Fabrication of adhesive lenses using free surface shaping

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Two approaches for fabricating polymer lenses are presented in this paper. Both are based on filling circular holes with UV curing adhesives. Initially, the viscous adhesive material creates a liquid and spherical free surface due to its own surface tension. This shape is then preserved by curing with UV-hardening light. For the first approach, the holes are generated in a 4 inch Si-wafer by deep reactive ion etching (DRIE) and for the second, a polydimethylsiloxane (PDMS) mould is manufactured. Three types of UV-curing adhesives are investigated (NOA 61, NOA 88 and NEA 121 by Norland Products). Preliminary to the determination of the lens curvature, a contact angle goniometer is used for taking side view images of the lenses. The radius of curvature is then extracted via image processing with the software MATLAB®. Furthermore, the surface roughness of the PDMS mould and the generated lenses is measured with a white light interferometer to characterize the casting process. The resolution power of the generated lenses is evaluated by measurement of their point spread functions (psf) and modulation transfer functions (mtf), respectively.
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1 INTRODUCTION

There are several manufacturing processes for micro or small lenses, and microlens arrays, respectively, which have been developed. For example the thermal reflow process is widely used for generating arrays of microlenses [1]–[3]. Other processes are diffuser lithography [4], UV imprint lithography [5, 6], ink-jet printing [7] or solvent droplet for forming master structures [8]. Free surface shaping to generate lenses is described for example in [7] and [9]. Polydimethylsiloxane (PDMS) is used for generation of moulding forms [1, 3, 10] or as material for lenses [1, 4, 11]. Adhesives and especially UV-curing adhesives are widely used for fabrication or replication of optical elements [5]–[7], [9]–[12]. Most of the described approaches are using expensive photolithography processes to generate a master structure which can used for fabrication of lenses with only one fixed focal length or a fixed configuration.

The research presented in this paper is motivated by the possibility to generate a small number of polymer lenses with different focal length in a very simple, cost effective process. Therefore, two approaches were prepared for preserving the shape of a liquid lens. The general concept is to fill a circular hole with a low viscosity UV-curing adhesive. The free surface of the liquid adhesive forms a spherical cap the same way a liquid lens of any other material (e.g. water) does [7, 9, 13, 14]. To preserve the shape of this liquid lens, the adhesive is hardened with UV light. For the first approach, a Si-wafer with holes is used and for the second, a PDMS mould is manufactured by casting of a SU-8™ master structure.

2 FABRICATION

For the fabrication of the lenses with the first approach, the holes are generated in a Si-wafer by etching and for the second, a PDMS mould with cavities is manufactured.

2.1 Si-wafer frame approach

A 4 inch (1 0 0) p-type Si-wafer with a thickness of about 525 μm is used as substrate for the first approach. The holes are etched through the wafer by applying DRIE. A layer of the positive photoresist AZ®9260 is spin coated onto the wafer. After a prebake, about 800 circular structures with a diameter of 1.75 mm are fabricated by photolithography. The structured

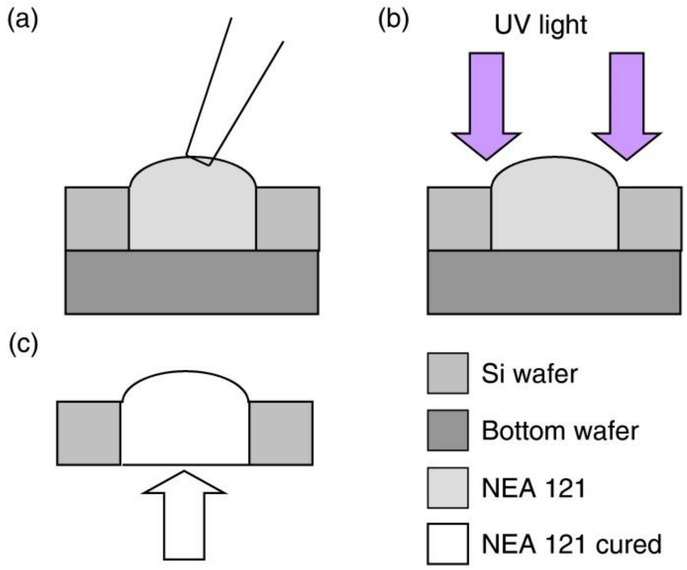

FIG. 1 Schematic fabrication process for adhesive lenses (first approach): (a) filling hole with adhesive; (b) curing with UV light; (c) backside polishing.

photoresist serves as an etching mask for the DRIE. After the etching step the photoresist is stripped with acetone.

