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Potential of dry etching for the fabrication of fused silica micro-optical elements

Ph. Nussbaum[1], K. J. Weible[2], M. Rossi[3], H. P. Herzig[1]

[1]Institute of Microtechnology, University of Neuchâtel
Rue A.-L. Breguet 2, CH-2000 Neuchâtel, Switzerland
Phone: +41 32 718 32 72, Fax: +41 32 718 32 01
E-mail: philippe.nussbaum@imt.unine.ch
[2]WeibleOptech, Rue A.-L. Breguet 2, CH-2000 Neuchâtel, Switzerland
[3]CSEM, Badenerstrasse 569, 8048 Zürich, Switzerland

ABSTRACT

We report on recent progress in the fabrication of fused silica micro-optical elements, such as blazed gratings, refractive microlenses and microprisms. The elements are first made in photoresist and then they are transferred into fused silica by reactive ion etching. High selectivity etching is needed to realize structures with a high aspect ratio. Results are shown using various metallic etch masks. The shaping of optimized profiles is also presented to generate microlenses which are aspheric, or which have a low numerical aperture.

Keywords: Micro-optical elements, microfabrication, dry etching, fused silica.

1. INTRODUCTION

In modern fabrication techniques of photonic devices, dry etching plays an important role. The application of this technology to optical materials, such as glass and fused silica is of increasing interest. The possibility to transfer photoresist structures into hard materials shows several advantages, such as the robustness of the elements, as well as the extension of the range of application wavelengths. Dry etching is easily integrated in the micro-optical fabrication facilities allowing to transfer, modify and control the dimensions and the shape of micro-optical structures. An amplification or reduction of the structure's vertical dimension is possible.[1,2]

In this paper, recent results on dry etching of micro-optical elements in fused silica are presented. We present the transfer of continuous-relief structures, such as laser-written blazed gratings and microprisms generated by gray-tone lithography. Precise control of the etch selectivity is achieved, as well as low surface roughness necessary for optical applications. High selectivity etching is used for the amplification of the structure depth in order to generate high aspect ratio features. Low selectivity etching is applied for the fabrication of refractive microlenses that have a low numerical aperture ((NA > 0.02). Finally, we show results of micro-optical elements with aspheric surfaces.

2. INDUCTIVELY COUPLED PLASMA ETCHING

A plasma assisted dry etch process can be defined as an etch process in which a solid surface is etched in a gaseous environment. Dry etch techniques can be divided into glow discharge and ion beam techniques. In ion beam techniques, the plasma is generated in a separate chamber from which ions are extracted and directed towards the substrate. In glow discharge techniques, the plasma is created in the vacuum chamber where the substrate is located. For our applications, we use a glow discharge system from Surface Technology System Limited (STS Ltd.). The STS inductively coupled plasma source (ICP) operates at a high density / low-pressure mode (HDLP). The major benefit of operating in HDL mode is the reduction in ion collision probability as the sheath thickness decreases at higher density and the ion mean free path increases at lower pressures. Thus, improved ion directionality enhances the control of anisotropy.[3]

The ICP RIE system we use is schematically illustrated in Figure 1. The antenna is powered at the same frequency (13.56 MHz) as the independently drive 100 mm diameter substrate electrode. Both RF generators operating at 13.56 MHz are driving the coil and the platen at up to 1 kW and are matched to each other by a phase shift controller. Multipolar magnetic confinement serves to reduce plasma losses to the chamber sidewalls and to maintain uniform, high-density plasma. The electrode is held at a temperature of typically 20° C using a recirculating deionised water-cooling chiller. A helium flow between the substrate and the electrode ensures a good thermal contact. During the dry etch transfer process, atoms from the fused silica substrate material are removed by energetic ions. On the areas which are covered with a mask (metallic or photoresist), the fused silica is protected and remains intact during the process.

