Polydimethylsioxane Fluidic Interconnects for Microfluidic Systems

Shifeng Li and Shaochen Chen

***Abstract*—This paper presents novel polydimethylsioxane (PDMS) based interconnects for microfluidic systems with a low dead volume. Through-hole type and "⌈" type PDMS interconnects have been designed, fabricated, and tested for glass and plastic capillary tubing. Oxygen reactive ion etching and epoxy bonding methods are employed to bond PDMS interconnects to different substrate materials including silicon, glass, polymer and other thin film materials. Leakage pressure, leakage rate, and pull-out force are characterized for these interconnects. For reusable PDMS interconnects, the maximum leakage pressure reaches 510 kPa (75 psi) and the maximum pull-out force is about 800 mN. For nonreusable PDMS interconnects, the maximum leakage pressure is found to be 683 kPa (100 psi) and the maximum pull-out force is 2 N. For both types of PDMS interconnects, the leakage rate test demonstrates that the leakage is not detectable at a working pressure of 137 kPa (20 psi).**

***Index Terms*—Bonding, fluidic interconnect, microfluidics, polydimethylsioxane.**

I. INTRODUCTION

DUE TO THE difficulty in fabricating monolithic microfluidic systems, interconnects are becoming more and more important in integrated microfluidic systems that may involve micropumps, microvalves, micromixers, or microchannels. Interconnects are also imperative to bridge a microfluidic component to its macro-environment. Gonzalez *et al.* fabricated a modular type coupler that used deep reactive ion etching [1]. Yao *et al.* developed a reusable silicone rubber coupler for microfluidic interconnection. After several times of use, the silicone coupler still has a similar performance [2]. Wijngaart *et al.* directly melted polyethylene capillary tubes on the silicon substrate and then applied epoxy to reinforce the tubing [3]. Armani *et al.* developed polydimethylsioxane (PDMS) based pressure-fit-type interconnectors with molding [4]. Puntambekar and Ahn fabricated a self-aligning fluidic interconnect. Due to its self-aligning nature, this interconnect has a significant reduction of dead volume and pressure drop [5]. Gray *et al.* developed several novel interconnects for micro-fluidic systems. These interconnects can be easily assembled [6]. Tsai and Lin presented a method to insert Mylar into a micro-to-macro interconnection discretely and integrally [7]. Recently, Pattekar and Kothare melted plastic tubing and applied epoxy to achieve high performance interconnectors [8].

PDMS is receiving increasing interest in the field of micro-electro-mechanical systems (MEMS) [9]–[11]. Many PDMS-related micro and nano-fabrication techniques have been developed [9]. Unlike traditional materials such as silicon and glass used in MEMS, PDMS is a low cost material. Moreover, microfabrication processes for PDMS are simple and rapid compared to traditional etching and bonding approaches in MEMS. The primary advantages of PDMS material for microfluidic applications include ease of bonding, optical transparency (from 230 nm to 700 nm wavelength) for precise alignment, softness for molding, and biocompatibility in a biological environment. Moreover, one can bond PDMS to different materials reversibly and irreversibly. These materials include conventional microfludic substrates such as silicon and glass, thin films like $\mathrm{SiO_2}$ and $\mathrm{Si_xN_y}$, and polymer substrates such as polystyrene and PDMS.

This paper reports new PDMS-based interconnects for microfluidic system applications. Through-hole type and "⌈" type PDMS interconnects for glass and plastic capillary tubing will be designed, fabricated, and tested. We will investigate bonding PDMS interconnect to different substrate materials such as glass, silicon, and polymer, as well as thin films including $\mathrm{SiO_2}$ and $\mathrm{Si_xN_y}$ using oxygen reactive ion etching (RIE) bonding and epoxy bonding. The maximum leakage pressure, leakage rate, and pull-out force will be measured for the PDMS interconnects.