For manufacturing the lenses the etched wafer is bonded to a plate of polytetrafluoroethylene (PTFE) or a second Si-wafer. The holes of the etched wafer are then filled with the adhesive NEA 121 by Norland Products using a pipette (Eppendorf research 0.1-2.5 μl). This adhesive can be cured by UV light. Because of its low viscosity of 300 cps, it is quickly forming a spherical cap when filled into the holes of the wafer. The adhesive is cured using the UV light source Blue Wave 50 by Dymax for 10 s to preserve the geometrical form of the lenses (see Figure 1). Lenses with various convex radii of curvature were fabricated by dispensing different volumes of adhesive. Figure 2 shows an array of nine lenses after hardening.

After curing, the bond between the two wafers is released. The advantage of the PTFE plate as bottom substrate compared to the usage of a second Si-wafer is the easy removal with little effort. The disadvantage of using the PTFE-plate is that the backside of the lenses is not as sufficiently transparent as necessary to be used for a lens. Because of that fact, the backside of the lens has to be polished to minimize the surface roughness and light scattering effects in order to generate a transparent surface. When the Si-wafer frame is bonded on a second Si-wafer, no polishing of the lens' backsides is needed. Afterwards, the lenses are released from the Si-wafer frame. De-bonding from the bottom wafer and releasing the lenses, wears off the Si-wafer frame and it can be re-used only a few times for lens fabrication. The advantage of fabricating the lenses with such a Si-frame is the possibility of integration into Si-based optical systems. In this case, a release of the lens could be unnecessary. For an easier release of the adhesive lenses, the second approach with a PDMS mould was evaluated. Furthermore, the manufacturing of a PDMS mould is substantially more inexpensive.

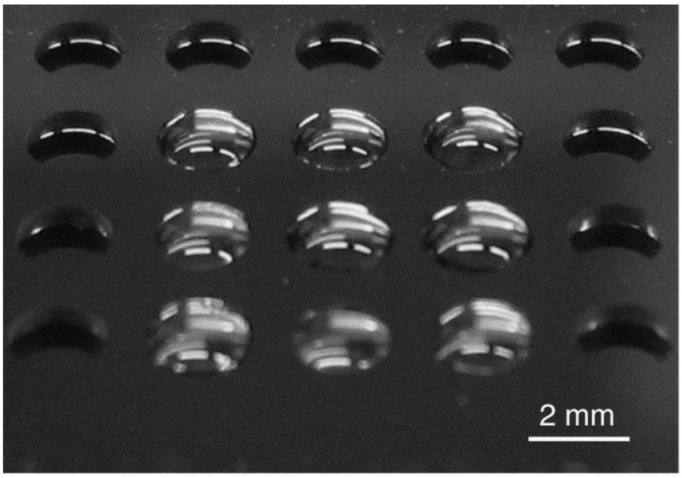

FIG. 2 Array of nine lenses in a Si-wafer after hardening.

2.2 PDMS mould approach

The manufacturing of the PDMS mould also starts with a 4 inch Si-wafer. The negative photoresist SU-8™ 100 is spin coated onto the wafer. After the soft bake, the resist is exposed using an i-line filter and the same photolithography mask utilised for the first approach. Then, a post exposure bake is done followed by the development with mr-Dev 600. This process ends with a flood exposure and a hard bake and is resulting in cylindrical SU-8™ structures on the wafer surface. These structures have a diameter of 1.75 mm and a height of about 200 μm and serve as master for PDMS moulding process.

For moulding, liquid PDMS SYLGARD® 184 silicone elastomer is mixed with its curing agent (both form Dow Corning) and degased under vacuum. The liquid mixture is poured onto the wafer and cured at 80°C for 60 min on a hotplate. Afterwards this thermal treatment the PDMS mould can easily be released from the master. The Si-wafer with SU-8™ master structures can be used many times for production of PDMS moulding forms (see Figure 3).

