

Microfluidic systems with on-line UV detection fabricated in photodefinable epoxy

Rebecca J Jackman¹, Tamara M Floyd¹, Reza Ghodssi^{2,3},
Martin A Schmidt² and Klavs F Jensen^{1,4}

¹ Department of Chemical Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

² Microsystems Technology Laboratories, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

E-mail: kfjensen@mit.edu

Received 11 December 2000, in final form 28 March 2001

Abstract

This paper describes a method for fabricating microfluidic devices in a photodefinable epoxy (SU-8). This technique is compatible with, and complementary to, conventional fabrication techniques. It allows microstructures formed in SU-8 to be bonded to produce sealed microfluidic channels. A micromixer fabricated entirely in SU-8, using this technique, for performing liquid-phase reactions is shown to be suitable for visible spectroscopy. This fabrication method also allows the incorporation of materials that are often difficult to integrate. By fabricating hybrid devices that incorporate quartz windows, we demonstrate that these devices are compatible with organic solvents and that *in situ* ultraviolet detection in a microfluidic system is possible.

(Some figures in this article are in colour only in the electronic version; see www.iop.org)

1. Introduction

There has been recent, rapid development of microfluidic systems for use in micro total analysis systems (μ TAS) [1] and for microchemical synthesis applications [2]. For microfluidic systems to become widespread in chemical, biochemical and biological fields will require: manufacturable methods for the production of fluidic structures—low-cost, or even disposable devices are desirable; systems that are compatible with organic solvents for synthesis or analysis of organic compounds (for example, DMSO is used frequently as a solvent in drug discovery); and the integration of detection methods *on-chip* to maximize throughput and allow dynamic optimization of reaction conditions. In this paper, we describe a method that we have developed for fabricating these types of microfluidic devices by using SU-8 (a photodefinable epoxy with good chemical resistance). This technique is compatible with conventional microfabrication techniques and takes advantage of the parallel processing that microfabrication affords. These

advantages suggest that fabrication schemes incorporating SU-8 could potentially be scaled for mass production and could be used in systems for organic synthesis and chemical analysis. The technique we present also allows us to incorporate materials into these devices that are often difficult to integrate (e.g. quartz) and that are important for developing on-line detection methods (e.g. ultraviolet (UV) spectroscopy).

Many microfluidic devices are currently fabricated in silicon or glass. Both of these materials function well as substrates for microchemical reactors. Silicon is often selected as the substrate for these devices because processing techniques are well developed and they offer the opportunity to produce fully integrated structures. In a microfluidic device, the fluidic channels can require large depths (up to 500 μ m) to minimize pressure drops in the reactor. This type of microchannel geometry (lateral dimensions and depths ranging from 50–500 μ m) is typically achieved either by deep reactive ion etching (DRIE) of silicon [3], or by using LIGA (lithographie, galvanofornung, abformung (lithography, electroforming, molding)) [4] to produce structures in metal. In both cases, access to specialized equipment—either a deep reactive ion etcher or

³ Current address: Department of Electrical Engineering and Computer Engineering, University of Maryland, College Park, MD 20740, USA.

⁴ Author to whom correspondence should be addressed.

an x-ray synchrotron source—is required. This need limits the availability of these techniques. The construction of microfluidic devices in glass is widely practised, but is limited by the lack of DRIE chemistries for glass.

For some applications, a different material (e.g. a polymer or ceramic) that could be patterned and processed at less expense or with a shorter cycle time would be preferable to silicon or glass. The high cost of, long cycle time for, and limited accessibility of silicon (or glass) processing has driven interest in exploring other materials and methods for fabrication. The increasing use of plastics for the fabrication of microfluidic devices results from the lower cost of polymers and the ease and speed with which they can be processed. Many replication techniques exist for forming plastics at the microscale: embossing [5]; casting [6]; injection molding [7]; and imprinting [8]. While these techniques have been shown to work well, they are typically not compatible with silicon processing (which is problematic for hybrid structures) and many polymer systems are dissolved by organic solvents.

SU-8, an epoxy-based, negative photoresist developed by IBM and EPFL [9–11]; has properties that make it a useful alternative material for producing polymeric microfluidic structures for some applications and may reduce processing costs. Unlike many other polymers, SU-8 is compatible with standard silicon processing conditions and can be patterned using a standard i-line mask aligner. Films as thick as 1 mm can be patterned in a single coat with nearly vertical side-wall profiles. High-aspect ratio structures (greater than 14:1) have also been achieved. These dimensions are competitive with structures formed by DRIE or LIGA. During the patterning and post-exposure step, the SU-8 resist is crosslinked and becomes relatively resistant to most organic solvents. It can be difficult to remove SU-8 in applications where it is used as a resist. This chemical resistance, however, makes it suitable as a material for a variety of microchemical applications for which other polymers may not be candidates. The surface of SU-8 is not well defined. It presents, however, some unreacted epoxy groups that could be used for further derivatization of the interior walls of the fluidic channel. While the suitability of these systems for harsh chemical environments has yet to be proven conclusively, their applicability to exploring biological systems has been demonstrated [12].

