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TECHNICAL PAPER

Improvement of dynamic characteristics of polydimethylsiloxane based microvalve

Gyu-Sik Ra · Sandeep Kumar Jha · Tae-Sik Yoon · Hyun Ho Lee · Yong-Sang Kim

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Abstract Microfluidics is an indispensable part of micro total analysis system (μ-TAS) and lab-on-a-chip analysis systems. While most of the work in this area has focused on MEMS based actuation with micropumps and microvalves, polymer based Paraffin actuator is an attractive alternative in terms of ease in fabrication and low cost. While we made previous attempts in fabricating polydimethylsiloxane (PDMS) based devices, it suffered a drawback of low flow rates in the microchannel due to adherence of PDMS to the channel substratum. In the current work, we focused on improvement of mechanical properties of the PDMS membrane by altering prepolymer to crosslinker ratio. We found that a ratio of 100:15 produced sufficient tensile strength to the membrane and also enhanced actuation characteristics of microvalve fabricated with it.

1 Introduction

Microfluidics is an important element in micro total analysis system (μ-TAS) (Lee and Lee 2004) or lab-on-a-chip (LOC) and requires close integration of micro-components like pumps, valves, channels, mixers and dividers. As fluid switching is a vital process in microfluidics, it makes microvalves often one of the most important component in an integrated microfluidic system such as a micro-PCR device (Zhang et al. 2007). Microvalves can be broadly classified into two groups: active and passive, involving mechanical and non-mechanical moving parts, as well as external systems. While passive microvalves built with micro electro mechanical systems (MEMS) are more commonly used (Yih et al. 2005), yet there are large advantages of using polymeric materials in fabrication of these devices due to their chemical inertness, disposability, bio-compatibility, non-fragility during handling and optical clarity. Different polymers, such as polydimethylsiloxane (PDMS), polymethylmethacrylate (PMMA) and polycarbonate (PC) have been widely investigated for microfluidic fabrications (Hsu and Chen 2007). PDMS in particular, have been used during past for fabrication of paraffin-actuators, which have the advantage over conventional mechanical actuators for causing large deflections and resultant increase in fluid flow rate (Yoo et al. 2006b).

In past, our group have been involved in development of PDMS based microfluidic systems for better bio-compatibility and simplification of fabrication process (Yoo et al. 2006a, b). A DC powered microvalve actuated with melting and resolidification of paraffin wax in the block offered a scope for dynamic control of liquid flow rate. The microvalve operated with a controlled switching function of ITO (indium/tin oxide) heater (Fig. 1). The closing/opening times for the valve were around 10 and 20 s, respectively. But, when the microvalve operated repeatedly between open and closed positions by powering the system on or off, the flow rate reduced due to the sticking of the PDMS membrane to the valve seat after closing. To overcome these difficulties, we attempted to enhance the tensile strength of PDMS membrane in the present work, by altering the polymerization conditions. We studied the effect of varying monomer and crosslinker solutions during preparation of PDMS membrane on its strength and resulting change in dynamics of the microvalve.

G.-S. Ra · S. K. Jha · T.-S. Yoon · H. H. Lee · Y.-S. Kim (✉)
Department of Nano Science and Engineering, Myongji University, Gyeonggi 449-728, South Korea
e-mail: kys@mju.ac.kr

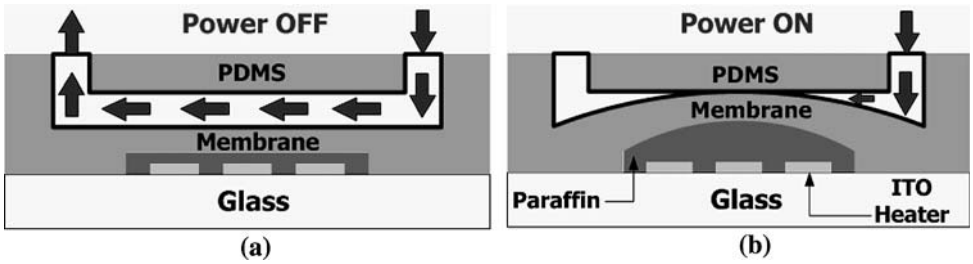

Fig. 1 Schematic representation of the microdevice operation: **a** normal water flow in the microfluidic channel during power-off condition and **b** blocking the fluid flow by PDMS membrane due to paraffin actuation under power-on condition

