NOTE

Rapid prototyping of microfluidic systems using a laser-patterned tape

L W Luo, C Y Teo, W L Ong, K C Tang, L F Cheow and L Yobas

Institute of Microelectronics (IME), 11 Science Park Road, Science Park II, Singapore 117685

E-mail: leventy@ime.a-star.edu.sg

Received 30 August 2007, in final form 4 October 2007 Published 31 October 2007 Online at stacks.iop.org/JMM/17/N107

Abstract

We introduce a laser-patterned tape as a master for replica moulding microfluidics in poly(dimethylsiloxane) (PDMS). Normally, a laser is applied to scribe microchannels directly on poly(methyl methacrylate) (PMMA) substrates. This direct engraving usually offers a faster turn-around time than conventional soft lithography but generates rough surfaces which perform poorly under phase-contrast microscopy imaging. Using a laser-patterned tape as the master template for replica-moulding microfluidics in PDMS, we combine the rapid turn-around time of laser ablation and relatively smooth surface finish of soft lithography. Hence, microfluidic devices suitable for optical microscopy imaging can be obtained within several hours.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Research in microfluidics has flourished since the introduction of rapid prototyping methods, particularly the widely accepted soft lithography [1]. Such methods have made the field of microfluidics accessible to a large community of scientists and engineers from various disciplines. Moreover, with soft lithography, the construction material for microfluidics has shifted from silicon, which is a hard and opaque substrate demanding advanced microfabrication techniques and facilities, to less demanding soft and transparent polymers. Since these material characteristics suit particularly well for biomedical applications, these rapid prototyping methods have been used for DNA sequencing [2], gene-expression profiling [3], protein analysis [4] and drug delivery systems [5].

Conventional soft lithography has a rapid turn-around time, typically less than 24 h. Yet, it demands a photolithography tool and does not easily cater for immediate design modifications. To further improve the design flexibility and reduce the fabrication cost, recent replica-moulding techniques [6–8] avoid the photolithography step and make use of alternative patterning techniques. A common approach is the print and mould method [9, 10] whereby microfluidic

networks are formed in PDMS by replicating printer-generated patterns. A recent example uses a wax printer to fabricate a master pattern [11]. This method is inexpensive and the whole fabrication process can be completed within several hours. A further innovative approach uses a liquid master by patterning water droplets via plasma-activated templating [12]. Nevertheless, these methods may not easily control the aspect ratio of microchannels.

An alternative prototyping technique uses a CO₂ laser to scribe microfluidic channels directly on PMMA through thermal ablation [13]. Despite having a fairly rapid turnaround time, there exist certain disadvantages in this method. Laser-ablated microchannels are usually not optically clear, and the height and width of these microchannels cannot be independently varied due to their inherent correlation. Therefore, it is difficult to vary the aspect ratio of the microchannels fabricated by this direct laser ablation. An improved method uses a CO₂ laser to cut microchannels in a double-sided adhesive film with a fixed thickness [14, 15]. The channel height can be varied by laminating multiple layers of the film together. The channels are sandwiched between glass or PMMA plates which have smooth surfaces suitable for optical microscopy. A further technique uses a CO₂ laser to cut

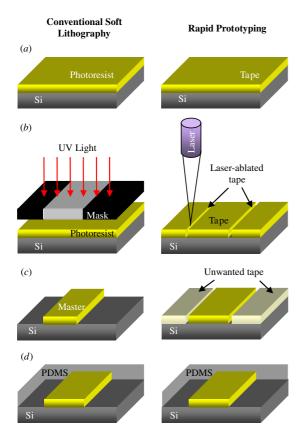


Figure 1. Schematics highlighting key process differences between conventional soft lithography versus the rapid prototyping method introduced here. (*a*) Substrate coating: spinning photoresist versus laminating tape. (*b*) Pattern registration: exposing the photoresist to UV light through a photomask versus thermal ablating the tape through a laser beam. (*c*) Pattern generation: developing the photoresist versus peeling off the unwanted segments of the tape. (*d*) Replica moulding the photoresist or the tape pattern in PDMS.

channel structures in multiple layers of thin polymer sheets, each having a unique pattern. Subsequently, the patterned sheets are aligned and laminated using a commercial hot laminator to form a three-dimensional network [16–18].