When constructing microreactors using SU-8, the formation of sealed, fluidic channels is problematic (*vide infra*). Some groups [13, 14] have approached the problem by sealing the defined fluidic structures one-by-one to a glass coverslip with quick-setting glue. Researchers at EPFL [15, 16] have found other solutions to the problem, but each requires additional processing steps or access to thin-film laminates of SU-8. We have developed a method for bonding that simply uses spin-coated films of SU-8 supported on a transparent substrate to form sealed microchannels. Using SU-8 as a bonding layer also allows different materials to be incorporated into devices that would be otherwise hard to integrate (for example, quartz). The compatibility of SU-8 with standard microfabrication facilitates the integration of substrates with, for example, metallic electrodes, heaters or sensors. No planarization step is required to bond over these types of structures because the SU-8 planarizes them during patterning.

We have previously demonstrated the use of micro-fabricated devices to perform chemical reactions [17, 18]. In developing a microchemical reaction system, it is preferable to have a detection scheme integrated with the reactor. An on-line detection scheme serves several purposes: it enables feedback control of the reactors to optimize reactant conversion [19]; it allows reaction kinetics to be obtained *in situ*; it may facilitate the fabrication of portable, point-of-use devices; and it may increase throughput in a system. Here, we present the use of the hybrid quartz/SU-8 devices that we have formed by bonding with SU-8. We show that our hybrid devices are suitable for on-chip, UV spectroscopy. UV absorption spectroscopy is an important method for detection in macroscale analytical systems (e.g. capillary electrophoresis and high-pressure liquid chromatography (HPLC)). It is not, however, widely used in microfluidic systems because of the difficulty of incorporating quartz windows into these devices [20]. We believe that the flexibility offered by this approach to microfabrication may extend the capabilities of microfluidic systems and serve as a complement to traditional fabrication methods.

2. Experimental section

2.1. Fabrication of multilayered structures

To improve the adhesion of SU-8 films, we prepared silicon wafers (4" diameter; Wafernet Inc., San Jose, CA) by cleaning in a piranha solution (sulphuric acid:hydrogen peroxide, 3:1; *caution*—this solution can explode when mixed with organics), and then dehydrating the wafers on a hot plate at 200 °C for at least 20 min immediately prior to use. For films thinner than ~200 μm , we typically used SU-8 (50) (Microlithography Chemical Corporation, Newton, MA). Spin-coating the resist at 500 rpm for 15 s, followed by 3000 rpm for 15 s produced a film approximately 50 μm thick.⁵ We soft-baked the resist on a hot plate by ramping the temperature from room temperature to 105 °C over ~8 min, holding the hot plate at 105 °C for 15 min, and allowing the wafer to cool back to room temperature. After exposure of the resist to UV light (Karl Suss MA4 Mask Aligner, Waterbury, VT) through an appropriate mask, we post-baked the resist using the same schedule as for the soft-bake step. We repeated the spin-coating and soft-bake steps to coat a second layer of resist onto the first. The change in the index of refraction of the resist on exposure to light permitted us to align features in the second layer of resist to the first to within a few micrometres. After exposure of the resist and the post-bake step, both resist layers were developed in propylene glycol methyl ether acetate (PGMEA) for about 5–10 min.

If the substrate for the SU-8 was pyrex (4"; Bullen Ultrasonics, Eaton, OH) or quartz (4"; Hoya, San Jose, CA), we prepared the wafers as for silicon. We increased the time of the dehydration bake to at least 40 min, however. In cases where we would later release the SU-8 structure from the substrate, we typically used oxide-coated silicon wafers and we did not perform the dehydration bake before processing.

⁵ For thicker films (>200 μm), we used SU-8 (100) resist. As an example, spin-coating the resist at 500 rpm for 15 s, followed by 3000 rpm for 15 s gave a film approximately 300 μm thick. The schedules for the soft bake and post-exposure bake were as for the 50 μm film; the bake times, however, were increased to 2 h and 30 min, respectively.

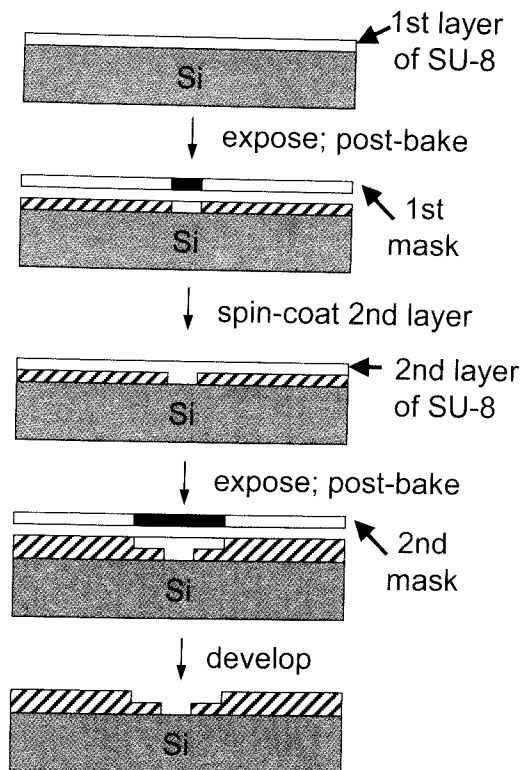


Figure 1. Schematic illustration of the use of SU-8 to produce multilayered structures. Exposure of a first layer of resist through a mask, followed by a post-baking step, resulted in crosslinked resist in the exposed regions. We then spin-coated a second layer of SU-8 onto the first layer of resist, exposed it through a second mask, and post-baked the structure. Development of the SU-8 produced a two-layered structure.

