UNIFORM 2D PLASTIC MICROLENS ARRAYS MADE WITH DLP: A FOCUS ON FABRICATION AND CHARACTERISATION ISSUES.

H. Ottevaere[1], B. Volckaerts[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 and uniform 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 the critical parameters involved in the fabrication of plastic microlenslet arrays using Deep Lithography with Protons (DLP). We highlight the geometrical dimensions, the shape, the uniformity and the optical characteristics of the individual 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

Refractive micro-optical and mechanical structures are playing more and more important roles in many optical systems. 2D arrays of spherical microlenses are likely to be combined with other micro-optical structures and with opto-electronic emitters, receivers and optical fibres to play a key-role in optical sensor arrays, in high definition display and projection systems, in biomedical technology and in optical interconnection technology [1]. In this paper we will focus on spherical microlenses for which different fabrication technologies already exist today. Photothermal techniques, photoresist reflow, ion diffusion, e-beam or laser direct writing and microjet printing are some conventional fabrication methods for high-quality 2D arrays of microlenses [2]. However, technologies that fabricate arrays of uniform refractive microlenses with different diameters and a wide range of numerical apertures are scarce. Therefore we have chosen for the DLP process that consists of a proton irradiation of a PMMA-layer in well-defined regions, followed by a volume expansion of the bombarded zones caused by a diffusion of an organic monomer vapour. This fabrication method allows fabricating monolithic, robust, replicable and therefore low-cost modules that integrate these microlenses with other micro-optical components.

FABRICATION

Deep Lithography with Protons (DLP) in Poly Methyl MethAcrylate (PMMA) is a MOMS-technology where the lens fabrication process consists of two basic steps: the selective bombardment of a PMMA substrate with high-energy protons followed by a swelling of the irradiated regions with an organic monomer vapour. 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 high-aspect ratio mask that is only transparent for the proton beams at the apertures. The circular shape of this non-contact mask is directly projected onto the PMMA sample where impinging high-energy protons create free radicals and well-defined domains with reduced molecular weight. The process is based on the fact that ions transfer 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. 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 a polymerisation 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 high-aspect ratio mask. A thermal stabilisation procedure finally prevents the out-diffusion of the MMA monomers and fixes the shape of the microlenses by further polymerisation. Two factors of the above mentioned irradiation process are influencing the fabrication process: the free radicals and the average molecular weight in the irradiated region and the volume of this region.

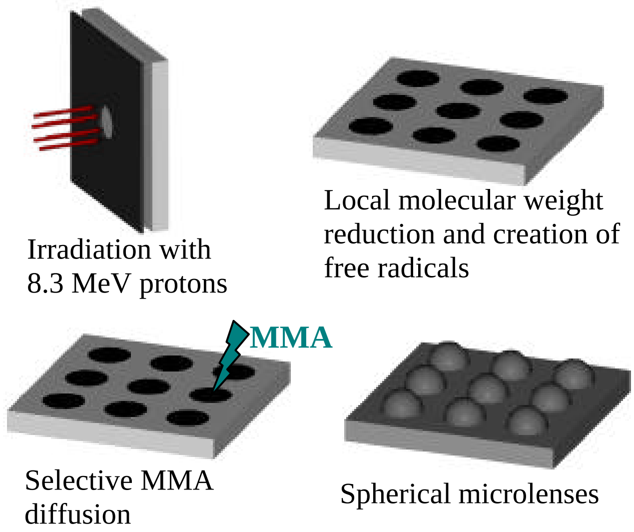

Figure 1: Basic fabrication process of deep lithography with protons for an array of spherical microlenses

- The molecular weight can be controlled by the proton charge 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 that destroys the sample during the irradiation.
- 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 thickness of the sample.

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 vapour phase while too high a temperature will start the substrate material to flow.

SET-UP AND OPTICAL CHARACTERISATION METHODS

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 proton charges 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 (Figure 2), 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 200 µm microlenses were stabilised by reducing the temperature to 70 °C and sustaining it for 4 hours.

