Deep proton writing of high aspect ratio SU-8 micro-pillars on glass
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Deep proton writing (DPW) is a fabrication technology developed for the rapid prototyping of polymer micro-structures. We use SU-8, a negative resist, spincoated in a layer up to 720 µm-thick in a single step on borosilicate glass, for irradiation with a collimated 12 MeV energy proton beam. Micro-pillars with a slightly conical profile are irradiated in the SU-8 layer. We determine the optimal proton fluence to be $1.02 \times 10^4 \text{µm}^{-2}$, with which we are able to repeatedly achieve micro-pillars with a top-diameter of $138 \pm 1 \text{µm}$ and a bottom-diameter of $151 \pm 3 \text{µm}$. The smallest fabricated pillars have a top-diameter of $57 \pm 5 \text{µm}$. We achieved a root-mean-square sidewall surface roughness between 19 nm and 35 nm for the fabricated micro-pillars, measured over an area of $5 \times 63.7 \text{µm}$. We briefly discuss initial testing of two potential applications of the fabricated micro-pillars. Using ~100 µm-diameter pillars as waveguides for gigascale integration optical interconnect applications, has shown a 4.7 dB improvement in optical multimode fiber-to-fiber coupling as compared to the case where an air-gap is present between the fibers at the telecom wavelength of 1550 nm. The ~140 µm-diameter pillars were used for mold fabrication with silicone casting. The resulting mold can be used for hydrogel casting, to obtain hydrogel replicas mimicking human tissue for in vitro bio-chemical applications.

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1. Introduction

Micro-optical components are used more and more in many domains, including medical imaging [1], solar energy [2], telecommunication [3] and gigascale integration optical interconnects [4,5]. Today, many micro-fabrication technologies exist that are capable of fabricating a myriad of micro-optical components. For research and development, maskless direct writing technologies are preferred, since they enable rapid prototyping of components. Over the past 15 years, our group has developed such a micro-fabrication technology called deep proton writing (DPW), originating from LIGA [6,7] (German acronym for Lithography, Electro-foming and molding). As opposed to LIGA, where X-rays are used for irradiating a target material, we employ highly energetic protons. In DPW a target material is irradiated with a collimated proton beam with a proton energy between 8.3 MeV and 16 MeV. The energy and shape of the proton beam used, are the differentiating factors between DPW and what is known as proton beam writing (PBW). For PBW, focussed proton beams with proton energies smaller than 3 MeV are typically used [8–11]. The more energy the protons have, the farther they can penetrate into the target material, thus enabling us to write far deeper structures than possible with PBW. In the past, we have written 2 mm-deep structures in polymethylmethacrylate (PMMA) with 16 MeV protons [12]. In the case of PMMA (a positive resist), the protons will create scissions in the long polymer chains enabling a selective development of the irradiated zones. For SU-8 (a negative resist), the protons activate a photoacid-initiator (triarylsulfonium hexafluoroantimoniate), which starts a cross-linking reaction in the SU-8 resin. With an aperture selection mask we can choose to irradiate with proton beam sizes ranging from 33.5 µm to 300 µm. Since the mask is only used for selecting the beam size, DPW is a direct writing technology with which we can write arbitrary 2.5D patterns. This makes DPW a versatile rapid prototyping technology capable of fabricating high aspect ratio structures with optical surface quality [12,13]. In this paper we discuss the use of a 12 MeV collimated proton beam to fabricate SU-8 micro-pillars on borosilicate glass. We aim to create 500 µm or higher pillars with a diameter of ~50 µm and ~140 µm, since these dimensions are of interest for two particular applications. The 50 µm-diameter pillars could function as optical waveguide structures to aid in the interconnection between optoelectronic input/output chips and optical waveguides in printed circuit boards for gigascale integration optical interconnects [5,14,15]. The 140 µm-diameter pillars could serve to create a micro-villi environment, mimicking human tissue for in vitro bio-chemical applications [16,17]. In the past, SU-8 micro-pillars have been fabricated by X-ray lithography up to

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7 mm high with an aspect ratio up to 389 [18] and by UV-lithography up to 1.5 mm high with an aspect ratio of up to 15 [19]. With proton-irradiation, micro-pillars have been achieved up to 55 µm-high with an aspect ratio of 5 [20] with PBW and up to 96 µm-high with an aspect ratio of 4.5 [21] with DPW. In this paper, we aim to improve on the maximum achieved height and aspect ratio of SU-8 micro-pillars and hence pushing the limits of proton-based lithography.