II. DESIGN AND FABRICATION PROCESSES

Two types of PDMS interconnects were designed as shown in Fig. 1: through-hole and "⌈" type, used for both glass and plastic tubing. To fabricate these interconnects, a curing agent and PDMS prepolymer (SYLGARD 184 Silicone Elastomer Kit, Dow Corning, Midland, MI) in a 1:10 weight ratio were first thoroughly mixed. Then the prepolymer mixture was degassed in a 20–25 mm Hg vacuum chamber for one hour to remove air bubbles from the mixture and to ensure complete mixing between the two components. After placing a 4 in polished silicon wafer on a 5 in glass plate and heating the stack to 145 °C for several minutes, the prepolymer mixture of 20 ml was poured onto the silicon wafer and covered with a transparency film with care to prevent any bubble formation at the interface. The transparency film provided an easy way to separate the cover plate from the PDMS layer after curing. The entire stack was then cured for 1 h at 145 °C on a hot plate. After curing, the PDMS layer was peeled off from the silicon substrate. The thickness of the PDMS film is approximately 2–3 mm.

The PDMS layer was then cut into squares of 4 mm × 4 mm with a blade. A glass capillary (O.D. 0.84 mm and I.D. 0.60 mm,

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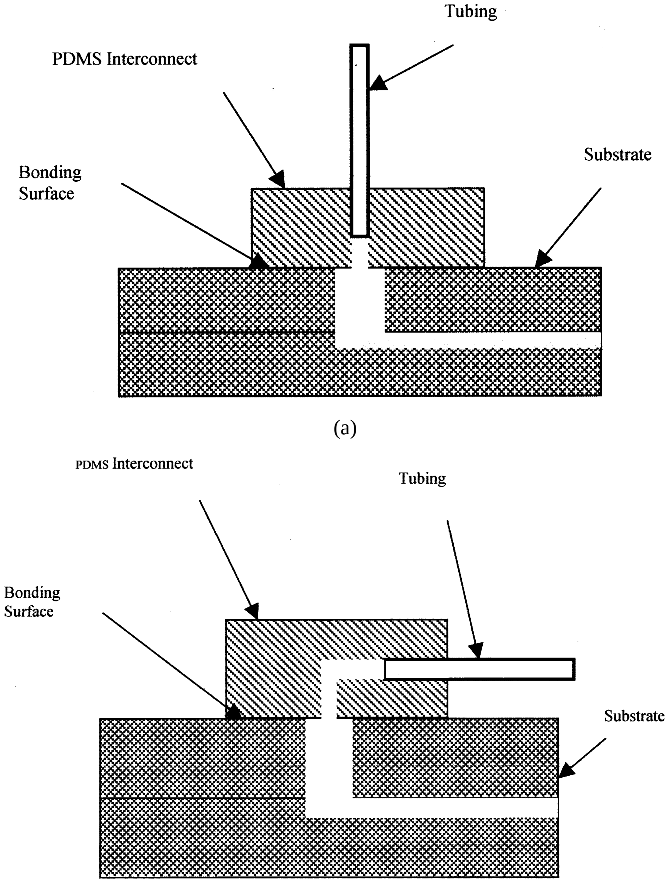


(a)

(b)

Fig. 1. Schematic of the PDMS interconnect: (a) through-hole type and (b) “⌈” type.

Vitrocom. Inc, NY) was used to punch connecting holes in the PDMS squares. We found punching the hole is critical for PDMS interconnects as PDMS is a soft material with Young’s modulus of 700–800 kPa, which is much less than that of silicon or glass. If punched improperly, the holes will not be circular as shown in Fig. 2(a). A noncircular interconnecting hole can not hold the capillary at a high pressure. In order to get circular holes, one has to punch the PDMS square slightly at first using the capillary tube and then slowly rotate the tube until the glass tube is punched through the PDMS square [Fig. 2(b)].

After punching the hole, the substrate and PDMS interconnect were put into a petri dish for ultrasonic cleaning using de-ionized (DI) water and isopropyl alcohol for 5 min, respectively. This is to ensure a clean surface for follow-up bonding. The petri dish was then put into a baking oven for 30 min at 90 °C to remove the residual water molecules, followed by oxygen plasma surface activation in a Plasma Thermo RIE system. The working parameters of the RIE were set as 70 W at 75 mtorr with an oxygen flow rate of 20 sccm and 15 s etching time. After activation, the PDMS interconnects were bonded onto the substrate immediately and put on a hot plate for 30 min at 145 °C in order to enhance bonding strength. If precise alignment is necessary, isopropyl alcohol could be used to avoid immediate bonding. The alignment can be controlled with a reasonable accuracy (less than 50 μm) since PDMS is transparent in the UV and visible ranges [10]. In Fig. 3, a through-hole type PDMS interconnect was successfully bonded onto a glass substrate [Fig. 3(a) and (b)] and “⌈” type PDMS interconnect was bonded onto a PDMS substrate [Fig. 3(c)].

