IOP Publishing — Journal of Micromechanics and Microengineering
J. Micromech. Microeng. **19** (2009) 065015 (6pp) doi:10.1088/0960-1317/19/6/065015

Solving the shrinkage-induced PDMS alignment registration issue in multilayer soft lithography

Christopher Moraes[1,2,3], **Yu Sun**[1,2] **and Craig A Simmons**[1,2]

[1] Department of Mechanical and Industrial Engineering, University of Toronto, 5 King's College Road, Toronto, Ontario, M5S 3G8, Canada
[2] Institute of Biomaterials and Biomedical Engineering, University of Toronto, 164 College Street, Toronto, Ontario M5S 3G9, Canada

E-mail: chris.moraes@utoronto.ca

Received 11 February 2009, in final form 15 March 2009
Published 20 May 2009
Online at stacks.iop.org/JMM/19/065015

Abstract
Shrinkage of polydimethylsiloxane (PDMS) complicates alignment registration between layers during multilayer soft lithography fabrication. This often hinders the development of large-scale microfabricated arrayed devices. Here we report a rapid method to construct large-area, multilayered devices with stringent alignment requirements. This technique, which exploits a previously unrecognized aspect of sandwich mold fabrication, improves device yield, enables highly accurate alignment over large areas of multilayered devices and does not require strict regulation of fabrication conditions or extensive calibration processes. To demonstrate this technique, a microfabricated Braille display was developed and characterized. High device yield and accurate alignment within 15 μm were achieved over three layers for an array of 108 Braille units spread over a 6.5 cm^2 area, demonstrating the fabrication of well-aligned devices with greater ease and efficiency than previously possible.

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

1. Introduction

Multilayer soft lithography (MSL) is a fabrication paradigm in which layers of patterned elastomeric polymers are aligned, stacked and bonded to create complex three-dimensional monolithic structures. The ability to fabricate three-dimensional microstructures enabled the fabrication of complex microfluidic control components [1–8], which have, in turn, enabled the consolidation of various experimental techniques in biology, chemistry and materials synthesis onto a single microfabricated platform [9–13].

The most commonly used structural material in developing these microfabricated systems is polydimethylsiloxane (PDMS), due to a number of suitable properties of this polymer [14]. However, PDMS undergoes a small degree of shrinkage during curing, and this shrinkage can greatly impact process flow in rapid prototyping of array-based multilayer systems. The shrinkage-induced alignment registration problem arises when layers containing dense device arrays are fabricated by multiple methods and stacked, as is often the case in MSL. The most frequent example occurs when cast PDMS is peeled from a mold; features on the bulk slab no longer align with those fabricated by spin coating onto a master.

Several approaches to this problem have been utilized, including modifying the PDMS material [15], curing samples at room temperature [16] and designing devices with high tolerances to misalignment, or which have a small footprint, to minimize the total displacement of features due to shrinkage. Unfortunately, PDMS is not easy to chemically modify, takes prohibitively long to completely cure at room temperature, and can undergo a small degree of shrinkage in spite of these measures. Designing systems with large alignment tolerances limits the potential for miniaturization, and may not be desirable in many applications. Designing devices over a small footprint severely limits the ability to prototype high-throughput systems.

[3] Author to whom any correspondence should be addressed.

The most common solution to this fabrication problem has been to characterize the degree of shrinkage of PDMS and scale the master size accordingly [9]. This approach has been successfully used to create functional large-area microdevices [17]. However, the devices must be designed to tolerate large misalignments, and using the iterative characterization technique to fabricate arrayed structures with exacting alignment requirements remains challenging. Furthermore, the degree of shrinkage of PDMS is not constant but dependent on several factors including cure temperature and time, PDMS component ratios and layer thickness [18]. These parameters introduce further issues with the characterize-and-scale approach to the shrinkage-induced alignment registration problem. First, curing temperatures and environmental parameters must be strictly controlled, in order to achieve a consistent degree of shrinkage. In a non-cleanroom, multi-disciplinary, multi-user environment, maintaining tight control of these curing parameters can be difficult. As demonstrated by Lee *et al* [18], small variations in temperature can cause a change in shrinkage, which, depending on the microdevice size, will cause a misalignment between layers. This variability leads to low yield in fabricating multilayer devices. Second, because the amount of shrinkage is dependent on layer thickness, a single calibration result cannot be used in the fabrication of multiple prototype designs. Thus, individual calibration experiments need to be performed for each design. The same applies to using various PDMS component ratios, as is often done to improve adhesion in multilayer devices [1]. Third, shrinkage calibration techniques will never provide a perfectly accurate scaling factor, and while small errors may be acceptable for low-throughput, proof-of-concept devices, this technique cannot be scaled up to larger-area devices with high feature densities, without extensive time-consuming and iterative calibration studies.

