Deep Lithography with Protons for mastering refractive micro-optical components and modules

B. Volckaerts, H. Ottevaere, M. Vervaeke, P. Vynck, C. Debaes, R. Krajewski, P. Tuteleers, A. Hermanne and H. Thienpont

Department of Applied Physics and Photonics (TW-TONA),
Vrije Universiteit Brussel, Pleinlaan 2, 1050 Brussels, Belgium
tel.: ++ 32 2 629 3451, fax: ++ 32 2 629 3450, bvolckaerts@tona.vub.ac.be

In this paper we present the state-of-the-art of Deep Lithography with Protons, a technology that we have optimized to rapidly prototype three-dimensional refractive micro-optical components and high aspect-ratio micro-mechanical structures in optical-quality PMMA. We illustrate the potentialities of this technology by highlighting the characteristics of various in-house made components.

Introduction and rationale

During the last decades the use of photonics in numerous industrial applications brought plenty of prospects for innovation and opened different unexplored market opportunities [1]. Refractive micro-optical and mechanical structures like 2D arrays of spherical micro-lenses, micro-prisms and cylindrical micro-lenses or mechanical positioning structures like 2D fibre array holders are likely to be combined 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 invasive medical technology and in optical interconnection technology. This vast domain of applications is a major driving force behind the recently increased interest in the fabrication of these micro-optical and mechanical structures (MOMs) and their accurate alignment and integration in opto-mechanical modules. Today different technologies exist that allow the fabrication of individual high-quality micro-optical refractive components. Technologies that allow to fabricate monolithic, robust and replicable modules that integrate these individual micro-optical components are however scarce. To our knowledge only two generic technologies have been engaged up-to-now to combine high-quality optical surfaces and micro-lenses with micro-mechanical alignment features. A first technology is “silicon surface micro-machining” and allows the fabrication of poly silicon micro-opto-electro-mechanical structures (MOEMs) [2, 3, 4]. Deep lithography with UV-light and X-rays is a second group of fabrication technologies for MOMs. The main advantage of this so-called LIGA-technology (Lithografie, Galvanotechnik and Abformung) is its compatibility with hot-embossing and injection-molding so that the plastic master components can be mass-produced at low cost in a variety of high-tech materials [5, 6, 7].

In this paper we present a third candidate technology dedicated to the fabrication of three-dimensional micro-opto-mechanical systems, namely Deep Lithography with Protons (DLP or p-LIGA). Its concept is somewhat similar to that of LIGA, but it uses ions rather than electromagnetic radiation to structure and shape the PMMA-layers. The fabrication process consists of three basic procedures: a patterned proton irradiation of polymethyl metacrylate (PMMA) samples followed by either an etch removal of the irradiated regions with a specific developer or a swelling procedure involving a diffusion of an organic monomer vapor. If required both processes can be applied to the same sample [8, 9].

Patterned irradiation with high-energy ions

The principle of the DLP process is based on the fact that ions transfer energy to the PMMA molecules while propagating in the substrate [10]. These interactions cause molecular chain scissions, reduce the molecular weight of the polymer and change the chemical properties of the material. In our experiments we have used protons with a specific energy of 8.3MeV making it possible to cut through 500µm thick PMMA samples. By accurately controlling the dose of the irradiated zones we can engineer the change in molecular weight such that we make the irradiated zones susceptible to either a binary chemical solvent or an in-diffusion of a monomer vapor (Fig. 1).

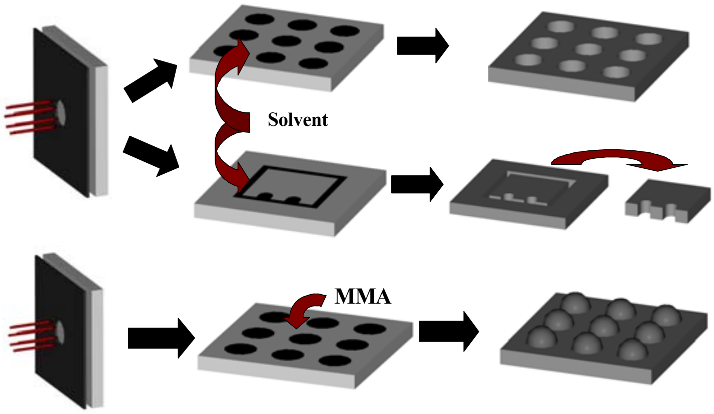

Fig. 1: Basic fabrication processes of DLP.

Selective development of micro-opto-mechanical components

The irradiated domains can be selectively dissolved with a special solvent, because they show higher solubility than the non-irradiated domains. In this way a huge variety of micro-structures can be micro-drilled or cut with high precision. The quality of the resulting structures during the irradiation is determined by the magnitude of the scattering effect of the impinging protons, by the precision of the movement of the translation stages and by the homogeneity of the deposited dose. A first micro-structure, we will report on, is a 2D optical fiber holding plate consisting of a micro-hole array with well-defined circular shapes corresponding to the cladding diameter of the optical fibers to be inserted. By enforcing the scattering effect of the protons in the irradiated zones, conical micro-hole profiles can be realized featuring a diameter enlargement over the depth of the coupling plate of 40µm and more. We proved that these conical shapes allow for an easier fiber insertion which opens perspectives to meet the stringent requirements of fiber connecting elements in Local Area Network applications. We depict in Figure 2 a part of a large array of micro-holes featuring a pitch of 250 ± 0.5µm and an individual hole diameter of 125 ± 2 µm [11].