Here, we introduce an approach that combines the rapid turn-around time of laser ablation and smooth-surface finish of soft lithography. As schematically described in figure 1, adhesive tape and laser scribing replace photoresist and photomask exposure in soft lithography. The tape is first laminated on a hard and smooth surface such as a polished silicon wafer and then patterned according to a given digitized layout through a computer-controlled laser beam. patterning involves laser ablation of the tape into sections and then removal of the unwanted sections by peeling them off from the substrate. The remaining tape pattern serves as a master template for replica-moulding microchannels in PDMS. Our approach differs from the aforementioned methods which also make use of the laser patterning adhesive films or polymer sheets in that the laser-patterned tape here is used as a template for PDMS moulding, instead of being part of the final device. This enables us to repeatedly produce the device without the necessity of going through the laser ablation process again. Furthermore, since our approach implements the final device in PDMS, the device can benefit from some

of the well-known material properties in realizing compliant and gas permeable parts and forming tight seals with fluidic inlets and outlets [19]. Our technique can also be further developed to fabricate a three-dimensional microstructure in a single laser-ablation step.

2. Experimental procedures

A grinding single-sided adhesive tape at a thickness of 130 µm (Furukawa Electric) was laminated on a polished surface of an 8 in. silicon wafer with no bubbles trapped in between the tape and the wafer. A digitized microfluidic layout was then transferred onto the tape by thermal ablation from a computer-controlled CO2 laser machine. We used the Universal M-360 Laser Platform (Universal Laser Systems Inc.) with a maximum laser power of 30 Watt and a maximum beam speed of 1905 mm s⁻¹. Unwanted segments of the tape were then peeled off from the silicon surface without leaving any visible residue behind to obtain a clean relief structure for the subsequent PDMS moulding. PDMS (Dow Corning, Sylgard® 184) pre-polymer mixture was prepared by thoroughly mixing the base monomer and curing agent at a ratio of 10:1 by weight, degassed and then poured onto the patterned tape. The PDMS curing took place at 80 °C for 2 h in a vacuum oven (Model 280A, Fisher Scientific). The cured PDMS replica was cut and peeled off from the relief structure. The single-sided adhesive relief structure separated easily from the PDMS due to their non-interacting surfaces and remained attached to the wafer due to its high adhesive strength. This relief structure can be repeatedly used for subsequent moulding. Next, the PDMS microfluidic device was punched to create the fluidic inlet and outlet holes and then irreversibly bonded to a plain PDMS slab after exposing both pieces to oxygen plasma (70 W, 60 s). The bonded pair was, subsequently, annealed at 150 °C for 2 h to reinforce their bonding strength.

3. Results and discussion

The lower limit of the resolution in the introduced patterning process is determined by the width of the laser-ablated track lines on the tape. The line width is mainly determined by the power and translational speed of the laser beam as shown by experimental plots in figure 2. In figure 2(a), at the minimum power and speed offered by the current laser system (0.3 W, $5.72 \,\mathrm{mm \, s^{-1}}$), the beam is sufficient to cut through the tape with a track-line width of 150 μ m and increasing the laser power further increases the track-line width. Figure 2(b) shows that increasing the beam translational speed decreases the trackline width to an extent (\sim 90 μ m). However, the beam at a translational speed beyond 13 mm s⁻¹ cannot produce a complete cut in the tape as the track lines get discontinuous. Figure 2(c) analyses the relationship between the track-line depth and the beam translational speed. For a given beam power and translational speed, one has to take into account the offset created by the track-line width and depth when designing the microfluidic layout. Relief structures having a feature size of 200 μ m or more can be reliably produced for repeated moulding without the tape delaminating from the silicon surface.