2.2. Bonding with SU-8 to form sealed microfluidic channels

A transparent substrate (either a pyrex or quartz wafer) was prepared by piranha cleaning, and a dehydration bake as described above. After coating the wafer with resist (SU-8 (50) at 500 rpm for 15 s, followed by 3000 rpm for 15 s), we soft-baked the resist partially on a hot plate. The temperature of the hot plate was ramped from room temperature to 105 °C over ~8 min, held at 105 °C for 10 min, and then allowed to cool to ~75 °C. We then immediately brought this layer of SU-8 into contact with a wafer bearing the multilayered SU-8 structures that we had formed. Prior to contact, the second wafer had been placed on a hot plate at 75 °C. As the wafers were contacted, we applied pressure with a pair of tweezers to ensure that there was contact over the majority of the wafer and that air bubbles were eliminated. After the wafer had cooled to room temperature, blanket exposure of the resist through the pyrex wafer and a post-bake schedule as described previously (ramp up to 105 °C, hold at 105 °C for 15 min, cool down to room temperature) produced a sealed microstructure in SU-8.

In cases where we had created fluidic ports in the first layer of SU-8 (rather than in the substrate), we released the microstructure from the substrate by placing the devices (one-by-one) into water and sonicating. The device separated from the oxide-coated silicon substrate, but remained attached to the pyrex support.

If fluidic ports already existed in the top wafer (e.g. drilled quartz wafers), we modified the bonding procedure. The quartz/SU-8 devices were fabricated by first preparing the two

quartz wafers (both the one with holes drilled and without) as described above. We then coated the undrilled wafer with SU-8 (50) to form a film approximately 50 μm thick. The pre-bake procedure was as for bonding other wafers with SU-8: the resist was ramped up to 105 °C (over ~8 min), held at 105 °C for 10 min, and then cooled to 75 °C, at which point the drilled wafer was brought into contact with the film of SU-8, pressed to seal, and cooled down to room temperature. We exposed the resist through an appropriate mask aligned to the drilled ports. After the post-exposure bake, the resist was developed by flowing PGMEA in through the fluidic ports.

2.3. On-line detection with quartz/SU-8 devices

The experimental set-up for packaging the microfabricated devices to interface with the macroscale has been described in detail elsewhere [18], but will be outlined briefly here. The hybrid devices were mounted on a Teflon holder that had been machined with ports whose spacing matched those of the device. These ports were connected through the holder to threaded holes designed to interface with standard HPLC fittings (Upchurch Scientific, Oak Harbor, WA). Fluids were pumped through the device using a syringe that was connected with standard fittings and driven by a syringe pump. The device was held in place using a compression plate. A gasket material between the device and the holder ensured that a good fluidic seal was achieved. Both the compression plate and the Teflon holder were designed to hold an optical fibre (using an SMA adapter (Control Development, South Bend, IN)) against the top and bottom of the device respectively. One of the fibres brought light from a deuterium lamp (D-100, Ocean Optics Inc., Dunedin, FL) to the device and the other connected to a UV detection card (Control Development, South Bend, IN) that was interfaced with a PC, running Control Development software.

3. Results and discussion

3.1. Formation of multilayered structures with SU-8

SU-8 has many attractive properties for microfluidic systems. In particular, SU-8 is a negative resist and so is crosslinked on exposure to UV light. Its increased chemical resistance after exposure may make it suitable as a material for a variety of microchemical applications. As figure 1 illustrates and as Guerin *et al* [15] have demonstrated, another advantage of SU-8 is that many types of complex, multilayered structures can be produced in it relatively easily. After spin-coating and pre-baking a first layer of SU-8 (typically 50–75 μm thick), we exposed it through the first level mask and then post-baked it to crosslink the exposed resist. Without developing the first layer of resist, we then spin-coated a second film of SU-8 (usually 50–75 μm thick) and repeated the exposure and post-bake process with a second mask. Exposure of the resist to propylene glycol monomethyl ether acetate (PGMEA) developed both layers in a single step.

Figure 2 illustrates the two masks used to fabricate a fluidic micromixer [18] by multilayer lithography. The first mask generated fluidic inlet and outlet ports, and the second mask produced the fluidic channels of the micromixer. The roughness of the side walls of the channel is a result of the

