J. Micromech. Microeng. **18** (2008) 095028 (11pp) doi:10.1088/0960-1317/18/9/095028

PDMS as a sacrificial substrate for SU-8-based biomedical and microfluidic applications

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Received 13 February 2008, in final form 25 July 2008
Published 20 August 2008
Online at stacks.iop.org/JMM/18/095028

Abstract

We describe a new fabrication process utilizing polydimethylesiloxane (PDMS) as a sacrificial substrate layer for fabricating free-standing SU-8-based biomedical and microfluidic devices. The PDMS-on-glass substrate permits SU-8 photo patterning and layer-to-layer bonding. We have developed a novel PDMS-based process which allows the SU-8 structures to be easily peeled off from the substrate after complete fabrication. As an example, a fully enclosed microfluidic chip has been successfully fabricated utilizing the presented new process. The enclosed microfluidic chip uses adhesive bonding technology and the SU-8 layers from 10 μm to 450 μm thick for fully enclosed microchannels. SU-8 layers as large as the glass substrate are successfully fabricated and peeled off from the PDMS layer as single continuous sheets. The fabrication results are supported by optical microscopy and profilometry. The peel-off force for the 120 μm thick SU-8-based chips is measured using a voice coil actuator (VCA). As an additional benefit the release step leaves the input and the output of the microchannels accessible to the outside world facilitating interconnecting to the external devices.

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

1. Introduction

The last few decades have seen a rapid growth in micro-electromechanical systems (MEMS) and microfluidics technology in various materials including silicon, glass and polymers. Early microfluidic systems as reported in [1] have typically been fabricated from silicon or glass by micromachining techniques based on fabrication processes utilized by the microelectronics industry, and bonding technologies. Although these technologies provide high precision and good yield, the costs for material and production render them uneconomical if large area devices are fabricated. Ideally, microfluidic systems consist of complex structures in a single 'lab-on-a-chip' (LOC) [2]. The μ-TAS (micro total analysis system) or LOC systems have been extensively developed with a view to exploiting high-throughput, low-cost analysis [3–8]. In many medical and pharmaceutical applications disposable devices are mandatory which particularly requires the use of low-cost materials and processes, such as plastics. Disposable devices should be cheap to produce in large volumes by polymer replication technologies such as injection molding or hot-embossing. These technologies are well suited for large volume production; however, for design, test, prototyping and production of small quantities they are too expensive due to their high setup costs.

Promisingly, some products utilizing polymers are already emerging in the biotechnology market. Abbott Laboratories successfully markets i-stat® and a cartridge for blood analysis consisting of a silicon biosensor embedded in a capsule fabricated by molding and lamination [9]. Micronics Inc. manufactures and sells disposable 'lab cards' made of laser cut plastic films laminated together [10]. Fluidigm Corporation also markets new devices based on multilayered soft lithography to produce labcards for protein crystallization [11–13]. In addition to these products, a large number of products are already on the market which utilizes a wide range of different polymers.

In addition to polydimethylsiloxane (PDMS) [13] and Mylar [9, 14], the negative photoresist EPON SU-8 (hereinafter referred to as SU-8) has been popular for microfluidic and MEMS technology [15–17]. Because of its advantageous characteristics such as stability against solvents and compatibility with CMOS [18–24], SU-8 has been used for obtaining microfluidic channels [25–35], movable micromechanical components (such as membranes and cantilevers) [36, 37], optical waveguides [38, 39] and UV-LIGA components [40–42].

Many microfluidic and bio-medical microdevices are required to be free-standing and thus must be released from their substrates after successful fabrication. Two techniques that would enhance the fabrication of SU-8 free-standing microstructures would be the development of (i) an easy-to-use sacrificial layer, and (ii) a technique allowing release of complex SU-8 multilayer structures from the substrate.

Regarding the sacrificial layer, different sacrificial materials such as electroplated copper [36], polystyrene [37] and chromium [43] are used to produce free-standing structures by etching them away, leaving subsequently deposited and patterned layers free-standing. Nevertheless, these sacrificial methods are time consuming, and the prolonged exposure to the etchant may damage the released devices. Metz *et al* have used heat-depolymerizable polycarbonate embedded in SU-8 for the generation of microchannels and sealed cavities [44]. This sacrificial layer decomposes into volatile monomer compounds that diffuse through the cover layer. The removal of this sacrificial layer requires more than 1 h and temperatures between 200–300 °C. Foulds *et al* [45] presented the planar self-sacrificial multilayer SU-8 (PSALMS) process. The PSALMS process is capable of making structures similar to those possible with the popular three-layer surface micromachining process PolyMUMP®, offered by MEMSCAP [46]. However, in this type of process, a mixture of SU-8 and positive photoresist is used which is not a reliable process. Further, this phenomenon limits the thickness of the sacrificial layer because very thick SU-8 is hard to mix with positive photoresist. In other works, Chronis *et al* have released a microgripper fabricated on SU-8 making a blind cut on the backside of the silicon wafer, prior to releasing it by XeF_2 dry etching [47].

Alternatively, the possibility of using a substrate that poorly adheres to SU-8 simplifies the fabrication of released SU-8 microstructures. Gadre *et al* have used Teflon for this purpose [48]. Nonetheless, this process does not allow easy alignment and bonding of structures fabricated in SU-8 since Teflon is not transparent and does not allow visual alignment of multiple substrates through the substrate material.

Previously, an SU-8 fabrication process to create complex multilayer microstructures using successive wafer-level bonding and releasing steps using polyimide film has been presented [15]. However, polyimide has fair adhesion with SU-8 so that high forces were required to release the free-standing devices, which may delaminate the bonded SU-8 structures. Furthermore, polyimide is not optically transparent which limits the ability to align or to expose using UV after bonding.

An improved technique for the fabrication of the enclosed microfluidic devices using dry films of uncrosslinked SU-8 for lamination is described by Abgrall *et al* [49]. The polyester (PET) has been used as a low adhesion material to laminate SU-8 films before UV exposure. Furthermore, the pressure (approx. 2 bar) and the oxygen plasma activation of the SU-8 surface are required to laminate the film with desired functionality.

