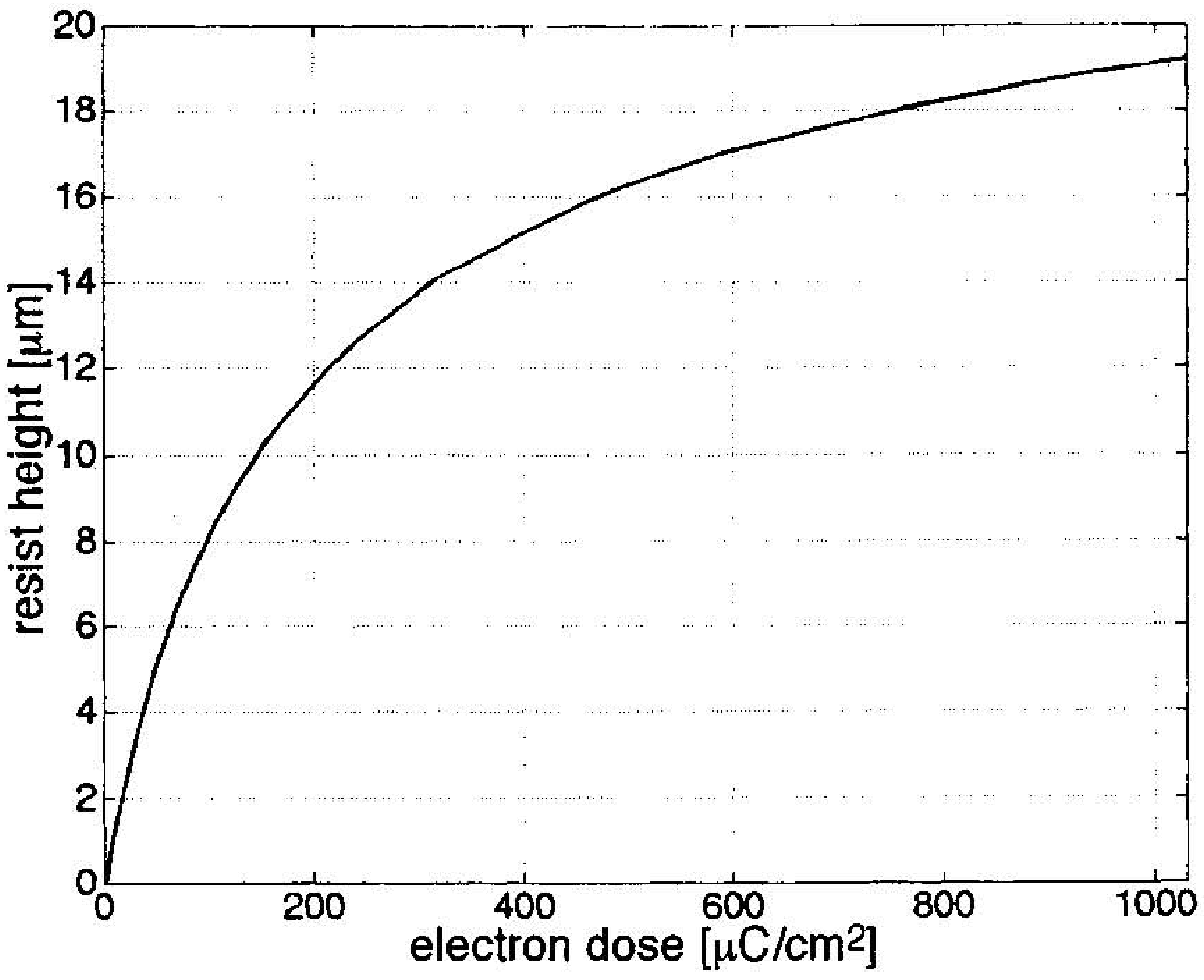

Fig.4. Calibration curve for HEBS-glass graytone lithography.