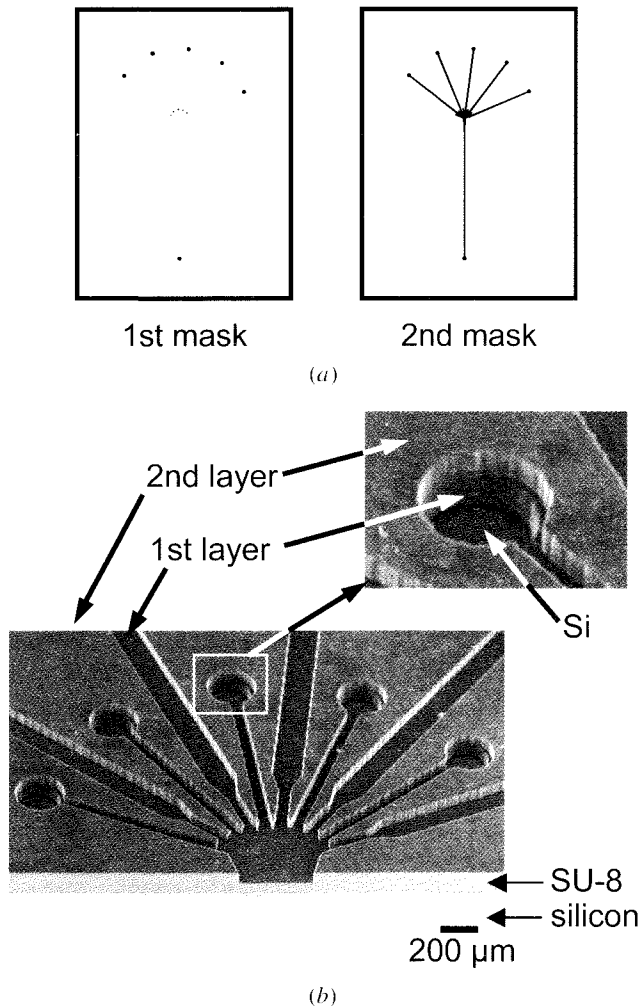


Figure 2. Multilayered structures formed in SU-8 by using the scheme illustrated in figure 1. The roughness of the side walls of the channel is a result of the rapid prototyping method we used to make the masks [21]. We used a high-resolution transparency as the photomask and the SU-8 reproduces the roughness in these features. (a) Two masks used to produce microfluidic structure—the first mask defines fluidic inlet and outlet ports, and the second mask defines fluidic channels. (b) Scanning electron micrographs (SEMs) of multilayered SU-8 channels.

rapid prototyping method we used to make the masks [21]. We used a high-resolution transparency as the photomask; the SU-8 reproduces the roughness of features on these masks.

3.2. Bonding with SU-8 to form sealed microfluidic channels

This procedure for making multilayered structures can be extended to more than two layers. There is, however, a restriction in the types of structures that can be made. Because SU-8 is a negative resist, features in the second (or subsequent) mask(s) must cover the features in the first (or previous) mask(s) so as to prevent further exposure (and the resulting crosslinking) of the first (or previous) layer(s) of resist. As figure 3(a) illustrates, structures with features that increase in size in each subsequent layer are possible, but designs where a feature is smaller or absent in a subsequent layer cannot be made by this method. This limitation means that the technique cannot be used to produce the sealed microchannels necessary for microfluidic applications. To create a sealed microfluidic

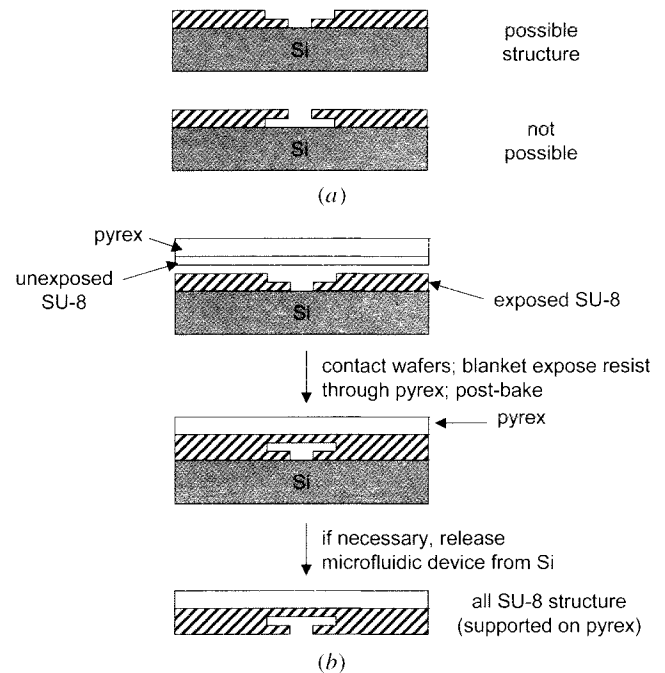


Figure 3. (a) Schematic illustration of the types of structures that are possible and not possible using multilayered lithography. (b) Scheme illustrating the use of SU-8 as a bonding layer to produce sealed microfluidic channels. We spin-coated a layer of SU-8 onto a 4" pyrex wafer and, after soft-baking the resist, we brought that wafer into contact with a second wafer with a multilayered SU-8 structure. Blanket exposure of the resist through the pyrex wafer and a subsequent post-baking step produced sealed microfluidic channels.

structure in SU-8 requires a different approach. Researchers at EPFL formed channels by depositing a layer of metal over unexposed features (before developing) to protect them from UV exposure [15]. A final layer of SU-8 was then spin-coated over the protected structures and processed. Resist in the channel was then slowly removed as the developer penetrated the SU-8. Other methods they have used included either precisely filling the fluidic channels with a sacrificial material (not crosslinked by UV light) that could be removed slowly after a capping layer was coated onto the structure, or using a free-standing, thin film of SU-8 and laminating it to the structure. Simpler approaches have been taken by other groups [13, 14] who used a quick setting glue to seal the channels in devices against glass coverslips one-by-one.

