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Flexible polymeric rib waveguide with self-align couplers system

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Abstract

The authors report a polymeric based rib waveguide with U shape self-align fiber couplers system using a simple micromolding process with SU8 as a molding material and polydimethylsiloxane as a waveguide material. The material is used for its good optical transparency, low surface tension, biocompatibility, and durability. Furthermore, the material is highly formable. This unique fabrication molding technique provides a means of keeping the material and manufacturing costs to a minimum. The self-align fiber couplers system also proves a fast and simple means of light coupling. The flexible nature of the waveguide material makes this process ideal for a potential wearable optical sensor.

I. INTRODUCTION

Recently polymeric optical devices have drawn a lot of attention due to their low cost, as well as simple and low temperature fabrication.¹ Polymer based optical devices are also ideal due to the fact that many of polymers' optical properties can be easily manipulated by temperature and fabrication procedures.² With the fact that devices can be manufactured using batch processing, devices can be constructed in consistent and large quantity.³ Among all optical devices, integrated optics is especially of interest due to their compatibility with existing microelectronic fabrication processes.⁴ The most important elements of integrated optics are waveguides.⁵ Various polymers and fabrication techniques have been reported, such as photoexposure and reactive ion etching (RIE),⁶ electron-beam direct writing,⁷ hot embossing,² laser direct writing,⁸ molding,⁹ and photobleaching.¹⁰ In this paper, a different and simpler process to fabricate flexible elastomeric multimode waveguides with a self-aligned coupler system is presented. The proposed waveguide design is a three-layered rib waveguide design with Sylgard 184 (Dow Corning Corp., MI), OE 43 (Gelest, Inc., PA) and air as a substrate, film, and cover, respectively. The rib width, total waveguide height, and slab height are designated as W , H , and h , which are 10, 15, and 5 μm , respectively. In addition, the refractive indices are 1.398, 1.417, and 1.000 for substrate, film, and cover, respectively (Fig. 1).

The waveguide fabrication process includes a simple SU8 mold and polydimethylsiloxane (PDMS) casting. SU8, an epoxy-based negative photoresist (MicroChem Corp., MA.), has been widely used for the fabrication of molds,¹¹ due to its strong structural stability¹² and good layer to layer adhesion.¹³ PDMS, a silicone based polymer, is highly transparent over a large frequency range.¹⁴ The absorption band and refractive index will shift depending on

the substituents attached to the backbone. Many earlier reports^{14,15} have demonstrated successfully using this material for waveguide systems.

II. FABRICATION

The fabrication process mainly involves casting a two-layered PDMS structure from a three-layered SU8 mold (Fig. 2). The SU8 mold consists of a rectangular waveguide trench and a fiber coupler mount [Fig. 3(b)].

For the SU8 mold substrate, a *p*-type single sided polished silicon wafer was used. The substrate was cleaned by immersing a diluted HF (10:1) solution to remove any naturally grown oxide layer. The wafer was then rinsed thoroughly in DI water, blown dry using nitrogen gas, and then dehydrated in an oven at 110 °C for at least 30 min. In order to create a good adhesion between SU8 and Si wafer, a thin layer (2 μm) of SU8-2002 (MicroChem, MA.) was spin coated onto the silicon substrate, following instructions provided by the MicroChem Corp. To fabricate a waveguide trench, a 10 μm SU8-2010 resist was spun on top of the SU8-2002 layer. In order to reduce the intrinsic stress that occurred during prebaking, the temperature was ramped from 22 to 65 °C at a rate of 3 °C/min and held at that temperature for a minute before continuing ramping to the recommended temperature of 95 °C. We then held the sample at that temperature for 2 min before gradually ramping down to room temperature at a rate of 2 °C/min. The waveguide trench pattern was transferred from a quartz mask to the film by exposing the film on a contact aligner with a mercury broadband light source. Based on repeated trials, it was found that the film reproduces features best when exposed at 130 mJ/cm². For the postexposure bake, the film was placed on a hotplate for 30 min at 60 °C. This temperature was much lower than the post bake temperature of 95 °C recommended by the manufacturer. This greatly reduced the internal stress, which will be discussed in more detail in the result and discussion section. After cooling the film to room temperature, the film was then developed in SU8 developer (PGMEA, an ethyl lactate and diacetone alcohol, MicroChem, Corp. MA.) for about 2 min with mild agitation. For the coupler parts, we used SU8 50 (Micro-Chem Corp., MA.) to create two large rectangular shaped plateaus. The process is basically similar to the procedure described earlier for SU8-2010. For SU8 50, a 58.5 μm (actual average resulting height ~56.2 μm) thick film is spun on top of the SU8-2010 layer. The film was prebaked on a hotplate. The temperature was ramped from 22 to 65 °C at 3 °C/min and held for 7 min before ramping up to 95 °C. The temperature was held for 23 min and then ramped down to 22 °C at a rate of 2 °C/min. The film was then exposed with a coupler pattern from Quartz mask at 370 mJ/cm², and then post exposure baked at 60 °C for 30 min. The whole wafer was then immersed in SU8 developer for 6 min and 30 s. At this point, a three-layer SU8 waveguide mold is completed (Fig. 3). To accommodate higher tolerance of coupling, the width of the waveguide trench was purposely made to the size of optical fiber diameter, 125 μm [Fig. 3(b)]. The 125 μm waveguide is then tapered down to the final 10 μm waveguide width [Fig. 3(a)]. The sidewall of the trench appears slightly curved.