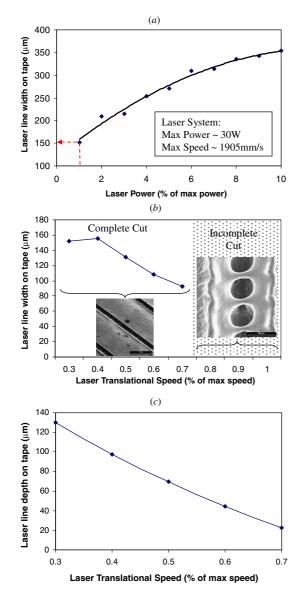


Figure 2. Experimental plots relating the width of the laser-ablated track lines to (a) laser power at a fixed translational speed (0.3% of the system maximum) and (b) translational speed at a fixed power (1% of the system maximum). Respective scales of SEM images: 1 mm and $100~\mu\text{m}$. (c) Experimental plot relating depth of the laser-ablated track lines to translational speed at a fixed power (1% of the system maximum).

To demonstrate the utility of the tape-based templating, we fabricated microfluidic devices containing simple T-junctions. Figures 3(a) and (b) show a picture of the patterned tape on silicon and its detailed close-up image under scanning electron microscopy (SEM). In figure 3(b), the mirror-finish surface of silicon near the tape remained unaffected and there was no visible trace of laser penetration. The patterned tape has a relatively smooth and flat surface which is suitable for moulding microchannels in PDMS. In figures 3(c)–(f), we compared microchannel profiles in PDMS replicated from the tape master and in PMMA directly ablated by CO_2 laser. The surface finish of the PDMS microchannel (figure 3(f)) is smoother than that of the PMMA microchannel (figure 3(e)) which shows many irregular pits. The smoothness

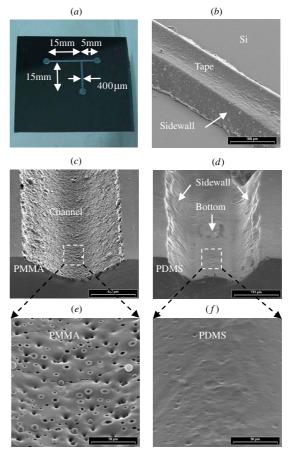


Figure 3. (a) Picture of a laser-patterned tape on silicon for replica-moulding microfluidic T-junctions using laser parameters (0.3 W, 5.72 mm s⁻¹). SEM images: (b) close-up view of the patterned tape; (c) and (e) laser-ablated PMMA microchannel and its close-up view; (d) and (f) tape-replicated PDMS microchannel and its close-up view. Respective scales: 300, 422, 231, 50 and 50 all in μ m.

of the microchannel is critical in microfluidic applications, particularly when optical microscopy imaging is required.

Next, we compared the clarity of optical microscopy images when the T-junctions were put to test for the generation of water-in-oil droplets (figure 4). We observed that the droplets in the laser-ablated PMMA microchannels are difficult to resolve and hardly distinguishable solely based on their phase-contrast microscopy images (figure 4(c)). In consequence, we had to resort to epi-fluorescence microscopy to observe the droplets and their formation mechanism in the laser-ablated PMMA microchannels (figure 4(e)). On the contrary, figures 4(d) and (f) show that both the phase contrast as well as epi-fluorescence microscopy images of the PDMS microchannels replicated from a tape master are on par with those achievable with conventional soft lithography. The comparison between these two fabrication techniques substantiates the advantages of using a laser-patterned tape for prototyping of microfluidic systems.

Our method can be further extended to fabricate a threedimensional network by laminating multiple tapes together on a silicon wafer. By varying the laser power, different layers of tape can be cut and removed, resulting in a multi-step network. Network, having feature-to-feature separation of

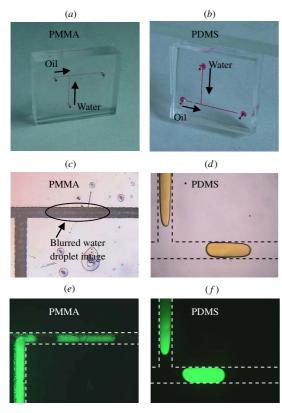


Figure 4. Images of microfluidic T-junctions laser-ablated in PMMA and tape-replicated in PDMS comparing their optical clarity in (a) and (b) device photographs; (c) and (d) phase-contrast microscopy images; and (e) and (f) epi-fluorescence microscopy images captured during the generation of water-in-oil droplets.

