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Low numerical aperture refractive microlenses in fused silica

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1 Introduction

The realization of high quality refractive microlenses is well known and has been reported several times in the past.[1] Various fabrication techniques have been used to obtain accurate surface-relief refractive microlenses. Well known are direct writing techniques and graytone lithography. In direct writing, a laser or an e-beam shapes the surface of the microlens in photoresist.[2,3] In the case of graytone lithography, the photoresist layer is exposed by UV light passing through a mask that has different graytone densities over the surface.[4] Another promising technique for the fabrication of refractive microlenses is the so-called melting resist or reflow method.[5,6,7] Photoresist cylinders are formed by photolithography and subsequent melting. Surface tension forms plano-convex microlenses.[8] Because of the physical properties of the fabrication step, the possible geometry of the microlenses is limited. In addition, a minimum photoresist volume is required to enable the formation of a spherical surface. Thus, numerical apertures (NA) of refractive microlenses realized by melting resist technology are limited to $\mathrm{NA} > 0.1$.

Dry etching plays an important role in the fabrication of micro-optical elements.[9,10] The transfer of photoresist structures into rigid materials, e.g., fused silica, shows several advantages, such as the robustness of the elements and the higher transmission at UV wavelengths. In addition, the dry etching transfer step allows the modification and control of the dimensions and shapes of refractive microlenses. A variable amplification or reduction of the vertical dimension of the structure is possible. Melting resist technology combined with low selectivity etching present a big potential for the fabrication of low NA refractive microlenses. This fabrication method reveals new domains of applications where the use of melting resist microlenses has been limited up to now. Recent results on the realization of fused silica refractive microlenses having low numerical apertures are presented. We summarize the limitation of the melting resist method with respect to the dimensions and forms of the microlenses. Nonproportional transfer using reactive ion etching is explained and commented. In particular, low selectivity etching is applied for the fabrication of low numerical aperture refractive microlenses in fused silica.

2 Melting Resist Technology and Its Limitation

The most promising fabrication technique for refractive microlenses is the so-called melting resist or reflow technology. Photoresist cylinders are formed by lithography and subsequent melting. Surface tension forms plano-convex microlenses.[8] Lithography into thick photoresist layers (10 to 50 μm) is limited by diffraction to an aspect ratio of 4. Thus, with the standard fabrication process, the gap between the lenses has to be larger than one quarter of the thickness of the photoresist layer.

Another limitation is the contact angle at the rim of the lens given by the materials (lens and substrate). Therefore, the ratio between diameter and height of the microlens is important to avoid a deformation of the microlens in the center. For example, this ratio (diameter/height) should be less than 16 for a microlens of diameter 350 μm. Consequently, the numerical aperture of refractive microlenses realized by the melting resist technique is limited to values higher than 0.1. For smaller NA, a dip occurs in the center during the melting process.

The possible surface shape generated by the melting resist process (in the ideal case spherical) may differ from the desired geometry of the microlens (aspheric shape and low NA). Corrections are therefore required during the etching process.

3 Nonproportional Transfer Using Reactive Ion Etching

The transfer of photoresist micro-optical structures into rigid materials such as glass, fused silica, or silicon is possible using reactive ion etching (RIE).[7,9,10] In dry etching, using RIE, atoms from the photoresist surface and the fused silica substrate material are removed simultaneously by energetic ions until the shape is completely transferred into the fused silica substrate. We work with an inductively coupled plasma (ICP) reactive ion etching system from Surface Technology Systems Limited (STS Ltd.). By using a fluorocarbon-based chemistry, standard selectivity between photoresist and fused silica ranging from 1.2 to 0.8 are obtained at etch rates around 300 nm/mn.[11,12] With the use of an adequate wafer cooling, pitting of the surface can be avoided and the surface roughness measured with an atomic force microscope is in the order of 3 nm (RMS).