Figure 2: Experimental diffusion set-up

A good knowledge of the actual lensprofile is required for the optimisation of the fabrication procedure. Various optical and mechanical methods are available to characterise the physical and optical properties such as surface profile, surface roughness, wave aberrations, uniformity of the focal length, transmission, refractive index, ... In this paper we will focus our attention on some of these characteristics obtained by interferometric measurements.

Non-Contact Optical Profilometer

The geometrical dimensions and the height of the microlenses were measured in reflection mode with a vertical scanning non-contact optical profiler. All lenses in this 10x10 array had a diameter of 200 ± 2 µm, a pitch of 250 ± 4 µm and a RMS roughness on top of the lens of λ/30 @ 632 nm (Figure 3). Their heights ranged from 9.77 to 69.73 µm 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 error margin of the instrumentation. The studied 10x10 lenslet arrays have a lens density D_n of 16.66 mm^{-2} and a fill factor η of 52.3%. The latter can be enhanced by using a hexagonal packed array or by increasing the lens diameter while retaining the pitch at 250 µm.

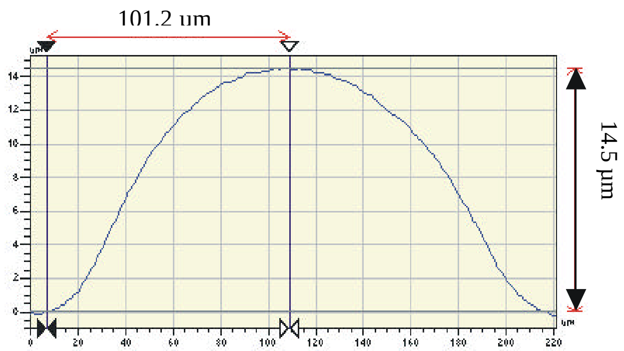

Figure 3: 14.5-µm high spherical microlens measured with a non-contact optical profiler (WYKO NT2000)

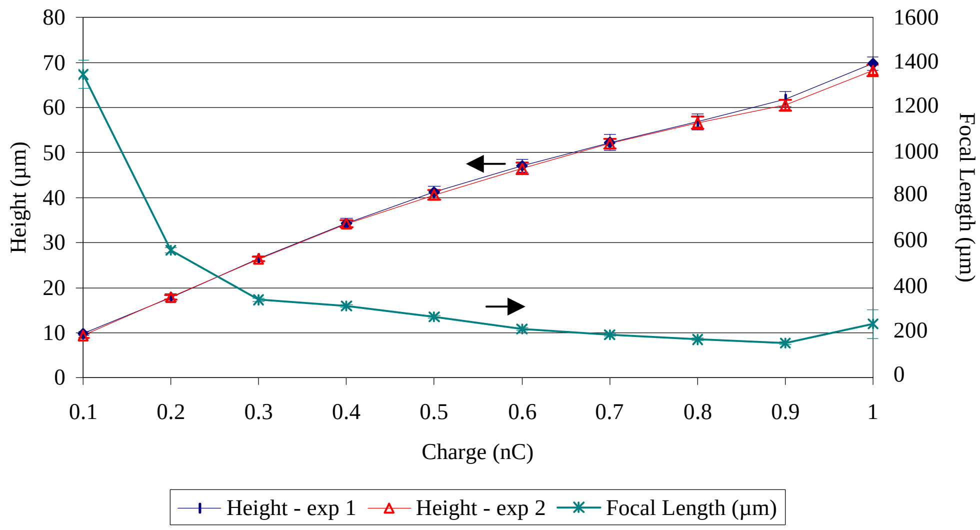

Figure 4: Height and Focal Length (µm) as a function of the Proton Charge (nC)

