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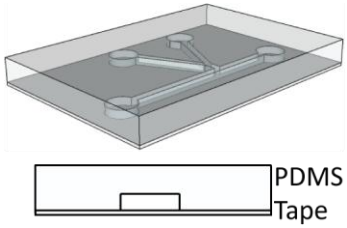

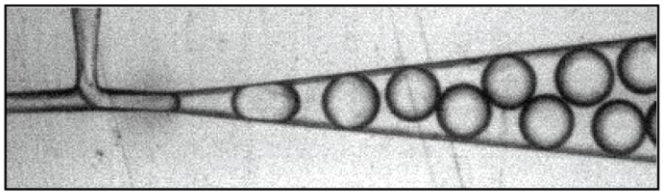

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COMMUNICATION

Adhesive-based bonding technique for PDMS microfluidic devices

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We present a simple and inexpensive technique for bonding PDMS microfluidic devices. The technique uses only adhesive tape and an oven; plasma bonders and cleanroom facilities are not required. It also produces channels that are immediately hydrophobic, allowing formation of aqueous-in-oil emulsions.

Introduction

Soft lithography in polydimethylsiloxane (PDMS) is a ubiquitous method for rapid prototyping of microfluidic devices.[1] A critical step in the fabrication involves sealing the devices by bonding the PDMS channels to a substrate. Numerous PDMS bonding strategies have been reported,[2-5] but oxygen plasma treatment is the most common. While oxygen plasma is effective and produces strong bonds, the necessary equipment is expensive and access to cleanroom facilities is limited. Other methods, like partial cure bonding or the use of chemical crosslinkers, can also be used to bond devices, but often require hours, if not days, to complete the bond before the devices can be used. As interest in microfluidic methods moves beyond specialized engineering laboratories, alternative techniques for bonding PDMS devices will be useful. In particular, methods that are simple and inexpensive will enable the broadest adoption of these techniques by researchers in other fields.

In this Communication, we present a simple and inexpensive bonding technique for PDMS devices that requires only adhesive tape and an oven. Adhesive tape is applied to the bottom surface of the PDMS device and the device baked at 65°C for 2 hours. The baking increases the bond strength to the tape, allowing the devices to support pressures of tens of kilopascals for hours of operation. A variety of common adhesive tapes can be used, including optically transparent tapes that enable brightfield microscopy of the channels and double-sided tapes that can be adhered to another substrate, like a rigid glass plate, providing even stronger bonds. We demonstrate the biocompatibility of the method by using a tape-bonded device to generate droplets for emulsion PCR. The simplicity, low cost, and reproducibility of our method should allow it to be adopted by researchers lacking access to cleanroom facilities.

To test the burst strength of PDMS devices bonded with tape, we fabricate smooth PDMS slabs with holes punched into them. PDMS elastomer (Sylgard) is prepared by mixing the elastomer base with crosslinker at a 10:1 weight ratio using a Dremel hand drill. The mixture is degassed under vacuum for 30 minutes, poured into a plastic Petri dish, and cured for 2 hours at 65°C. The cured PDMS is sectioned into 3 x 3 cm^2 slabs using a razor blade. A 0.75 mm diameter tubing inlet hole is cored into the center of the device (Harris Unicore). The slab is washed with isopropyl alcohol and dried with compressed air. One of three adhesive tapes (Scotch®Magic™ Tape, Scotch® Permanent Double Sided Tape, Scotch® MultiTask Tape) is then applied to the slabs and the slabs are baked at 65°C for 0, 1, 2, 4, or 16 hours. Specifications for the adhesive tapes studied are described in ESI Table 1†.