This fabrication issue lengthens the concept-to-prototype turnaround time for MSL devices. It also effectively limits the massive parallelization theoretically possible in such microsystems. Furthermore, it limits miniaturization and causes difficulties in implementing designs that have more stringent alignment requirements in fabrication. In order to address these concerns and provide a scalable fabrication solution, we made use of a technique termed ‘sandwich mold fabrication’ first described by Jo *et al* [19]. This exclusion molding method has been used for a variety of purposes [20, 21], but has remained unrecognized as an effective solution in solving the shrinkage-induced PDMS alignment registration issue. In this paper, we rapidly microfabricate a precisely aligned multilayer, densely-packed, large-area, Braille display to illustrate the advantages of this technique in overcoming the alignment complications caused by PDMS shrinkage.

2. Experimental methods

2.1. Fabrication of mold masters

SU-8 photoresist (Microchem, Newton, MA) was patterned onto 3″ × 2″ glass slides (Fisher Scientific, Ottawa, ON, Canada) using parameters outlined by the manufacturers. Single and multi-layer masters were fabricated with heights ranging from 40 to 350 μm. After standard processing, the masters were hard baked at 80 °C for three days, and treated with the silanization agent (tridecafluoro-1,1,2,2-tetra-hydrooctyl)-1-trichlorosilane (United Chemical Technologies, Bristol, PA), under vacuum conditions [22], to facilitate mold release of the patterned PDMS layers.

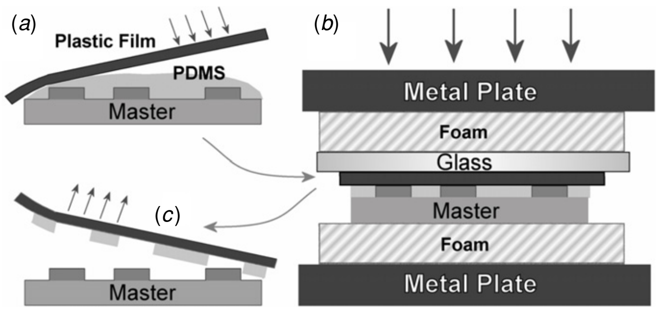

Figure 1. Schematic of the sandwich mold fabrication process [19]. (*a*) Liquid PDMS is sandwiched between the microfabricated mold and a plastic film. (*b*) The sandwich is then placed in a multilayer stack of rigid metal plates, foam pads and a glass slide. The stack is clamped, and cured at elevated temperatures. (*c*) The stack is then disassembled and the plastic film and patterned PDMS layer is peeled away from the microfabricated mold.

2.2. Materials

The sandwich mold fabrication process requires a 3″ C-clamp and two 3.5″ × 2.5″ metal plates. Transparencies for inkjet printers (Grand & Toy, Toronto, ON, Canada) were cut to an appropriate size and used as the plastic backing film. Foam pads (Silver Dollar, Toronto, ON, Canada) were purchased from a craft supply store, and cut to size. A 3″ × 2″ microscope slide was silanized and used as a flat compressive surface.