As an improved alternative to the previously proposed polyimide [15] or Teflon [48] based fabrication technology and as a complimentary technology using PET [49], in this paper we demonstrate PDMS as a sacrificial substrate material to fabricate fully enclosed SU-8 channels using adhesive bonding technology. The poor adhesion between PDMS and SU-8 allows the free-standing devices to be released after SU-8 to SU-8 adhesive bonding. However, the adhesion is still enough to carry out photolithography on the structural SU-8 layers. Therefore, complex multilayer SU-8 structures such as fully enclosed microchannels are fabricated by successive bonding steps without using a special sacrificial layer. An additional benefit of PDMS is its optical transparency, which allows UV exposure of the patterned devices through the substrate even after the adhesive bonding. The optical transparency is also important for aligning the peg and hole structures specially designed for an accurate alignment during the adhesive bonding process.

The presented hybrid polymer fabrication process can easily be carried out with the basic equipment and materials available in any microfabrication facility. Even the masks can be fabricated using inexpensive photoprinting. The fabrication technology can be used for batch fabrication of biomedical and microfluidic devices and also several other relevant types of devices improving performance and cost factors. The presented designs are very simple to fabricate, easy to release after complete fabrication and ready for testing immediately after releasing the devices.

To demonstrate the successful fabrication technology for generalized microfluidic and biomedical applications, an example device typical of microfluidic system (a microfluidic channel network) is presented here. The device is a free-standing microfluidic network of channels utilizing our adhesive bonding and selective releasing processes. This device demonstrates that our new fabrication technology can be utilized for a wide range of applications.

2. SU-8 and PDMS-based fabrication technology

The developed fabrication technology, shown schematically in figure 1, consists of the following four steps: (i) substrate preparation, (ii) photolithography of the first SU-8 structural layers, (iii) adhesive bonding of the SU-8 layers and (iv) a final releasing step of the SU-8 structures from the PDMS layer.

The following sub-sections describe these four steps in detail.

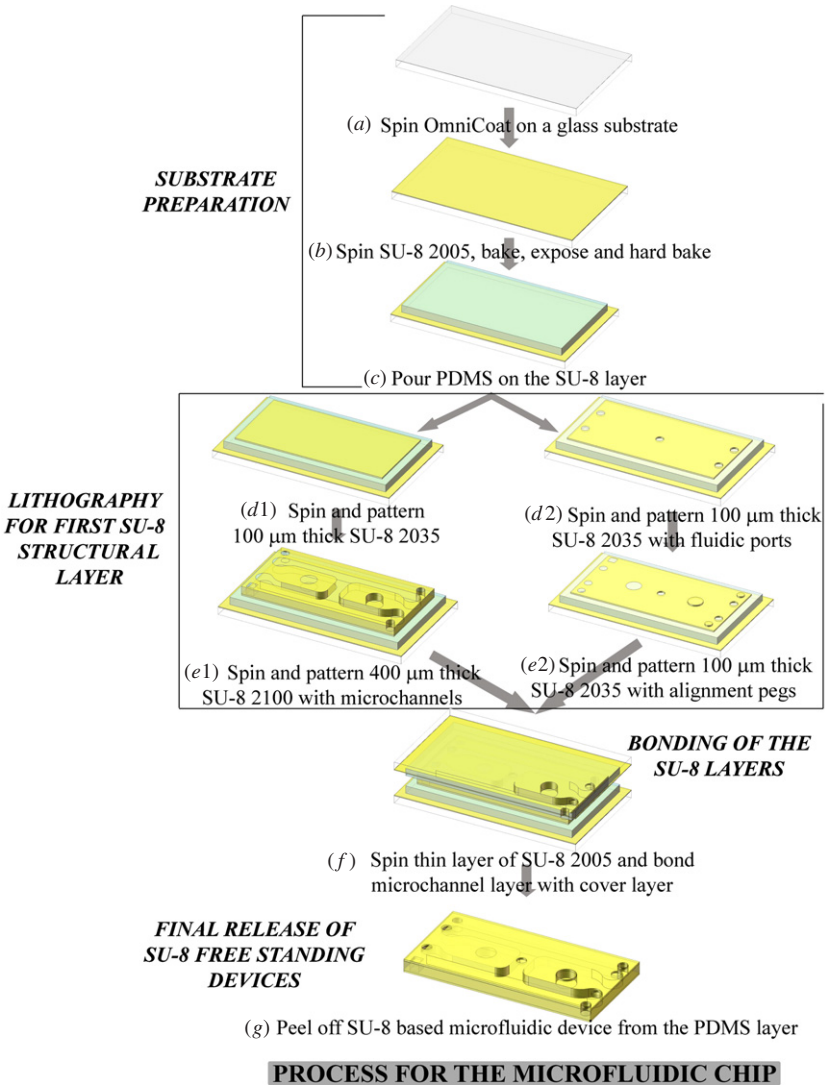

Figure 1. Hybrid polymer fabrication process: (*a*) spin OMNICOAT on glass substrate and bake, (*b*) spin SU-8 2005 ∼5 μm thick, soft bake, flood expose, post exposure bake (PEB) and hard bake, (*c*) prepare PDMS mixture (Sylgard 184 elastomer and Sylgard 184 curing agent (10:1)) and pour it on the substrate. Cure PDMS at 85 °C for 2h and 30 min. (*d*.1) *For microchannel substrate:* spin SU-8 2035 ∼100 μm thick, soft bake, expose with the bottom layer mask, PEB and develop, (*d*.2) *for top cover of microchannels:* same process as *d*.1 but the mask for exposure is for the top cover, (*e*.1) *for the microchannel substrate:* spin SU-8 2100 ∼400 μm thick, soft bake, expose with channel mask, PEB and develop, (*e*.2) *for the fluidic chip cover:* spin SU-8 2035 ∼100 μm thick for making the alignment features, soft bake, expose, PEB and develop, (*f*) spin a 5 μm thick layer of SU-8 2005 on the top cover (prepared in step (*e*.2)), flip the top cover substrate onto the channel network substrate, align and bond them together using alignment patterns (hole and peg structure shown in step (*e*.1) and (*e*.2)), soft bake, flood expose the assembly through the glass, PEB, and (*g*) peel off the PDMS layer and substrate from the top cover, hard bake at 200 °C for 20 min and peel off the SU-8 based free-standing structures from the PDMS layer.

2.1. Substrate preparation

The number of required substrates depends on the number of microchannel layers. For a single layer of microchannel network, only two substrates are required.