The photoresist elements, fabricated by direct laser writing and HEBS-glass graytone lithography, can also be transferred into fused silica afterwards by reactive ion etching.[10]

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.5. The same element, fabricated by binary mask technology as 8-level diffractive element in fused silica, is shown in Fig.6. The two different elements fabricated by direct laser writing in photoresist, are displayed in Fig.7. The element B, fabricated by HEBS-glass graytone technology, is shown in Fig.8. The two elements fabricated by graytone technology show an additional line pattern which is superposed on the designed surface profile. It is related to the e-beam writing procedure of the HEBS-glass mask and can be further reduced.[11]

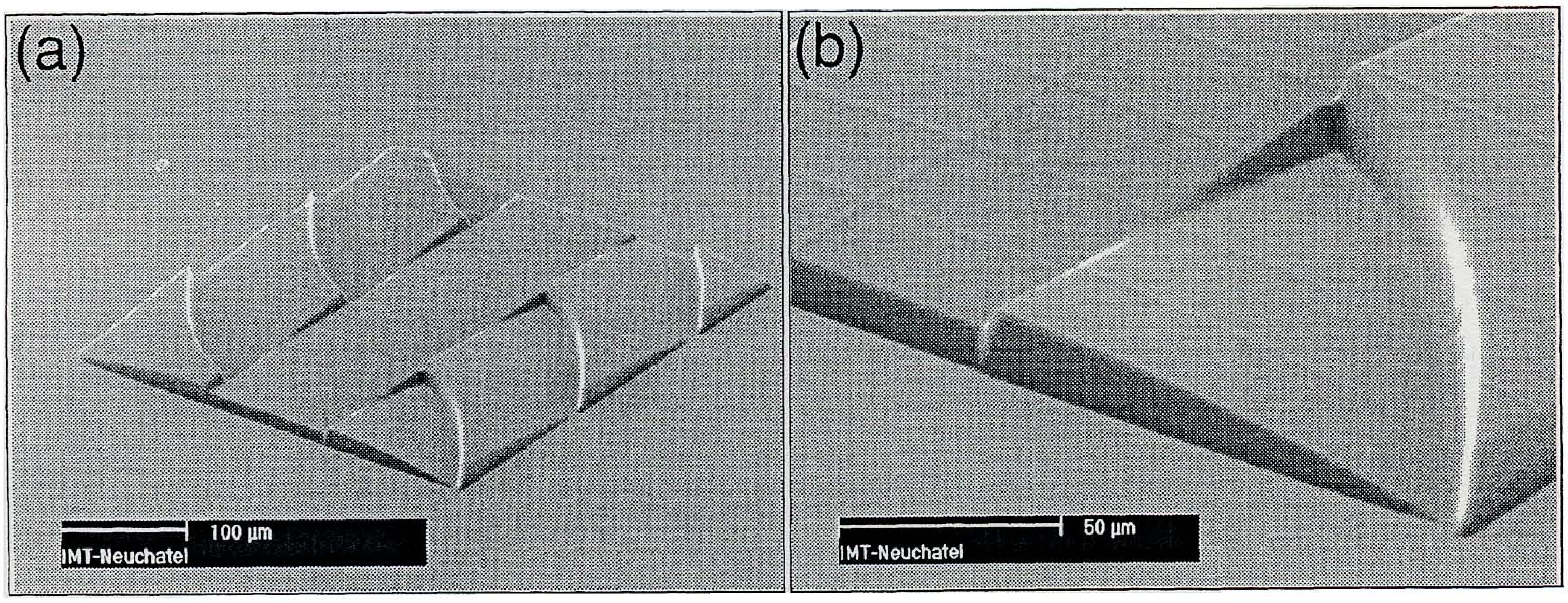

Fig.5. SEM image of element A fabricated by HEBS-glass graytone lithography in photoresist: (a) overview, (b) enlarged detail.