2. Materials and methods

2.1. SU-8 layer deposition

To be able to spincoat thick SU-8 layers, we use the SU-8 2150 formulation from MicroChem Corp., which comes in a very viscous (80,000 cSt) liquid form [22]. This means that the SU-8 should be deposited on a substrate, to be able to use it in the DPW setup, in which the sample is positioned vertically [13]. We choose to work with a 175 ± 15 µm-thick, 30 mm-diameter borosilicate substrate from Schott. The spincoating process consists of 10 s of spinning at 500 rpm after an acceleration of 86 rpm/s followed by 30 s of spinning at 1000 rpm after an acceleration of 258 rpm/s. After spincoating, the substrate is soft baked for 15 min at 65 °C, 12h at 85 °C and 20 min at 65 °C, before returning to room temperature. Every temperature increase occurs at 6 °C/min and cooling down happens at approximately 2 °C/min. Since baking at high temperature can lead to lower sensitivity to irradiation, slower polymerization and poor adhesion [23,24], we used 85 °C rather than 95 °C which was suggested in the datasheet [22]. To remove all but ~4% of the solvent content, a soft bake time of 12 h is used [18] rather than the 30 min suggested in the datasheet. The reason for the controlled temperature ramping and waiting period at 65 °C is to give the SU-8-resin time to re-order at its glass transition temperature to release internal stress and thus avoid cracks in the SU-8 layer after irradiation and post exposure bake [25]. By controlling the temperature of the SU-8 before spincoating, we can further influence the achieved layer thickness. With a single spincoating process, we are able to spincoat ~500 µm-thick layers using SU-8 at room temperature and layers up to 720 µm-thick with SU-8 at ~10 °C. After soft baking, we characterized the SU-8 layer, shown in Fig. 1(a). We measured the surface roughness with a Bruker Contour GT-I non-contact optical profiler. Using the largest measurement window of 2230.3 × 1672.7 µm with a lateral sampling of 3.485 µm, we measured a maximum height variation on the profile \( R_h \) of 4.5 ± 1.5 µm, after removing the tilt from the measured data.

Using the smallest measurement window of 63.7 × 47.8 µm with a lateral sampling of 0.1 µm, we measured a root-mean-square surface roughness \( R_q \) of 1.3 ± 0.2 nm, after removing the tilt from the measured data.

2.2. Deep proton writing

To irradiate patterns with DPW, we use a CGR-MeV model 560 cyclotron capable of generating quasi-monoenergetic (\( \Delta E/E = 1\% \)) proton beams in the 3 MeV to 45 MeV energy range [26]. In this work we use a proton beam with an energy of 12 MeV which is directed towards our DPW setup in a vacuum chamber (< 10⁻⁴ mbar to avoid scattering of the protons on air molecules). Our DPW setup, depicted in Fig. 2, consists of a collimator, a shutter, a stopping mask, the sample (first the SU-8, then the glass substrate) and a coulomb meter with integrator, respectively in the order that the proton beam reaches them. The collimator first limits the proton beam diameter to roughly 2 mm diameter after which the beam shape and size is selected with the stopping mask. This mask consists of a stack of three ~210 µm-thick nickel plates containing apertures in different shapes (circular, square, hexagonal, rectangular and elliptical) with sizes ranging from 33.5 µm to 300 µm, fabricated by LIGA [27,28]. Transmission range of ions in matter (TRIM) simulations [29] show that this stopping mask is capable of stopping protons with an energy up to 16 MeV. This means that only the protons traveling through an aperture in the mask will reach the sample. After penetrating through the sample, the proton-current is measured by a coulomb meter with an accuracy < 250fC and an integrator [26]. We can control the proton fluence of the irradiation by closing and opening the shutter, which can block the proton beam completely. Patterns are written by moving the sample perpendicularly to the proton beam with high-accuracy (0.3 µm) piezo-stages with a travel range of 50 mm. Arbitrary patterns can be written, where the depth of the irradiation is determined by the thickness of the sample, with as an upper limit the thickness through which the protons can fully penetrate the sample (such that the proton fluence can be monitored). As mentioned earlier, our sample in this work consists of a spincoated layer of SU-8 on top of a 175 ± 15 µm-thick glass substrate. With the substrate taken into account, the maximum thickness of SU-8 which would still allow 12 MeV protons to protrude through the glass substrate and the SU-8 is ~900 µm, according to TRIM simulations. In Fig. 3 the simulated penetration of \( H^+ \) ions with an energy of 12 MeV in SU-8 and borosilicate glass is shown, based on stopping range in ions (SRIM) data [29]. The pro-