For fabrication of the lenses, the PDMS moulding form is placed on an even and levelled surface. The cavities of the moulding form are filled with adhesive using the dispensing device Ultra 2400 from EFD with a micro pen attachment. The parameters for adjusting the dispensed volume of adhesive are time, high pressure, and low pressure. This dispensing method is used to achieve a higher reproducibility of the lens curvature than using a pipette. Additional to NEA 121, the adhesives NOA 61 and NOA 88 by Norland Products are utilised for forming lenses. These two are also UV-curing adhesives. The viscosity of NOA 61 is 300 cps and of NOA 88 250 cps. The refractive index of the used adhesives is 1.56 for the cured polymer [15].

With each adhesive 30 lenses are fabricated to allow a statistically analysis. While the dispensing parameters for each material are constant, they differ slightly between the three types of adhesives. After dispensing the adhesive in the holes, the resulting spherical cap is cured by UV-light. The generated lenses can easily be released from the PDMS moulding form.

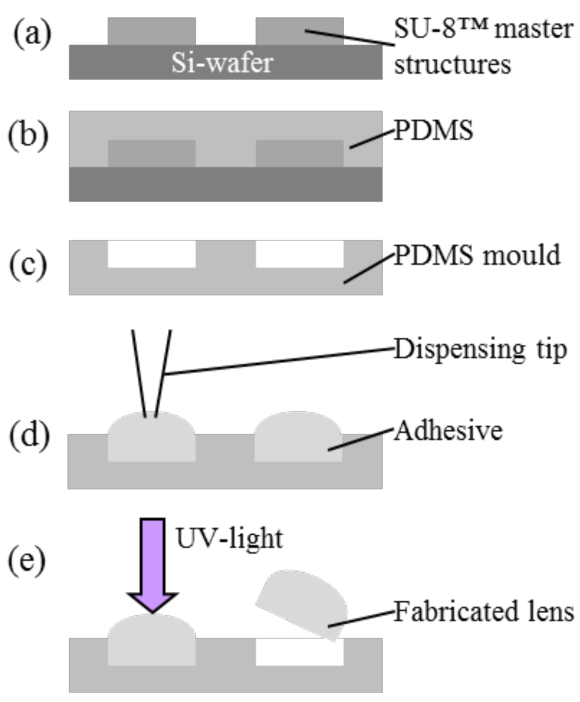

FIG. 3 Schematic fabrication process for adhesive lenses (second approach): (a) SU-8™ master structures generated by photolithography; (b) casting with PDMS; (c) generated PDMS moulding form; (d) filling holes with UV-curing adhesive; (e) curing with UV light and releasing lens.

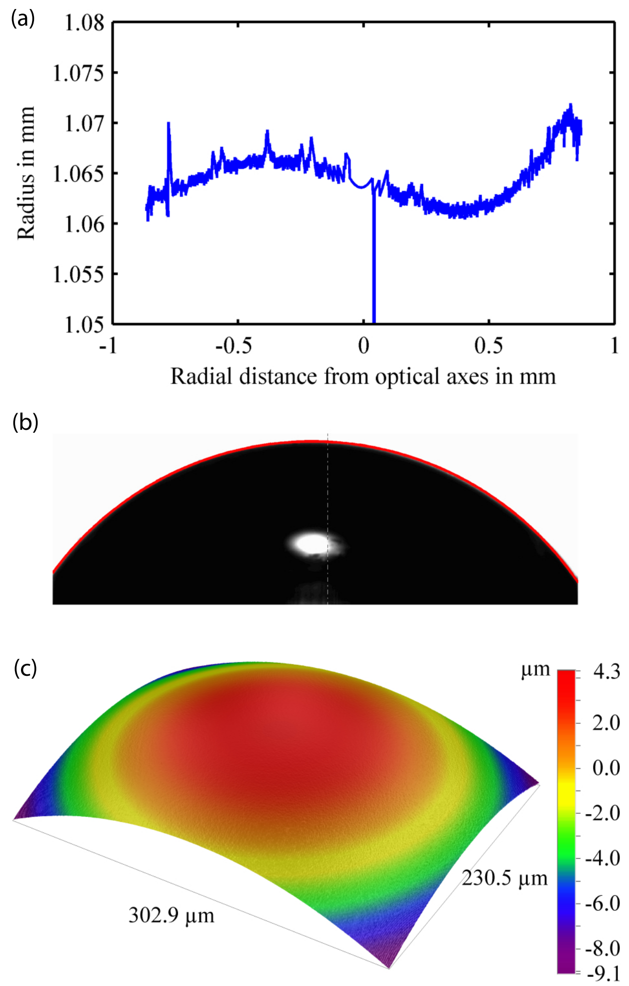

FIG. 4 Side view of lens (diameter 1.75 mm) with spherical fit; (b) detected curvature; (c) 3D image of lens shape taken with a white light interferometer.

