

Rapid prototyping of microfluidic systems using a PDMS/polymer tape composite†

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Received 17th October 2008, Accepted 26th January 2009

First published as an Advance Article on the web 10th February 2009

DOI: 10.1039/b818389a

Rapid prototyping of microfluidic systems using a combination of double-sided tape and PDMS (polydimethylsiloxane) is introduced. PDMS is typically difficult to bond using adhesive tapes due to its hydrophobic nature and low surface energy. For this reason, PDMS is not compatible with the xurography method, which uses a knife plotter and various adhesive coated polymer tapes. To solve these problems, a PDMS/tape composite was developed and demonstrated in microfluidic applications. The PDMS/tape composite was created by spinning it to make a thin layer of PDMS over double-sided tape. Then the PDMS/tape composite was patterned to create channels using xurography, and bonded to a PDMS slab. After removing the backing paper from the tape, a complete microfluidic system could be created by placing the construct onto nearly any substrate; including glass, plastic or metal-coated glass/silicon substrates. The bond strength was shown to be sufficient for the pressures that occur in typical microfluidic channels used for chemical or biological analysis. This method was demonstrated in three applications: standard microfluidic channels and reactors, a microfluidic system with an integrated membrane, and an electrochemical biosensor. The PDMS/tape composite rapid prototyping technique provides a fast and cost effective fabrication method and can provide easy integration of microfluidic channels with sensors and other components without the need for a cleanroom facility.

Introduction

A major challenge in microfluidic system fabrication is how to integrate multiple microfluidic components simply and how to create microfluidic systems in a rapid, inexpensive manner. To address these challenges, in this paper a new technique is presented that is designed to decrease fabrication time and cost, as well as alleviate many packaging issues associated with microfluidic systems. This new, unconventional, rapid prototyping technique combines soft lithography^{1–4} with xurography,^{5–7} eliminating some of the drawbacks of both. In particular, the combination of tape with PDMS eliminates many bonding challenges, the need for using any cleanroom equipment or UV exposure sources and can be completed much more quickly than traditional soft lithography. The technique is implemented by spin coating double-coated adhesive polymer tapes with liquid PDMS and allowing the PDMS to cure to create a PDMS/tape composite structure. The PDMS/tape composite can then be cut with a knife plotter to make a microfluidic pattern. In this method, one side of the tape is coated with PDMS and allowed to dry. The other side of the tape, which is coated with an adhesive layer, is left unchanged. The microfluidic pattern made using this technique can then be bonded to nearly any substrate, such as; silicon, glass or most polymers. By using this technique, any

membrane, microelectrode, or microheater system can be integrated into a microfluidic system quickly and easily. In particular, the results will indicate that nearly any commercial membrane can be integrated into a microfluidic system easily, and the process does not depend on the membrane properties, because of the robust bonding associated with the PDMS/tape composite. This prototyping technique should play an important role in decreasing the fabrication cost, time and design cycle for microfluidic systems.

Experimental

Without the use of a clean room facility, a rapid prototyping technique for microfluidic systems based on a PDMS/tape composite was developed. To create the composite, first, double-sided tape (3M™ Double Coated Tape 444, 3M Corp., MN) was fixed on a flat substrate. This tape was chosen because of its strong adhesion to multiple surface types and high temperature stability. Other tapes can be chosen depending on applications. Degassed liquid PDMS was poured over the double-sided tape and spun at 1000, 2000 and 3000 rpm to find the correlation of spin speed with PDMS film thickness. Then, the double-sided tape with a coating of PDMS was cured at 65 °C for an hour or less. The microfluidic channel was then cut into the PDMS/tape composite using a knife plotter, which received instructions based on a CAD design. The unwanted part of the PDMS/tape structure was then peeled off and removed. The next step was the creation of an inlet and outlet in the microfluidic channel. This step was completed with the help of a coring tool.⁸ To complete one side of the microfluidic channel, the patterned PDMS/tape composite was bonded to a PDMS slab by using a corona discharge method.⁹

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† Electronic supplementary information (ESI) available: Fig. S1 and S2. See DOI: 10.1039/b818389a