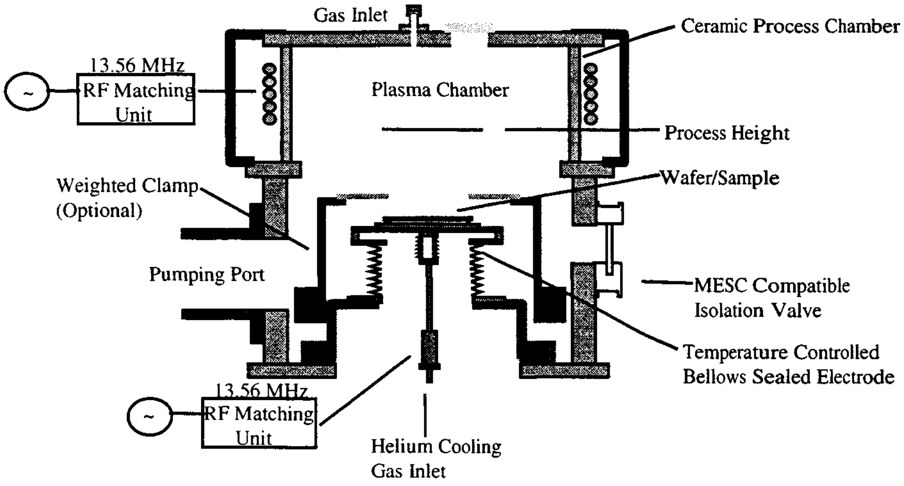

Figure 1: Schematic setup of the STS ICP system (courtesy of Surface Technology System Ltd.).

Process gases used during this work were mainly based on fluorocarbon and fluorosulfate chemistries. Oxygen was also used to allow plasma cleaning of the chamber and to be added to the main process gas if faster removal of photoresist is required. Etch rates of fused silica around 300 nm/mn have been obtained with optimized process parameters.

3. DYNAMIC OF THE ETCH SELECTIVITY

Depending on the type of elements, we wish to transfer the original structure with an accurate 1:1 ratio (section 3.1). For deep structures, we would like to amplify the structure depths (section 3.2) and for e.g. low aperture microlenses, we would like to reduce the depths (section 3.3). The shape modification, important for aspheric lenses, is presented in section 3.4.

3.1 Transfer of continuous structures

Continuous-relief micro-optical elements can be fabricated in photoresist by direct writing or by reflow technique. The transfer of such structures into fused silica is an essential fabrication step (cf. Figure 2). In contrast to the fabrication of multilevel optics, where an etch process to a given (uniform) depth is performed after each exposure and development step, this process involves only one etch step. However, since the complete micro-relief structure has to be transferred at once, the accuracy and especially the selectivity have to be controlled very precisely.

Experiments were done with elements fabricated by direct laser beam writing in photoresist.[4] Test structures and diffractive lenses with continuous-surface relief profiles of up to 3 µm depth were transferred into the fused silica substrate. The parameters of the etch process were adjusted to give an equal etch rate for photoresist and fused silica in order to keep the profile shape constant. Figure 3 shows profilometer measurements. It is not always necessary or desired to have an etch rate of 1:1. In order to change or to correct the depth of a photoresist profile also other ratio can be required. In all cases the reproducibility of the transfer process is extremely important. A series of experiments similar to the one in Figure 3 revealed depth variations of less than 5% for etch depths between 0 and 3 µm.

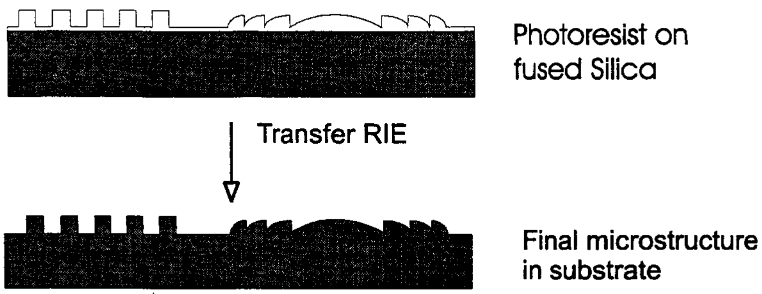

Figure 2: Tranfer of continuous-relief microstuctures fabricated in photoresist into a fused silica substrate.