Here, we present a simple method that requires little further processing and that allows us to form sealed fluidic channels over a 4" wafer in a single step (figure 3(b)). The method uses SU-8 itself as a bonding layer. We coated a transparent substrate (typically, a pyrex or quartz wafer) with a layer of SU-8 and partially pre-baked the resist. Rather than allowing the layer of resist to cool to room temperature, we cooled it to $\sim 75^\circ\text{C}$ and brought it into contact with the substrate to which we wanted it to bond. At this elevated temperature, SU-8 is still above its glass transition temperature ($\sim 65^\circ\text{C}$) and so is pliable when pressed into contact with the other substrate. Blanket exposure of the resist to UV light through the pyrex, followed by a post-baking step, crosslinked the bonding layer to the other substrate and produced a sealed epoxy channel. Typically, this substrate was a multilayered SU-8 structure supported on a silicon wafer; it could, however,

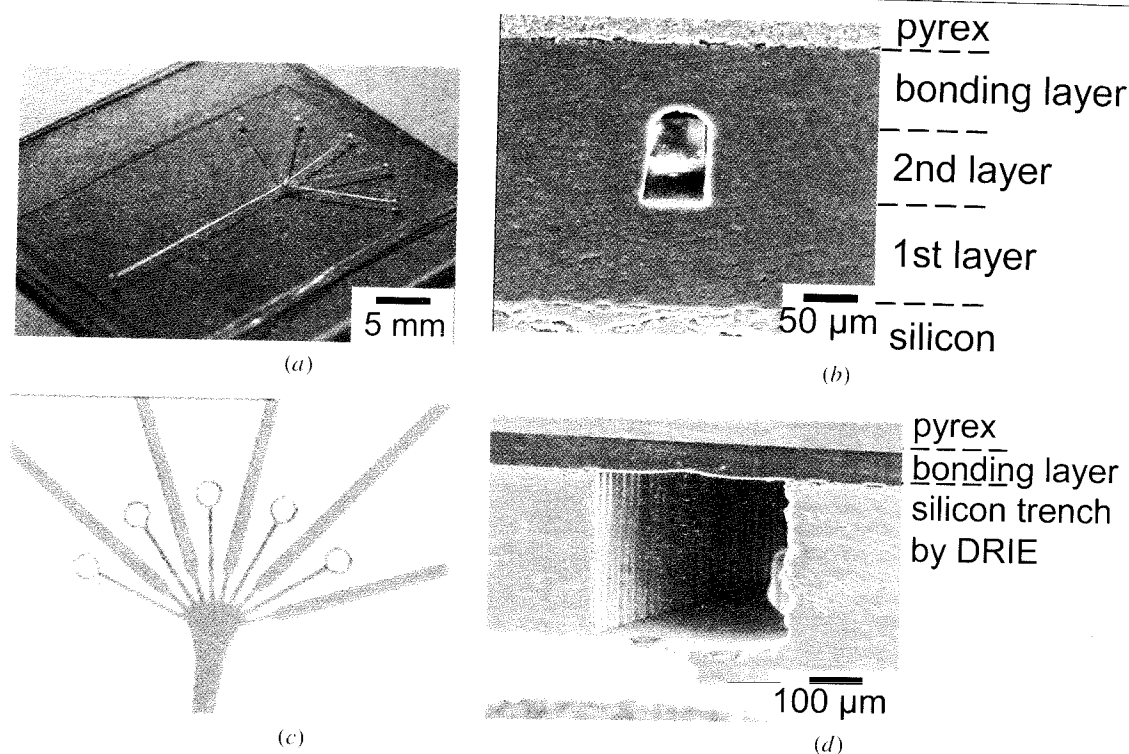


Figure 4. Sealed microfluidic channels formed using the SU-8 bonding technique illustrated in figures 2 and 3. (a) Photograph of the whole SU-8 micromixer formed using SU-8 bonding technique. (b) SEM showing a cross section through sealed SU-8 channels. (c) Image showing a solution of phenol red in microfluidic channels. (d) SEM showing a cross section through hybrid structure formed by bonding a deep reactive ion etched channel in silicon to a pyrex wafer using SU-8 as bonding layer.

be one of many other substrates, for example, a silicon wafer with structures etched into it by DRIE. When the fluidic inlet and outlet ports for the device are defined in the first layer of resist, we can release the structure from the supporting substrate (typically an oxide-coated silicon wafer) to open up access to the fluidic ports. Figure 4(a) shows a sealed fluidic micromixer formed in SU-8 by this bonding technique (after release from the substrate).

Cross sections through a device similar to the structure in figure 4(a) (still supported on silicon) show that there is no interface apparent between the bonded layers of SU-8 (figure 4(b)). The bonding process maintains the dimensions and integrity of the multilayered structure. We have not quantified the strength of the bond formed between the layers of SU-8, but devices can withstand flow rates of at least 0.1 mL min^{-1} corresponding to a pressure drop across the channels significantly greater than 1 atm. The photograph in figure 4(c) shows that the device is sealed—an aqueous solution of phenol red is contained within the micromixer device. It is also apparent that this type of all SU-8 devices is suitable for performing *in situ* visible spectroscopy in these channels.