After completing the fabrication of the PDMS/tape composite, the paper backing was peeled off the polymer tape and the entire structure was then attached to various substrates, such as glass, metal deposited glass or polymer sheets by applying moderate pressure. For the glass substrates, regular microscope slide glass (VWR international Inc.) was cleaned with methanol and isopropyl alcohol (IPA) and dried with N_2 gas. Then the adhesive layer surrounding the microfluidic channel was pressed to the cleaned glass to create a bond. For the case of a plastic substrate, a polycarbonate sheet (Bayer Material Science, Germany) was cleaned only with IPA and then bonded with the microfluidic structure. The third substrate that was used was a glass slide coated with platinum in several areas. The microfluidic system was then bonded to the patterned glass substrate as with the other substrates. The bond strength between the PDMS/tape composite and a glass substrate was characterized by performing a leakage test of the microfluidic system before moving to testing of the function of the system. For this bond strength test, a dead end channel setup was used. The pressure was slowly increased until the channel separated from the substrate, at which point the pressure was recorded ($N = 4$). This failure pressure was compared with results obtained using the oxygen plasma bonding method. After evaluating the bond strength, the flow profile in the microfluidic channel was investigated using a microscope to check for leaks or poorly bonded areas. Multiple flows were then simultaneously pushed through the microfluidic channels to check the flow profile with different colors of dye. In particular, we were looking for abnormal mixing, which might be indicative of unintended fabrication errors.

Nucleic acid extraction

After the validation tests using the various substrates, the PDMS/tape composite was used to build a microfluidic sample filtration/extraction system.¹⁰ Usually, the most difficult challenge in creating a membrane embedded microfluidic system is to obtain a complete seal.¹¹ Embedded membrane systems must have a high bond strength due to the high pressure conditions required to drive samples through the membrane. To build an embedded membrane system, a patterned circle was cut with the knife plotter into two pieces of PDMS/tape composite and then a third PDMS substrate containing molded microfluidic channels was bonded onto the PDMS side of one of the composite layers using a corona discharge technique. After removing the backing paper from the composite structure, a nanoporous aluminum oxide membrane (200 nm pore size, 60 nm thickness from Whatman Inc., UK) was bonded between the two pieces, resulting in a membrane sandwiched between two microfluidic channels capable of being used for DNA extraction experiments. The experimental samples used to validate the extraction devices consisted of $25 \text{ ng } \mu\text{L}^{-1}$ of genomic DNA (gDNA) in Tris-EDTA buffer (pH 8) with an LCgreenTM (Idaho Technology, Salt Lake City, UT) intercalating dye used to visualize the DNA on the surface of the capture membrane. A syringe pump (Harvard Scientific) was used to push the sample through the membrane at 0.4 mL h^{-1} . After the tagged gDNA was captured on the membrane, the fluorescence of the captured gDNA molecules was observed with a high resolution CCD camera (iXon, Andor Technology, South Windsor, CT).

Electrochemical sensor

Another demonstration of applications of the PDMS/tape composite was completed by creating microfluidic channels leading to an electrochemical biosensor. Microfluidic channels made using soft lithography or PDMS casting generally bond poorly to metal-coated substrates, which are typically required for electrical connections and were present in the electrochemical biosensor system. The PDMS/metal bonding problem arises because of difficulties in producing activated bonding regions between metal and organic ligands. To demonstrate the ability of the PDMS/tape construct to overcome these challenges, a PDMS/tape composite microfluidic channel was bonded to a glass substrate that had patterned Pt electrodes (the counter electrode) and Ag/AgCl electrodes (the reference electrode) on the surface. An additional electrode array (the working electrode) was bonded on the opposite side of a reservoir cut in the microfluidic system, which allowed electrical connection through the fluid to the counter and reference electrodes. 4 mM potassium ferrocyanate was used as the active electrochemical probe and was dissolved in a 1.0 M KCl solution before being flowed into the microfluidic system using a 3 mL plastic syringe (BD medical Inc). A potentiostat (Eco Chemie Autolab, Metrohm, USA) was connected to the 3 electrode system and used to generate a voltammogram. The scan rate was 20 mV s^{-1} .

Results and discussion

The rapid prototyping of the microfluidic channels was completed without the use of a cleanroom facility. The PDMS/tape composite method was used to fabricate several two-dimensional microfluidic systems within 60 min of creating a design using a CAD program. $50\sim 60 \text{ min}$ were needed to make the PDMS/tape composite and PDMS slab, and $2\sim 3 \text{ min}$ were needed for cutting the pattern into the double-sided tape. To peel it off and bond it with the substrate took about a minute. Three-dimensional systems should be only slightly longer as they involve the assembly of multiple 2-D layers. The first demonstration of this method was the creation of a single inlet–single outlet serpentine channel with a rectangular cross-section of $240 \mu\text{m} \times 400 \mu\text{m}$. The microfluidic channel depth was controlled by the thickness of the PDMS layer on top of the double-sided tape, which is $100 \mu\text{m}$ thick in this case.

