# Replication of Refractive Micro Opto-mechanical Components Made with Deep Lithography with Protons.

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**Deep Lithography with Protons (DLP) is a rapid prototyping technology for the fabrication of 3D micro-optical precision components. In this paper we will demonstrate how we made this DLP technology compatible with commercially available injection-molding and vacuum casting techniques, allowing to mass-replicate high-quality micro-optical modules at low cost. We will illustrate our technology by presenting optical characteristics of different refractive components made in optical-grade plastics such as polymethyl-methacrylate (PMMA), polycarbonate (PC) and semiconductor compatible plastics with high glass-transition temperatures such as COC.**

## Introduction

The technology of DLP [1,2] is a high-precision rapid prototyping technology for the fabrication of 3D micro-optical elements and micro-mechanical structures in PMMA. With this technology different optical components can be structured in one block to form monolithic micro-optical modules. In addition mechanical positioning and support structures can be integrated. This approach however is unpractical for mass-fabrication because an irradiation session, to obtain a single component, can take several hours. We investigated whether we could make DLP compatible with LIGA-adapted injection molding techniques, allowing for the mass replication of 3D plastic micro-optical components. We also looked at vacuum casting for the replication of micro-lenses.

## The concept of DLP

The fabrication process of DLP consists of the following basic procedures: we start with a selective proton irradiation (8.3 MeV) of a 500 μm thick PMMA free-standing substrate followed by an etch-step that develops the irradiated regions. The impinging high-energy protons create well-defined domains with chemical properties different to those of the bulk-material. Irradiated domains can therefore be selectively dissolved with a special developer, since they show a higher solubility than the non-irradiated domains. The surfaces obtained with this procedure have a high optical quality and can be used e.g. as micro-mirrors [3], as shown in Figure 1a. Surface roughnesses of 32 nm are typical over a measuring length of 300μm.

Alternatively to dissolving the irradiated zones we can swell them by exposing them to an organic monomer vapor such as MMA. This brings about a volume expansion resulting in a hemi-spherical surface. Hence refractive micro-lenses can be fabricated with low focal numbers (7.4-1.9) over a wide range of diameters (20µm-1mm), corresponding to the circular apertures available on the Ni-mask. Figure 1b shows a micro-lens array (200 µm diameter, 220 µm pitch) made by selective diffusion.

Figure 1 a. free standing micro-prism (3.9 mm mirror), b. SEM image of a micro-lens array

## Injection Molding of a DLP sample

To make the technology of DLP compatible with injection molding and the LIGA [4] electroplating apparatus we have to abandon the idea of working with free-standing PMMA foils and start working with a layer of cross-linked PMMA casted on a Ti-wafer as basic material. We performed a stydy to determine the optimum degree of cross-linkage in the PMMA. Variations between 0% and 3% of cross-linker product have been tested with an optimum (minimum cracks and maximum flatness) at 1 %.

Figure 2a shows a structured 650 µm thick PMMA layer on a Ti-carrier. Different test-structures and a set of micro-prisms can be identified on this image. After the sample is irradiated and developed, the electroplating can take place using standard LIGA-replication, to create a negative metal part. This is done in three steps: 1) the growth of a 750 µm Ni layer to fill the polymer structure with metal, 2) the sputtering of a thin Cu layer to make the whole surface conductive and thus to ensure that the surface is evenly overgrown, 3) the growth of a 2 mm Ni layer for effecting the backfill (figure 2b). Then the Ni-part is separated from the Ti-wafer using EDM (electro discharge machine) and chemical etching. Finally the remaining PMMA is removed and the Ni-plate is mechanically processed to a mold insert (figure 2c).

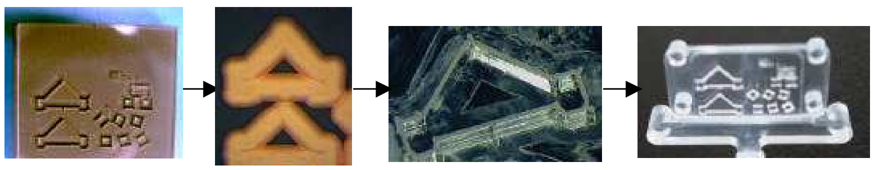


Figure 2 a) irradiated and developed sample. b) Ni-filled structure, c) mold insert, d) replica

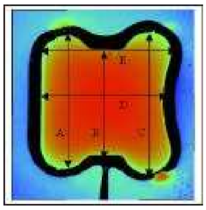
After the mold insert is fitted into the injection molding machine, we can fabricate the replica in different types of plastics, depending on the material characteristics required for the application (figure 2d). It is obvious that for optical MEMS only high optical quality polymers[5] (e.g. PC, PMMA, MABS, COC) will be used.

