Refractive Microlens Arrays made by Deep Lithography with Protons: technology and characterisation.

H. Ottevaere[1], B. Volckaerts[1], M. Muruzabal[1], A. Vila[1], P. Vynck[1], P. Tuteleers[1], V. Baukens[1], J. Lamprecht[2], J. Schwider[2], A. Hermanne[3], I. Veretennicoff[1] and H. Thienpont[1]

[1] Vrije Universiteit Brussel, Dept. of Applied Physics and Photonics (TW-TONA), Pleinlaan 2, 1050 Brussels, Belgium
tel.: ++32 2 629 34 51, fax: ++32 2 629 34 50, e-mail: hottevaere@alna.vub.ac.be
[2] Universität Erlangen-Nürnberg, Physikalisches Institut, 91058 Erlangen, Germany
[3] Cyclotron Department VUB, Laarbeeklaan 103, 1090 Brussels, Belgium

ABSTRACT

The development of high-quality microlens arrays with MicroOptoMechanical (MOMS) fabrication technologies is of crucial importance if we want to integrate these micro-optical components with optoelectronic devices and take full advantage of their utilisation potential in photonic information processing applications. In this paper we discuss critical parameters such as the applied proton dose, the diffusion temperature and diffusion time involved in the fabrication of microlenslet arrays using deep lithography with protons. We highlight their influence on the shape, the dimensions and the uniformity of the microlenses. Finally we present the experimental optical performances of e.g. 10x10 lenslet arrays with focal numbers ranging from 0.83 to 7.22.

INTRODUCTION

Deep proton lithography in PMMA (Poly Methyl MethAcrylate) is a MOMS-technology where the lens fabrication process consists of two basic steps: the selective bombardment of a PMMA substrate with low-energy protons followed by a swelling of the irradiated regions with an organic monomer vapor [1]. In this way refractive microlenses can be fabricated with high numerical apertures for a wide range of diameters. During the irradiation the PMMA sample is covered with a patterned high-precision metal LIGA-mask which is only transparent for the proton beams at the apertures. The shape of this non-contact mask is directly projected onto the PMMA sample where impinging high-energy protons create well-defined domains with reduced molecular weight. The process is based on the fact that ions transfer

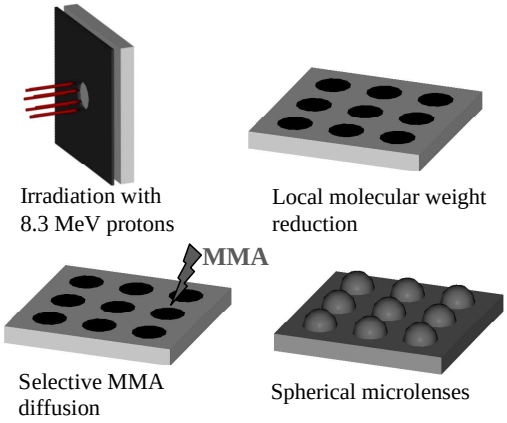

Figure 1: Basic fabrication process of deep proton lithography for an array of spherical microlenses

energy to the PMMA molecules while propagating in the substrate. This interaction causes molecular chain scissions, reducing the molecular weight of the polymer and changing the chemical properties of the material [2]. Only those zones featuring a low enough molecular weight will be receptive to organic monomer material through an in-diffusion process of an organic monomer material. During this process there is almost no chemical reaction between the broken polymer chains and the in-diffused molecules. However the in-diffusion of the monomer causes a volume expansion resulting in a hemi-spherical surface. Thus refractive microlenses can be fabricated with low focal numbers over a wide range of diameters D, corresponding to the circular apertures available on the lithographic LIGA-mask. A thermal stabilization procedure finally prevents the out-diffusion of the MMA monomers and fixes the shape of the microlenses. Two factors are influencing the above mentioned irradiation process: the average molecular weight in the irradiated region and the volume of this region.

- The molecular weight can be controlled by the dose deposition. We have observed that when the dose is too low the molecular weight of the irradiated region is too high to allow a sufficient in-diffusion of the MMA monomer to cause a volume expansion. Too high a dose on the other hand will result in a local temperature increase which destroys the sample.
- The shape of the irradiated volume is a cylinder with a circular footprint diameter D equal to the circular aperture in the mask and a height determined by the penetration depth d_{pen} of the protons and therefore by their energy (Figure 2).