![Fig. 1. SU-8 Spincoated on a 175 ± 15 µm-thick, 30 mm-diameter borosilicate glass substrate (a) after soft bake and (b) after irradiation and post exposure bake, after which the DPW-irradiated patterns are clearly visible.](image-url)
tons will penetrate up to a depth of about 1100 μm in SU-8 and 800 μm in glass, the depth at which the so-called Bragg-peak of the mass stopping power is located and the protons come to a complete stop. The irradiation-path throughout the sample is slightly conical due to the divergence of the proton beam (estimated at 23 mrad) and the scattering of the protons within the target material [28,30]. Since we irradiate the sample with the SU-8-side towards the proton beam, the top-diameter of the irradiated micro-pillars will be smaller than the bottom-diameter on the glass substrate.

From the simulated penetration of \( H^+ \)-ions in SU-8, depicted in Fig. 3, we obtain a value of 0.0416 MeV cm\(^2\)/g for the linear energy transfer (LET) of protons with an energy of 12 MeV in SU-8. From the SU-8 data sheet we know that for a layer of 500 μm an exposure energy of 600 mJ/cm\(^2\) is recommended with ultraviolet (UV) light, with ideally a wavelength above 350 nm [22]. Recalculating the recommended exposure energy, assuming a layer thickness of 500 μm and using the LET, we can determine that the corresponding proton fluence is 1.16 \( \times \) \( 10^7 \) protons/cm\(^2\). Of course, protons do not transfer energy to the target material as UV-light does. Protons could be assumed to penetrate with a more or less constant energy transfer throughout the target material (if the above-mentioned Bragg peak is located behind the sample), while the UV-radiation will lose energy exponentially while traveling through the target material, as the Beer–Lambert law describes [31]. Taking this into account, the minimum required exposure energy for UV-light mentioned in the SU-8 datasheet could be recalculated to obtain a minimum required proton fluence of 4.65 \( \times \) \( 10^7 \) μm\(^2\)/cm\(^2\). To experimentally verify this, we investigate the irradiation of SU-8 with a proton fluence ranging from 3.18 \( \times \) \( 10^7 \) μm\(^2\)/cm\(^2\) to 1.11 \( \times \) \( 10^8 \) μm\(^2\)/cm\(^2\) in Section 3.

### 2.3. Post exposure bake and development

After DPW irradiation, the SU-8 samples are baked for 5 min at 65 °C, 30 min at 95 °C and 20 min at 65 °C, before returning to room temperature. As in the soft baking step, every temperature increase is ramped at 6 °C/min and every decrease is ramped at approximately 2 °C/min. The waiting time at 65 °C when cooling down, is there to release the internal stress. Due to the cross-linking reaction continuing and completing (after initialization by irradiation), the irradiated patterns become visible during the post exposure bake, as visible in Fig. 1(b). Finally, after the post exposure bake, the SU-8 sample is developed in propylene glycol monomethyl ether acetate (PGMEA) at 38 °C, for faster development than at room temperature. After 60 min the sample is submerged in fresh PGMEA at 38 °C for 30 min, to avoid possible saturation of the PGMEA developer.

