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Creation of convex microlenses in PDMS with focused MeV ion beam

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ABSTRACT

In this work the creation of convex microlenses is presented in polydimethylsiloxane using shrinkage of the polymer due to energetic ions. The creation process is based on the observation that the PDMS shrinks due to irradiation and the surface of the unirradiated areas will have a regular curvature between the irradiated places. The created microlenses were arranged in arrays, the diameters were varied between 15 and 200 μm. The properties of the lenses were investigated using an AFM and a profilometer. The profile of the lenses turned out to be parabolic, the focal lengths were found to be between 18 and 180 μm, that can be adjusted with the delivered ion fluence and the lens diameter.

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1. Introduction

The research and development of microfluidics and microanalytical techniques are popular fields of science, receiving increasing attention recently [1]. They are used for more and more applications successfully while there is a huge need to develop new devices with new capabilities for novel purposes. The spread and advance in microtechnologies enable the fabrication of more advanced and higher integrity level lab-on-a-chip devices.

Polydimethylsiloxane (PDMS) is a popular material for creating microfluidic chips because of its cost efficiency and attractive material properties. PDMS is an organic, silicon-based, elastic, cross-linkable polymer, it is chemically inert and stable over a wide temperature range [2]. Its surface is hydrophobic, it has a low surface energy [3] and high surface resistivity. PDMS is also non-toxic and biocompatible [4] therefore it is widely used to fabricate microfluidic biochips and biosensors [5–7]. In microfabrication techniques the polydimethylsiloxane is also frequently used for creating micro-electro-mechanical systems (MEMS) [8], microfluidic devices [9,10], or micro-stamps [11–13]. Since PDMS is optically clear and transparent in the visible and near infrared range [14–17] it is a good choice for optical applications [18]. Due to MeV proton irradiation the polymer changes its refractive index significantly [19] so it is capable for creating integrated optical components e.g. waveguides [10], or binary phase type diffraction gratings and Fresnel zone plates [20]. The irradiation has also a remarkable effect on the surface topography [21], the relation between the rate of shrinkage/compaction, the irradiation dose and structure spacing is also known [22]. The shrinkage of the polymer is the result of chain scissioning and the splitting of functional groups due to energetic ion irradiation, because the formed volatile products – mainly hydrogen, methane and ethane gases [23–25] – leave PDMS decreasing the irradiated volume.

This work is based on the finding that the polydimethylsiloxane shrinks at the irradiated areas and the surface between the irradiated places, at the unirradiated areas, becomes curved [22]. Since this curvature is regular and symmetric, the creation of curved surface microstructures, such as microlenses, is possible. In this work we present the creation of convex microlenses in PDMS using shrinkage/compaction of the polymer due to energetic ion irradiation. The created microlenses were arranged in arrays and their properties were investigated with different techniques.

The applied proton beam writing (PBW) technique is a rapid, precise and single step method for the creation of microlenses, there is no need of mould creation or further sample treatment. By the nature of this direct-writing method, structures can be positioned precisely on the sample surface.

The presented microlenses are the first direct-written three-dimensional microstructures in PDMS.

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2. Experimental

To create the PDMS samples Sylgard 184 kit (Dow-Corning) was used. The base polymer and the curing agent were mixed in the volume ratio 10:1, respectively. The polymer was spin coated on a 2.5 cm × 2.5 cm glass substrate with 1500 RPM for 25 s and then baked at 125 °C for 30 min. The created layer was about 85 μm thick. The density of the prepared polydimethylsiloxane samples was 1.011 g cm^{-3}, which was determined with a pycnometer. The Stopping and Range of Ions in Matter (SRIM) [26] calculations showed that the penetration depth for 2 MeV protons is about 85 μm in polydimethylsiloxane prepared this way, so the incident protons just reach the glass substrate but they lose almost all of their energy in the polymer.

All irradiations in this work have been performed at the nuclear microprobe facility at HAS-ATOMKI, Debrecen, Hungary [27]. The samples were irradiated with a focused 2 MeV proton microbeam, the spot size of the beam was 2 μm × 2.5 μm. According to previous investigations the rate of compaction in PDMS is close to its maximum at about 1500 nC mm^{-2} [22], so this value was chosen as the irradiation fluence. The beam current was 500 pA. The irradiated pattern was a matrix of annuli, which inner diameters were 15, 30, 60, 100 and 200 μm (see an example of the 100 μm annuli arrays on Fig. 1).