For elastomer casting, different two-part silicone elastomers from two vendors were used: OE 43 ($n=1.417$ at $\lambda=1.55$ μm from Gelest Inc.) for core and Sylgard 184 ($n=1.398$ at $\lambda=1.55$ μm from Dow Corning) for cladding. The refractive indices of TE and TM polarizations for both elastomers were found to be the same. Based on the measurement, the optical property of material seems to be isotropic. In order to release the elastomer from the mold, the mold was first silanized by exposing the film to the vapor of (tridecafluoro-1, 1, 2, 2-tetrahydrooctyl) trichlorosilane (Gelest, Inc.) in a vacuum chamber for 30 min. Both elastomers come with a two-part kit: a prepolymer and a curing agent. Both elastomers also require the same preparation steps: mix base and curing agent thoroughly with a ratio of

10:1 and then degas the air bubbles generated during mixing. For the core layer, the OE 43 was spun at 5500 rpm creating a 5 μm thick film. The film was then cured at 60 $^{\circ}\text{C}$ for 4 h on a hotplate and then Sylgard 184 (~ 500 μm thick) was cast on top of OE43 and cured at 60 $^{\circ}\text{C}$ overnight in an oven. Then the elastomer was carefully separated from the mold to form the finished rib waveguide structure (Fig. 4).

III. RESULT AND DISCUSSION

SU8 has been widely used as a molding material in microfluidic systems due to its strong structural stability, and high chemical and thermal resistance.¹⁶ However, SU8 has been proven to be very sensitive to process conditions¹⁷ and one of the resulting consequences is the large internal stress generated during this process,¹⁸ which causes feature distortion, dimensional change, and cracks. From this design, it was found that the post exposure bake temperature (PEB) and exposure area are important factors that define feature fidelity.

Several issues were found in the PEB process. One was residues forming on the edges of a high aspect ratio trench structure when recommended 95 $^{\circ}\text{C}$ PEB temperature was used. This phenomenon is usually referred to as capping effect, where undeveloped residues appear on the edges and corners of the top surface of a trench structure (Fig. 5). The solution we found was to lower the PEB temperature to 60 $^{\circ}\text{C}$. The result produces more vertical sidewalls and minimum residue around the edges of the sidewalls (Fig. 6). The result was verified by several repeated trials where capping appeared at 95 $^{\circ}\text{C}$ PEB and not 60 $^{\circ}\text{C}$ PEB.

Based on literature, we found that there are many different explanations for the capping to occur.^{11,19,20} Chan-Park *et al.*¹¹ found that the same 10 μm trench can experience the same capping problem especially at the center of the wafer. The solution was to lower the exposed energy during pattern exposure. Dentinger *et al.*¹⁹ explains that capping is caused by the redeposition of the SU8. Becnel²⁰ explains that the diffusion of the exposed SU8 into the unexposed area forms the “cap.” The higher concentration of the exposed SU8 is always greatest near the top surface and hence the cap always formed on the top surface.

In our case, we believe that both the diffusion from the exposed region into the unexposed region²⁰ and the higher residual stress due to higher PEB temperature^{18,21} play a more key role in the capping effect. The diffusion is more likely to occur due to the fact that the corner is surrounded by three sides thus there is more area in the vicinity for the diffusion to occur. This might be the reason that we saw our cap occurred mostly around the corner region [Fig. 5(b)]. By reducing the PEB temperature with longer baking time, we believe the diffusion was decreased.