2.3. Sandwich mold fabrication

Sylgard 184 PDMS (Dow Corning, purchased through A.E.Blake Sales Ltd, Toronto, ON, Canada) was mixed in a standard 10:1 curing ratio and poured onto an SU-8 master. The uncured PDMS was then spread by tilting the master and degassed in a vacuum chamber. As per figure 1, the master was then placed on a foam pad on a metal plate. The plastic film was carefully placed on top of the PDMS so as to avoid trapping air bubbles. A silanized glass slide was then placed on top of the sandwich, followed by a second foam pad and a second metal plate. It was necessary to silanize this glass slide to enable easy removal from any PDMS that was squeezed out of the sandwich. The sandwich was then compressed in a C-clamp and cured at 80 °C for at least 4 h. Following curing, the sandwich stack was removed from the oven, disassembled and the transparency was carefully peeled from the master. The cured PDMS adheres preferentially to the transparency and can be trimmed to size. This procedure was repeated for each layer.

2.4. PDMS bonding

PDMS surface modification was achieved using a corona discharge treater (Electro-Technic Products, Chicago, IL) [23]. For the base layer, a cleaned glass substrate and the PDMS layer were plasma treated, placed in conformal contact and baked on a hot-plate at 80 °C for 20 min. Once cooled, the plastic backing film was peeled from the bonded structure, an easy process due to the permanent bond between the PDMS layer and the underlying substrate. The strength of this bond also prevented any warping or deformation of layers due to thermal stresses generated during fabrication. A similar process was followed when adding additional layers of PDMS; layers were aligned, plasma treated and bonded, before peeling away the plastic backing film.

2.5. Alignment of multiple layers

Alignment between multiple layers was achieved using a home-made alignment system, in which a micromanipulator (Siskiyou, Mission Viejo, CA) was fitted with an arm and a vacuum chuck, and was used to manually position a layer over the substrate. The substrates were mounted on a rotary platform (Newmark, Grants Pass, OR) to correct rotational errors. Alignment between the two layers was monitored using a Navitar 12× zoom system (Navitar, Rochester, NY), which provides a large depth of field at high magnifications. The PDMS layers were plasma treated, aligned manually and then carefully brought into contact with each other. While methanol has been used as a surfactant between PDMS layers during alignment, it has also been shown to swell PDMS to a small extent [24]. This could interfere with the fine alignment accuracy, and hence was not used. The structure was then placed on a hot plate at 80 °C for 20 min to complete the bonding process.

2.6. Demonstration structure: array of cylinders

An array of two-layer cylinders (figure 2) was produced using two fabrication methods: the conventional approach used in the Quake valve process [1] and sandwich mold fabrication. For both cases, the layers were aligned rotationally and at the bottom left corners of the arrays. In the conventional fabrication method, the two PDMS layers were prepared by casting and by spin coating. The two layers were cured in an oven at 80 °C for 4 h. The cast layer was peeled, aligned with the spin-coated layer and bonded. In the sandwich technique, two sandwich mold fabrication steps were used to produce two patterned layers. The layers were stacked, aligned and bonded as described. In each of the steps of this technique, the PDMS film is never released from a rigid substrate, thereby preventing shrinkage from occurring.

2.7. Demonstration structure: micro Braille display

Fabrication of the micro Braille array required three SU-8 mold masters. The process, illustrated in figure 3, began by fabricating three sandwich mold films from the SU-8 masters. The first film was bonded to a glass substrate, and the backing