### 3. Results

#### 3.1. Geometrical characterization

As mentioned earlier, we investigate an irradiation fluence ranging from 3.18 \( \times \) \( 10^7 \) μm\(^2\)/cm\(^2\) to 1.11 \( \times \) \( 10^8 \) μm\(^2\)/cm\(^2\). We irradiated 10 pillars per proton fluence value on 3 different samples with a 50 μm-diameter proton beam and measured their diameters with a contour GT-I non-contact optical profiler with a measurement window of 233.3 \( \times \) 167.5 μm and a corresponding lateral sampling of 0.349 μm. Because the edges of the top of the pillars are slightly rounded due to the chemical development step and light is reflected away from the profiler’s microscope objective on these angled surfaces, the diameter of the pillars is underestimated with this measurement. For proton fluences smaller than 1.59 \( \times \) \( 10^7 \) μm\(^2\)/cm\(^2\) (i.e. 3.12 \( \times \) \( 10^7 \) protons for a 50 μm-diameter area), the irradiated pillars either delaminate during development or are not irradiated due to limitations of the coulomb meter and integrator in the DPW-setup. We did not obtain repeatable measurements on the few pillars that were obtained and hence will not include measurement data of these pillars here. The origin of the above-mentioned limitations of the coulomb meter and integrator for these low proton fluence-range is twofold: the finite accuracy of the coulomb meter being <250 μC (i.e. <1.56 \( \times \) \( 10^6 \) protons) and the proton current from the cyclotron being too high compared to the integrator’s sampling time. If a very low amount of protons needs to be measured, either the leak-current triggers the shutter to stop the irradiation prematurely or the system reacts too slowly and the shutter stops the irradiation too late, resulting in the deposited proton fluence overshooting the desired value. This can be observed in Fig. 1(b), where the two 10 \( \times \) 11 micro-pillar arrays on the right-hand side are clearly not fully present after the post exposure bake. The measurements for pillars irradiated with proton fluences higher than 1.59 \( \times \) \( 10^7 \) μm\(^2\)/cm\(^2\) are summarized in Fig. 4. We can see that for increasing proton fluences we obtain larger top-diameters. We theorize that this happens due to a combination of a slight misalignment of the aperture stopping mask plates, scattered protons depositing a dose above the critical dose outside the intended irradiation area and in a limited
The diameter of pillars written with a 50 \( \mu \text{m} \)-diameter proton beam with different proton fluences on 3 samples, measured with a Bruker Contour GT-1 non-contact optical profiler. The linear regression takes all data from the 3 samples into account.

![Fig. 4](image)

**Fig. 4.** The diameter of the top of pillars written with a 50 \( \mu \text{m} \)-diameter proton beam with different proton fluences on 3 samples, measured with a Bruker Contour GT-1 non-contact optical profiler. The linear regression takes all data from the 3 samples into account.

The diameter of the top of pillars written with a 50 \( \mu \text{m} \)-diameter proton beam with different proton fluences on 3 samples, measured with a Bruker Contour GT-1 non-contact optical profiler. The linear regression takes all data from the 3 samples into account.

![Fig. 5](image)

**Fig. 5.** The diameter of pillars written with a 50 \( \mu \text{m} \)-diameter proton beam for different proton fluences, measured with the Werth UA400 coordinate measurement machine in vision mode.

The diameter of pillars written with a 50 \( \mu \text{m} \)-diameter proton beam for different proton fluences, measured with the Werth UA400 coordinate measurement machine in vision mode.

**Regression**

\[
D_l = 0.0006 \times F_p + 39.9
\]

\( R^2 = 0.89 \)

**Top of pillar**

- DPW sample 1
- DPW sample 2
- DPW sample 3

**Targeted diameter:** 50 ± 2 \( \mu \text{m} \)

![Fig. 6](image)

**Fig. 6.** The deposited dose of a 50 \( \mu \text{m} \), 12 MeV proton beam throughout 1100 \( \mu \text{m} \) of SU-8 with a proton fluence of 1.02 \( \times 10^4 \) \( \mu \text{m}^{-2} \), calculated based on SRIM data. The solid white line shows the conicity of the profile for the critical dose of 6.5 J/g for which the SU-8 cross-links. The vertical dashed lines represent the SU-8 thickness range we achieved with our DPW samples (500–700 \( \mu \text{m} \)).
last 25 agrees well with the previous measurements considering that the achieved significantly, from 96
proton-based lithography. We also increased the maximum height ratio of