In some cases, using oxygen plasma to activate the surface as mentioned previously may not be compatible with the device fabrication process since some critical dimensions may be changed due to plasma etching. A possible solution to such a case is to use UV or thermally curable epoxy to bond the PDMS interconnects onto the substrate as shown in Fig. 4. Following the previous processes, the PDMS squares (4 mm × 4 mm) were punched and then cleaned to keep the bonding surfaces particle and dust free. The substrate and PDMS interconnects were baked for 30 min at 90 °C to dry out the bonding surfaces. After that, the PDMS and the substrate were bonded together. But this bonding is reversible. In order to stand a high pressure during device operation, UV or thermally curable epoxy was used to reinforce the PDMS interconnect to the substrate as illustrated in Fig. 4. In this work, UV curable DYMAX epoxy (DYMAX 1186-M series, DYMAX Corporation) was used to seal the interconnect. After a 20-min curing in the aligner, the epoxy glued the PDMS interconnect to the substrate. Although this bonding is reversible, we found that there is no epoxy seeping to block the holes and channels during curing (Fig. 5). For precise alignment of the interconnect, we used isopropyl alcohol to spray the bonding surfaces in order to avoid immediate bonding during alignment. Then the entire stack was put on a hot plate to dry out the isopropyl alcohol for reversible bonding.

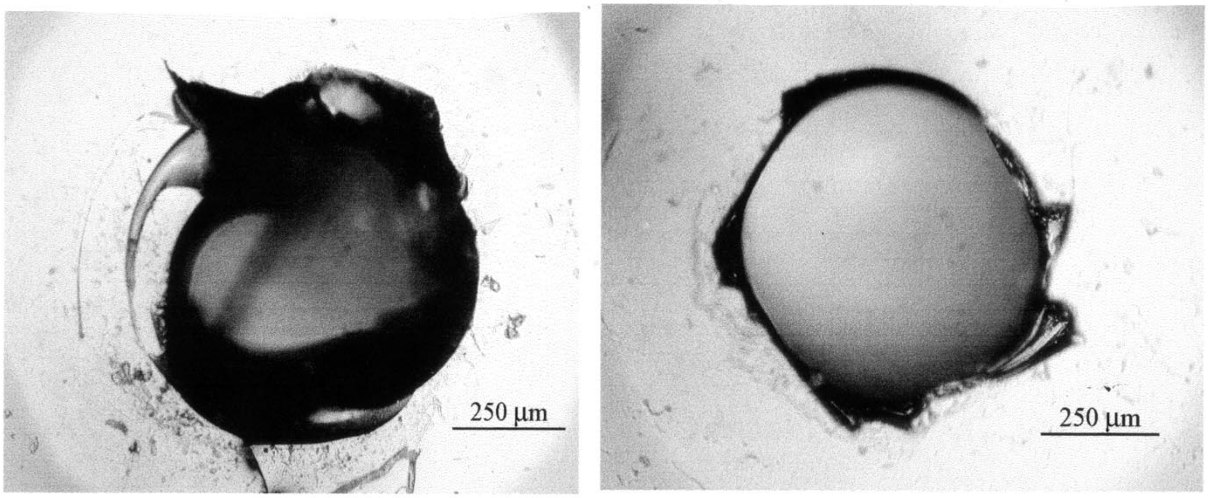
III. PDMS INTERCONNECT CHARACTERIZATION

In order to characterize the PDMS interconnect performance, three important measurements were conducted: leakage pressure measurement, leakage rate measurement, and pull-out force measurement.