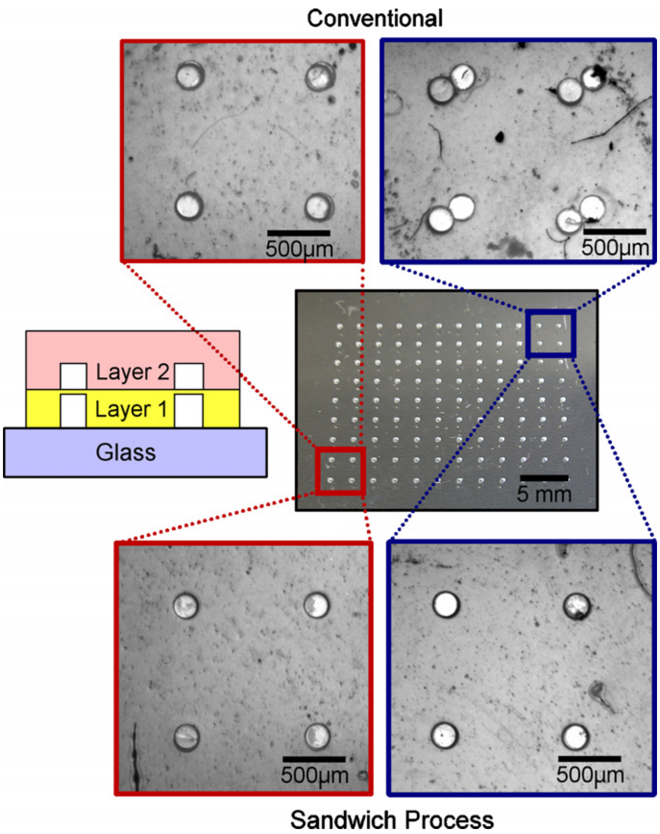

Figure 2. An array of two-layer structures fabricated by conventional and sandwich fabrication methods. The bottom left corner of both arrays was aligned, and the resulting registration error can then be observed across the array. No registration error was observed for the sandwich molding process.

film was peeled away. The second sandwich film acts as a mold for an additional layer of PDMS. To provide structural rigidity during fabrication, this mold was affixed to a glass slide using double-sided tape. The rigid mold was then silanized, and an 80 μm thick layer of uncured PDMS was spin coated onto it. This layer was partially cured in an oven for 15 min at 80 °C. After removing the glass slide from the mold, it was aligned and plasma bonded with the first sandwich film. A second partial curing step of 15 min at 80 °C strengthened the bond, and the silanized PDMS mold was peeled away from the structure. The third sandwich mold layer was then aligned and plasma bonded to complete the structure. Access ports were cored into the PDMS device, and Nanoport fittings (Upchurch Scientific, Oak Harbor, WA) were used to connect the micro Braille display to a Schwarzer rotary pump (Schwarzer Precision, Essen, Germany), capable of producing positive pressures up to 6 kPa.

2.8. Measurement of pin displacements

To demonstrate functional actuation and consistent operation of an array of precisely aligned microstructures, the distance over which the micro Braille display pins are displaced was measured on two 5 × 5 Braille display arrays, fabricated with varying geometries. A Wyko optical surface profilometer (Veeco Instruments Inc., Woodbury, NY) was used to

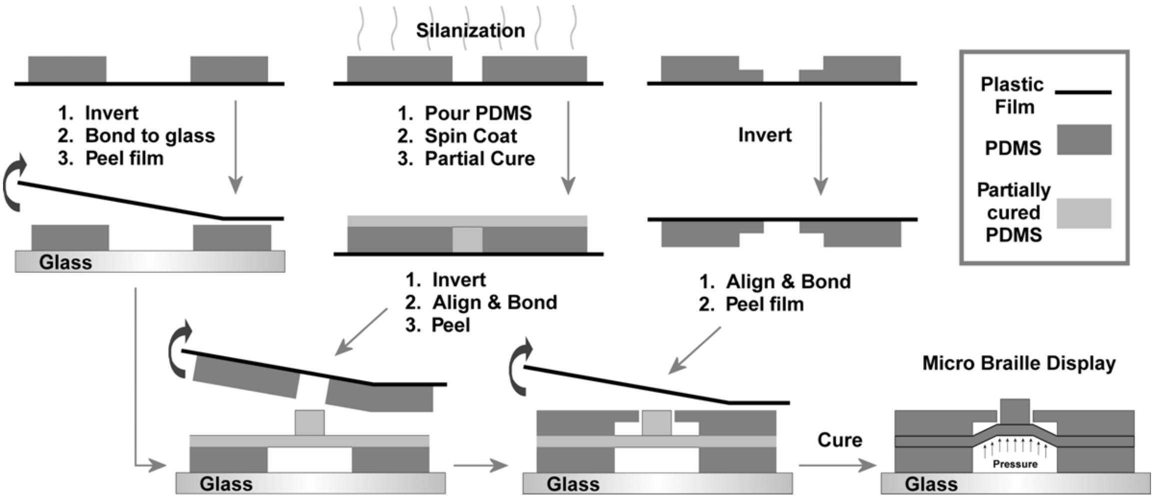

Figure 3. Schematic outline of the fabrication process for the micro Braille display.

determine heights of the pins at rest and when actuated. The results were grouped based on the geometry of each micro Braille unit and presented as a mean displacement distance ± standard deviation for measurements of at least three Braille units (figure 6; see section 3).