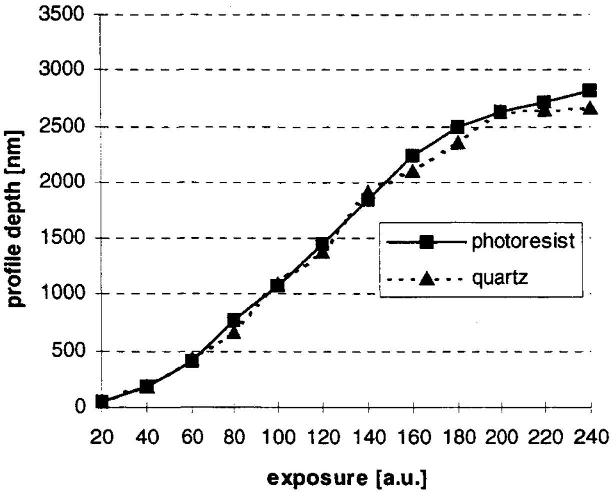

Figure 3: Depth values of calibration structures in photoresist (solid line) and etched in fused silica (dashed line). The depths have been measured by a surface profilometer.

For larger structures with lateral dimensions in the order of 100 μm and heights of several 10 μm, RIE transfers have also been performed. Refractive microprisms have been realized in photoresist by using grayscale lithography with high energy beam sensitive (HEBS) glass.[5,6] The HEBS glass consists of a silver ion doped low expansion zinc-borosilicate glass blank. By exposing the HEBS glass to a high-energy electron beam, it is possible to modify the transmission for the graytone mask. After the mask fabrication, only one subsequent lithographic step is required to transfer the mask pattern into a three-dimensional continuous photoresist relief. Using this technique, we have realized various refractive microprisms in photoresist. Symmetric and right angle microprisms with lateral dimensions ranging from 10 μm up to 100 μm, heights between 6 and 20 μm and angles at the base of 20 and 40 degrees have been obtained. An RIE transfer step has been applied to the microprisms to transfer the photoresist shape into fused silica.

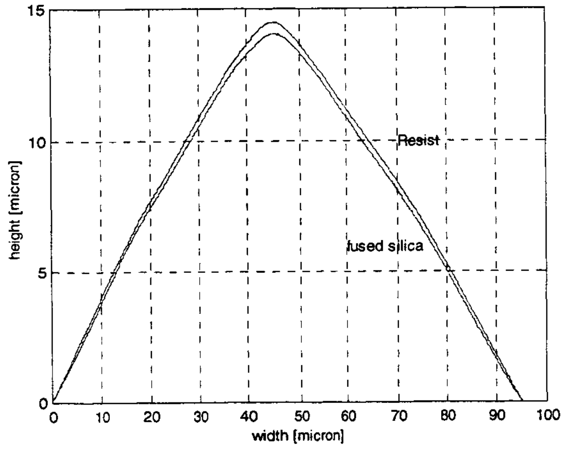

Figure 4: Surface profile of a 14.5 μm high and 95 μm large microprism before and after dry etching.

Figure 4 shows the profile of a 14.5 μm high and 95 μm large microprism before and after dry etching. The profiles have been measured with a Tencor Alpha-Step profilometer. It can be noticed that the overall dimensions have been nearly maintained. The difference between the two microprisms is in the order of 3%. In addition, an atomic force microscope (AFM) measurement showed a surface roughness in the order of 5 nm (RMS).

3.2 High selectivity etching

Several different approaches have been used to achieve high selectivity etching in fused silica. In contrast to the transfer of continuous-relief structures the goal here is to deeply etch the glass substrate while maintaining the integrity of the masking layer. Results have been obtained using standard photoresist as the masking layer, although the plasma chemistry was greatly modified. Highest selectivity has been achieved using metal masking layers, such as chromium and aluminum.

The addition of methane gas to the plasma chemistry greatly increases the selectivity when etching fused silica with photoresist masks. We have obtained selectivity as great as 10 to 1, Figure 5. The etched glass maintained very good surface roughness, but the photoresist masking layer was severely pitted and rough. This approach could not be applied to the transfer of continuous-relief structures due to the damage suffered by the photoresist during the attack.