The volume expansion strongly depends on the amount of monomer diffused into the irradiated zones. We can control this amount through the injected monomer volume, the diffusion time and the temperature. Furthermore both diffusion time and temperature limit the range in which lens-like shapes are practically achievable. Too short a diffusion time leads to an insufficient volume expansion while too long a diffusion time will destroy the sample. On the other hand the temperature has to be sufficiently high to create the monomer vapor phase while too high a temperature will start the substrate material to flow.

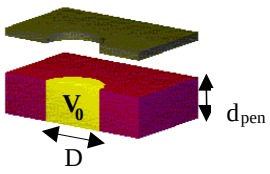

Figure 2: Definition of the parameters after the irradiation process

FABRICATION & CHARACTERIZATION PROCESS

An accurate calibration of the swelling process is necessary to perfectly predict the height and the radius of curvature R of the lenses, and hence their focal lengths f and focal numbers f/#. All these parameters are related by the formulas $R = \frac{h^2 + \left(\frac{D}{2}\right)^2}{2h}$, $f = \frac{R}{n-1}$ and $f/\# = \frac{f}{D}$ in the paraxial approximation with h and D respectively the height and the diameter of the microlenses.

For calibration purposes we have irradiated a sample with 8.3 MeV protons with doses ranging from 0.1 nC to 1 nC in steps of 0.1 nC. After irradiation this sample was placed in a temperature controlled reactor at 90°C, next MMA was injected with a syringe while a pressure probe was used to detect a possible leakage of the reactor. Diffusion

then took place during 50 minutes. Finally the microlenses were stabilised by reducing the temperature to 70°C and sustaining it for 4 hours (Figure 3). The dimensions of the microlenses were measured in transmission mode with a Mach-Zehnder Interferometer and in reflection mode with a vertical scanning non-contact optical profiler. All lenses in this 10x10 array had a diameter of 200µm and a pitch of 250 ± 4 µm. Their heights ranged from 9.77 to 69.73 µm corresponding to a range of focal numbers between 0.83 and 7.22 with standard deviation flags as plotted in Figure 4. To investigate the reproducibility of these results we have done the same experiment on another irradiated sample using the same irradiation and diffusion parameters. From Figure 4 we can conclude that both experiments (exp 1 & 2) give the same results within the deviation error.

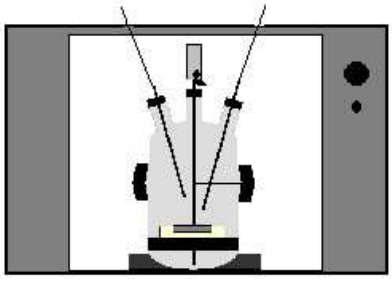

Figure 3: Experimental diffusion set-up

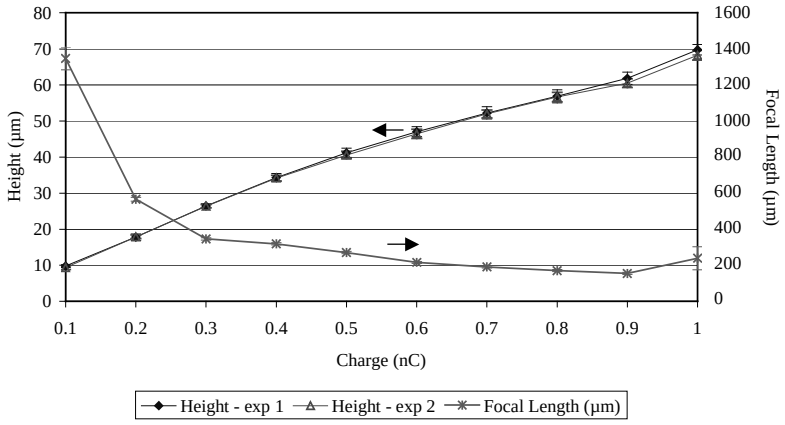

Figure 4: Height and Focal Length (µm) as a function of the proton charge (nC)