The values mentioned before for the etch selectivity allow the modification of the initial surface shape to fabricate aspheric lenses.[12] However, this modification is not enough to realize flat microlenses with $\mathrm{NA} < 0.1$. If we want to use the melting resist technology, a much lower etching selectivity between photoresist and fused silica is required. This is possible by using a gas mixture composed of SF_6 and O_2. We have obtained selectivity smaller than 0.1 by using a gas mixture composed of SF_6 and O_2. Since the photoresist plano-convex microlenses with a height of 31.5 μm for a diameter of 300 μm present a good spherical shape, it is used as a starting point for the transfer. The process parameters for the etching step are: platen power 250 W, coil power 600 W, chamber pressure 3 mT, wafer temperature 20°C, the SF_6 flow rate 3 sccm, and the amount of O_2 was reduced from 33 to 18 sccm over the whole process. This

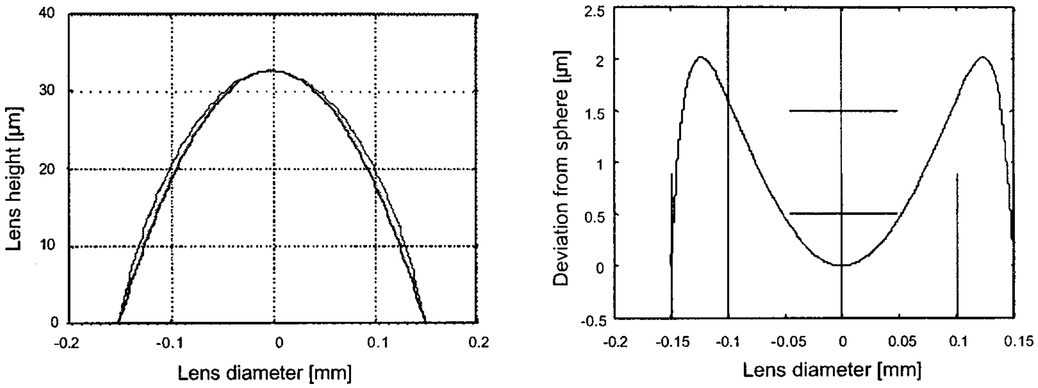

Fig. 1 Surface profile and deviation from sphere of a photoresist plano-convex microlens (diameter 300 μm, height 31.5 μm), measured with a Mach-Zehnder interferometer.

reduction of the amount of O_2 in the gas mixture reduces the selectivity between photoresist and fused silica, avoiding the final fused silica microlenses to become too steep in the rim region. The total etch process time was around 50 min. After processing, fused silica plano-convex refractive microlenses with a diameter of 300 μm and a height of 3 μm have been obtained.

4 Characterization Methods

Various accurate measurement systems are available for the characterization of micro-optical elements. However, adequate and dedicated tools have to be used.[7] At the different stages of the fabrication process, inspections and measurements take place. A first general visual inspection is performed with a standard optical inspection microscope. Eventual defects and overall aspect are observed. A mechanical stylus profilometer from Tencor is used to measure various heights of the photoresist layer and the final height of the microlenses. A mechanical stylus profilometer is an accurate tool for the measurement of height differences in microtechnology, but has poor performances for the measurement of the lens shape because of the mechanical contact of the stylus to the micro-optical structure during the scan. Another problem is the size of the stylus. The rim region of the microlenses cannot be inspected because the stylus is in general much larger than the small gap between the microlenses. For a more accurate measurement of the microlens shape, interferometric inspection is applied.[13,14] We used a Mach-Zehnder interferometer with a quantitative phase evaluation based on phase shifting interferometry. In the test arm of this interferometer, the microlens under test is illuminated with an expanded plane wave from a Helium-Neon laser ($\lambda = 633\,\text{nm}$). The plano-convex microlens generates a spherical wavefront. This spherical wavefront is recollimated using a high quality microscope objective having very small aberrations. The superposition of the plane waves of the reference and the test arm produces an interferogram that describes the aberrations of the wavefront generated by the microlens. From the wavefront deviations, it is possible to calculate precisely the surface profile of the microlens. The Mach-Zehnder interferometer is working in transmission. Special care has to be taken for the measurement of photoresist microlenses because of the eventual inhomogeneity of the refractive index. For the final elements in fused silica, this effect is less important.