Glass substrate preparation. Both microscopic glass slides and Pyrex wafers are suitable because of their optical transparency. However, 3 inch × 3 inch glass slides are used as a support substrate for the PDMS layer. Optical transparency of the substrate gives flexibility to the process by allowing exposure of the SU-8 layer from the backside (through the substrate). Moreover, the alignment of multiple SU-8 layers can be verified optically because of the transparent substrate and the PDMS layer. The glass substrate is cleaned with acetone followed by isopropanol (IPA) rinse. Finally, the glass substrate is rinsed with de-ionized water and dehydrate baked at 120 °C for 15 min (using Fisher Scientific 825 F oven). The clean glass substrate is now ready for a coating of SU-8 2005 (Microchem Corporation, USA), which works as a low adhesion coating for the PDMS layer.

In general, PDMS can be peeled off from the glass substrate by applying sufficient mechanical force. In order to make the peeling process easier, a thin layer of SU-8 2005 is used as a low adhesion coating for the PDMS layer. Hence, a thin layer of SU-8 2005 is coated by using OMNICOAT (Microchem Corporation, USA) as an adhesion promoter between the glass and the SU-8 2005 coating.

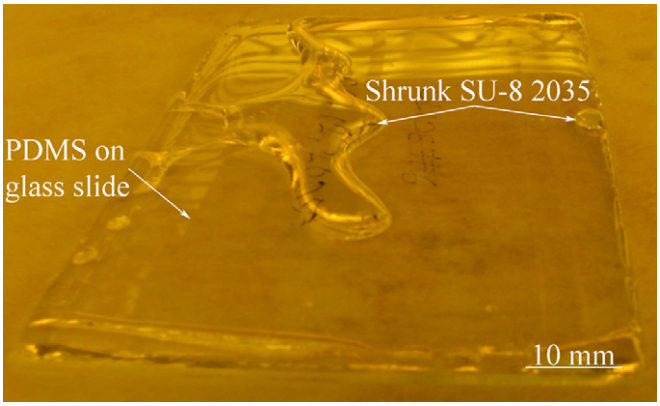

Figure 2. The SU-8 2035 shrinks from the edges on the PDMS layer if soft baked at more than 70 °C due to surface energy.

The OMNICOAT is spun at 1200 rpm (using Headway Research Inc. spin coater) and baked at 200 °C for 1 min (using Torrey Pines Scientific ECHOthermTM Digital Hot plate (ceramic)) (figure 1(*a*)). Then, SU-8 2005 is spun at 1200 rpm and soft baked at 95 °C for 3 min (figure 1(*b*)). The SU-8 2005 layer is flood exposed with a 180 mJ cm^{-2} dosage under an i-line UV system (Quintel Corporation Q-2001CT). The SU-8 layer is baked again for 3 min at 95 °C and finally hard baked at 200 °C for 20 min.

The PDMS layer preparation (figure 1(c)). PDMS mixture is prepared by mixing Sylgard 184 elastomer and Sylgard 184 curing agent (Dow-Corning Corporation, USA) in 10:1 proportion by weight. The mixture is degassed in a vacuum for 15 min. The degassed PDMS mixture is poured on the SU-8 2005 coated glass substrate. The glass slide is left on a level surface at room temperature for 30 min to evenly spread the PDMS mixture on the substrate. The PDMS is cured at 85 °C for 2 h and 30 min. The thickness of the PDMS layer is ∼500 μm.

2.2. Lithography for the first SU-8 structural layer

The processing of the first SU-8 layer on the PDMS surface is very important due to the difference in co-efficient of thermal expansion and adhesion of SU-8 with the PDMS layer. Additionally, the surface uniformity of the SU-8 layer is very important for successful adhesive bonding. Initially, different process parameters are studied to optimize the process for reliability and repeatability. The soft bake temperature higher than 70 °C releases the solvent rapidly from the SU-8 which will decrease the volume of the prepolymer as well as its ability to wet a surface. Hence, the SU-8 layer shrinks from the edges during the soft bake (figure 2).

After several trials with soft bake process parameters, 65 °C is chosen as the most optimum soft bake temperature. To avoid large overshoot using the hot plates, a very controlled temperature profile with controlled temperature ramp and time duration is chosen. The spin-speed and time required for the soft bake process depends on the desired thickness. The softbake parameters for different thicknesses are described in table 1.

The thick SU-8 layers are spun in two continuous cycles. The first cycle is the spread cycle in which the substrate is spun at 350 RPM for 10 s to evenly spread SU-8 on the PDMS substrate. The spread cycle is followed by the actual spin cycle in which the substrate is spun for the desired thickness of the SU-8 layer (as described in table 1).

After spinning the SU-8 layer, the SU-8 is soft baked with a controlled temperature ramp (table 1). The soft baked SU-8 layer is then exposed using UV light with appropriate energy for the thickness (table 1). Finally, the SU-8 layer is baked for post exposure bake at 90 °C and the uncrosslinked SU-8 is dissolved in the SU-8 developer (propylene-glycol-monoether-acetate (PGMEA) from Microchem Corporation) with ultrasonic agitation to quickly remove the uncrosslinked SU-8.

The bottom and the top layers are fabricated using the process described above. The bottom layer of the microfluidic chip is a simple rectangular layer which is also useful to separate out microfluidic chips (figure 1(*d*.1)). For the top cover of the fluidic chip, the layer is exposed with the top cover mask, which includes inlet and outlet holes (figure 1(*d*.2)). Furthermore, another SU-8 layer with alignment pegs and holes is also prepared for accurate alignment during the adhesive bonding process (figure 1(*e*.2)).

To pattern the microchannels, a second layer of thick SU-8 (Microchem Corporation) is spun on the bottom SU-8 layer and patterned with the microchannels mask (figure 1(*e*.1)).

2.3. Adhesive bonding of the SU-8 layers

SU-8 2005 is used as an adhesive layer between two SU-8 layers to realize fully enclosed microchannels [50]. When individual SU-8 layers are patterned and processed, they are baked at 90 °C for the post exposure bake. This lower baking temperature does not fully cross-link the UV exposed SU-8. Hence, during the bonding process, when the baking temperature is 100 °C, the two separate SU-8 layers soften and attach together with SU-8 2005 mediator which results in strong bond of the two layers (see figure 1(*f*)).

To align the separate SU-8 layers during the bonding process, unique peg and hole features are designed. These unique designs of the peg and hole features allow them to fit only in one position, which avoids any possibilities of misalignment in the bonded device. The clearance between the peg and hole periphery changes the degree of misalignment, which is discussed further in section 4.1.