However, diffusion alone cannot explain why the capping only occurs in the free standing structures that are closely packed but not in the structures that are further separated. One other factor contributes to capping is that there is a large mismatch in the thermal expansion coefficients of Si and SU8. It has been found that this residual stress is greatest in the center of the wafer.^{18,21} We suspected that the capping only happens at the trenches near the center of the wafer¹¹ was due to the fact that greater internal stress was induced in the region. The actual physical process of this capping might be far more complicated (i.e., capping might also be caused by high exposed energy or redeposition after development¹⁹). However, in our case, the PEB temperature seems to be the major factor in creating the capping problem in our structure.

Cracks were also found on patterns that are in a large exposed area [Fig. 8(a)]. Besides controlling the PEB temperature, the size of the exposed areas also play a role in introducing

internal stress.²² In order to reduce the exposed area, a quartz mask covered with an opaque transparency film with 3 mm wide transparent window around the trench pattern was used (Fig. 7). The sample with transparency mask showed no cracks at the corners of the tapered waveguide trench [Fig. 8(b)]. The results implied smaller stress levels built up during the baking process. However, rounded and less sharp sidewalls were observed. This was due to the fact that a low quality lithography mask generated with a 2450 dpi horizontal, 300 dpi vertical printer was used as shown in Fig. 7, where the optical diffraction effect and scattering effect from the free particles of the transparency mask causes a poor quality pattern transferring. It should be noted that the sidewall of the SU8 tapered inward towards the bottom of the trench; hence, the rough edges in Fig. 8(b) has nothing to do with the slanted sidewall. This problem can be easily eliminated in the future by incorporating quartz masks instead of transparencies.

A completed rib elastomeric waveguide is shown in Fig. 4. Due to the high compliance of elastomer, the concave sidewall did not seem to cause any stiction during release of the elastomeric waveguide from the SU8 mold. However, the surface of the cross section was slightly rough due to the fact that a razor blade cannot cut the surface cleanly. Field confinement in the waveguide was demonstrated using a HeNe laser ($\lambda = 632.8$ nm). The beam was shown to be confined within the waveguide region (Fig. 9). However, some scattering was observed on the end face of the slab region, which is likely due to the fact that the end face in that region was rougher than the ridge region due to dissection.

It has been shown by Lee and Lee,²³ who reported that the PDMS shrinks after curing and the shrinkage is proportional to the curing temperature. They also stated that when the PDMS was cured at 65 °C, the shrinkage could reduce down to around 1%. We also observed the shrinkage in the PDMS after 65 °C curing temperature. However, a larger deviation in the geometry between the SU8 mold and the elastomeric waveguide was observed. The results show that the top and bottom widths of waveguide trench on the SU8 were 11.2 and 12.7 μm , respectively, while the height was 9.7 μm . The replicated elastomeric waveguide on the other hand had widths of 8.8 and 7.9 μm on top and bottom, respectively, and a height of 9.0 μm . The measured SU8 coupler height was 56.17 μm , and the elastomeric waveguide groove was 54.35 μm (average from four samples). The overall shrinkage is about 30% in waveguide region and about 3.2% in the coupler region. One likely cause of this big deviation in the waveguide region is due to the fact that the cross section was distorted by the dissection of the waveguide. It was difficult to dissect the waveguide without distorting the end face. A more extreme case of the distorted cross section is shown in Figs. 10(a) and 10(b). The figures show an example of extreme distorted cross sections due to the cutting. The arrows in the figures show the direction of the two shear forces caused by the knife motion. During the cutting, the sample experiences the force exerted by blade. The resulting force can be divided into two shear forces (downwards and direction of cutting). We believe the extent of distortion depends on the cutting speed and angle and also the cutting creates some rough surface. However, at this point we do not have any quantitative data. The image shown in Fig. 4(a) is a less distorted cross section. Another reason for this large deviation in the waveguide region between SU8 and the PDMS replica was that the measurement from a scanning electron microscope was affected by the shadow which appeared at the edges of the cross section, which could affect measurements of the profile [Fig. 4(a)].