5 Results

Refractive cylindrical microlens arrays have been realized in photoresist by using the melting resist technique. The elements in photoresist have been analyzed by measuring their profile with a Mach-Zehnder interferometer. The corresponding deviation from a perfect sphere has been calcu-

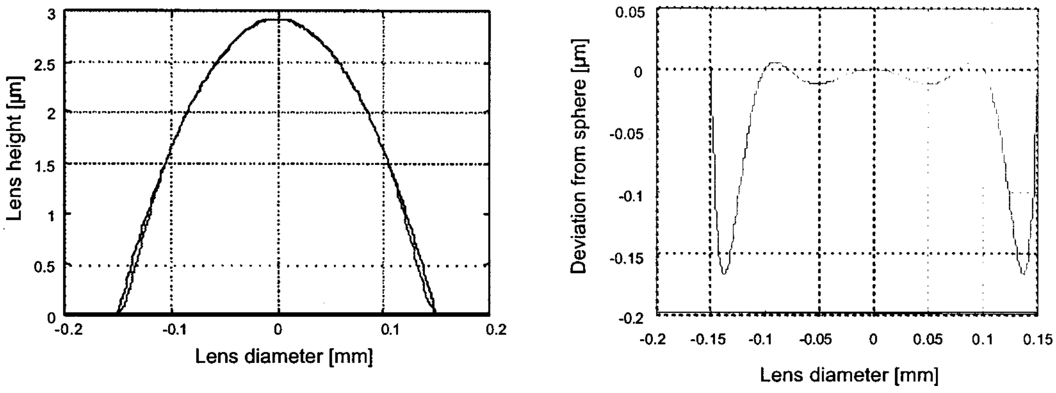

Fig. 2 Surface profile and deviation from perfect sphere of a fused silica plano-convex microlens (width 300 μm, height 3 μm), measured with a Mach-Zehnder interferometer.

lated from the measured wavefront. Figure 1 shows the surface profile and the deviation from the sphere of a photoresist plano-convex microlens having a diameter of 300 μm and a height of 31.5 μm. The NA is $=0.21$.

From Fig. 1, it can be noticed that the maximum deviation from the perfect sphere is in the order of $+2$ μm. The measurement of the height of the photoresist microlenses using a mechanical stylus profilometer revealed a homogeneity of $\pm 2\%$ over the 75-mm round area of the microlens array.

From this microlens array in photoresist ($\mathrm{NA}=0.21$), low NA refractive microlenses have been realized in fused silica by RIE. With the low selectivity etching process described, we obtained microlenses with a final height of 3 μm. The resulting NA is 0.018. Figure 2 illustrates the surface profile and the deviation from a perfect spherical profile of the transferred fused silica element.

With the Mach-Zehnder interferometer, we measured a maximum deviation from a perfect spherical profile of -0.17 μm.

6 Conclusion

We present the results of our work concerning the fabrication of fused silica microlenses with low NA. The original photoresist element has been realized by the melting resist technology and has then been transferred into fused silica by reactive ion etching. Low selectivity etching has been applied to realize the low NA microlenses. An etch selectivity between photoresist and fused silica down to 0.1 has been achieved by using SF_6 and O_2 gases. Refractive microlenses with NAs down to 0.018 have been obtained. Smaller NAs are possible by using a lower concentration of the SF_6 gas. Low NA refractive microlenses are required for Shack-Hartman wavefront sensor applications to increase the sensitivity of the sensor. Of course, other microfabrication methods (laser beam writing and graytone lithography) allow the realization of this type of element, but the melting technique yields a very well defined and smooth surface profile. The measured surface roughness is in the order of 3 nm (RMS). Reactive ion etching is an ideal method to transfer, modify, and reduce the surface profile of refractive microlenses. However, because of the big amount of burned photoresist and the generation of a lot of polymer material, this transfer process is rather dirty for the etching chamber. Regular mechanical cleaning of the system is required to ensure good quality and a reproducible process.

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