To bond two separate SU-8 layers, the SU-8 2005 is spun on the substrate with the top cover and peg structures at 1200 RPM for 30 s (figure 1(*f*)). The SU-8 2005 layer is approximately 10 μm thick. One of the substrates is flipped over and aligned using the peg and hole structures given in both substrates. The assembly of the bonded substrates is then soft baked at 95 °C for 5 min followed by the flood expose of the whole assembly. The assembly is then post exposure baked at 100 °C for 3 min. A higher temperature for the post exposure bake is chosen to properly crosslink the previously patterned SU-8 layers and the SU-8 bonding layers [29].

Table 1. Process parameters to obtain SU-8 films of different thicknesses.

SU-8 layer thickness	Type of SU-8	Spin profile	Soft bake	Expose (in mJ cm^{-2})	Post exposure bake	Development
10 μm	2005	30 s at 1250 RPM	35–50 °C at 300 °C h^{-1} Hold time: 2 min 50–65 °C at 15 °C h^{-1} Hold time: 10 min	200	35–90 °C at 300 °C h^{-1} Hold time: 3 min	In ultrasonics with visual verification
40 μm	2035	10 s at 350 RPM 40 s at 4000 RPM	35–50 °C at 300 °C h^{-1} Hold time: 2 min 50–65 °C at 15 °C h^{-1} Hold time: 40 min	240	35–90 °C at 300 °C h^{-1} Hold time: 6 min	In ultrasonics with visual verification
75 μm	2035	10 s at 350 RPM 30 s at 2250 RPM	35–50 °C at 300 °C h^{-1} Hold time: 2 min 50–65 °C at 15 °C h^{-1} Hold time: 50 min	300	35–90 °C at 300 °Ch^{-1} Hold time: 9 min	In ultrasonics with visual verification
120 μm	2035	10 s at 350 RPM 40 s at 1250 RPM	35–50 °C at 300 °C h^{-1} Hold time: 2 min 50–65 °C at 15 °C h^{-1} Hold time: 90 min	360	35–90 °C at 300 °C h^{-1} Hold time: 12 min	In ultrasonics with visual verification
450 μm	2100	10 s at 350 RPM 40 s at 1250 RPM	35–50 °C at 300 °C h^{-1} Hold time: 2 min 50–65 °C at 15 °C h^{-1} Hold time: 7:30 h	720	35–90 °C at 300 °C h^{-1} Hold time: 30 min	In ultrasonics with visual verification
450 μm (optimized)	2035	10 s at 350 RPM 40 s at 4000 RPM	35–50 °C at 300 °C h^{-1} Hold time: 2 min 50–65 °C at 15 °C h^{-1} Hold time: 40 min	240	Not required	Not required
	2100	10 s at 350 RPM 40 s at 1250 RPM	35–90 °C at 240 °C h^{-1} Hold time: 2:30 h	720	35–90 °C at 240 °C h^{-1} Hold time: 30 min	In ultrasonics with visual verification

2.4. Final release of SU-8 free-standing devices

For the microchannel network, after the bonding and full fabrication is carried out, the glass substrate and the PDMS layer are easily detached from the SU-8 stack. To detach the SU-8 stack, the fabricated wafers are hard baked on a hot plate by ramping up the temperature from room temperature. The hard bake is done at 200 °C for 20 min. Subsequently, the glass substrate and the PDMS layer are separated by force applied via the insertion of a razor blade or a scalpel. Next, the PDMS layer is easily peeled off from the SU-8 coated glass substrate (figure 1(*g*)). The SU-8 surface remains undamaged after the peeling process as a consequence of the poor adhesion between SU-8 and PDMS. Nonetheless, it is crucial to have excellent adhesion between bonded SU-8 layers to withstand the peeling process. The high thermal stability of the PDMS layer, its chemical resistance, and above all, its poor adhesion to the SU-8 makes PDMS a suitable material for the described purpose.

2.5. Packaging

Since all the structural layers (SU-8) are photopatternable, the input and the output of the microchannels are kept in contact with the outside world after the PDMS releasing step. This fact avoids slow drilling or etching steps of a cover, radically simplifying the packaging.

3. Experimental designs

To test the authenticity of the presented novel fabrication technology, three designs (figures 3–5) of the microfluidic network are designed and fabricated. Each of the designs is explained briefly in the following sub-sections.

3.1. Design 1

The first design consists of a microfluidic H network (figure 3). This microfluidic H network is designed using three SU-8 layers. Among these three layers, the bottom layer and the middle layer are fabricated on the same substrate and the top cover layer is fabricated on a separate substrate. The SU-8 layers are finally bonded using a thin layer of SU-8 2005 using the adhesive bonding technique [51]. Each H-shaped microchannel chip is 5 mm × 10 mm in size. All other dimensions are clearly mentioned in figure 3.

The microchannels are fabricated in an 'H' shape with five ports (figure 3). All the ports can be used as either inlet or outlet ports. Other important features are the coarse and fine alignment features. The alignment marks are included for accurate and easy alignment of the layers during the bonding process. Two large circular holes with 1 mm diameter and two pegs with 0.8 mm diameter (figure 3) are designed for the coarse alignment features. Additionally, three small circular holes with 0.5 mm diameter and a square hole with 0.5 mm side are designed for fine alignment. The pegs are 0.48 mm

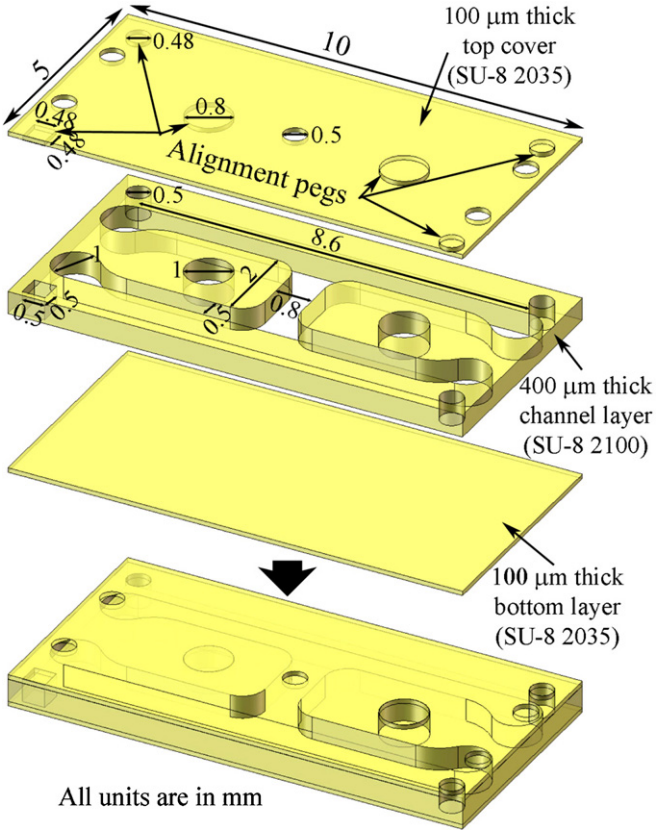

Figure 3. Exploded view of design 1.