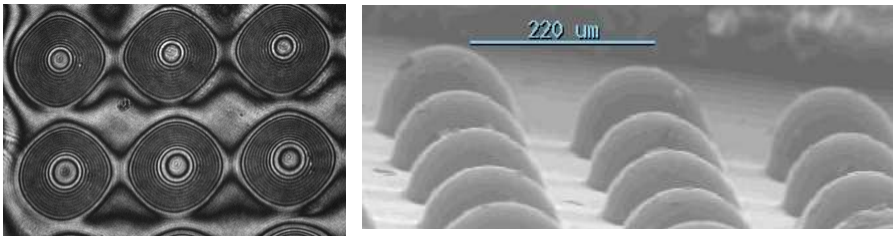

Figure 5: (a) Mach-Zehnder transmission interferogram of an array of spherical microlenses illuminated with a plane wave; (b) SEM picture of lenslet array

The optical quality of the microlensarrays has also been studied with the Mach-Zehnder Interferometer. From the obtained interferometric results (Figure 5(a)) one can calculate the aberrations and point spread function of the microlenses under test via a Fast Fourier Transformation (FFT). Figure 6 (a,b,c) shows respectively the Spherical Aberration, Coma and Astigmatism of the studied microlensarray, obtained after fitting with the Zernike polynomial [3]. The Strehl Ratio is defined as the normalized peak intensity of the point spread function of the lens and is displayed in Figure 6(d). In the future we will continue to use this characterization method to give a feedback to the deep proton lithography fabrication parameters and to further optimize the quality of the microlenses.

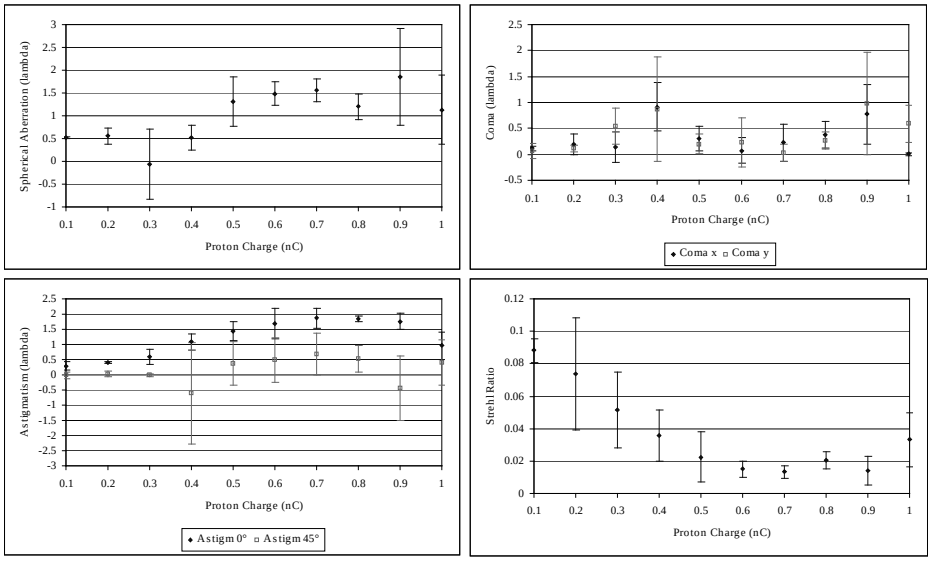

Figure 6: (a) Spherical Aberration; (b) Coma; (c) Astigmatism; (d) Strehl Ratio as a function of the proton charge (nC)

CONCLUSION

In this paper we have described a method to fabricate spherical microlenses by deep proton lithography. We discussed the impact of different process parameters on the microlens characteristics and reported on the first successful realization of uniform arrays of these components.

REFERENCES & ACKNOWLEDGMENTS

This work is funded partially by the European Commission ESPRIT-MELARI project 22641 “OIIC”, partially by DWTC IUAP 13, FWO, GOA, IWT ITA II-GBO and the OZR of the Vrije Universiteit Brussel. The authors thank Stefaan Helderweirt for the technical support during this work.

[1] H. Thienpont, et al, “Plastic Micro-Optical Interconnection Modules for Parallel Free-Space intra MCM Data Communication”, *Proceedings of the IEEE, Special Issue on 'Short distance Optical Interconnects for Digital Systems*, Vol. 88, No. 2, June 2000.
[2] B. Volckaerts et al., “Deep lithography with protons for the fabrication of refractive micro-optical modules”, *in Proceedings of 5th Annual Symposium of the IEEE/LEOS Benelux Chapter*, 2000.
[3] http://www.optik.uni-erlangen.de/Move/