Interferometric microlens testing

A Mach-Zehnder interferometer that makes use of the method of phase shifting interferometry, was used here to measure the optical aberrations of the lenses [3]. Additionally, the focal lengths of the lenslet array under study have been determined and vary between 166 and 1444 µm corresponding to a range of heights between 9.77 and 69.73 µm (Figure 5). In our applications refractive microlenses are used for on-axis imaging. In that case only the spherical aberration (SA) will differ from zero and not the other 3th order aberrations like coma and astigmatism. Therefore we will only discuss here the SA and compare the measured value with the theoretical SA value of a perfect spherical shaped microlens for the same lens height. The theoretical SA values for each corresponding height are obtained via raytracing simulations with the software package SOLSTIS. As can be seen in Figure 5, from a certain proton charge the measured SA decreases when the height increases. The aspherical shape of the higher lenses that compensates the SA is responsible for this effect. In the future we will continue to use this characterisation method to give a feedback to the DLP fabrication parameters and to further optimise the quality of the microlenses.

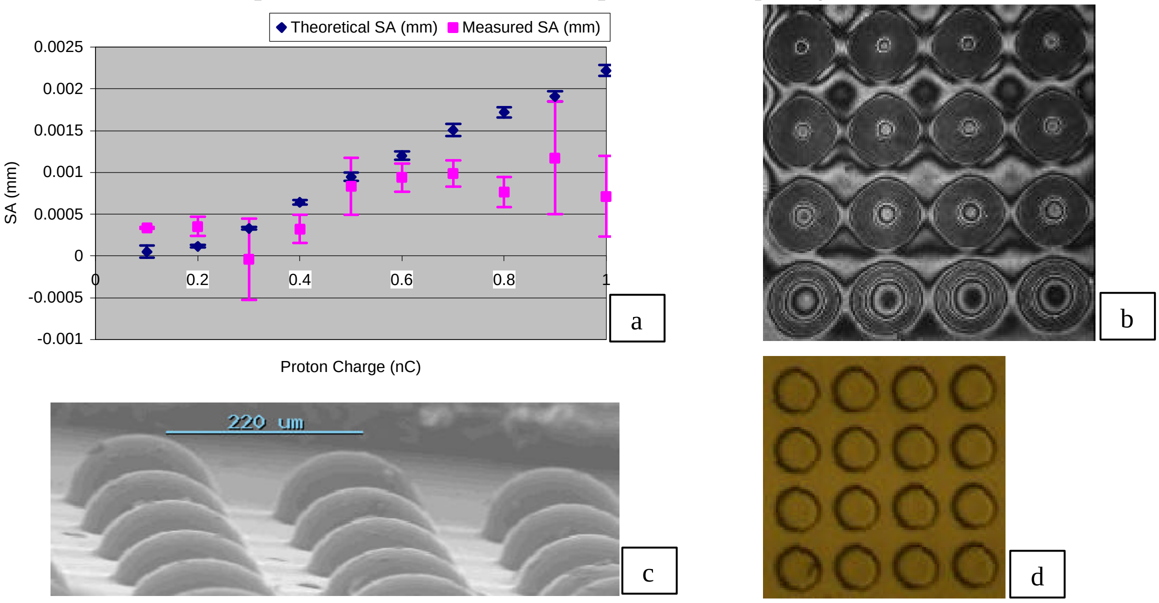

Figure 5: (a) Comparison of theoretical SA of a perfect shaped microlens and measured SA as a function of the proton charge; (b) Mach-Zehnder transmission interferogram of an array of spherical microlenses illuminated with a plane wave; (c) SEM picture of the lenslet array; (d) Picture of the microlens array under test

CONCLUSION

In this paper we have described Deep Lithography with Protons as a fabrication method for spherical microlenses. We reported on geometrical and optical characteristics of our first successfully realised uniform microlens arrays. At the conference we will highlight our latest results on the fabrication and the characterisation of spherical microlenses made with DLP and compare our results to state-of-the-art fabrication technologies.

REFERENCES & ACKNOWLEDGMENTS

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