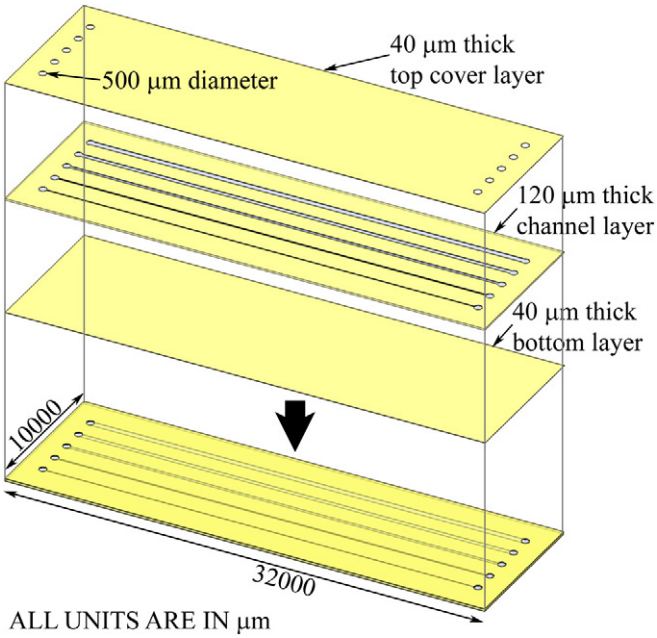

Figure 4. Exploded view of design 2.

in size (for fine alignment) which leaves 10 μm clearance on each side (20 μm in total). The smaller clearance helps in accurately aligning the two layers. The transparency of the glass substrate and the PDMS layer is very important to easily align and bond the microchannel network using this method.

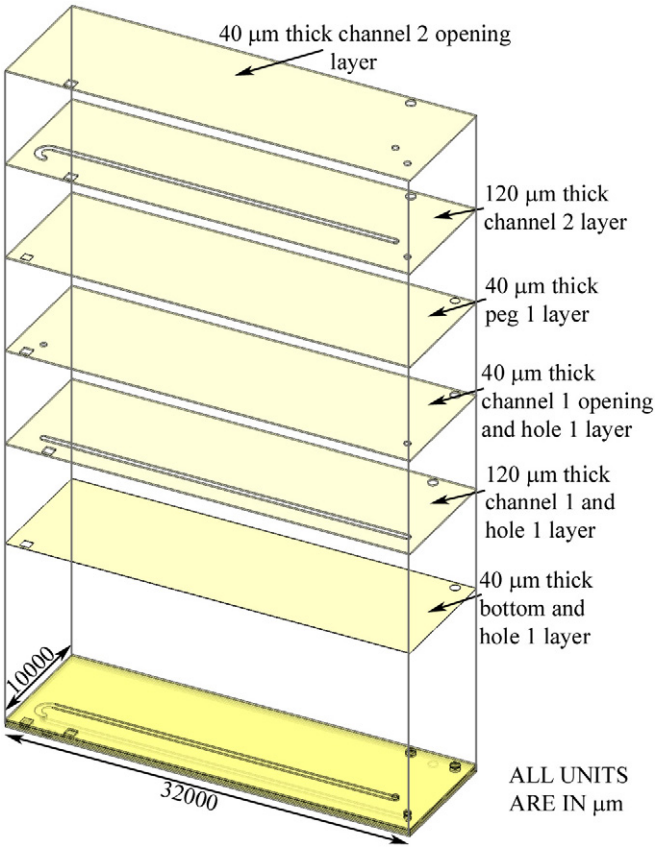

Figure 5. Exploded view of design 3.

3.2. Design 2

The second design is fabricated to check the minimum and maximum microchannel widths possible using the adhesive bonding process (see figure 4). The simple design is carried out for channel widths of 50 μm, 100 μm, 200 μm, 300 μm and 400 μm. All the channels are connected with individual inlet and outlet ports with 500 μm diameter.

3.3. Design 3

The third design is fabricated to check the maximum stacks possible using the novel fabrication technology (see figure 5). The multilayer chip is designed in such a way that it can be used for a maximum of five stack layers of SU-8. The design is such that it can be used to fabricate up to two layers of microchannels on a single chip.

Each channel layer has two stacks of SU-8 layers. Each channel layer has one cover layer with inlet and outlet ports and a channel layer with a microchannel patterned in it. All the microchannels are 500 μm wide and the inlet and outlet ports are also 500 μm in diameter. All the channel layers have another SU-8 layer for alignment of peg and hole structures, which is not counted as a stack layer. The alignment features are very important to align inlet and outlet ports of consecutive layers.

Table 2. Target thickness and measured values after successful fabrication.

	Measured values	
Target thickness in μm	Thickness in μm	Standard deviation in μm
10	11.01	2.12
40	42	8.01
75	73	3.98
120	118	13.47
450	458	21.03
450 (optimized)	456.25	15.56

4. Test results and discussion

After successful fabrication of all three designs, all the devices were tested to verify the successful fabrication of the microchannels and other fabrication aspects. Each factor that was tested (bonding strength, peel-off-force and microfluidic pressure) is discussed individually in the following subsections.