3. Results and discussion

Cited advantages of the sandwich mold fabrication technique include the ability to reproducibly fabricate patterned layers of controlled thicknesses, and the ease of handling and transferring delicate films of PDMS. Not previously recognized, however, is the fact that throughout the fabrication process, the PDMS is never released from a rigid substrate: either the plastic backing film or the underlying substrate. Because PDMS is never given the opportunity to shrink, this method enables the fabrication of multilayered structures without a registration problem between layers.

As a demonstration of this feature, the conventional and sandwich mold fabrication methods were used to produce identical multilayer structures: a rectangular array of 108 cylinders, fabricated over a 2 cm × 2.5 cm area (figure 2). Both samples were aligned such that rotational errors were eliminated, and the bottom left corners of the array registered accurately.

Using the conventional fabrication process resulted in an increasing registration error across the array, culminating in a 210 μm misalignment at the top right corner. This corresponds to a 0.7% shrinkage of the cast layer of PDMS, which is within the range of accepted values of PDMS shrinkage, but not for similarly reported curing conditions [18]. This demonstrates the variability in shrinkage seen when working in a multi-user environment without tightly controlled fabrication conditions. In terms of comparing this with conventional fabrication methodologies, the demonstration of poor registration shown here is admittedly biased, because no attempt was made to optimize the master size to account for shrinkage, as is often the case when using this technique. However, with relatively lax control over processing conditions, and without any time-consuming optimization or calibration procedures, the sandwich mold fabrication produced a device with no measurable alignment error across the array.

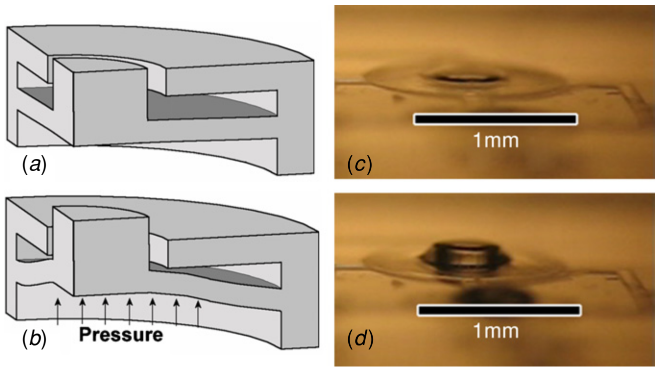

Figure 4. (*a*), (*b*) Schematic quarter-section views of each micro Braille actuator at rest and while actuated. (*c*), (*d*) Demonstrated functionality of the micro Braille actuator.

To demonstrate a functional application of this technique, we developed a miniaturized Braille display. Commercially available refreshable Braille displays have been used as actuators in microfluidic devices as a simple, quick, robust and inexpensive alternative to on-chip valve components. The Braille display has been used to actuate valves, pump fluid [25] and to apply mechanical stimuli to adherent cells [26]. The platform developed in this study further miniaturizes the Braille display system and can be used as a modular base for various end-user defined applications in complex microfluidic control.

The working principle of the Braille unit is demonstrated in figure 4. The three-layer structure consists of a lower actuation cavity beneath a microfabricated Braille pin. The pin is raised by applying a positive pressure to the actuation cavity (figure 4). A third structural layer provides a mounting platform to support microfluidic channels or membranes. Because of the small spacing between the pin edge and this structural support, each Braille structure requires alignment accuracies of better than 15 μm to operate. Figure 5