\[
\frac{C_2}{C_1} \text{ of } 140 \text{ m-diameter beam and } 2 \text{ pillars irradiated with the } 140 \text{ m-diameter beam, with respectively a proton fluence of } 1.59 \times 10^4 \text{ m}^{-2} \text{ and } 1.02 \times 10^4 \text{ m}^{-2}. \text{ The obtained results are shown in Fig. 8, where we can see that the pillar-broadening agrees well with the previous measurements considering that the last } 25 \text{ m of the pillars cannot be measured with the WFP. We measure (with the CMM WFP) an average broadening of } 14 \text{ m for an average top-diameter of } 60 \mu \text{m over a scanned height of } 440 \mu \text{m and } 12 \mu \text{m for an average top-diameter of } 137 \mu \text{m over a scanned height of } 450 \mu \text{m. This can be compared to the values measured earlier with the vision mode of the CMM which are respectively } 15 \mu \text{m and } 13 \mu \text{m. From the scanning electron microscope (SEM) images, taken with the sample positioned under an angle of } 45^\circ, \text{ depicted in Fig. 9(b), we can see that the } 140 \text{ m-diameter pillars at the outer edge of the array show some extra broadening at the bottom of the pillar, near the glass substrate. At this moment we cannot explain why this happens. Considering the minimum achieved bottom-diameter of } 90 \mu \text{m as the smallest feature fabricated on sample 2 (from Fig. 4) with a height of } 721 \mu \text{m, we achieved a maximum aspect ratio of } \sim 8. \text{ The maximum aspect ratio for the } 140 \mu \text{m-diameter pillars is } 4.3, \text{ for a height of } 640 \mu \text{m, as depicted in Fig. 9(b). With an achieved aspect ratio of } \sim 8 \text{ we improved on the maximum aspect ratio achieved up to now (which was } 5 [20]) \text{ for SU-8 micro-pillars fabricated with proton-based lithography. We also increased the maximum height achieved significantly, from } 96 \mu \text{m [21]} \text{ to } 721 \mu \text{m.}

![Fig. 7](image7.png)

**Fig. 7.** The deposited dose of a 50 μm, 12 MeV proton beam throughout 1100 μm of SU-8 with a proton fluence of $4.78 \times 10^4 \text{ m}^{-2}$, calculated based on SRIM data. The solid white line shows the conciety of the profile for the critical dose of 6.5 J/g for which the SU-8 cross-links. The vertical dashed lines represent the SU-8 thickness range we achieved with our DPW samples (500–700 μm).

![Fig. 8](image8.png)

**Fig. 8.** The sidewall-profile (radius as a function of height) of 2 pillars written with a 50 μm and 140 μm-diameter proton beam with a proton fluence of respectively $1.59 \times 10^4 \text{ m}^{-2}$ and $1.02 \times 10^4 \text{ m}^{-2}$, measured with a Werth UA400 coordinate measurement machine in Werth fiber probe mode.

![Fig. 9](image9.png)

(a) 

(b)

**Fig. 9.** SEM picture taken under an angle of 45° of DPW micro-pillar arrays irradiated with (a) a 50 μm-diameter proton beam with a proton fluence of $1.59 \times 10^4 \text{ m}^{-2}$ to $7.96 \times 10^4 \text{ m}^{-2}$ (10 \times \text{array with a pitch of } 600 \mu \text{m}) and (b) a 140 μm-diameter proton beam with a proton fluence of $1.02 \times 10^4 \text{ m}^{-2}$ (20 \times 20 \text{array with a pitch of } 250 \mu \text{m}). Most of the pillars in (a) with a dose of $1.59 \times 10^4 \text{ m}^{-2}$ are delaminated or not irradiated due to limitations of the irradiation-monitoring equipment.

### 3.2. Surface roughness

The surface roughness of the micro-pillars is of great importance if they are to be used as optical waveguides in optical interconnect applications, since a high surface roughness will cause severe scattering of the light propagating in the pillar. In addition, the surface roughness should also be as low as possible to allow a smooth demolding when the fabricated structures are to be replicated. Hence we investigate whether the proton fluence of the DPW-irradiation has a significant effect on the surface roughness of the fabricated micro-pillars. Since systematically measuring the roughness of the sidewalls of the pillars is very difficult, we characterize the surface roughness of the top of the micro-pillars.

The surface roughness was measured over a circular area of 490 μm² on top of the pillars, with the Bruker Contour GT-I profiler using the smallest measurement-window, as discussed in Section 2.1. The results are summarized in Fig. 10. For proton fluences equal to or higher than $6.37 \times 10^4 \text{ m}^{-2}$ we can see that there is no measurable change in the top surface roughness, taking the standard deviation on the measurements into account. For lower proton fluences a larger deviation on the measurement is obtained. This can be explained by the fact that micro-pillars irradiated with lower proton fluences have smaller top-diameters. Hence the

![Fig. 10](image10.png)