2 Experimental

The PDMS microfluidic system was fabricated as per method described earlier (Yoo et al. 2006a). In order to construct the microchannel and microvalve seat cavity of the device, the PDMS (Sylgard 184, Dow Corning Corporation, viscocity 23°C 5,500 mPa s) prepolymer mixture was poured onto the 220 μm-thick SU-8 photoresist patterned on silicon wafer. The PDMS replicas were peeled off upon curing and reservoirs were made at the end of each channel using a 3-mm circular punch. For fabricating the PDMS membrane and paraffin chambers for the device, SU-8 was patterned and the PDMS prepolymer mixture was spin-coated on top of it. On the other hand, 1.8 μm thick photoresist (AZ-1512) was spin-coated on an ITO-coated glass and patterned to make the heaters in the microfluidic system. The sputter deposited ITO layer was etched with a $FeCl_3$/HCl solution. Paraffin (Yakuri Pure Chemicals, Osaka, Japan) block was prepared using PDMS replica block and was introduced between ITO-glass and PDMS membrane before all three units were sandwiched together by UV Ozone bonding. The microchannel width and depth were 400 and 220 μm, respectively and the PDMS membrane thickness was 270 μm. The dimensions of the PDMS paraffin chamber were 3.0 × 3.0 mm^2 in area, while the valve seat diameter was 1.5 mm.

In order to avoid the problem associated with reduced flow rate due to sticking of PDMS membrane to the valve seat during repeated opening and closing of microvalve, the composition of PDMS was altered by mixing different proportions of prepolymer and crosslinker. The polymer strength was measured using tensile testing machine (UTM, model LLOYD LR5K).

Once the devices were fabricated, the inlet of microchannel was connected to water tank placed at certain height, to allow flow of water to microchannel by siphon action via silicone tube. ITO electrode was connected with a fixed power source of 150 mW. The dynamic characteristic of microvalve was evaluated by switching the power source on or off in a fixed interval: switched on for 1 min and off for 3 min. The liquid flow rate was measured by the displacement variation of the outlet tube under inlet pressure.

3 Result and discussion

The actuation mechanism in the microvalve was based on a thermally triggered phase change in the paraffin. The resulting volumetric expansion of paraffin was up to 30%, which facilitated larger displacement of PDMS membrane. But as observed in our previous works, when the fabricated microvalve repeatedly operated from a closed to opening position, the flow rate was reduced due to the sticking of the PDMS membrane to the substratum upon closure (Yoo et al. 2006a, b). Therefore, it was desirous to enhance the mechanical strength of PDMS membrane.

PDMS sylgard 184 is available commercially as a two-part kit consisting of pre-polymer and cross-linker components. Although, the manufacturing company recommends that the pre-polymer and cross-linker be mixed at a 10:1 weight ratio, in this study, we mixed PDMS prepolymer and cross-linker in various weight ratio (5–30 ml of cross-linker to 100 ml of prepolymer) and investigated possible alterations in PDMS properties. The Young's modulus and load at breakpoint were obtained for membranes prepared using these compositions (Fig. 2). The composition consisting of 100 ml prepolymer and 15 ml of cross-linker solutions showed highest Young's modulus (78.9 kgf/cm^2) and load at breakpoint (7.3 kgf), indicating greater flexibility as well as strength of the PDMS membrane.