Based on the results shown in Fig. 1, the channel thickness can be controlled by regulating the spin speed when applying the PDMS and by selecting the appropriate double-sided polymer tape. Thinner PDMS layers can likely be achieved by using a PDMS with lower viscosity or a higher spin speed. Bonding strength failure tests were performed with dead-end channels set up to measure the failure pressure and the results presented in Fig. 2. were comparable with oxygen plasma bonding, which is usually used for PDMS bonding, and a partial curing method.⁹ At $586 \pm 34 \text{ kPa}$, the PDMS/tape composite structure started to separate and leak between the tape and the bonded substrate. These bond strength results for the PDMS/tape composite were better than published results for oxygen plasma bonding, which is usually used for PDMS-PDMS bonding and PDMS-glass bonding (maximum bond strength: 510 kPa). The bond strength was clearly high enough for use in nearly any proposed

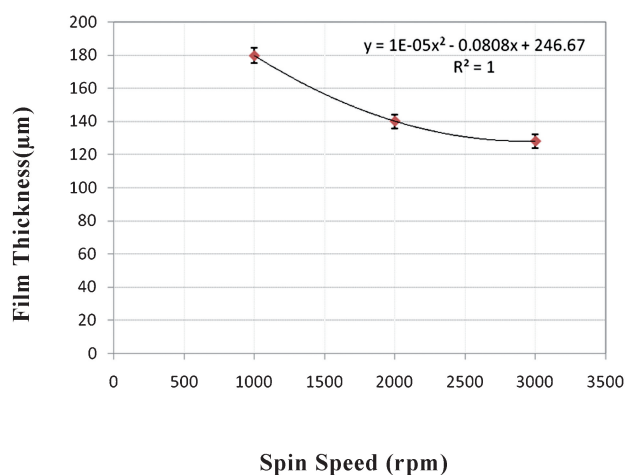


Fig. 1 The effect of spin speed on the PDMS thickness on the polymer tape. Based on this information, the microfluidic channel thickness and associated volumes can be estimated ($N = 4$).

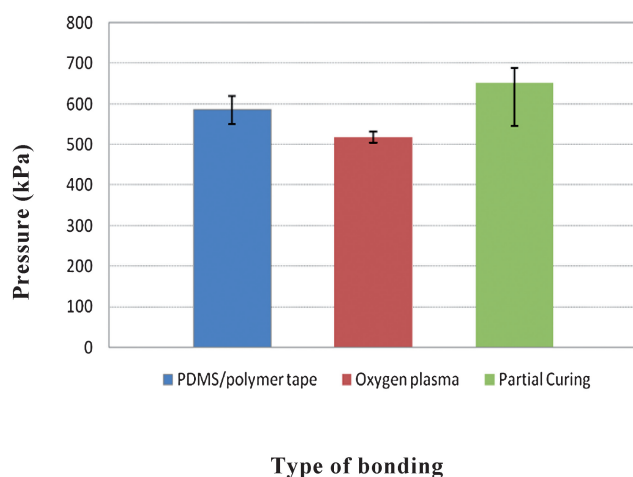


Fig. 2 Bond strength of the PDMS/tape composite to glass was compared to that of PDMS to glass using a traditional oxygen plasma method. The bond strength was tested with dead end channel and then compared with the oxygen plasma and partial curing methods.^{9,12}

application, including high-flow rate applications, as pressures in most microfluidic systems only occasionally exceed 100 kPa. The results of the microfluidic channel fabrication are shown in Fig. 3B, which also show testing of the system with colored dye. The microfluidic systems operated successfully without any channel blockage or leakage problems. The uniformity of the channel walls in the microfluidic systems was investigated through a microscope and by observing the flow profile of two different colored solutions traveling through the channels simultaneously. The flow appears perfectly laminar and no mixing was observed (see Fig. 3B), as is the case with most well-fabricated microchannels.

Nucleic acid extraction

To show the robustness of this PDMS/tape composite technique, the embedding of a nanoporous membrane for extracting nucleic