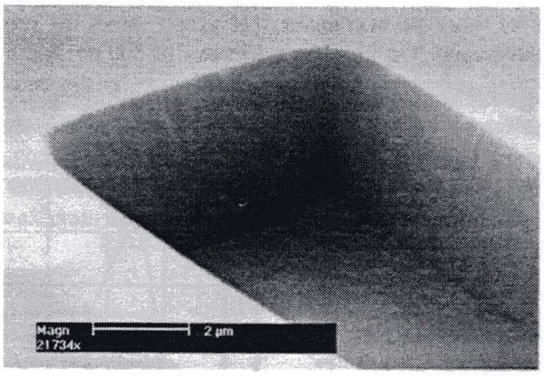

Figure 5: Fused silica channel obtained from photoresist mask.

Metal masking layers can achieve even higher selectivity. Chromium masks have produced the best results in our tests. Selectivity as high as 100 to 1 have been obtained. Very good surface roughness and steep sidewalls can be obtained, Figure 6 (left), but care must be taken to avoid residue problems during the etching, Figure 6 (right). Other masking layers such as aluminum and zinc oxide have been used with good results. Aluminum has the advantage of being less susceptible to the residue problems observed with the chromium.

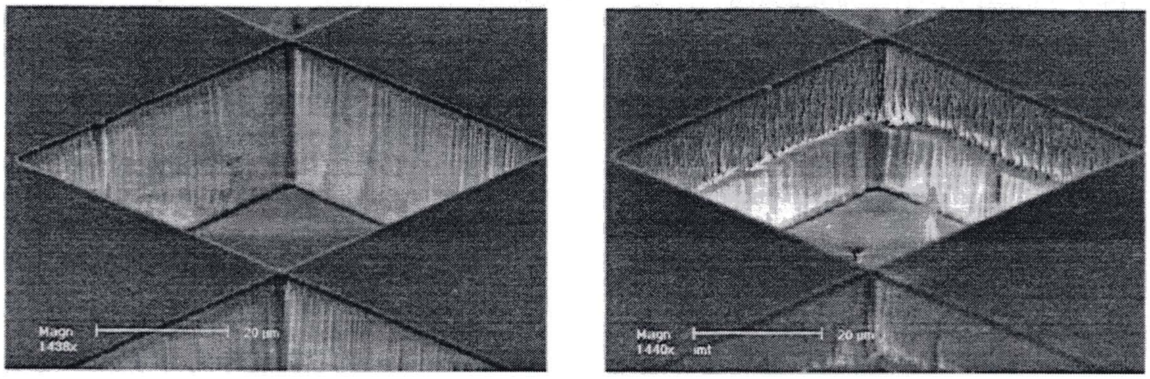

Figure 6: High selectivity with chromium masking layers and residue problem observed using chromium masking layers.

3.3 Low selectivity etching

As described in section 3.2, high aspect ratio structures are realized by using high selectivity etching between the masking structure and the substrate material. In some cases, such as the modification of the surface roughness or the structure geometry, one has to apply a dry etch transfer process with a low selectivity between the masking structure and the substrate material.

Using the melting resist technology for example, it is possible to realize high quality refractive microlenses.[7,8] Because of the surface tension, the melting resist microlenses are limited to numerical apertures (NA) higher than 0.1. For lower NA, one obtains very bad quality microlenses having even a dip in the center. The solution that we propose is to use a high NA, good quality refractive microlens in photoresist and etch it with a low selectivity process into fused silica by using fluoro-sulfate chemistry.

Figure 7 illustrates a good example for this type of transfer. The graph shows the profile and the deviation from a perfect sphere of a refractive microlens in photoresist. The lens has a diameter of 300 μm and a height of 31.5 μm. After the dry etch transfer process, the resultant fused silica microlens shows a height of 3 μm for the same diameter.