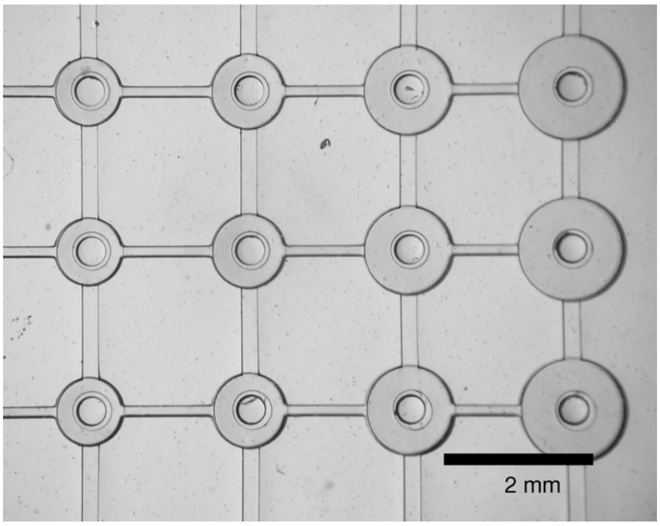

Figure 5. Top–down view of a section of the micro Braille display, demonstrating stringent alignment requirements of the array. The small misalignments observable away from the center of the image are due to perspective distortion artifacts inherent in using a standard imaging lens.

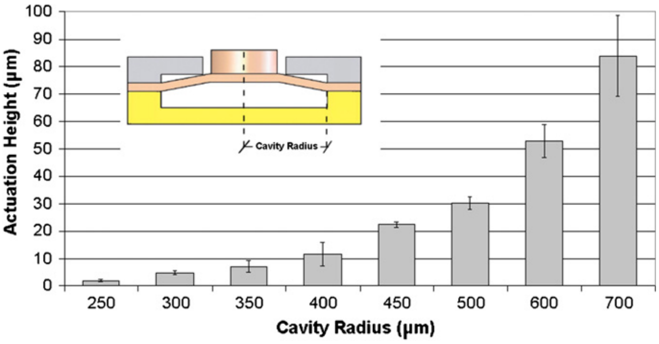

Figure 6. Actuation heights of the micro Braille pins for a pressure of 60 mbar, for cavity radii varying from 250 to 700 μm.

displays a top–down view of the structure and demonstrates accurate layer alignment and the stringent tolerances required. For this application, the size of each actuation cavity was increased across the array, to produce Braille pins with varying actuation characteristics. Figure 6 demonstrates the changing actuation heights of the pins as a result of the change in device dimensions across the array, for an applied pressure of 6 kPa. The results indicate the ability to create vertical displacements ranging from 2 μm to 84 μm using a single pressure source, demonstrating functional actuation of an array of microstructures which require a high degree of alignment accuracy to operate. To further demonstrate the scalability of the sandwich mold fabrication technique, we increased the number of devices per chip and successfully fabricated an aligned array of 108 Braille units over a 1″ × 2″ area (figure 7).

With no observable registration errors across the large array, we believe that the scalability of this technique is limited only by the size of masters that can be fabricated. The technique is robust to variations in fabrication conditions, a situation common in most multi-disciplinary

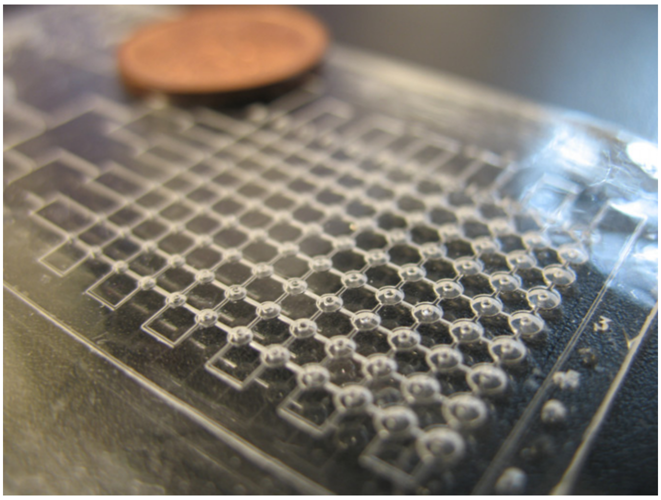

Figure 7. A 9 × 12 array of micro Braille actuators, across a 6.5 cm^2 area.

labs. Furthermore, besides solving the shrinkage issue, the plastic backing films act as support structures for the PDMS layers during alignment, eliminating handling problems caused by the deformability and thermal expansion of PDMS.