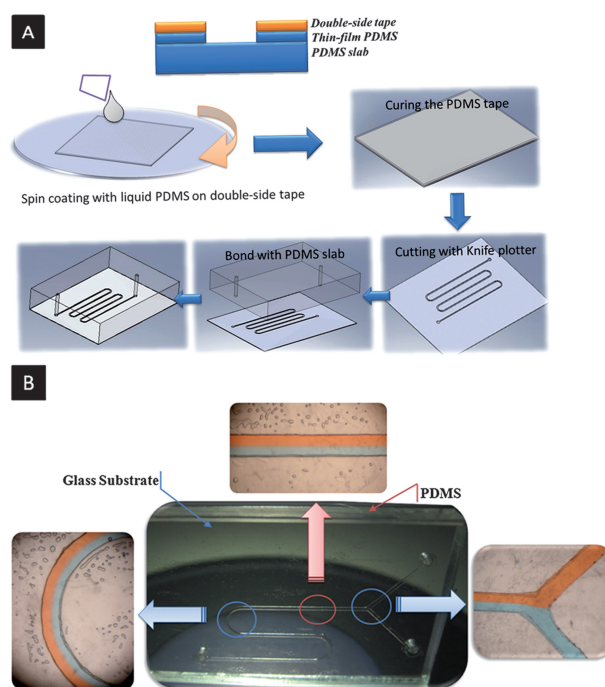


Fig. 3 (A) Process steps for the rapid prototyping of microfluidic structures using a PDMS/polymer tape composite. The double-coated adhesive tape is fixed on a flat plastic sheet with an exposed adhesive side face-up. Degassed liquid PDMS is poured on the double-sided tape and spun at about 2000~3000 rpm. The thin film PDMS is cured at 65 °C for about an hour. This creates the PDMS/tape composite. From this structure, microfluidic channels patterned from a CAD design are cut, and the unwanted material removed. For the final step, the patterned PDMS/tape composite is bonded with a PDMS slab using a corona discharge to activate the surface of the PDMS slab. (Other PDMS/PDMS bonding methods may be used as well.) The microfluidic system made using the PDMS/tape composite is attached to various substrates, such as glass, plastic and silicon without any treatment. (B) The serpentine microfluidic channel fabricated using the PDMS/polymer tape composite method was tested with blue and orange dye to show the functionality of the rapidly prototyped microfluidic device. The channel wall was clean and smooth enough for a microfluidic assay to be completed without any problems. (Channel width = 400 μm.)

acids was demonstrated.⁹ Images of the completed device are available in the ESI.† For this membrane embedded system, the nanoporous aluminum oxide membrane required careful handling due to the membrane's mechanical characteristics (thin and brittle). The bond strength around the membrane was sufficient to endure the pressure driven flow without any leakage. gDNA was clearly collected on the top surface of the nanoporous membrane as shown in fluorescence images. Using this method nearly any thin or sheet-like membrane used for sample concentration, filtration, or cell growth should be able to be integrated within a microfluidic system quickly and easily.

Electrochemical biosensor

A further demonstration of the PDMS/tape composite method involved bonding a microfluidic channel above a deposited metal layer. The completed device is shown in the ESI.† By testing the

channels with a flowing colored dye, this system was shown to work as designed without any leakage. The electrodes in the system were then tested in a voltammetry experiment (see ESI†) and the electrochemical results are shown to closely reproduce a similar experiment using a standard laboratory setup in a beaker. Thus, it appears the PDMS/tape composite had no adverse effects on the electrochemical cell, while still making a leak-free bond. This system was also tested with a variety of biomolecules, and found to work well, with few adverse affects for any of them. From time to time, the double-sided tape attracted biomolecules which stuck to the channel side wall and then trapped bubbles due to the change in surface characteristics. Coating the channels with BSA(Bovine Serum Albumin) or a Pluronic⁶ was used to provide a stable surface on the wall and eliminate this problem.

Conclusion

To decrease the design cycle time and to overcome the limitation of PDMS bonding methods, a PDMS/tape composite method was developed and applied to create several unique and functional microfluidic systems. The microfluidic channel geometries cut with a knife plotter were similar to those generated using other soft lithography methods and performed as expected. The flow profile in the microchannels was observed in microscope images and flow tests showed no abnormal mixing or leakage. The depth of the microfluidic channel can be precisely controlled by modifying the spin speed used to apply the PDMS to the double-sided tape and thin film PDMS composite. When the bond strength of the PDMS/tape composite was measured, the PDMS/tape composite method showed a higher bond strength than that for a typical oxygen plasma method that is usually used for bonding PDMS microfluidic channels to glass or PDMS. A variety of membrane-embedded and electrochemical

microfluidic systems were built, demonstrating the usefulness of the method in a range of applications. A wide range of geometries for microfluidic channels fabricated in around an hour without any cleanroom facility or the creation of a micromold. If the backing tape is not removed, peel off, microfluidic channels can be made in advance and used anytime needed and on just about any surface.

Acknowledgements

This research was supported by Synergy and TCP (Technology Commercialization Project) grants from the University of Utah and the State of Utah Center of Excellence Program.

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