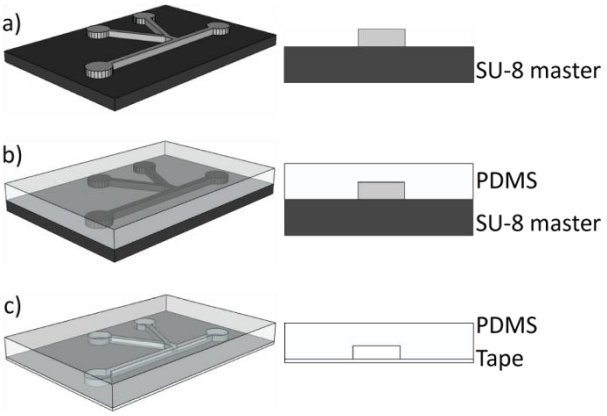

Fig. 1 Fabrication process for bonding PDMS with adhesive tape. (a) SU-8 master is fabricated on a silicon wafer using photolithography. (b) PDMS is cast on the master and cured. (c) The PDMS replicate is removed, punched with inlet ports, washed, and adhesive tape is applied to its bottom surface. The device is baked at 65°C for 2 hours to complete bonding.

To produce microfluidic devices with this approach, PDMS replicates are molded from an SU-8 master using the techniques of soft lithography.[1] The device is punched with inlet ports, washed, tape-bonded, and baked, as illustrated in Fig. 1.

Microfluidic bonding techniques must produce strong bonds that prevent fluid leakage at the PDMS-substrate interface. To measure the strength of the PDMS-tape bonds and identify the optimal bake time for strengthening the bonds, we use burst pressure testing. Polyethylene tubing is inserted into the inlet port of the tape-bonded PDMS slabs, through which regulated air pressure is applied. We increase the air pressure in increments of

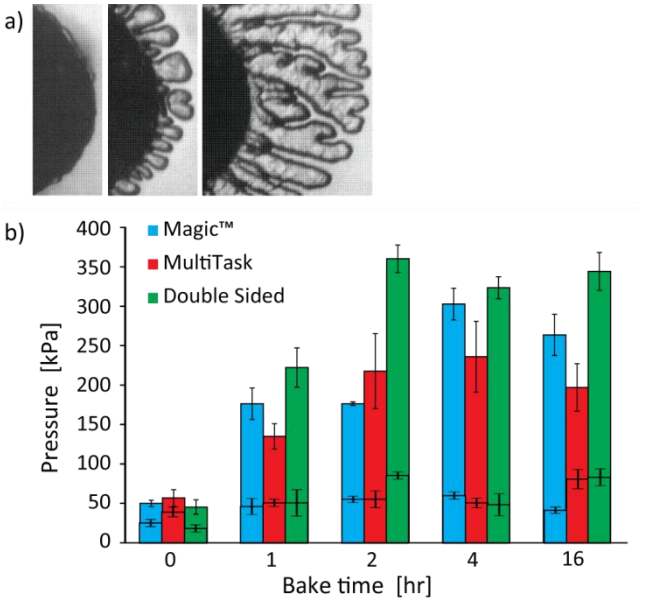

Fig. 2 (a) Brightfield microscopy image of the formation of Saffman-Taylor fingers as pressure is applied to a PDMS-tape bond through an inlet port; the inlet port is a circular hole, the right edge of which is visible in the left of the images. The pressure increases from left to right. (b) A comparison of bond strengths for three adhesive tapes baked for different times. For each bar, the lower value is the pressure at which Saffman-Taylor fingers form and the higher value the pressure at which the bond fails. Each bar is the average of three experimental measurements with different devices and error bars denote the standard error of the mean of these values.

7 kPa at time intervals of 30 s until the PDMS-tape bond breaks. We monitor the bond integrity under a brightfield microscope to determine when the bond begins to fail. To verify there are no air leaks at the device inlet, we monitor a soap-water solution applied at the device-tubing interface.

Results

The PDMS-tape bond is stable up to pressures at which Saffman-Taylor fingers form around the inlet.[6,7] Saffman-Taylor fingers are characteristic of the interface that forms when a viscous fluid, such as the adhesive from the tape, separates between two diverging surfaces. As the applied pressure increases, the Saffman-Taylor fingers continue to develop, up until the point that the bond fails, as depicted in Fig 2a.