A. *Leakage Pressure Measurement*

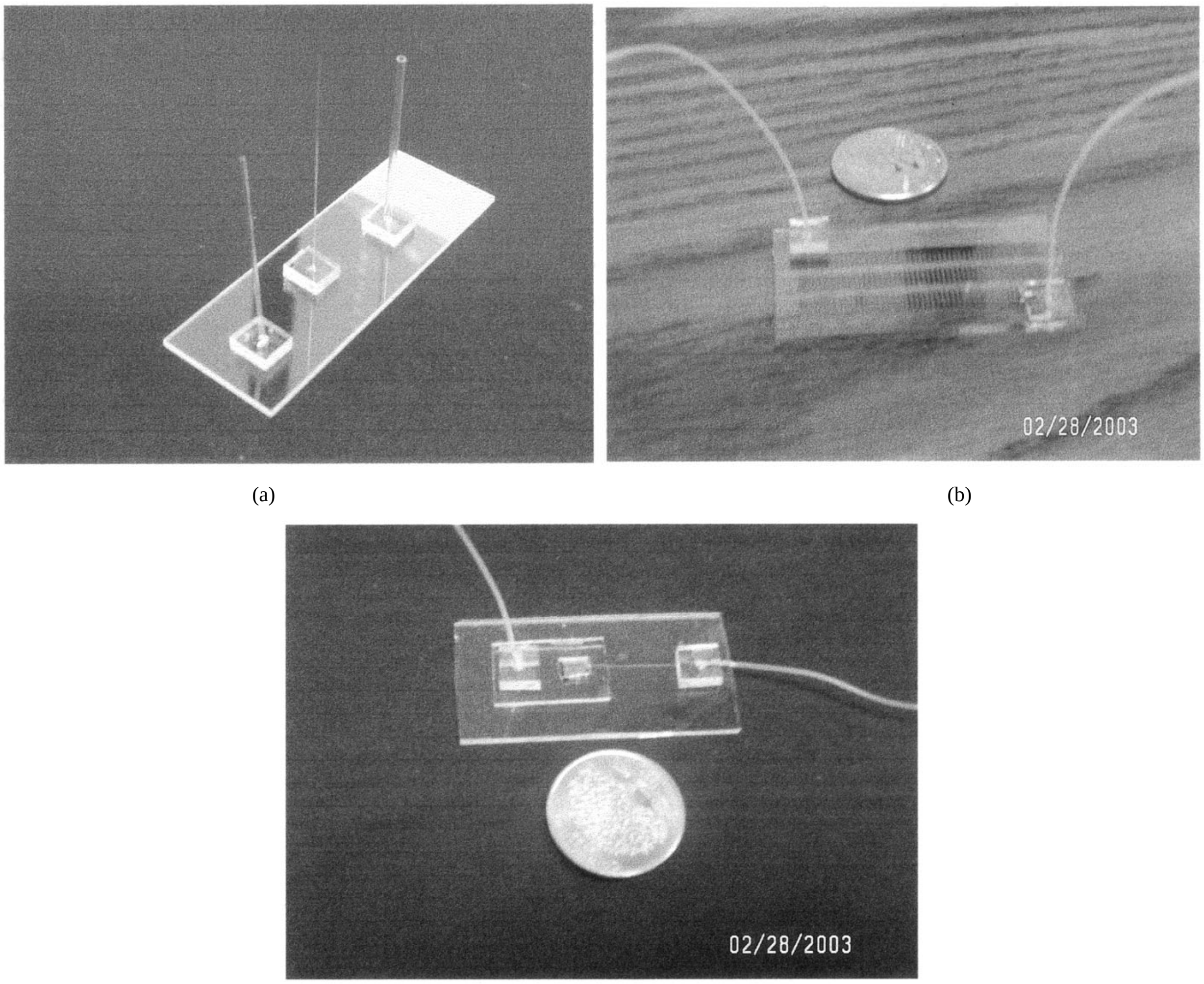
The leakage pressure characterizes the maximum working pressure that the PDMS interconnect can stand. The measurement was conducted by connecting a syringe to the PDMS interconnect as illustrated in Fig. 6. A pressure gauge (Cole-Parmer 1202–5000, Cole-Parmer Instrument Company) was coupled with the syringe by a three-way pressure gauge tee (Upchurch U.433, Upchurch Scientifics). The PDMS interconnect was bonded to different substrate materials by O_2 RIE bonding and UV epoxy bonding. A force was applied to push the syringe cylinder until leakage occurs. From the coupled pressure gauge, the leakage pressure was recorded and summarized in Table I for different substrate materials.