4.1. Multi-layer bonding characterization

The most critical parameters for obtaining good bonding results between the SU-8 layers are: (i) the thickness uniformity of the photopatterned SU-8 films, (ii) the polymerization level of these films producing adequate adhesive properties, (iii) the bonding pressure and finally (iv) the temperature applied to bond the SU-8 layers. While the first two parameters depend on the number of bonding steps carried out, the other two are fixed during the whole process. Therefore, uniformity and polymerization changes of these films were investigated using a profilometer (from Tencor Instruments Alpha-Step 500) and a micrometer screw (Fred V. Fowler Co. Inc., Model IP54) for thicker SU-8 layers.

Previously, Blanco *et al* obtained films of 20 $\pm$ 0.3 μm thick SU-8 on silicon wafers [29]. The present work makes use of the new photolithographic recipe on the PDMS layer instead of silicon. The measured thickness for different target thicknesses and the standard deviation based on statistical analysis of at least five substrates are shown in table 2. Although the quality and uniformity of the SU-8 fabricated on the PDMS layer is lower than that achieved directly on silicon, it is good enough to obtain a strong bond between multiple SU-8 layers.

In addition to the uniformity of the films, the polymerization level of the SU-8 layers is also a crucial parameter for achieving a proper bond. As mentioned in section 2.2, the post baking temperature of the two SU-8 layers is 90 °C. Adhesive bonding layers of sufficient quality are obtained at this temperature. However, during the bonding steps, the temperature is increased up to 100 °C. Therefore, after the first bonding process, the polymerization level of the first two layers is increased and their adhesive properties should be, in turn, decreased [29]. This suggests that even though the polymerization level of the first two layers is increased, the temperature of 100 °C is enough to bond them as long as the following new layer is partially polymerized (post bake at 90–95 °C). Therefore, the functional groups of the polymer chains on the surface of the new layer can diffuse across the interface and react with the previously bonded layer. It is important to note that due to this phenomenon, multi-layer structures can be fabricated.

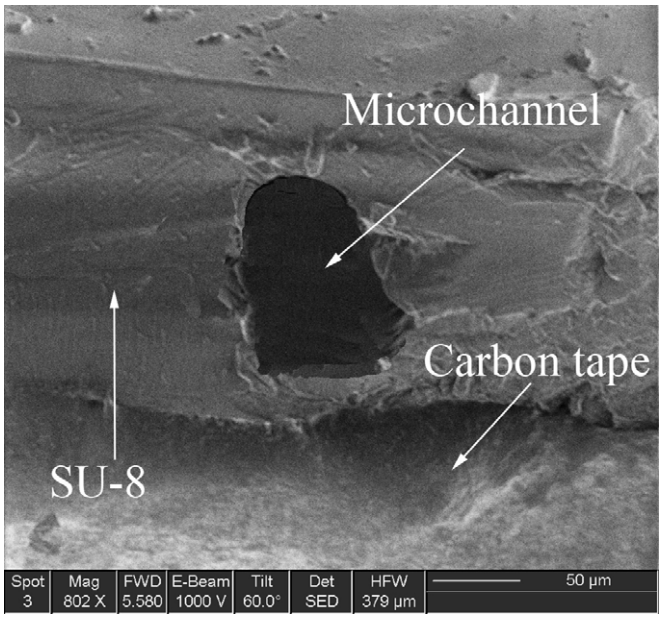

Figure 6. SEM image of the 50 μm wide microchannel with an aspect ratio of 2.4.

Using the novel fabrication technology, a 50 μm wide microchannel in a 120 μm thick SU-8 layer (aspect ratio: 2.4) is successfully fabricated (see figure 6). The shape of the channel is little distorted. However, the channel is fully open without blockage due to the SU-8 reflow in the microchannels. In addition, a 500 μm wide channel in a 120 μm thick layer (aspect ratio: 0.24) is also successfully fabricated. The top and bottom cover layers are 40 μm thick and are very strongly bonded together, which is clearly visible from the SEM image in figure 6.

After verification of the aspect ratio based on our proposed novel fabrication technology, the maximum possible stacks for the proposed technology are verified. As mentioned in the previous section, two layers of the microchannels with five layers of stacked SU-8 are successfully fabricated (see figure 7).

As is clear from the figure, there is no clear separation between the lid and the channel layer, which indicates a strong bond between both the layers. The fabricated channel width is 500 μm and height is 120 μm. The fabrication of more than two layer channels is under investigation at this stage.

In addition to the bond strength, alignment precision for multilayer bonding is very important. To solve the layer-to-layer alignment problem faced in all previous designs [15, 48, 49], we propose alignment structures using unique peg and hole combinations. Different shapes and sizes of alignment patterns (holes and pegs) can be designed to obtain the desired alignment. From the alignment precision point of view, the worst-case alignment is equivalent to the clearance left between the peg and hole edges. For the microfluidic

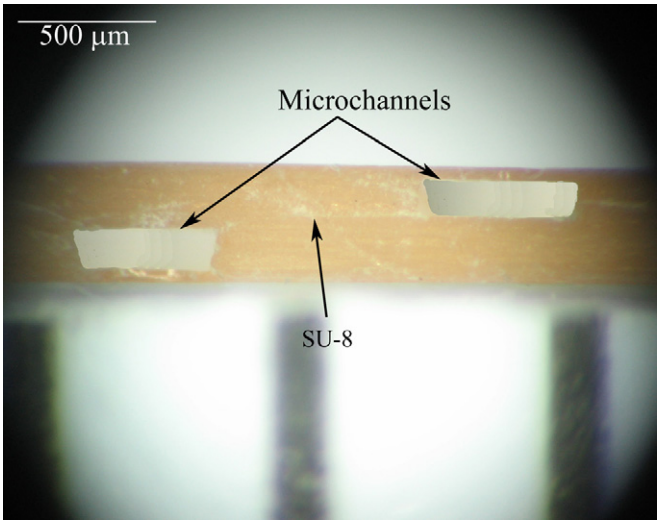

Figure 7. Microscopic image of the 500 μm × 120 μm microchannel with two microchannel layers and five SU-8 stack layers

chips fabricated during our experiments, the diameter of the coarse alignment pegs is 800 μm with the hole diameter of 1000 μm. The diameter of the fine alignment pegs is 480 μm with the hole diameter of 500 μm leaving 20 μm as clearance. The measured worst-case misalignment is always less than ± 9 μm. Hence, by considering the worst-case alignment as a clearance factor for the alignment structures, desired alignment can be obtained. For very precise and easy assembly, rough and fine alignment marks are designed. The rough alignment marks have larger clearance than the fine alignment marks. Additionally, the rough alignment marks are larger in size than the fine alignment marks. Hence, using this novel and unique idea, very precise alignment is achieved.