We test the bond strengths of three commonly available adhesive tapes, a comparison of which is provided in Fig. 2b. For each column, the lower value represents the pressure at which Saffman-Taylor fingers begin to develop and the higher value the pressure at which the bond fails. The bond strength increases with baking time from 0-2 hours for all adhesive tapes but, for baking times greater than 2 hours, does not increase. The double-sided tape reproducibly yields the strongest bonds, and bonding the bottom surface of the double-sided tape to a rigid glass slide can increase the bond strength further. The maximum bond strength achieved after 2 hours of baking is comparable to that of oxygen plasma and corona discharge,[8] but the PDMS-tape bond is not permanent and fails after minutes to hours under the maximum applied pressure. These data show that the bond strengths obtained with common adhesive tapes are sufficient for many microfluidic applications.

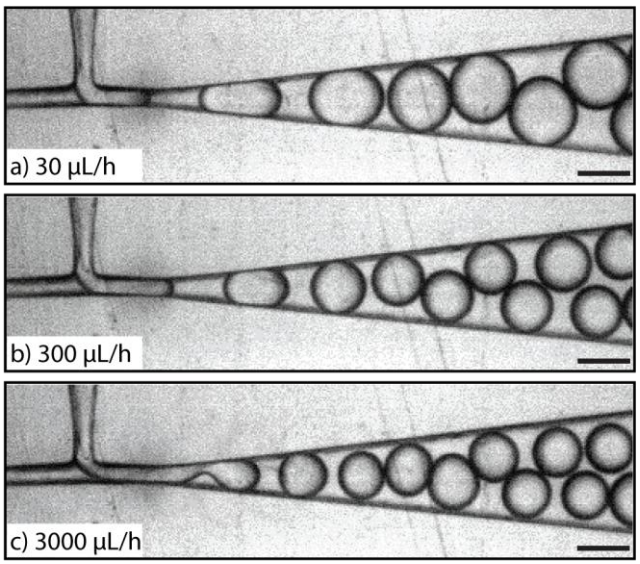

Fig. 3 PDMS-tape bonded T-junction drop maker used to create monodisperse microdroplets. We vary the flow rates over two orders of magnitude for a fixed oil-to-aqueous fraction of 2:1: Total flow rate (a) 30 µL/h, (b) 300 µL/h, and (c) 3000 µL/h. Scale bars represent 50 µm.

An important consideration when fabricating microfluidic devices for droplet-based applications is producing channels with the desired hydrophobic wettability, so as to allow the formation of aqueous-in-oil emulsions. Commonly used methods like oxygen plasma bonding or chemical bonding often render PDMS hydrophilic,[9] necessitating additional steps of processing to regain hydrophobicity. These include baking the devices for long durations to allow the PDMS to revert to its native hydrophobic state[10] or functionalizing the surfaces of the channels with hydrophobic silanes[11,12] and other chemical modifications like Aquapel.[13] In addition to increasing fabrication time and complexity, these steps are prone to failure, yielding channels with improper wettability and preventing the robust formation of emulsions. By contrast, our adhesive tape bonding method reliably produces channels with the needed hydrophobic wettability and also allows the devices to be used immediately without additional processing steps. This is because the PDMS remains in its native hydrophobic state throughout the bonding process and the adhesive of the tape, which comprises the bottom surface of the channels, is hydrophobic as well.

To illustrate that tape-bonded devices have the requisite hydrophobic wettability to form aqueous-in-oil emulsions, we fabricate a T-junction drop maker bonded to Scotch® MultiTask tape. We choose this tape because it is transparent, allowing brightfield monitoring of droplet formation. For the emulsions we inject distilled water into the dispersed phase inlet and the fluorinated oil HFE-7500 with a biocompatible fluorinated surfactant[14] into the continuous phase inlet. These fluids intersect at the T-junction, where drops are formed, as shown in Fig. 3 for three different flow rates. We vary the flow rates over two orders of magnitude to demonstrate that our adhesive-tape bonding method has the strength needed to operate devices under relevant flow conditions. Indeed, the highest flow rate, depicted at Fig. 3c, is the maximum at which drop formation in this device is possible; at this flow rate the device no long forms drops in a