**Fig. 10.** The root-mean-square surface (RMS) roughness, measured over a circular area of 490 μm² on top of the pillars, irradiated with a 50 μm-diameter proton beam on 2 different samples, measured with a Bruker Contour GT-I non-contact optical profiler.
rounded top edges of the pillars can be taken into account at the edges of the measurement window, leading to a higher measured roughness and deviation. The proton irradiation, post exposure bake and development process do cause an increase of surface roughness since the soft baked SU-8 layer had an original measured surface roughness of 1.3 ± 0.2 nm, as discussed in Section 2.1. However, the sidewall roughness is of higher importance than the top roughness for demolding or when using the micro-pillars as optical waveguides. Therefore, three pillars were cut down at their base with a scalpel and their sidewall roughness was measured with the optical profiler. Since the surface is cone-like, it is difficult to measure the surface roughness over a large area using an optical profiler. We measured a surface roughness between 19 nm and 35 nm for both 50 μm and 140 μm-diameter pillars over an area of 5 μm × 63.7 μm, with removal of tilt and cylindrical curvature of the measured data. If we consider a surface roughness below 40 nm, our micro-pillars achieve optical surface quality for wavelengths upwards from at most 320 nm with the /2-requirement or for wavelengths upwards from at most 800 nm with the more stringent /8-requirement for optical surface quality [34].

3.3. Applications

In the introduction we mentioned that the pillars with a 50 μm-diameter could be used as optical waveguides for gigascale integration optical interconnect applications. We have performed initial light transmission performance testing of the waveguide micro-pillars irradiated with the 50 μm-diameter proton beam with a proton fluence of 7.96 × 10^8 on borosilicate glass. These pillars have a top-diameter of 93 ± 2 μm and a bottom-diameter of 113 ± 2 μm and are thus significantly larger than the targeted 50 μm, which is the typical dimension of the core of printed circuit board-integrated multimode waveguides [13]. We measured the insertion loss for multimode fiber-to-fiber coupling at the telecom wavelengths of 1550 nm, as depicted in Fig. 11(a). Both fibers have a numerical aperture of 0.22. When a gap of 910 μm exists between both fibers, the insertion loss could be improved by 4.7 dB by positioning a waveguide micro-pillar on glass in-between both fibers. By moving the launch-fiber in the XY-plane, a 3 dB-loss increase was observed only at ±22 μm lateral misalignment. This means that even with this degree of lateral misalignment, the micro-pillar waveguides still improve the coupling efficiency, significantly (1.7 dB at 22 μm lateral misalignment). These initial tests prove that the micro-pillars could be used to improve the coupling efficiency between optoelectronic input/output chips and optical waveguides in printed circuit boards, where an air gap typically exists between the waveguide and the optoelectronic due to the chip flip-chip bonding process typically used to mount these chips on the printed circuit board. [5,14,15], as depicted schematically in Fig. 11(b).

As a second application, the 140 μm-diameter pillar-arrays could serve to mimic human tissue for in vitro biochemical experiments [16,17]. For these applications hydrogels, and not SU-8, are the material of choice. Nevertheless, the SU-8 master component can be used to create a mold for subsequent hydrogel casting. We have performed initial mold formation tests by silicone-casting [35] on a 10 × 10 array of micro-pillars fabricated in SU-8 on glass. To this end, we embed the DPW master-component into a liquid silicone, which is a mixture of a rubber (10 parts by weight) and a catalyst (1 part by weight). The silicone rubber (Rhodorsil RTV 246A) contains approximately 90% (by weight) methyl-vinyl-polysiloxane, <1% hexamethydisilazane, 9% amorphous silica and <0.5% modified chloroplatinic acid. The silicone catalyst (MCP-HEK CAT750) is a hydride-terminated polydimethyl-siloxane. The CAT750 catalyst ensures hardening of the silicone over a period of 24 h after mixing with the silicone rubber. Once hardened, the master-component is removed from the silicone mold, which causes approximately 50% of the micro-pillars to break off from the glass substrate. The micro-pillars can easily be removed from the silicone-mold by rinsing it with de-ionized water and subsequent blowdrying. The DPW master-component is thus lost after mold formation. A SEM picture of the master-component and a stereo-microscope image of the silicone mold can be seen in Fig. 12. We measure an outer diameter of the micro-holes of 167 ± 4 μm in the mold with the non-contact optical profiler. Considering that the profiler overestimates this value by about approximately 10 μm (due to the rounded edges), a good dimensional agreement of the silicone mold with the master-component is achieved. In-depth analysis of the fabricated mold, larger micro-pillar array (50 × 50) mold formation and hydrogel casting using the resulting silicone mold are the subject of future work.