From Table I, the PDMS interconnect can stand a pressure up to 510 kPa (75 psi) for O_2 RIE bonding. The leakage took place around punched holes. This implies that the friction force between the sidewall of the PDMS hole and the capillary surface is critical for a high leakage pressure of the PDMS interconnect. Therefore, the circularity of the hole punched is important for PDMS interconnects. For the interconnect with a noncircular hole, the experiment showed the leakage pressure could be less than 6.8 kPa (1 psi). For UV epoxy bonding, the measured leakage pressure ranges from 68 kPa (10 psi) for $\mathrm{Si_xN_y}$



(a) (b)

Fig. 2. (a) Noncircular hole and (b) a circular hole punched with a glass capillary (O.D. 0.84 mm).

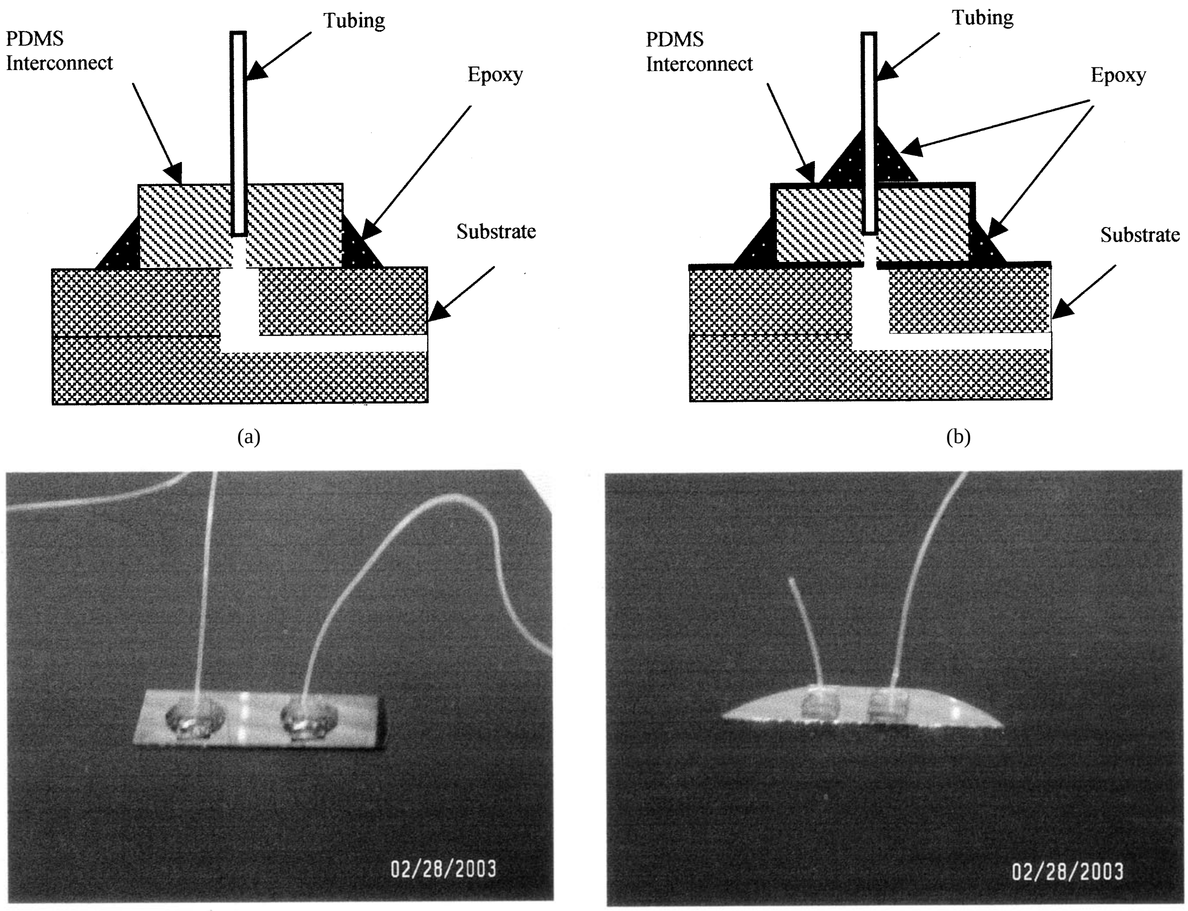


(a) (b)