The details of the bonding procedure determine the exact profile of the flow channels—there is a range of temperatures over which bonding works well ($\sim 70\text{--}85^\circ\text{C}$). If the structure and the bonding layer are contacted at a temperature that is too high ($>85^\circ\text{C}$, i.e. significantly above the glass transition temperature of the SU-8), then the viscosity of the unexposed SU-8 is too low, and it will flow into and block the channels. If the temperature is too low (i.e. below the glass transition temperature), then the layer of SU-8 will not be soft enough to make contact with the structure to be bonded. We anticipate

that it may be difficult to bond structures formed in thick films of SU-8 (greater than a few hundred micrometres) over a full 4" wafer because compressive stress in the film of SU-8 can cause significant bow in the supporting silicon wafer [22]. In these cases, however, the problem may be solved by using a thicker layer of SU-8 to act as the bonding layer or by bonding individual devices.

3.3. Incorporation of other materials using SU-8 bonding techniques

SU-8 has the advantage that the conditions required to process it are compatible with standard techniques for silicon processing. This flexibility allows for the fabrication of hybrid structures that combine SU-8 with other materials. For example, this methodology may be suitable to bond wafers that bear sensitive devices and that cannot be exposed to the high temperatures required for conventional bonding. Figure 4(d) shows a fluidic structure etched into silicon by DRIE that has been bonded to a pyrex wafer using this bonding technique.

We have also produced hybrid devices in SU-8 and quartz. These devices consist of channels defined in SU-8 that are capped on either side by quartz to give UV transparent windows suitable for spectroscopy. The procedure takes advantage of the ability of SU-8 to act both as a bonding layer and as a resist (it can be selectively crosslinked). These devices are formed using the SU-8 bonding technique described. Rather than a blanket exposure of the resist during bonding, however, the resist is exposed through a photomask. Figure 5(a) illustrates the steps for producing a quartz/SU-8 device with open quartz windows for *in situ* UV detection. Developing the resist (to open up the quartz windows) requires that one of the substrates

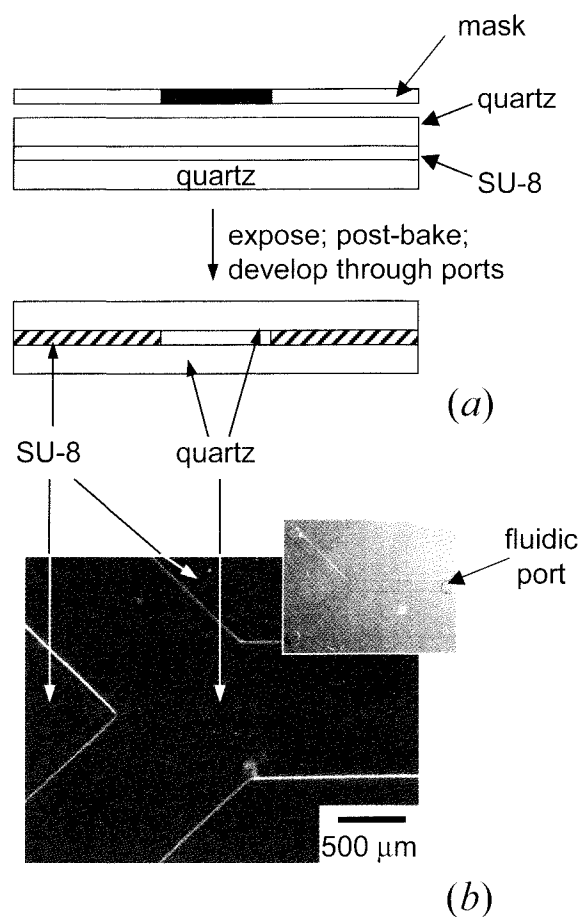


Figure 5. (a) Quartz/SU-8 devices formed using a technique similar to that shown in figures 2 and 3 can be used for *in situ* UV detection. The layer of SU-8 creates the fluidic microchannels and the quartz substrates cap the channels and form UV transparent windows in the device. (b) Optical micrographs of quartz/SU-8 device. The inset shows a large area image of the device.

contain ports through which to deliver the developer. This requirement necessitates a small modification of the bonding procedure because spin-coating SU-8 resist onto a wafer that contains holes results in an uneven film of resist that will tend to retract from the holes. Attempts to bond wafers of this type will tend to result in poor bonding around the ports. To prevent this problem, we take the undrilled quartz wafer and prepare it with a layer of resist for bonding (figure 5). We pre-bake the resist, allow it to cool to $\sim 75^\circ\text{C}$, and then bond it to an uncoated, drilled quartz wafer. This procedure produces a sandwich structure that is exposed, baked, and developed through the ports.⁶ Figure 5(b) shows an optical micrograph of a section of a quartz/SU-8 device that was formed by this technique.