As an alternative to mold formation by silicone molding, we have investigated mold formation through electroforming in the past for several PMMA components fabricated with DPW [36,27]. The advantage of this type of mold formation is that the resulting mold is made of metal. With a soft mold, like in the case of silicone molding, the mold degrades quickly with replication and it doesn't

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**Fig. 11.** (a) Schematic representation of the initial optical coupling efficiency measurement setup. Light is coupled into the launch fiber and the detector fiber is connected to an optical power meter. The lateral misalignment is measured by moving the launch fiber in the XY-plane. (b) Schematic representation of an optical chip with optical sources (and detectors) flip-chip bonded with a ball grid array (the black solid circles) on a printed circuit board. Light is emitted from the source (in red) and diverges while traveling to the mirror and waveguide in the printed circuit board. Our measurements show that a micro-pillar waveguide between the two chips (dotted line), would strongly improve the achievable coupling efficiency. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
allow the use of high temperatures or pressures. A metal mold on the other hand can be used with high temperature and pressure and thus allows for the replication by micro-injection molding or hot embossing [37,38]. To achieve mold formation by electroforming, the sample should be bonded to a conductive substrate and be coated with a conductive seed-layer to achieve a good mold quality [27]. Subsequent to the mold formation, the SU-8 and glass substrate need to be removed from the metal with reactive ion etching [39]. This strategy would be feasible for fabricating a mold of the SU-8 micro-pillars on borosilicate glass.

4. Conclusions

We presented the fabrication of high aspect ratio micro-pillars with deep proton writing (DPW), a versatile micro-fabrication technology for the rapid prototyping of micro-components with optical surface quality. In this work we used a collimated proton beam with an energy of 12 MeV to irradiate SU-8 layers spincoated on borosilicate glass substrates with a 175 ± 15 μm thickness and a 30 mm diameter. Within a single spincoating step we achieved SU-8 layers up to 720 μm-thick with a root-mean square surface roughness of 1.3 ± 0.2 nm measured over an area of 63.7 × 47.8 μm. We determined that the optimal proton flux for irradiating SU-8 with 12 MeV protons is 1.02 × 10⁴ μm⁻², which corresponds to an exposure energy of 526 mJ/cm² and critical dose of 6.35 J/g, assuming a mass stopping power of 0.0416 MeV cm²/g. The fabricated micro-pillars were characterized geometrically by non-contact optical profilometry and a coordinate measurement machine. We showed that the profile of the pillars broadens from top to bottom, near the glass substrate, due to the scattering of protons within the SU-8 and the divergence of the proton beam used for irradiation. With the 50 μm proton beam we achieved micro-pillars with a maximum aspect ratio of ~8, a minimum feature size of 90 μm (on the broader bottom-side) and a height of 721 μm. Pillars with top-diameters lower than 57 ± 5 μm could not be achieved due to limitations of the present irradiation-monitoring equipment. With the 140 μm-diameter proton beam, we were able to repeatedly achieve 138 ± 1 μm top and 151 ± 3 μm bottom diameter pillars, with a maximum achieved height of 640 μm and an aspect ratio of 4.3. We achieved a sidewall surface roughness between 19 nm and 35 nm for the fabricated micro-pillars, measured over an area of 5 × 63.7 μm, which classifies them as being of optical quality. Finally, we looked at the fabricated micro-pillars from an application point-of-view. The micro-pillars fabricated with the 50 μm show great potential for optical interconnect applications, since an improvement of coupling efficiency of 4.7 dB and a 3 dB-lateral misalignment tolerance of 20 μm was shown, for multimode fiber-to-fiber coupling at the telecom wavelength of 1550 nm. As a second application example, pillars fabricated with the 140 μm-beam were used as a master-component for mold formation via silicone-casting. An initial mold formation test was successful for a 10 × 10 array of micro-pillars. When a hydrogel is cast in this silicone mold, samples mimicking human tissue for in vitro biochemical application could be obtained. In-depth analysis of the fabricated mold, larger micro-pillar array (50 × 50) mold formation and hydrogel casting are the subject of future work.

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