4.2. Peel-off force characterization

The force required to detach the SU-8-based structures from the PDMS layer is characterized using a voice coil actuator (VCA) [52] (H2W Technologies NCM06-06-004-3JB). The test setup to measure the force is shown in figure 8. To our knowledge, this is the first time that peel-off force for SU-8 from PDMS has been characterized.

Twelve SU-8 structures were detached using the voice coil actuator and force for each one was measured and plotted (figure 9). The average force required to peel off the SU-8 structures from the PDMS layer is 180.9 mN with a low standard deviation of 56.39 mN. Hence, the SU-8-based structures can easily be detached from the PDMS layer and the chances of damaging the SU-8 structures or bonds are very unlikely and, indeed, none of the 128 fabricated devices experienced damage due to the releasing process step.

4.3. Process yield and free-standing microstructures

The fabrication process described in this paper is very flexible and opens new possibilities of obtaining complex free-standing structures in SU-8. It also dramatically simplifies the process by avoiding long times for sacrificial layer removal by etching.

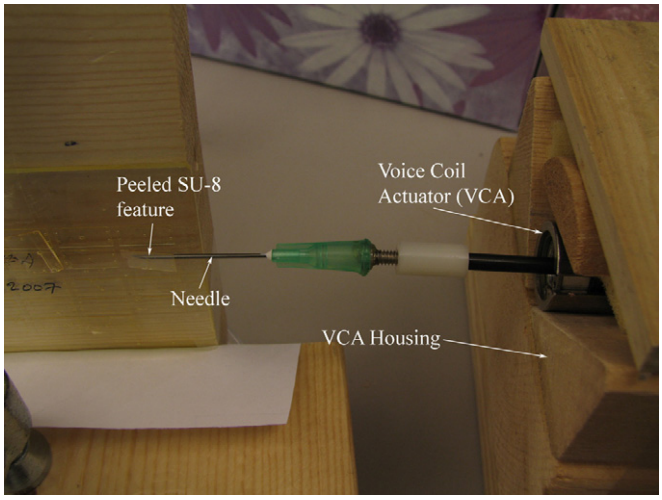

Figure 8. Test setup to measure the peel-off force between the SU-8 layer and the PDMS layer.

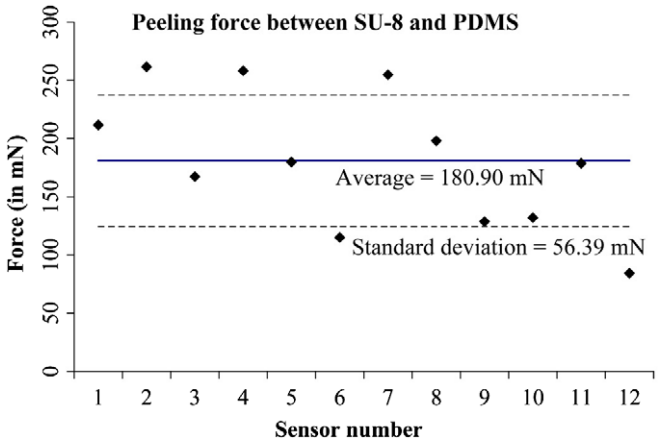

Figure 9. Measured force to peel off the SU-8 layer from the PDMS layer. An average force of 180.9 mN is required to peel off the two layers with a standard deviation of 56.39 mN.

We successfully released the microchannel network from the PDMS layer. The reliability of this release process is studied using optical microscopy (using Olympus MX40). In addition, any devices with fabrication defects like surface non-uniformity and micro-cracks are also discarded.

In a previous fabrication process presented by other researchers for realizing free-standing SU-8 structures [15], caution must be taken during the polyimide releasing step, because the free-standing structures become free immediately when the etch is complete and the structures are not directly attached to the bottom silicon substrate. However, in our process, the structures remain attached until peeled off from the substrate. In addition, the force required to peel off the PDMS layer is very low (as discussed in section 4.2). However, the force required to peel off the polyimide film from the substrate is very high [15] which can damage the bonded sensors during the peel-off process.

Using the novel process described here, the SU-8 sheet with whole substrate dimension can be peeled off. An SU-8 sheet of 66 mm × 64 mm with 120 μm thickness is successfully peeled off (figure 10). Furthermore, same

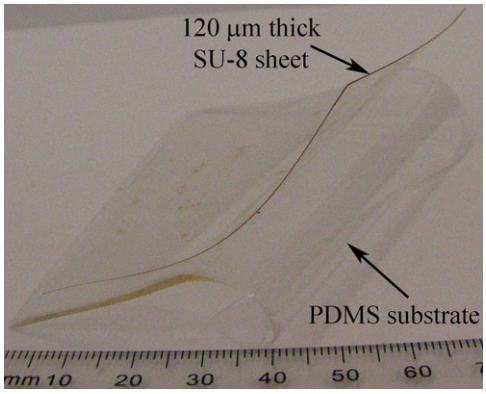

Figure 10. 120 μm thick SU-8 sheet (66 mm $\times$ 64 mm) peeled off from the PDMS substrate.

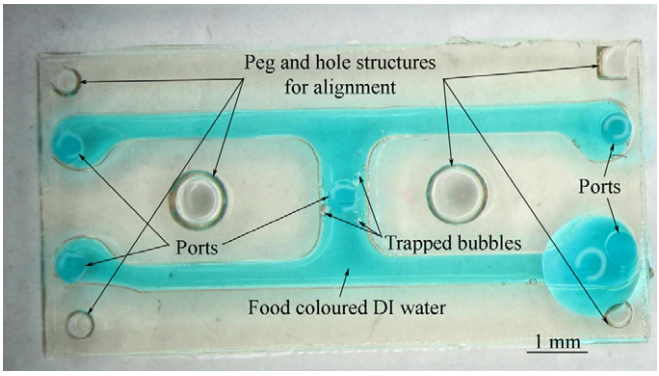

Figure 11. Bonded microfluidic channel network with ports and alignment features filled with colored water to test for leakage.

size SU-8 sheets with different thicknesses from 10 μm to 450 μm are successfully fabricated and peeled off from the PDMS substrate.

4.4. Microfluidic characterization

In our new fabrication process, microchannels have the input and output ports on the top layer. Consequently, we do not need to etch the top SU-8 layer after releasing the free-standing devices. Hence, when the devices are released, they are ready to test without additional process steps.