more than 500 μ m, can be reliably produced using this multiple tape technique. To achieve a more complex and smaller three-dimensional microstructure, we adopted another method by adding a laser engraving step in the original templating process. This step partially penetrated the tape segments to be retained on the template. These partial penetrations produced protrusions in the microchannel bottom after replica moulding. We demonstrated such a technique in fabricating a threedimensional chaotic micromixer. Specifically, we fabricated a slanted-rib micromixer (figures 5(a) and (b)) similar to the one by Stroock et al [20]. Our slanted-rib micromixer was made from a single layer of 130 μ m thick grinding tape. The microchannel was cut with laser parameters (0.3 W, 5.72 mm s⁻¹) while the partial penetrations, 92 μ m wide and 22 μ m deep, were made using parameters (0.3 W, 13.34 mm s⁻¹). The slanted-rib patterns in the microchannel have been shown to induce chaotic advection, thereby improving the mixing efficiency of co-flowing laminar streams. We studied the mixing performance by observing coflow of plain and fluorescein-labelled water streams through the microchannels with and without protrusions and were able to replicate similar results [20]. In figure 5(c), mixing in the slanted-rib microchannel starts to occur in the first interval whereas in figure 5(d), no mixing can be observed in the microchannel without protrusions. Figures 5(e) and (f)show the normalized fluorescence intensities at equal intervals of 2.2 mm along the microchannels with and without the

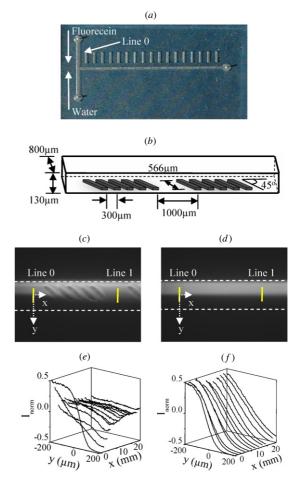


Figure 5. (a) Photograph of a tape-replicated slanted-rib micromixer design in PDMS. (b) Schematic view of the design with stated dimensions; (c) and (d) epi-fluorescence microscopy images of the microchannels with and without the slanted ribs during coflow of plain and fluorescein-labelled water streams, both at $4 \mu l \min^{-1}$; (e) and (f) normalized fluorescence intensity distribution along the microchannels with and without the slanted ribs.

slanted ribs, respectively. The fluorescent readings indicate the level of mixing along the imaginary yellow lines dividing the intervals and centered across the microchannels (figures 5(c) and (d)). A null value indicates a complete mixing since the normalization is according to [21]

$$I_{\text{norm}} = \frac{I - I_{\text{min}}}{I_{\text{max}} - I_{\text{min}}} - 0.5 \tag{1}$$

where $I_{\rm max}$ and $I_{\rm min}$ correspond to maximum and minimum fluorescent intensities measured along line 0, respectively, before the first interval. It is clearly visible from the normalized intensity plots that the slanted-rib protrusions lead to almost complete mixing after the third interval (figure 5(e)) while there is hardly any mixing throughout the microchannel without such protrusions (figure 5(f)).

4. Conclusion

We demonstrate a rapid prototyping method for microfluidics by which from concept to device realization takes only several hours without the use of photolithography tools. Novelty of the method lies with the template generation which simply involves laminating an adhesive grinding tape on a silicon wafer, thermally ablating the tape by a CO₂ laser beam and removal of the unwanted sections of the tape by peeling them off. Using such a template in PDMS replica moulding, microchannels having a surface finish quality suitable for optical microscopy imaging can be easily obtained. Moreover, the method can be further extended for complex multi-step microchannel profiles by adding a laser engraving step in the original templating process. We believe that the pattern density and the lower limit of resolution in the process can be addressed by switching to a high-energy pulsed laser and better heat-resistant tape.