(c)

Fig. 3. Through-hole type PDMS interconnect bonded to a glass substrate (a) for glass capillary tube, (b) for plastic capillary tubing, and (c) “⌈” type PDMS interconnect bonded to a PDMS substrate.

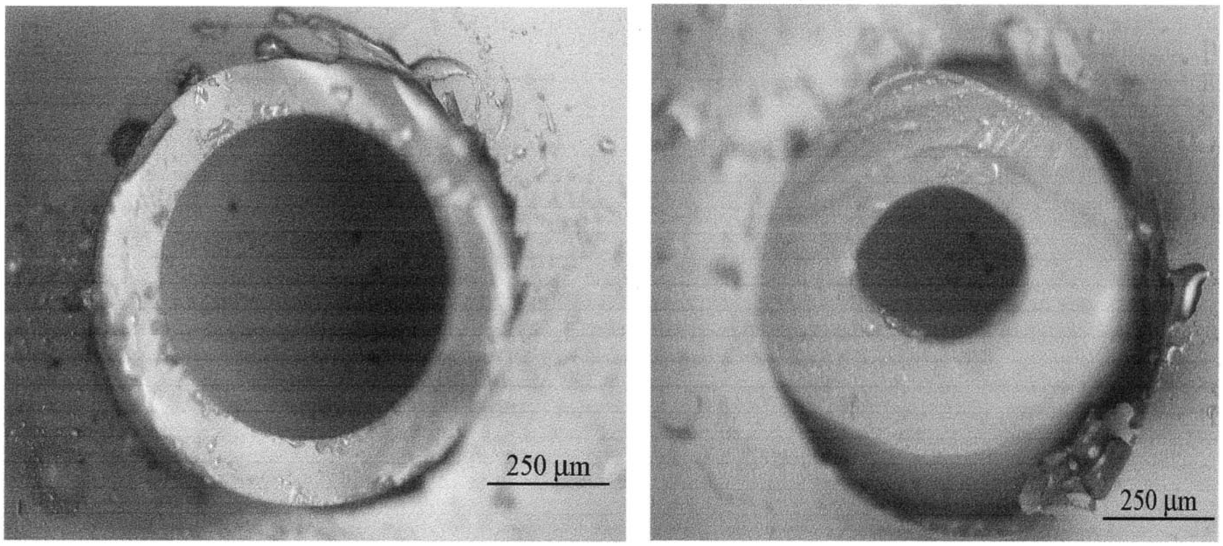
thin film to 485 kPa (71 psi) for the silicon substrate. Most of the time, the leakage occurs at the bonding interface. This is because UV epoxy is very sensitive to surface cleanness. We believe ultrasonic cleaning itself can not guarantee adequate cleanness for UV epoxy bonding. Our experiments demonstrated that ultrasonic cleaning followed by O_2 RIE cleaning of the bonding



(a) (b)

(c) (d)

Fig. 4. Schematic for (a) epoxy glued reusable PDMS interconnect and (b) nonreusable PDMS interconnect; (c) fabricated, reusable, and (d) nonreusable PDMS interconnect bonded to a silicon substrate using UV curable epoxy.



(a) (b)

Fig. 5. Optical micrograph of the PDMS interconnects using (a) a glass capillary tube (O.D. 0.84 mm) and (b) plastic capillary tubing (O.D. 1.02 mm), indicating no epoxy blockage in the tube.

surfaces for 15 s can stand a leakage pressure of about 683 kPa (100 psi) for UV epoxy bonded PDMS interconnect as shown in Fig. 4(b).