In designing a mask to be used in this type of scheme, the thickness of the top substrate must be taken into consideration. The mask is not in direct contact with the resist (it is separated by $\sim 500\ \mu\text{m}$ for a standard wafer), and the consequence is that

⁶ Developing resist through the fluidic ports can, depending on the dimensions of the channels, require exposure of the resist to PGMEA for extended periods (up to tens of hours) [15]. This prolonged exposure to PGMEA (a solvent for uncrosslinked SU-8) can cause gradual degradation of the SU-8—small cracks will begin to appear along the edges of the channels, probably due to the dissolution of low molecular weight, uncrosslinked material in the bulk. This problem should be solved by appropriate device design.

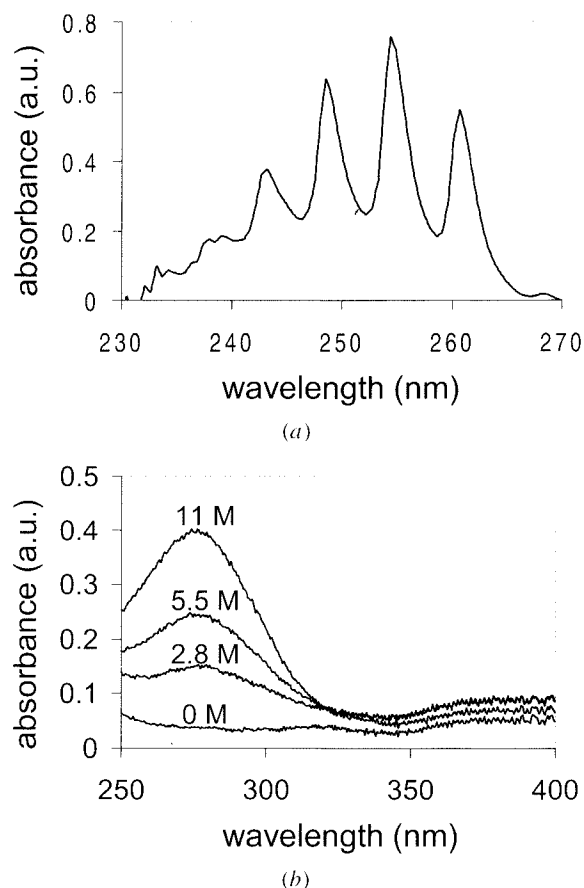


Figure 6. (a) Spectrum of benzene (1M) in hexane obtained in the hybrid quartz/SU-8 device. (b) Spectra of acetone at different concentrations in hexane obtained in the hybrid device.

the developed features in the resist are larger than they would be if they were in direct contact. If there are features, such as electrodes, however, on the surface of the top substrate, they can serve as their own masks.

3.4. On-line detection in hybrid SU-8 devices

In many microchemical systems, the ability to integrate detection schemes downstream from a reaction chamber and/or a separation column is critical. Optical absorption spectroscopy, in particular, UV spectroscopy, is widely used in macroscopic analytical systems as an on-line detection method. At the microscale, absorption spectroscopy can offer a simple method for incorporating on-chip detection into devices. Most materials from which microfluidic systems are constructed, however, cut off below 300–350 nm. This property makes spectroscopy in the visible range possible in conventional devices (e.g. those constructed in glass) and in devices constructed from some polymers (SU-8, for example), but makes UV spectroscopy impossible. To incorporate UV spectroscopy (down to 200 nm) into liquid-phase microreactors, requires a device with quartz windows. Methods for bonding silicon to quartz exist [23], but they require high-temperature steps and the thermal expansion of silicon and quartz are not well matched—these features make quartz difficult to integrate into devices. The hybrid quartz/SU-8 devices presented here offer a potential solution to this problem.

Figure 6 presents data obtained on-line in a quartz/SU-8 device. The data were obtained in transmission mode through the quartz windows on top and bottom of the microchannel ($\sim 60 \mu\text{m}$ deep). As a proof-of-principle, figure 6(a) shows the characteristic spectrum for benzene in one of these devices. Figure 6(b) shows data from acetone in hexane at various concentrations—these data show a Beer's law relationship between absorbance and concentration. These experiments illustrate the feasibility of performing on-line UV detection and the compatibility of these devices with organic solvents.

4. Conclusions

We have explored the use of SU-8 (an epoxy-based, negative resist) as a material for the construction of microreactors. A simple technique that uses SU-8 as a bonding layer enables the formation of sealed microchannels. The compatibility of this technique with conventional microfabrication methods has enabled the formation of hybrid devices that incorporate other materials. These methods may offer a complementary alternative to DRIE for some microchemical applications. Combining these and standard techniques for microfabrication offers the possibility of decreasing cycle times and cost in fabricating microchemical systems.

In these microchemical systems, the integration of detection methods on-chip is a difficult challenge. We demonstrate here that we can incorporate quartz windows into our microfluidic devices to extend the range of optical spectroscopies that are now possible in these systems. It is possible to envision a device that incorporated a reaction chamber, followed by a separation column, and UV detection on-line. In addition to on-line detection, the transparency of these devices down to $\sim 200 \text{ nm}$ also suggests that they might be well-suited to performing photochemical reactions in these devices.