3 CHARACTERIZATION

For characterization, the lens curvature and the surface roughness of the lenses are measured. Therefore a setup similar to one described by Zhang et al. [16] is used.

3.1 Lens Curvature

A contact angle goniometer is used for taking side view images of the lenses. For each lens two images from different directions are taken. The direction of view is turned 90° to detect asymmetric lenses. The radius of curvature of the lenses is then extracted via image processing with the software MATLAB®. First, in each image the highest point, the left side, the right side, and the bottom of the lens are manually marked. Starting from these marked points, the curvature is then automatically detected by the MATLAB® script that detects the edge of the lens by finding the maximum of the image gradient. Each measurement shows an artefact because of the raster in the image from the goniometer software. Figure 4(a) shows the detected radius of curvature plotted against the radial distance from the optical axis. A kind of waviness can be seen which can be effected by shrinkage because of mass loss during curing. The oscillation of the curve is caused by the resolution of the goniometer image. A spherical fitting in combination with the least square method is utilised for calculating the radius of curvature of the lens (see Figure 4(b)). The absolute differences in the calculated radius of curvature between the two viewing directions on one lens are on average between 13.7 µm and 21.0 µm. This means, the lenses are slightly asymmetric. Measurements with a white light interferometer show a smooth surface of the generated lenses (see Figure 4(c)).

Additionally, the variation of the radius of curvature is calculated as the deviation between the detected lens curvature and the calculated spherical fitting. This variation is between -0.03 mm and 0.09 mm. On average, this difference is below 1 µm (see Table 1). For each adhesive, the arithmetic average of the radius of curvature is calculated as well as the corresponding standard deviation. The best reproducibility of the lens curvature is found for NEA 121. NEA 88 shows on average the lowest differences between the viewing directions as well as between the detected and calculated lens curvatures. One explanation for this can be the lower viscosity of this adhesive.

For approximate calculation of the focal length, the formula for thin lenses is used [17]:

$$\frac{1}{f} = \frac{n_2 - n_1}{n_1} \times \left(\frac{1}{R_1} - \frac{1}{R_2} \right)$$

where f is the focal length of the lens, n_1 the refractive index of air, n_2 the refractive index of the lens material, R_1 the curvature radius of the lens, and R_2 the curvature radius of the lens backside. Because the backside of the lens is negligibly curved and thus, R_2 is almost infinity, the term $1/R_2$ approximately equals zero.

Adhesive	NEA 121	NOA 61	NOA 88
Average of lens curvature	1.296 mm	1.166 mm	1.038 mm
Standard deviation of lens curvature	0.036 mm	0.105 mm	0.062 mm
Average of absolute difference between viewing directions	20.3 μm	21.0 μm	13.7 μm
Average of difference between detected and calculated lens curvature	0.818 μm	0.757 μm	0.455 μm

TABLE 1 Analysis of lens curvature.

3.2 Roughness

The roughness of random samples is measured with a white light interferometer in phase-shifting mode. In detail, the roughness of the SU-8™ master structures, the PDMS mould and the backside of the fabricated lenses are measured. To differentiate between roughness and waviness, a high pass filter is used for the analysis. The rim of the structures is excluded from the analysis because the rim would add artefacts to the analysis. The roughness parameters R_a, R_q, and R_t are determined (see Table 2). The roughness parameters of the PDMS mould are lower than those from the SU-8™ master structures. This means, that the PDMS does not reproduce the roughness of the SU-8™ but has a kind of smoothing effect. Especially the peak-to-valley height R_t is considerable lower. For using the PDMS as a moulding form for lenses, this is a positive side-effect. The roughness parameters of the lens backside are clearly higher than those of the mould. This is an unexpected result because it was supposed that an adhesive would map the surface of the PDMS mould quite well. This effect will be examined in future experiments and analysis.