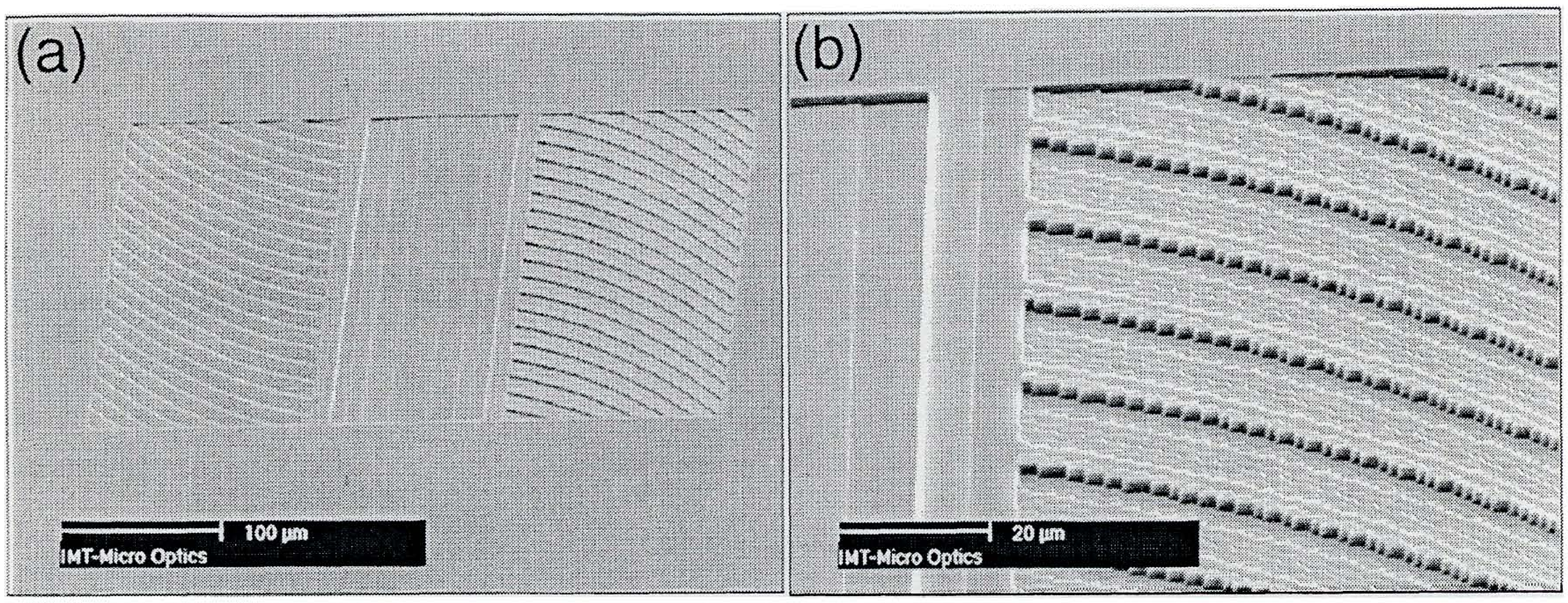

Fig.6. SEM image of element A fabricated by multiple projection lithography in fused silica: (a) overview, (b) enlarged detail.