Acknowledgments

This research was supported by the DARPA under the Microflumes Project and the National Science Foundation (Graduate Fellowship—TMF). The authors thank the staff of the Microsystems Technology Laboratories for technical assistance, Scott Brittain for his assistance with the photograph shown in figure 4(a), and Dr David C Duffy for helpful discussions.

References

- [1] See, for example, van den Berg A, Olthuis W and Bergveld P (eds) 2000 *Micro Total Analysis Systems 2000* (Dordrecht: Kluwer Academic)
- [2] Jensen K F 1999 Microchemical systems: status, challenges and opportunities *AIChE J.* **45** 2051–4
- [3] Ayon A A, Braff R A, Bayt R, Sawin H H and Schmidt M A 1999 Influence of coil power on the etching characteristics on a high density plasma etcher *J. Electrochem. Soc.* **146** 2730–6
- [4] Menz W 1996 LIGA and related technologies for industrial application *Sensors Actuators A* **54** 785–9
- [5] Becker H, Dietz W and Dannberg P 1998 Microfluidic manifolds by polymer hot embossing *Micro Total Analysis Systems 1998* (Dordrecht: Kluwer) pp 253–6
- [6] 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.* **70** 4974–84
- [7] McCormick R M, Nelson R J, Alonso-Amigo M G, Benvegna D J and Hooper H H 1997 Microchannel electrophoretic separations of DNA in injection-molded plastic substrates *Anal. Chem.* **69** 2626–30
- [8] Xu J, Locascio L, Gaitan M and Lee C S 2000 Room-temperature imprinting method for plastic microchannel fabrication *Anal. Chem.* **72** 1930–3
- [9] Lorenz H, Despont M, Fahrni N, Labianca N, Renaud P and Vettiger P 1997 SU-8: A low-cost negative resist for MEMS *J. Micromech. Microeng.* **7** 121–4
- [10] Lorenz H, Despont M, Fahrni N, Brugger J, Vettiger P and Renaud P 1998 High-aspect-ratio, ultrathick, negative-tone near-UV photoresist and its applications for MEMS *Sensors Actuators A* **64** 33–9
- [11] Shaw J M, Gelorme J D, LaBianca N C, Conley W E and Holmes S J 1997 Negative photoresists for optical lithography *IBM J. Res. Dev.* **41** 81–94
- [12] Heuschkel M O, Guerin L, Buisson B, Bertrand D and Renaud P 1998 Buried microchannels in polymer for delivering solutions to neurons in a network *Sensors Actuators B* **48** 356–61
- [13] L'Hostis E, Michel P E, Fiaccabrino G C, Strike D J, de Rooij N F and Koudelka-Hep M 2000 Microreactors and electrochemical detectors fabricated using Si and EPON SU-8 *Sensors Actuators B* **64** 156–62
- [14] Ayliffe H E, Frazier A B and Rabbitt R D 1999 Electrical impedance spectroscopy using microchannels with integrated metal electrodes *J. Microelectromech. Syst.* **8** 50–7
- [15] Guerin L J, Bossel M, Demierre M, Calmes S and Renaud P 1997 Simple and low cost fabrication of embedded microchannels by using a new thick-film photoplastic *Int. Conf. on Solid-State Sensors and Actuators, Transducers '97* pp 1419–21
- [16] Renaud P, van Lintel H, Heuschkel M and Guerin L 1998 Photopolymer microtechnologies and applications *Micro Total Analysis Systems 1998* (Dordrecht: Kluwer Academic) pp 17–22
- [17] Srinivasan R, Hsing I-M, Berger P E, Firebaugh S, Jensen K F, Schmidt M A, Harold M P, Lerou J J and Ryley J F 1997 Micromachined reactors for catalytic partial oxidation reactions *AIChE J.* **43** 3059–69
- [18] Floyd T M, Losey M W, Schmidt M A and Jensen K F 1999 Novel liquid phase microreactors for safe production of hazardous specialty chemicals *3rd Int. Conf. on Microreaction Technology* pp 171–80
- [19] Mitchell M C, Spikmans V, Bessoth F, Manz A and de Mello A 2000 Towards organic synthesis in microfluidic devices: multicomponent reactions for the construction of compound libraries *Micro Total Analysis Systems 2000* (Dordrecht: Kluwer) pp 463–5
- [20] Nishimoto T, Fujiyama Y, Abe H, Kanai M, Nakanishi H and Arai A 2000 Microfabricated CE chips with optical slit for UV absorption detection *Micro Total Analysis Systems 2000* (Dordrecht: Kluwer) pp 395–8
- [21] Qin D, Xia Y and Whitesides G M 1996 Rapid prototyping of complex structures with feature sizes larger than 20 μm *Adv. Mater.* **8** 917–9
- [22] Despot M, Lorenz H, Fahrni N, Brugger J, Renaud P and Vettiger P 1997 High-aspect-ratio, ultrathick, negative-tone near-UV photoresist for MEMS applications *IEEE Tenth Annual Workshop on MicroElectroMechanical Systems* pp 518–22
- [23] Berthold A, Sarro P M and Vellekoop M J 1998 Low-temperature quartz-to-silicon bonding for SAW applications *SPIE Conf. on Smart Electronics and MEMS* pp 81–5