There are a few limitations to this technique. First, although the sandwich mold fabrication process effectively eliminates shrinkage across a large area, significantly reduces calibration time for each designed device and improves functional device yield, it does require additional fabrication steps. Given the high degree of alignment accuracy and the high device yield that results from using this technique, we feel that this is an acceptable compromise during the conceptual prototyping phase of device development. However, it may be a concern during large-scale production of such devices. Second, the sandwich mold fabrication technique occasionally fails to completely clear PDMS from the master features, resulting in a thin film of PDMS, rather than a clear via. This happens more often with SU-8 masters greater than 100 μm in thickness, due to variations in height across the master. Often, this variability can be incorporated into the device design, such that a thin film of residual PDMS does not impact the device function, as in valve structures. However, if a clear via is essential, it may be necessary to use a needle to manually remove any remaining PDMS. This is a labour intensive process, and not suited for large devices. An alternative solution would be to modify the perforated membrane process outlined by Luo *et al* [27], or to use a photopolymerizable PDMS as demonstrated by Carlborg *et al* [28].

4. Conclusion

This paper reports the use of a method to overcome the shrinkage-induced alignment registration problem in prototyping multilayer PDMS microsystems. The sandwich fabrication method originally reported by Jo *et al* [19] enables rapid fabrication of dense, large-area, well-aligned structures in MSL, without strict regulation of fabrication conditions or extensive calibration processes. Because PDMS layers are never released from a rigid substrate throughout the procedure, polymer shrinkage does not occur, and hence the registration error between layers is eliminated. This aspect of the technique can significantly reduce the turnaround time in prototype development of well-aligned, high-throughput, multi-layered devices, and has been shown to be successful in rapidly fabricating a functional array of microstructures with stringent alignment requirements.

Acknowledgments

We thank staff at the Emerging Communications Technology Institute at the University of Toronto for cleanroom and microfabrication support. We acknowledge financial support from the Natural Sciences and Engineering Research Council of Canada and Canadian Institutes of Health Research (CHRPJ 323533-06), the Frank and Barbara Milligan Fellowship and Ontario Graduate Scholarship programs to CM, and the Canada Research Chairs in Micro and Nano Engineering Systems to YS, and in Mechanobiology to CAS.

References

[1] Unger M A, Chou H P, Thorsen T, Scherer A and Quake S R 2000 Monolithic microfabricated valves and pumps by multilayer soft lithography *Science* **288** 113–6

[2] Grover W H, Skelley A M, Liu C N, Lagally E T and Mathies R A 2003 Monolithic membrane valves and diaphragm pumps for practical large-scale integration into glass microfluidic devices *Sensors Actuators* B **89** 315–23

[3] Li N, Hsu C H and Folch A 2005 Parallel mixing of photolithographically defined nanoliter volumes using elastomeric microvalve arrays *Electrophoresis* **26** 3758–64

[4] Lam E W, Cooksey G A, Finlayson B A and Folch A 2006 Microfluidic circuits with tunable flow resistances *Appl. Phys. Lett.* **89** 164105

[5] Chou H-P, Unger M A and Quake S R 2001 A microfabricated rotary pump *Biomed. Microdevices* **3** 323–30

[6] Cha J, Kim J, Ryu S K, Park J, Jeong Y, Park S, Park S, Kim H C and Chun K 2006 A highly efficient 3D micromixer using soft PDMS bonding *J. Micromech. Microeng.* **16** 1778–82

[7] Skelley A M and Voldman J 2008 An active bubble trap and debubbler for microfluidic systems *Lab Chip* **8** 1733–7

[8] Keenan T M and Folch A 2008 Biomolecular gradients in cell culture systems *Lab Chip* **8** 34–57

[9] Marcus J S, Anderson W F and Quake S R 2006 Microfluidic single-cell mRNA isolation and analysis *Anal. Chem.* **78** 3084–9