The fact that we did not polish the end of the waveguide was due to the lack of proper polishing tool. The normal procedure is done by putting the waveguide in a ferrule and secured with epoxy and then proceed with the polishing. Two potential problems were likely to occur: (1) difficulty in removing the ferrule and the epoxy and (2) the index of PDMS is

so low (~1.40) compared to most of epoxy (~1.50) and this could cause a serious light leakage if the epoxy cannot be removed completely. In our own test, more than ten castings were done on the SU8 mold, the resulting PDMS waveguide and SU8 appeared to be clean and have the same replication each time under the microscope inspection. Based on previous finding by Jackman *et al.*²⁴ with similar process of casting PDMS on photoresist master, the author has stated that the mold could be reused more than 20 times. Although Jackman *et al.* did not state what kind of resist they were using, it has been known that epoxy-based SU8 has characteristics of strong structure stability, so we believe our SU8 mold can definitely be reused more than 20 times. We have not done any stability test on PDMS waveguide. However, Chang-Yen *et al.*¹⁴ have shown based on their tests that the material appears very stable under different temperatures and humidity conditions.

The waveguide with fiber coupler system was examined. Two samples were tested using a single mode fiber (core=8.2 μm , n_{eff} = 1.4682 at 1550 nm, Corning Inc., NY) and a 10 mW HeNe laser light source (λ =632.8 nm). For the first sample, the light was coupled into the waveguide using a fiber coupler (Figs. 4(b) and 4(c)) and the light was coupled out using the butt end technique. For the second sample, butt end coupling was used for both input and output light couplings. The actual light loss was measured based on the difference between the baseline intensity directly measured from the input fiber and the output light intensity via the waveguide. The results were summarized in Table I. In both cases, a significant amount of light was lost in the waveguide. This is believed to be due to the fact that a razor blade, which we use to cut the end surface, could not quite create a clean cut. Therefore the surfaces were quite rough, and a lot of reflection occurred at the coupling interface. Comparing samples 1 and 2, one can see a 17 dBm improvement with at least one end facing the fiber coupling system. However, due to difficulty in controlling the uniformity of the three-layer SU8 process which creates the coupler groove, we decided to test only one coupler to show the feasibility of light coupling.

IV. CONCLUSION

We have successfully demonstrated a simple technique for fabricating a flexible and soft PDMS rib waveguide by casting prepolymer into a three-layer SU8 mold. We have also discussed some technical issues regarding mold making using SU8 photoresist. Our waveguide has shown excellent beam confinement, and minimum light loss was observed using building coupling system. Combining the advantages of low cost, low toxicity, biocompatibility, and flexibility of PDMS, we believe PDMS waveguides have a big potential for applications in microanalysis systems.

Acknowledgments

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Fig. 1.
Sketch of a cross section of elastomeric three-layered rib waveguide.

Fig. 2.
(a) three-layer SU8 mold and (b) cross section of the SU8 mold with two-layer elastomeric casting.

Fig. 3.
(a) SU8 waveguide trench cross section and (b) SU8 the coupler bump and tapering 125 μm wide waveguide trench. The waveguide will eventually taper down from 125 μm to final 10 μm width.

Fig. 4.
 (a) Cross section of PDMS waveguide and (b) elastomeric coupler trench and (c) fiber inside the coupler.

Fig. 5.
(a) SU8 waveguide trench with capping on the top surface and (b) around the corner. PEB temperature was at 95 °C.

Fig. 6.
SU8 waveguide trench without capping on the top surface and corners. PEB temperature was at 60 °C.

Fig. 7. Illustration of the transparency mask used along with the waveguide trench pattern on top of the waveguide quartz mask.

Fig. 8. Top view of microscopic images of the tapered waveguide trench (a) without and (b) with transparency mask on top of waveguide chrome mask. Both PEB temperatures were at 60 °C.

Fig. 9. Microscopic image (a) cross section of waveguide. (b) The light is confined inside the ridge and slab. Images were taken from a charge coupled device camera (550×350 pixels resolution) with $400\times$ magnification.

Fig. 10.

(a) (Cross section) The dashed line indicates the distorted cross section of the dissected surface. The solid lines show the two shear forces introduced by the cutting (arrows do not indicate the scale of the forces) and (b) Warped surface becomes more obvious at 45° angle.

Table I

Light intensity comparison between setup with coupler and without coupler (units in dBm).

	Baseline int.	Waveguide int.	Loss int.
Sample 1	−28.7	−62.5	33.8
Sample 2	−21	−71.4	50.4