	SU-8™ master	PDMS mould	Lens backside
R_a in nm	0.60	0.32	1.02
R_q in nm	0.81	0.41	2.20
R_t in nm	39.33	7.89	69.00

TABLE 2 Average of measured roughness parameters.

3.3 Testing set-up for optical characterization

The lens under test (see Figure 5) is illuminated by collimated white light from a SMF-28® fibre. The magnified image of the focus spot of the lens is then measured by a CCD camera through a microscope objective. While Zhang et al. mounted the lens on a one-axis translation stage [16], in this setup the camera and microscope objective are mounted on a three-axis translation stage to allow for easier positioning of the small lenses under test.

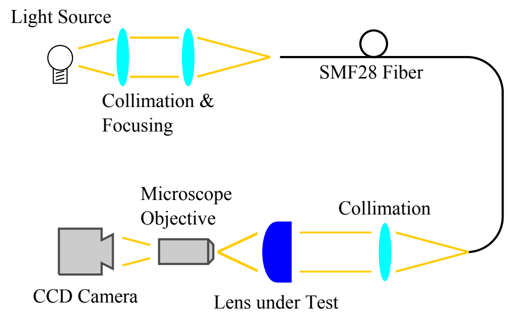

FIG. 5 Setup for measurement of OTF and MTF.

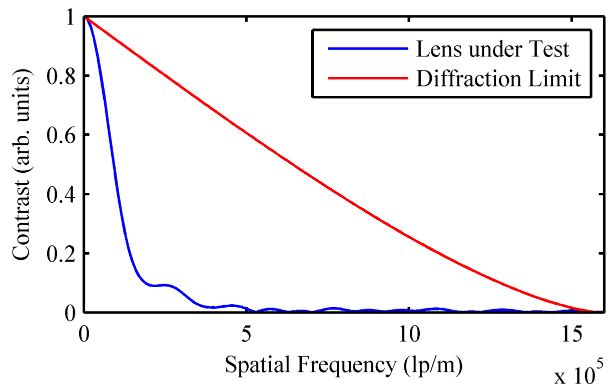

FIG. 6 MTF of lens under test and diffraction limited MTF.

As shown by Zhang et al., it is possible to compute the modulation transfer function of the lens from the point spread function that is measured by Fourier Transformation, assuming incoherent illumination and a point light source, which is represented by the SMF-28® Fibre in this work. Adjustments like that done by Zhang et al. for the non-infinite size of the point source were not carried out in this case due to the much smaller source that was used here. Constant illumination over the aperture of the lens was ensured by a wide collimated beam (diameter 25 mm) in comparison with the illuminated aperture of the tested lens (1.75 mm diameter).

The difficulty of finding the ideal focus spot of the lens was overcome by constant monitoring of the rms-radius (as defined e.g. in [18]) of the measured spot. In case of a minimal rms-radius the optimal focus is reached. The lenses where compared against the diffraction limited performance of an ideal system with an aperture of 1.75 mm and focal range of about 3 mm depending on the measured lens.

Figure 6 shows the horizontal modulation transfer function of a manufactured lens. As expected, the lens performs below the aberration limit and shows spherical aberration as indicated by the second peak at 3 x 10^5 lp/m. Structures of about 200 lp/mm can be imaged with a Michelson contrast of about 0.1 mm. Some lenses of the manufacture lot showed lower spatial resolution or non-symmetric psf images. This indicates that the reproducibility of the manufacturing process can be increased.

4 CONCLUSION

It has been shown, that adhesive lenses can be produced using a Si-wafer frame or a PDMS moulding form. The use of a Si-wafer frame could be an advantage for integration of the lenses in Si-based systems. Utilizing free surface shaping in combination with the PDMS mould, an easy and cost effective fabrication process for small lenses was obtained. This process can be used for fabricating lenses with different focal length in the same run and with the same mould. For the fabrication of the PDMS moulding form, a SU-8™ master is used. It turned out, that the roughness of the mould is lower than that of the master. Optical characterization of the lens showed spherical aberration as well as a fluctuation in image quality between measured lenses. The achievable resolution was as high as 200 lp/mm.

For future work, the Si-wafer with fabricated lenses will be used as master for the PDMS moulding form. The PDMS mould can be coated to change the contact angle between the surface and the adhesive. With a reduction of the lens diameter the process can be used to fabricate micro lenses.

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