The optical walls (as seen in figure 2b) have a height of 650 µm are 200 µm thick and are almost perfectly perpendicular to the bottom surface, which implies that the friction between the polymer and the walls is high. For this reason the ejection of the component is difficult and the replicated part can stick to the mold insert or be ejected under a small angle, due to some local friction problems. This usually results in the destruction of the optical walls. The usage of Teflon coatings to overcome these problems is not allowed because it will destroy the optical surfaces.

To achieve a good replication, the number of micro-optical components with such high walls must be kept to a minimum. To improve it even further the walls have to be polished down from 650 to 500 µm to reduce the friction. Contrarily to LIGA, the walls of DLP-made structures are thicker on the top than on the bottom. The combination of this effect and the friction implies that polymers with a low shrinkage will be hard to eject. After all these improvements, we succeeded in making good optical components, which we replicated in polycarbonate (PC) as a proof of principal. This polymer has a well-defined shrinkage that depends on its place in the structure (table 1) but has a day-to-day reproducibility. The highest shrinkage can be observed in corners. It is advisable to simulate the shrinkage and take it into account in the original design to achieve good replicated components with the desired dimensions.

Tabel 1. shrinkage on test-element.

| distance | Mold insert ± 3µm | Replica in PC ( µm) ± 3µm |
|---|---|---|
| A | 630 | 710 |
| B | 500 | 590 |
| C | 665 | 750 |
| D | 500 | 590 |
| E | 523 | 618 |



When a polymer with a smaller shrinkage (e.g. COC ) is used, the sticking effect becomes more and more important, resulting in the destruction of the optical surfaces. When the shrinkage is low, the polymer will stick so hard to the wall that the structure will be deformed locally during the unmolding. To achieve good replication with low shrinkage polymers, the ejection of the component from the mold must be perfectly parallel. This can be done by applying a dove tailed demolding tool for a thick residual layer or with a surface modified (high roughness) thin residual layer[6]. Further improvement can be made with the injection-molding machine by changing the mold-movement speed and injection system. The mold movement speed must be slowed down to reduce the risk of destroying the micro-optical components during the ejection. By using a smaller screw in the injection system the residence time of the melted polymer is shorter and polymer chain breakdown can be minimised. This is important for high-temperature polymers because the melting point and decomposition temperature are close together.

## Vacuum casting of a DLP micro lens array

Besides the injection molding we have also used vacuum casting to replicate micro-optical components. Here we present the results on the replication of a micro-lens array, which was made using the diffusion process of DLP.

Vacuum Cast Molding, a relatively new development in polyurethane prototyping, uses familiar principles with new materials to further enhance the accuracy of prototypes. The original part is embedded in a vulcanizing silicone and placed inside a vacuum chamber to de-aerate the silicone. This results in a very accurate replication of the part features. After curing, the mold is cut apart and the master element is removed. The mold is then taped together and inside a vacuum chamber a two-component resin is poured inside the prepared mold. After curing the resin, it is demolded, resulting in a copy of the original part. As figure 3 shows, the difference in

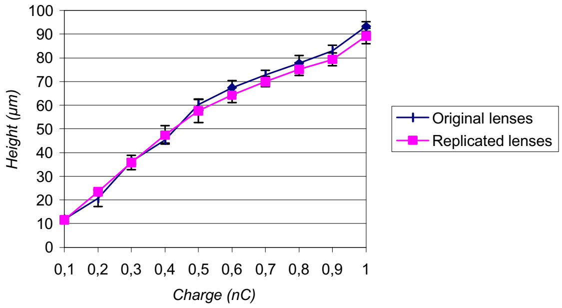



Figure 3. comparison between original and replicated lenses.

height of the lenses is less than 4.5 % and can be compensated by taking a slightly higher original lens. This technology allows us to copy very accurately monolithic 3D micro-optical modules.

## Conclusion

In this paper we have shown how Deep Lithography with Protons can be made compatible with injection-molding techniques and vacuum casting, thus allowing for the mass-replication of high-quality micro-optical modules. The combination of the rapid prototyping approach of DLP and injection molding techniques makes it now possible to advance very quickly from an idea to a demonstrator-component and finally to mass-production. Whereas injection molding is suitable for high volume fabrication, vacuum casting is a good alternative for small quantities. In both cases shrinkage is present and must be compensated in the master element to acquire the desired final dimensions.

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