B. Leakage Rate Measurement

Leakage rate is another important measure for interconnect performance. Usually, the leakage rate was measured under a

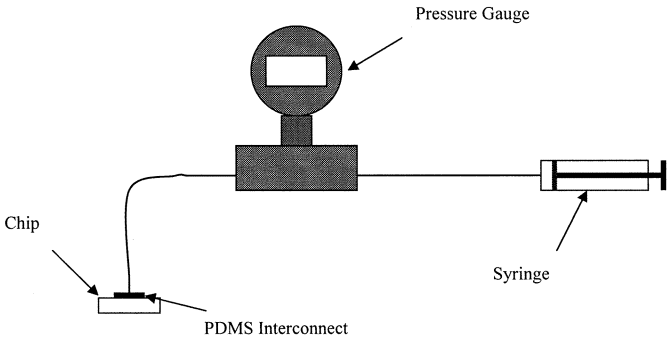


Fig. 6. Experimental setup for leakage pressure measurement.

TABLE I
LEAKAGE PRESSURE FOR DIFFERENT SUBSTRATE AND THIN FILM MATERIALS
(PRESSURE UNIT: kPa)

Substrate Material	O_2 RIE Bonding		UV Curable Epoxy Bonding	
	Sample #1	Sample #2	Sample #1	Sample #2
Silicon	435	422	435	483
Glass	503	456	184	136
PDMS	510	490	381	367
SiO_2 thin Film (100nm)	435	408	231	204
Si_xN_y thin Film (100nm)	374	292	88	68

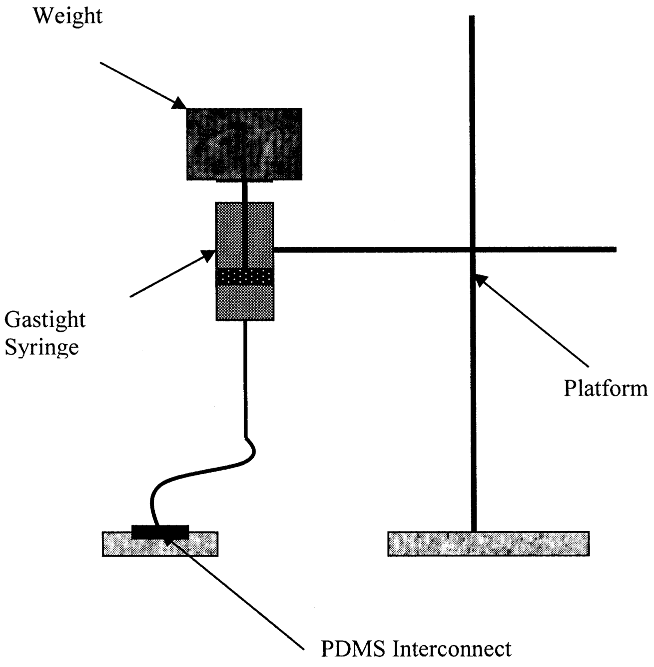


Fig. 7. Experiment setup for leakage rate measurement.

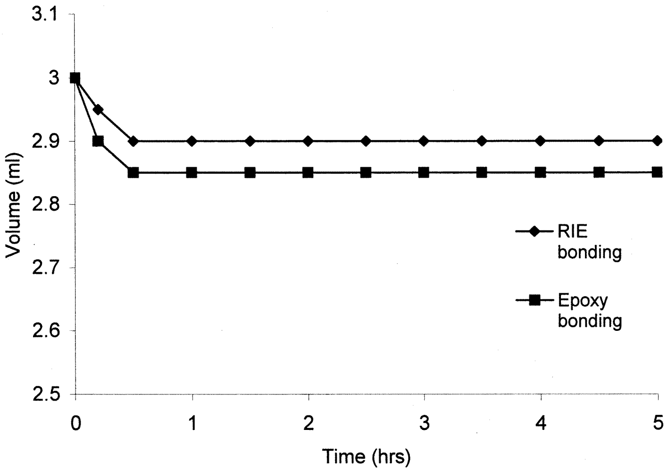


Fig. 8. Results of leakage rate measurement for the PDMS interconnect bonded to a silicon substrate via O_2 RIEI bonding and UV epoxy bonding.