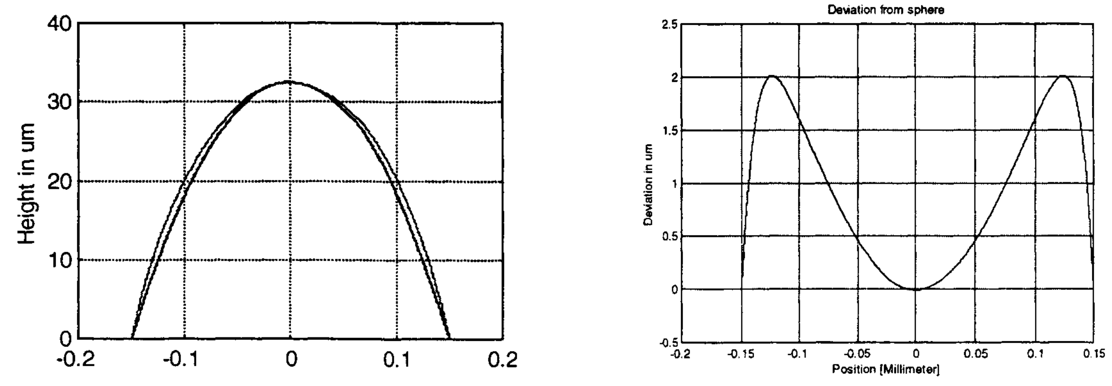

Figure 7: Surface profile and deviation from perfect sphere for photoresist microlens. The lens has a diameter of 300 μm and a height of 31.5 μm.

Figure 8 shows the obtained profile and the deviation from a perfect sphere after the transfer process. The selectivity between the original photoresist element and the final fused silica microlens is in the order of 10 to 1. As the dimensions are much smaller, spherical aberrations are also more tolerable.

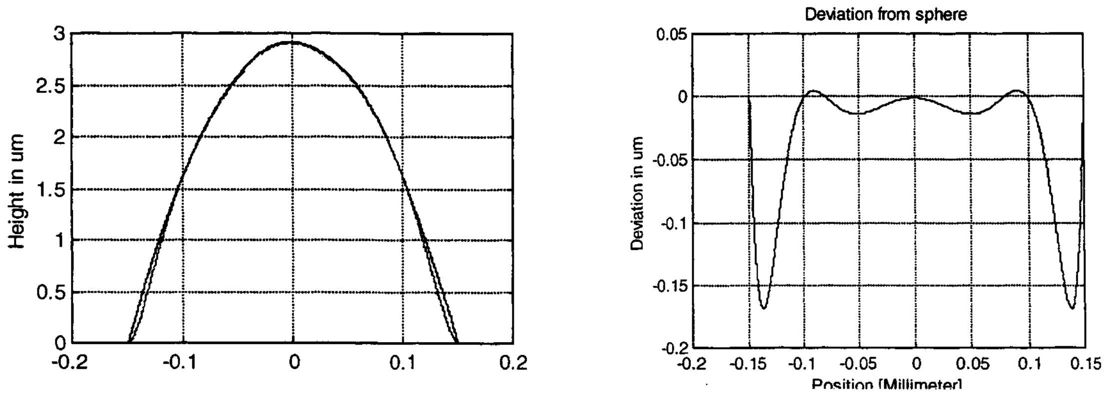

Figure 8: Surface profile and deviation from perfect sphere for very low NA fused silica microlens. The lens has a diameter of 300 μm and a height of 3 μm.

It can also be noticed that the shape of the lens has been modified. The original photoresist microlens has a maximum deviation from a perfect sphere of + 2 μm, whereas the final fused silica low NA microlens has a maximum deviation to a perfect sphere of - 0.16 μm.

3.4 Shape modification of micro-optical structures

The optical performance of refractive microlenses can be further improved by realizing aspheric surface profiles or by correcting errors of the ideal surface profile. Starting with a photoresist lens (melting resist technology), the shape of the profile can be modified during the etch process. Figure 9 shows the profile and the corresponding deviation from a perfect sphere of a photoresist refractive microlens having a diameter of 300 μm and a height of 31.5 μm. The surface profile presents a strong ellipticity with a maximum deviation from a perfect sphere of + 2 μm.