In subsequent experiments we used these membranes to fabricate microfluidic devices and observed the dynamic characteristics of microvalve. Power source connected to ITO heater underlying the paraffin was switched on or off a number of times and flow rate of water was monitored (Fig. 3). Even in this case, the 100:15 ratio of prepolymer to cross-linker seemed to favor the microvalve actuation. The flow rate in device built with this PDMS membrane was 16.23, 16.27, 12.53 and 12.5 μl/min for subsequent cycles of opening and closure of microvalve. The microvalve's reproducibility for this device was close to 80%, while other devices still showed sticking of PDMS to substratum, as evident by reduced flow rate and hence, the reproducibility. This proved our claim that a mechanically stable, yet flexible membrane can reduce the shortcomings of thermopneumatic microvalves. At present, we are trying

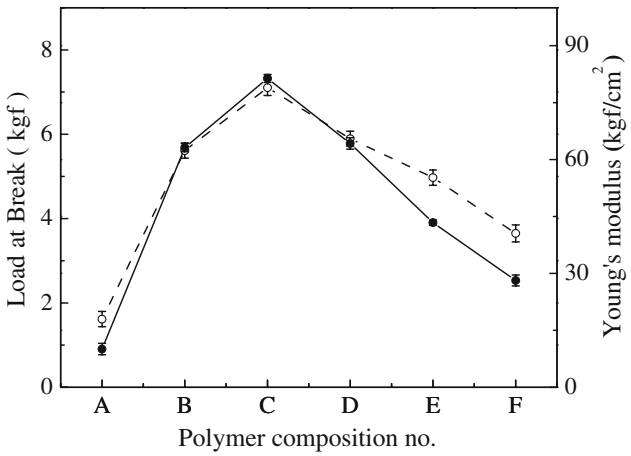

Fig. 2 Measurement of PDMS membrane strength: (*filled circle*) load at breakpoint and (*open circle*) Young's modulus for prepolymer to crosslinker ratio (V/V) of: *A* 100:5; *B* 100:10; *C* 100:15; *D* 100:20; *E* 100:25 and *F* 100:30

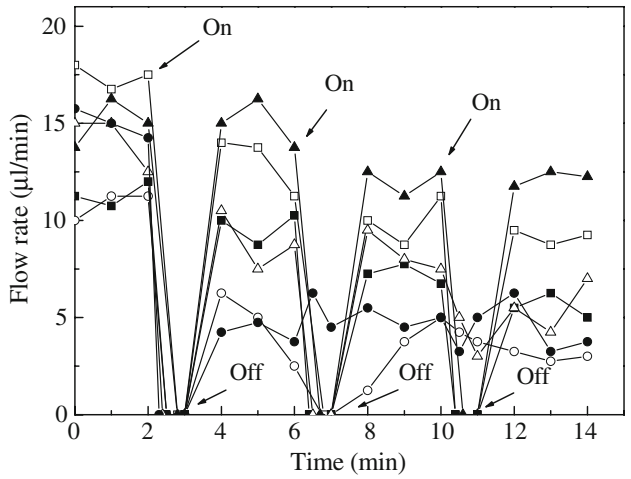

Fig. 3 Microvalve actuation with PDMS formed with prepolymer to crosslinker ratio (V/V) of: (*open circle*) 100:5; (*open square*) 100:10; (*filled triangle*) 100:15; (*filled square*) 100: 20; (*open triangle*) 100:25 and (*filled circle*) 100:30 when the power to the ITO electrode was switched on or off

to improve the switching efficiency of these microvalves by replacing PDMS with more flexible PMMA as the underlying membrane.

4 Conclusion

In the present work, we attempted to eliminate the problem of reduced liquid flow rate within microchannel due to sticking of PDMS on substrate during repeated cycles of opening and closure of microvalve. For this reason, physical strength of PDMS mold was enhanced by altering the ratio of prepolymer and crosslinker during polymerization. We found that a ratio of 100:15 produced sufficient tensile strength to the membrane and also enhanced actuation characteristics of microvalve fabricated using it. These preliminary results are indicator of unharnessed potential of thermopneumatic type microvalve in a microfluidics device and will direct various researchers into developing more robust polymers for fabrication of these microdevices.

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