After the irradiation the surface topography was investigated with different methods. In the cases of the smaller diameter lenses tapping mode Atomic Force Microscopy (AFM, NT-MDT Ntegra) was applied, and 3D topography images of the structures were recorded. In cases of the large, 100 and 200 μm, diameter lenses, where the scan size of the AFM was not wide enough (limited to 140 × 140 μm) to scan the necessary area, a profilometer (AMBIOS XP-I type) was used. These techniques allowed us to investigate the rate of shrinkage of the irradiated area, the height and the profile of the curved surface and the focal length of the microlenses.

3. Results and discussion

Due to the ion irradiation the surface topology of the PDMS changed, at the irradiated areas shrinkage/compaction occurred. The surface of the unirradiated polymer between the irradiated, and therefore compacted areas, is curved due to the rubbery nature of PDMS. An earlier study showed [22] that the rate of shrinkage depends on the irradiation fluence and the distance of the irradiated areas. The irradiation fluence was constant in every case, but the diameters of the lenses were varied. It means that the different diameter lenses have different rate of compaction, different surface curvature and thereby different focal length.

The refractive index of the PDMS also changed due to irradiation [19], so the created lenses are surrounded with different refractive index regions (Fig. 2). The topographical transition between the irradiated and unirradiated areas is not a step function, but it is continuous due to the elastic nature of PDMS. This results that the curvature of the lens surface begins inside the irradiated region, not exactly at the edge of it. The microlenses (unirradiated areas) near their edges consist of irradiated and therefore altered refractive index regions (Figs. 2 and 3).

During irradiation the rigidity of the PDMS polymer also changes [22] due to degradation and the formation of silicate derivatives (SiO_x) [28]. This results that the curvature of the surface of the microlens at the irradiated part differs from the curvature at the unirradiated, central part. The differences in refractive index and curvature modify the optical path length inside the lens and can cause spherical aberration.

As it was mentioned before, the topographical transition between the irradiated and unirradiated areas is continuous, so the surface curvature of the lens begins inside the irradiated region increasing the overall diameter of the lens. For example in case of the 200 μm diameter lenses the planned 200 μm diameter increases to 260 μm with a peripheral, different refractive index part (Fig. 2).

For the profilometer measurements a 0.1 mg load was applied. This load was small enough to make the accurate surface profiling possible but also allowed the visualization of the phase/rigidity differences on the surface of the elastic polymer. The different indentation due to the rigidity difference and the geometry of the lens together result peaks in the profile. These peaks are artefacts, they originate from the indentation of the stylus of the profilometer. In case of the 100 and 200 μm diameter lenses these peaks appear at the boundary of the irradiated and unirradiated areas as it is shown in Fig. 3.

The AFM images show the geometry of the microlenses. The 2D top view representation of the AFM data reveals that the lenses are not exactly circular in shape. In Fig. 4 a 30 μm in nominal diameter lens can be seen with the horizontal and vertical axes of 31 and 30 μm respectively. This is caused by the circular-path beam scanning and the not symmetric, rectangular beam spot. The geometrical distortion of the microlenses could be avoided with using a symmetric, circular beam spot.

The detailed investigation of the geometry revealed that the microlenses are not spherical, but they have parabolic profiles. With fitting the $y = Ax^2 + Bx + C$ parabolic function on the unirradiated part of the cross-sections of each microlens, a good fit was obtainable (Fig. 5). The accuracy of the fit is can be characterized with the square of the multiple correlation coefficient (R^2) that is higher than 0.992 in every case.

The focal lengths of the microlenses were also determined from the fitted functions. Since the lenses are not perfectly symmetrical due to the rectangular beam size, the focal points of the x and y planes slightly differ from each other, thus the lenses are

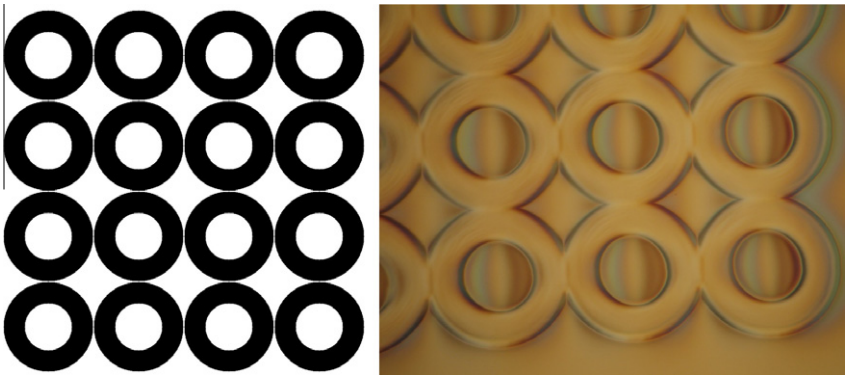

Fig. 1. The irradiation pattern and the differential interference contrast microscopy (DIC) image of the 100 μm in diameter microlens array.

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