[10] Gomez-Sjoberg R, Leyrat A A, Pirone D M, Chen C S and Quake S R 2007 Versatile, fully automated, microfluidic cell culture system *Anal. Chem.* **79** 8557–63

[11] Torisawa Y S, Chueh B H, Huh D, Ramamurthy P, Roth T M, Barald K F and Takayama S 2007 Efficient formation of uniform-sized embryoid bodies using a compartmentalized microchannel device *Lab Chip* **7** 770–6

[12] Wang J Y, Sui G D, Mocharla V P, Lin R J, Phelps M E, Kolb H C and Tseng H R 2006 Integrated microfluidics for parallel screening of an in situ click chemistry library *Angew. Chem., Int. Ed. Engl.* **45** 5276–81

[13] Hansen C L, Sommer M O A and Quake S R 2004 Systematic investigation of protein phase behavior with a microfluidic formulator *Proc. Natl. Acad. Sci. USA* **101** 14431–6

[14] McDonald J C, Duffy D C, Anderson J R, Chiu D T, Wu H, Schueller O J and Whitesides G M 2000 Fabrication of microfluidic systems in poly(dimethylsiloxane) *Electrophoresis* **21** 27–40

[15] Choi K M and Rogers J A 2003 A photocurable poly(dimethylsiloxane) chemistry designed for soft lithographic molding and printing in the nanometer regime *J. Am. Chem. Soc.* **125** 4060–1

[16] Wu H K, Odom T W, Chiu D T and Whitesides G M 2003 Fabrication of complex three-dimensional microchannel systems in PDMS *J. Am. Chem. Soc.* **125** 554–9

[17] Zhong J F, Chen Y, Marcus J S, Scherer A, Quake S R, Taylor C R and Weiner L P 2008 A microfluidic processor for gene expression profiling of single human embryonic stem cells *Lab Chip* **8** 68–74

[18] Lee S W and Lee S S 2008 Shrinkage ratio of PDMS and its alignment method for the wafer level process *Microsyst. Technol.* **14** 205–8

[19] Jo B H, Van Lerberghe L M, Motsegood K M and Beebe D J 2000 Three-dimensional micro-channel fabrication in polydimethylsiloxane (PDMS) elastomer *J. Microelectromech. Syst.* **9** 76–81

[20] Folch A, Jo B H, Hurtado O, Beebe D J and Toner M 2000 Microfabricated elastomeric stencils for micropatterning cell cultures *J. Biomed. Mater. Res.* **52** 346–53

[21] Toepke M W, Abhyankar V V and Beebe D J 2007 Microfluidic logic gates and timers *Lab Chip* **7** 1449–53

[22] Anderson J R, Chiu D T, Jackman R J, Cherniavskaya O, McDonald J C, Wu H, Whitesides S H and Whitesides G M 2000 Fabrication of topologically complex three-dimensional microfluidic systems in PDMS by rapid prototyping *Anal. Chem.* **72** 3158–64

[23] Haubert K, Drier T and Beebe D 2006 PDMS bonding by means of a portable, low-cost corona system *Lab Chip* **6** 1548–9

[24] Lee J N, Park C and Whitesides G M 2003 Solvent compatibility of poly(dimethylsiloxane)-based microfluidic devices *Anal. Chem.* **75** 6544–54

[25] Gu W, Zhu X Y, Futai N, Cho B S and Takayama S 2004 Computerized microfluidic cell culture using elastomeric channels and Braille displays *Proc. Natl. Acad. Sci. USA* **101** 15861–6

[26] Kamotani Y, Bersano-Begey T, Kato N, Tung Y C, Huh D, Song J W and Takayama S 2008 Individually programmable cell stretching microwell arrays actuated by a Braille display *Biomaterials* **29** 2646–55

[27] Luo Y and Zare R N 2008 Perforated membrane method for fabricating three-dimensional polydimethylsiloxane microfluidic devices *Lab Chip* **8** 1688–94

[28] Carlborg C F, Haraldsson T, Stemme G and Van Der Wijngaart W 2007 Reliable batch manufacturing of miniaturized vertical vias in soft polymer replica molding *Proc. MicroTAS 2007 11th Int. Conf.* 527–9