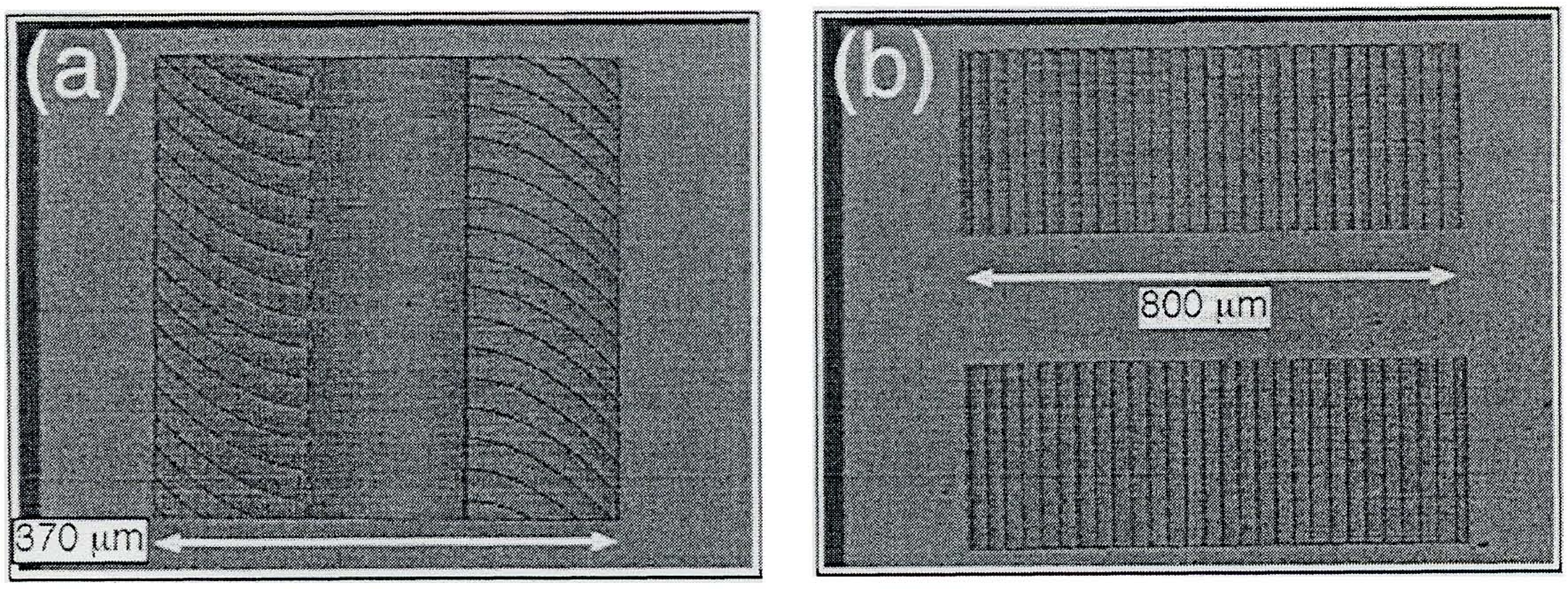

Fig.7. Microscope image of element A (a) and B (b) fabricated by laser direct writing in photoresist.

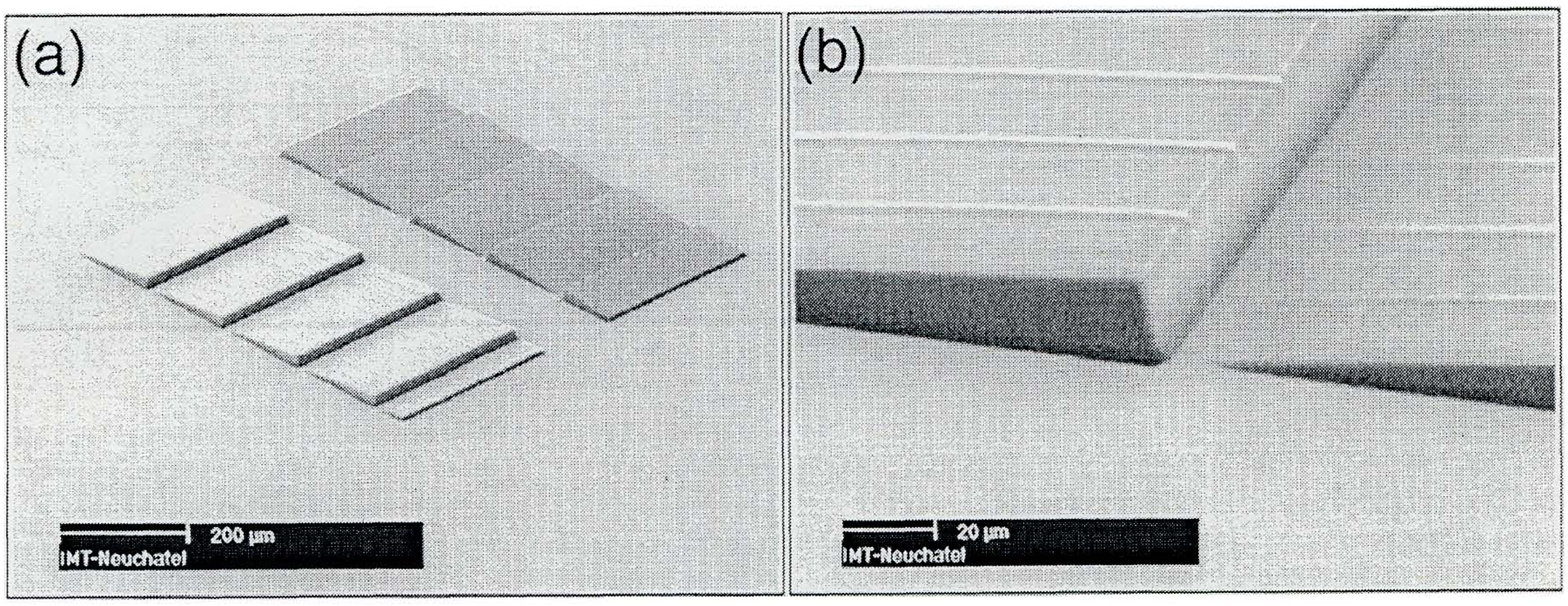

Fig.8: SEM image of element B fabricated by HEBS-glass graytone lithography in photoresist: (a) overview, (b) enlarged detail.