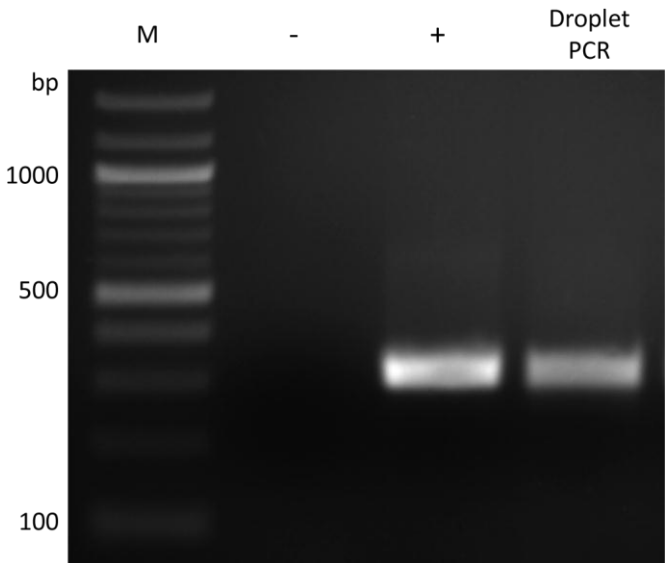

Fig. 4 Ethidium bromide stained agarose gel used to visualize the amplicons produced from an emulsion PCR carried out with our tape-based drop maker. Distinct bands are visible for the droplet PCR and positive control. M: 100bp ladder; -: no template control; +: positive control.

regular dripping process but rather jets, as can be seen by the fluid tongue extending into the expansion along the upper wall of the T-junction. This device behaves essentially identically to a T-junction of similar dimensions and wettability that is plasma bonded to glass or PDMS substrates.

A concern for any microfluidic device bonding technique is its biocompatibility. Hydrophobic surfaces, like those of our PDMS channels or of the adhesive of the tape, may adsorb biological molecules, depleting them from solution before they are encapsulated in drops, and interfering with downstream assays. To demonstrate that the method is sufficiently biocompatible so as to allow the encapsulation of commonly used biomolecules, including DNA and enzymes, we use our tape-bonded T-junction to form an emulsion for a droplet-based PCR. A PCR solution is prepared with 300 bp template DNA molecules, PCR primers, and Taq 1X Master Mix (New England BioLabs). The solution is divided in half, and one half is loaded into a PCR tube as the positive control and the other into a syringe. The solution in the syringe is then emulsified in fluorinated oil HFE-7500 with 4% (wt/wt) surfactant[14] using our tape-bonded drop maker and the drops are collected into another PCR tube. Both tubes are thermocycled in a PCR machine and the emulsion is broken by adding a breaking solution of perfluorooctanol and HFE-7500 at a ratio of 40:60 by weight. The contents of the ruptured drops pool as an aqueous layer above the fluorinated oil and are removed with a pipette and visualized on an agarose gel, alongside the in-tube positive and negative (no-template) controls. The positive and droplet PCR both show distinct bands at the expected 300 bp amplicon length, while the negative control shows no such band. This illustrates that tape-bonded channels are compatible with droplet PCR.

Conclusions

PDMS-tape bonding has several advantages over other bonding methods: It is inexpensive and uses materials that are commonly available. A variety of adhesive tapes can be used, including transparent tapes that enable optical visualization of the channels.† It allows devices to be bonded and used within 2 hours, which is convenient for rapid prototyping and testing. The bond is reversible, allowing the tape to be peeled away and the device washed to remove dust or contaminants, and then re-taped and re-used. Most importantly, because it does not require cleanroom facilities or a plasma bonder, it can be adopted by researchers who are not specialists in microfluidics. In addition, it should be useful for specialist microfluidic labs that simply want to bond and test their devices more quickly.

Acknowledgements

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† Electronic Supplementary Information (ESI) available: Adhesive tape specifications, high magnfication and fluorescence imaging with tape-bonded devices. See DOI: 10.1039/b000000x/

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