References

- Duffy D C, McDonald J C, Schueller O J A and Whitesides G M 1998 Rapid prototyping of microfluidic systems in poly(dimethylsiloxane) *Anal. Chem.* 4974–84
- [2] Kartalov E P and Quake S R 2004 Microfluidic device reads up to four consecutive base pairs in DNA sequencing-by-synthesis *Nucl. Acid Res.* 32 2873–9
- [3] Ryley J and Pereira-Smith O M 2006 Microfluidics device for single cell gene expression analysis in Saccharomyces cerevisiae Yeast 23 1065–73
- [4] Dodge A, Brunet E, Chen S L, Goulpeau J, Labas V, Vinh J and Tabeling P 2006 PDMS-based microfluidics for proteomic analysis *Analyst* 131 1122–8
- [5] Eddington D T and Beebe D J 2005 Development of a disposable infusion system for the delivery of protein therapeutics *Biomed. Microdev.* 7 223–30
- [6] McDonald J C, Chabinyc M L, Metallo S J, Anderson J R, Strock A D and Whitesides G M 2002 Prototyping of microfluidic devices in poly(dimethylsiloxane) using solid-object printing Anal. Chem. 74 1537–45
- [7] Zhao D S, Roy B, McCormick M T, Kuhr W G and Brazill S A 2003 Rapid fabrication of a poly(dimethylsiloxane) microfluidic capillary gel electrophoresis system utilizing high precision machining *Lab Chip* 3 93–9

- [8] Sudarsan A P and Ugaz V M 2004 Printed circuit technology for fabrication of plastic-based microfluidic devices *Anal*. *Chem.* 76 3229–35
- [9] Tan A, Rodgers K, Murrihy J P, O'Mathuna C and Glennon J D 2001 Rapid fabrication of microfluidic devices in poly(dimethylsiloxane) by photocopying *Lab Chip* 17–9
- [10] Liu A L, He F Y, Wang K, Zhou T, Lu Y and Xia X H 2005 Rapid method for design and fabrication of passive micromixers in microfluidic devices using a direct-printing process Lab Chip 5 974–8
- [11] Kaigala G V, Ho S, Penterman R and Backhouse C J 2007 Rapid prototyping of microfluidic devices with a wax printer Lab Chip 7 384-7
- [12] Chao S, Carlson R and Meldrum D R 2007 Rapid fabrication of microchannels using microscale plasma activated templating (μPLAT) generated water molds *Lab Chip* 7 641–3
- [13] Klank H, Kutter J P and Geschke O 2002 CO₂-laser micromachining and back-end processing for rapid production of PMMA-based microfluidic systems *Lab Chip* 2 242–6
- [14] Wu Z and Nguyen N T 2005 Rapid mixing using two-phase hydraulic focusing in microchannels *Biomed*. *Microdev.* 7 13–20
- [15] Wu Z and Nguyen N T 2005 Hydrodynamic focusing in microchannels under consideration of diffusive dispersion: theories and experiments Sensors Actuators B 107 965–74
- [16] Wang C, Nguyen N T and Wong T N 2007 Optical measurement of flow field and concentration field inside a moving nanoliter droplet Sensors Actuators A 133 317–22
- [17] Nguyen N T and Huang X 2005 Mixing in microchannels based on hydrodynamic focusing and time-interleaved segmentation: modelling and experiment *Lap Chip* 5 1320–6
- [18] Nguyen N T and Huang X 2006 Modelling, fabrication and characterization of a polymeric micromixer based on sequential segmentation *Biomed. Microdev.* 8 133–9
- [19] Quake S R and Scherer A 2000 From micro- to nanofabrication with soft materials Science 290 1536–41
- [20] Stroock A D, Dertinger S K W, Ajdari A, Mezic I, Stone H A and Whitesides G M 2002 Chaotic mixer for microchannels Science 295 647–51
- [21] Wu Z, Nguyen N T and Huang X 2002 Nonlinear diffusive mixing in microchannels: theory and experiments J. Micromech. Microeng. 14 604–11