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 and were realized as continuous, diffractive surface relief profile, designed for the second order, with a depth of 2.8 μm, the ideal depth for the design wavelength of 850 nm. Since the HEBS-glass graytone technology (as well as the laser writing) offers the possibilty to fabricate continuous relief elements with a large profile depth (15–20 μm), the elements can also be realized with much less zone transitions. In the example described here, the elements were realized as 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, again the ideal depth for the design wavelength of 850 nm. The small grating periods of the 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. This effect acounts for a theoretical reduction of 7% in diffraction efficiency (reduction from 95% to 88%) at the outer edge of the element A.

In order to quantify the performance of the fabrication technologies, 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 fabrication technologies for the elements A and B. The efficiencies were measured with a focused VCSEL laser diode from Honeywell at λ=850 nm where the spot size (full width at $1/e^2$ intensity level) at the plane of the element was 50 μm, determined by a knife edge measurement.

Table 1. Measured diffraction efficiencies (λ=850nm), 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% (incl. steps) 84% (purely refractive)	78% (incl. steps) 84% (purely refractive)	81% (incl. steps) 88% (purely refractive)

For the graytone elements the lower one of the two efficiencies includes the losses at the non-ideal profile steps, whereas the higher efficiency (purely refractive) is measured when the beam does not hit such a step. 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 of 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 (5 to 12%) and alignment errors between the different photolithography steps. For the laser written elements the main losses are caused by the finite width of the writing beam and surface roughness. The losses originating from the finite width of the writing beam could be reduced by working in higher diffraction orders. The main losses of the graytone elements originate from the non-ideal profile steps, the additional superposed line pattern, and surface roughness. A loss of about 7% can be attributed to the non-ideal profile steps.

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 (λ=850 nm) and designed deflection angles for the elements 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. When translating the deviations of the deflection angles from the design values into grating period variations, one finds for the multilevel elements errors of about 60 and 90 nm for the A and B element, respectively. For the laser written elements the grating period variation amounts to 220 and 280 nm, which is roughly half the pixel size of 400 nm which was used during writing procedure. Since the graytone elements are refractive type elements, we translated the deflection angle deviation into phase error per 2π phase difference. For the A element the phase error is then $\lambda/10$ and for the B element $\lambda/13$. For the B-element, fabricated by graytone lithography, we compared the designed and measured (Tencor Profilometer) surface profile. The comparison is shown in Fig.9.

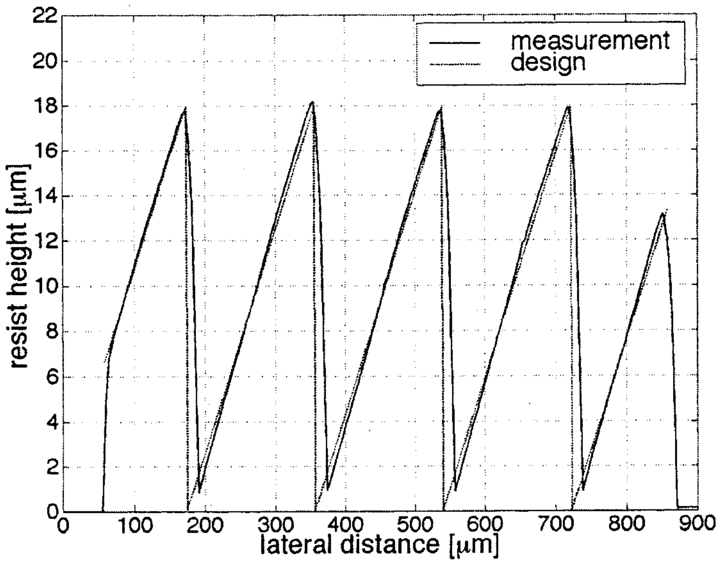

Fig. 9: Comparison between designed and measured surface profile for the B-element fabricated by graytone technology.

One can clearly observe that the measured profile form on the slopes agrees well with the designed surface profile, while the largest differences are observed at the four profile steps, which result in the measured reduction of diffraction efficiency of about 7% compared to the profile part without a step.

4. CONCLUSIONS

We have presented a comparison of three different technologies for the fabrication of micro-optical elements with arbitrary surfaces: 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 in photoresist. 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. ACKNOWLEDGEMENTS

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