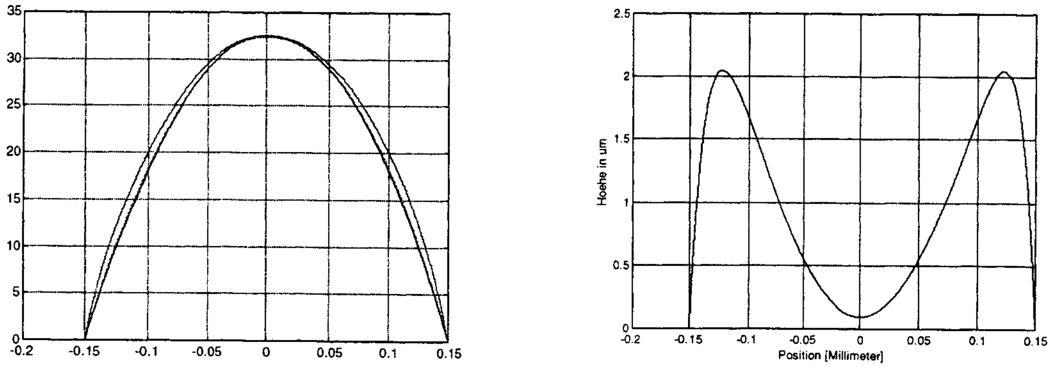

Figure 9: Photoresist microlens surface profile and deviation from perfect sphere. The lens has a diameter of 300 μm and a height of 31.5 μm.

After the transfer process using RIE, the obtained fused silica refractive microlens shows nearly the same overall dimensions. Figure 10 illustrates the surface profile and the corresponding deviation from a perfect sphere of the fused silica microlens. The diameter is still 300 μm but the height of the microlens has been reduced to 23 μm. The final fused silica element has a strong hyperbolic surface profile with a maximum deviation to a perfect sphere of - 1.8 μm.

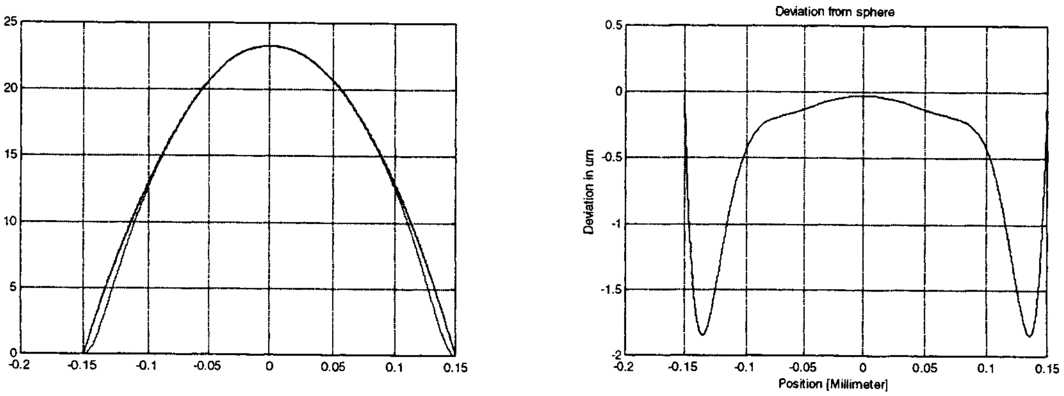

Figure 10: Etched fused silica microlens surface profile and deviation from perfect sphere. The lens has a diameter of 300 μm and a height of 23 μm.

4. CONCLUSION

We have presented the potential of reactive etching for the transfer of micro-optical structures into fused silica. The original photoresist surface-relief structures have been realized by various lithographic techniques, such as direct laser-beam writing, graytone lithography using HEBS glass mask blanks, melting resist technology and standard mask projection lithography. The photoresist elements include diffractive lenses with continuous surface-relief profiles, refractive microprisms, refractive microlenses and finally deep binary microstructures.

Reactive ion etching enables the accurate transfer of micro-optical structures from photoresist into fused silica. The transfer process can be adapted in order to get structures with the same depths as the original using a 1:1 selectivity. The vertical dimensions can also be amplified (selectivity of 1:100) or reduced (selectivity of 10:1). Finally, the transfer by etching can perform accurate surface shape modifications. We fabricated continuous surface-relief diffractive lenses, refractive microprisms, low aperture refractive microlenses, high aspect ratio binary microstructures and finally aspheric refractive microlenses. Using appropriate process parameters, etch rates around 300 nm/mn have been achieved. The surface of the etched fused silica micro-optical elements showed very smooth optical surfaces, values around 5 nm (RMS) have been observed.

Fused silica presents excellent performances for most optical applications. However, the transfer of structures by using reactive ion etching into other special materials, such as silicon, calcium fluoride, gallium arsenide, indium phosphide are more and more required. The fact that dry etching can be applied to other materials is a strong stimulation for future investigations.

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