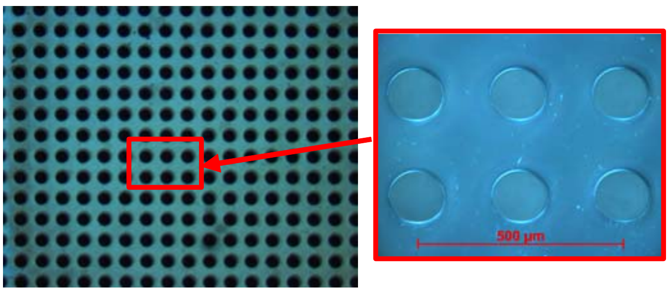

Fig. 2: Large micro-hole array for fiber positioning

Alternatively to the irradiation of 2D point arrays for the fabrication of micro-holes, we are able to continuously translate the PMMA-target plates in the proton beam while precisely defining rectangular volumes with a degraded molecular weight. After a chemical development, these bombarded zones can be removed and trenches with a depth of 500µm over lengths of several mm will be created. Because of the local energy deposition of the proton particles, we are able to fabricate high-quality surfaces with an optical flatness of lambda/10 over a length of 2.5mm and an RMS roughness of 20nm. These performances allow us to fabricate micro-optical prisms (Fig. 3).

Fig. 3: A micro-prism with mounting features before (a) and after (b) the etching process

By following the same irradiation procedure as for the micro-prisms, we can fabricate cylindrical micro-lenses by translating the PMMA-plate continuously in the proton beam according to predefined curved lines [12]. Here we take advantage of the 50nm precision of our two-axial translation stage to structure smoothly curved lens shapes. After applying a selective etching procedure on these samples we have been able to obtain arrays of cylindrical micro-lenses with curvatures ranging from 1mm to 2mm and chords from 200µm to 1mm. In Figure 4 we show a 1D fiber holder structure that monolithically integrates this type of cylindrical micro-lenses with fiber alignment grooves that are located along the optical lens axis.

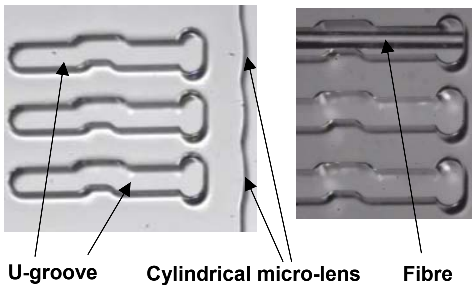

Fig. 4: Top view of a 1D fiber holder featuring cylindrical micro-lenses and U-grooves.

Monomer in-diffusion for the fabrication of 2D-spherical micro-lenses

Alternatively to dissolving the irradiated zones we can swell them by exposing them to an organic MMA monomer vapor. Indeed, when regions feature a low enough molecular weight they can be receptive to an in-diffusion process of an organic monomer which results in a volume expansion. This way an irradiated region with a circular footprint will result in a hemi-spherically shaped micro-lens [13]. A polymerization procedure finally prevents the out-diffusion of the monomers and fixes the shape of the micro-lenses. The detailed physics and procedures behind this process will be extensively described during this conference by H. Ottevaere et al. As a case study, we have fabricated an optical interconnection module (OIM) to realise an intra-chip 2D parallel optical data link. This structure consists of a micro-prism accurately positioned on a baseplate that features micro-lens arrays to improve the light coupling efficiency through the parallel data link (Fig.5).

After aligning the OIM above a 2D emitter and a detector array on a CMOS chip, we recently demonstrated high-bandwidth data communication of 622 Mb/s [14].

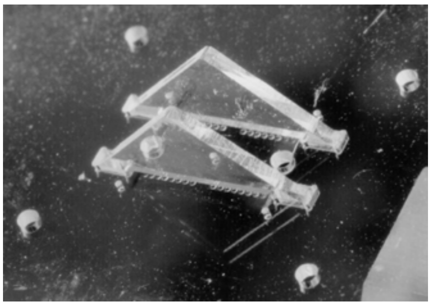

Fig. 5: Assembled free-space 2D multi-channel interconnection module with spherical micro-lenses with mechanical alignment holes.

Conclusions and perspectives

In this paper we have shown how we have developed the technology of Deep Lithography with Protons to a level where it can yield basic optical structures and components for the fabrication of precision three-dimensional refractive micro-optical systems. In the near future we will further improve our control on the different fabrication parameters and optimize the day-to-day reproducibility of DLP. Furthermore we will further explore this MOMs technology for the fabrication of new prototypes of both fiber-based and free-space optical interconnection modules in plastics.

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