Figure 11 shows a photograph of an H-shaped microchannel network together with its inlet and outlet ports and the alignment structures. The microchannels of the chip are filled with liquid to check for leakage. The figure clearly shows that there is no fluid leakage in the microfluidic devices.

After verifying fluid tight channels, a microfluidic pressurization test is carried out. De-ionized (DI) water with blue food coloring is introduced into the microchannels at different flow rates using a syringe pump (Harvard Apparatus '11') (figure 12) along with syringes from Hamilton Company, tygon tubing and hypodermic tubing. Fluidic pressure is measured at these different flow rates. Figure 12 shows the chip as tested, with tubing inserted into the channel ports and held in place by adhesive gaskets from Grace Biolabs. The inlet and outlet ports are connected to only one channel.

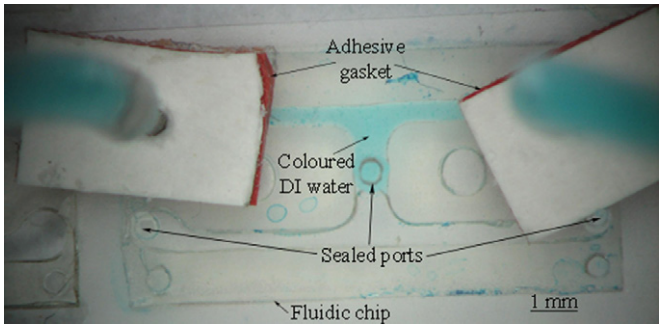

Figure 12. The microchannel chip with inlet and outlet tube connections for testing pressure versus flow rate.

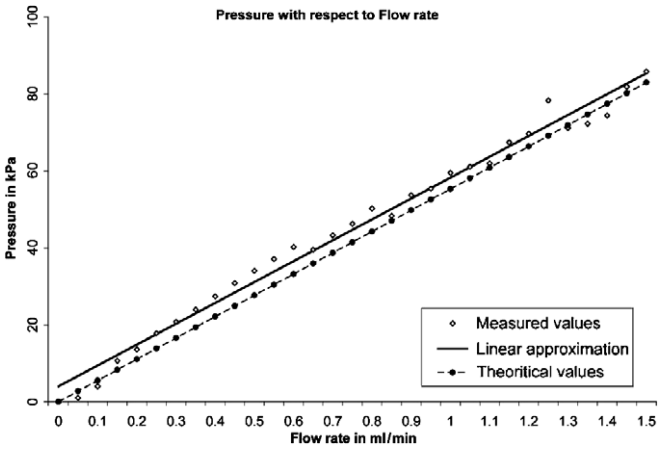

Figure 13. Pressure in a microfluidic channel versus the flow rate. The channels were tested for flow rates up to 1.5 ml min^{-1} with the pressure in the channel reaching 85.75 kPa before any detectable leakage.

The other connection ports are sealed to avoid unwanted fluid leakage from these ports. From figures 12 and 13, it is clear that the microfluidic channels are fluid tight and properly bonded using the multilayer SU-8 process.

For the pressure driven flow in the microchannel of the fabricated device, the flow rate can be calculated using Poisille's law:

$$Q = \frac{\pi D_{\text{eff}}^4 \Delta P}{128 L \mu}, \tag{1}$$

where Q is the flow rate in m^3 s^{-1}, D_{eff} is the effective diameter of the microchannel, ΔP is pressure drop, L is the length of the channel and μ is viscosity of water.

Using equation (1) and plugging into the numbers obtained for the fabricated microchannels, theoretical values of the pressure drop for the given flow rate can be calculated. The calculated values along with the actual measurement values are clearly plotted in figure 13. The values are calculated based on 460 μm height and 480 μm width for the channels.

In the laboratory test of the microfluidic device, the flow rate of the colored DI water was increased by steps of 0.05 ml min^{-1} from 0 ml min^{-1}. The pressure in the microchannel for each flow rate is measured using a pressure sensor (Omega PX26-005GV and Omega PX26-030GV) [52]. Figure 13 shows this pressure versus flow rate characterization for the

fluidic channel. The calculated values of the pressure using equation (1) are also plotted in the same chart. The fluidic pressure of the microchannels rises linearly with increasing flow rate.

The measured values and the calculated values show close agreement with each other. The error between the calculated and measured values is very nominal and may be due to variation in the microchannel dimension. The presented microchannel can withstand flow rates up to 1.5 ml min^{-1} without leakage. However, the microfluidic chip leaks for flow rates higher than 1.5 ml min^{-1}. The measured pressure for the 1.5 ml min^{-1} flow rate is 85.75 kPa.

5. Conclusion

A new fabrication technology utilizing PDMS as a peelable sacrificial substrate for free-standing SU-8-based structures is presented in this paper. The new process is intended for use in microfluidic and biomedical microdevices fabrication. Towards this goal, an SU-8-based microfluidic microchannel network is presented to demonstrate the technology for both microfluidic and biomedical applications. However, the presented process is not limited to these applications and can be used for many other applications in microfluidics and bio-medical microdevices, especially those involving combinations of metals and polymers, or those required to have some degree of mechanical flexibility.

SU-8-based fully enclosed microfluidic devices with different aspect ratios and thicknesses are presented. A multilayer microfluidic device with two layers of microchannels using five stack layers of SU-8 is successfully fabricated. To accurately align this multilayer bonding process, novel alignment structures using unique combination of pegs and holes are also presented.

The free-standing SU-8 chips for different microfluidic applications are successfully detached from the PDMS substrate material. The peel-off force required to detach the SU-8-based structures from the PDMS layer is only 180.9 mN with a standard deviation of 56.39 mN, which can easily be achieved manually or using automated equipment. Furthermore, the devices are fabricated using the photopatternable material (SU-8), which facilitates the patterning of the inlet and outlet ports directly on the top SU-8 layer. Thus, the fabricated devices are ready to use as soon as they are released from the PDMS layer.

Microfluidic chips in SU-8 are successfully fabricated and tested using a microfluidic pump and a fluidic pressure sensor with the results that the microchannel network can reliably withstand flow rates up to 1.5 ml min^{-1} and pressures up to 85.75 kPa. A linear response for fluidic pressure with respect to the flow rate is obtained as expected.

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