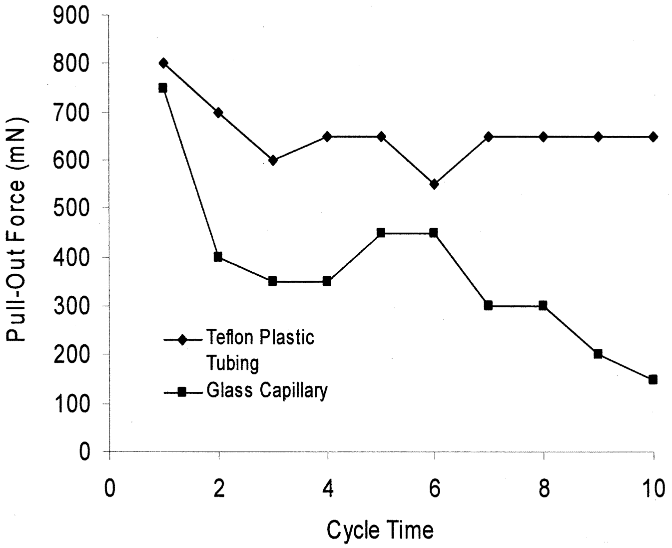


Fig. 9. Results of pull-out force measurement for plastic tubing and glass capillary.

constant working pressure [12]. Since a working pressure of 136 kPa (20 psi) is typical for microfluidic system applications [12], we used a weight of 1.25 kg to establish a pressure of 136 kPa (20 psi) in the gastight syringe with a diameter of about 10 mm. The experimental setup is shown in Fig. 7. The 5 ml syringe was connected to the PDMS interconnect via a Teflon PTFE tube (O.D. 1.02 mm, I.D. 0.56 mm, Hamilton Company). The interconnect was bonded to a silicon wafer through O_2 RIE bonding and UV epoxy bonding. The water volume in the syringe was recorded every 30-min over 5 h. Fig. 8 shows the results of leakage rate measurement. It is found that water filled the tubing and interconnect for the first 30 min during which the volume of liquid inside the syringe decreased significantly. After this the fluid volume inside the syringe remains constant indicating the leakage is so minimal it is difficult to detect.

C. Pull-Out Force Measurement

The required force to separate the interconnect from the microsystem was characterized by a pull-out test. A Teflon PTFE plastic tubing (O.D. 1.02 mm, I.D. 0.60 mm, Hamilton, 9064) and a glass capillary (O.D. 0.84 mm, I.D. 0.60 mm, Vitrocom, CV6084) were chosen to characterize the pull-out force. The plastic tubing was directly plugged into the interconnect and tightened on a force gauge tip. The pull-out force was recorded from a digital force gauge (CE, FG-20KG). We glued the glass capillary with a Teflon plastic tubing (O.D. 1.47 mm, I.D. 0.86 mm, Hamilton) and then plugged the glass capillary tube into the PDMS interconnect. One of the major advantages of PDMS interconnects is that they are reusable. After several times of plugging and unplugging, the results for the pull-out force measurement of the PDMS interconnects are similar. In Fig. 9, for the plastic tubing, there is no significant change of the pull-out force even after reusing the plastic tubing ten times. But for the glass capillary tube, the pull-out force decreases from 750 mN to 250 mN for the 10th cycle. This indicates that the glass tube tends to damage the side wall of the PDMS hole. When we used UV epoxy to seal the tubing and the sidewall of the hole for nonreusable interconnects [Fig. 4(b)], the pull-out force was found to be as big as 2 N.

IV. CONCLUSION

We have demonstrated that PDMS material can be used as interconnects for glass and plastic tubing in microfluidic applications. A PDMS interconnect can be easily applied in different microfluidic systems made of glass, silicon, polymer and other MEMS materials such as $\mathrm{SiO_2}$ and $\mathrm{Si_xN_y}$ thin films at the low cost using either UV curable epoxy or RIE plasma activation. Leakage pressure, leakage rate, and pull-out force testing showed that PDMS interconnects have excellent performance. Key factors for strong bonding strength are the circularity of the hole punched in the PDMS and cleanness of the surfaces to be bonded. Moreover, PDMS interconnects are re-usable and their fabrication is simple and cost-effective.

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