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The influence of hydrophobic surface to the manipulation of a reagent plug in a gas–liquid microsystem

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ABSTRACT

Precise and reliable manipulation of a reagent plug in a microfluidic network is critical to the performance of a plug-based microfluidic device. This study is aimed to quantify the influence of different surface property to the position controlling of a reagent plug inside a microfluidic channel. Two sets of Poly(methyl methacrylate) (PMMA) microfluidic devices were micromilled and thermal bonded for experiments, the first set was the original PMMA substrate and the second set was the hydrophobic-coated PMMA substrate. The purpose of applying hydrophobic coating was to reduce the contact area and the thickness of the liquid deposition layer between the reagent plug and the microchannel walls. A 1 μl reagent plug was loaded in both microchannels and shuttled forward and backward repeatedly with a Labview-controlled pneumatic system. The experiment results revealed that: (1) the reagent loss in a hydrophobic PMMA microchannel was dramatically less, 6.87% in a hydrophobic PMMA microchannel while 26.5% in an original PMMA microchannel after 40 cycles; (2) the reduced mass and the thicker liquid deposition layer caused the moving distance and the position controlling instable in the original PMMA microchannel; (3) the position controlling of a reagent plug is more precise and repeatable in a hydrophobic PMMA microchannel.

1. Introduction

Microfluidic technology has been gradually applied in various applications since a microfluidic gas chromatography was reported in 1979 [1]. The benefits of using microfluidic platform include less reagent demand, faster reaction rate, increased sample throughput, and minimized labor to reduce the cross contamination [2,3]. Within many types of microfluidic-based platforms, one major type is the continuous flow platform which has been used in many applications like polymerase chain reaction (PCR) [4,5], ligase detection reaction [6], and tumor cell isolation [7]. The main disadvantage of a continuous flow platform is the non-negligible dead volume left in the microchannel, which increased the cost of each reaction assay and limited its extension to the high throughput microfluidic device. Plug microfluidics is a subfield of microfluidics and has been majorly applied in parallel bio/chemical analysis since the early 2000s: in the plug microfluidics, each plug can be seen as an individual and self-contained reactor and each plug can be differentiated by gradually changing the composition via careful design of microfluidic network [8,2]. With plug microfluidics, the cost of each reaction assay in a high throughput system can be reduced and the output efficiency can be increased dramatically [9,10].

Plug microfluidics is capable of precisely controlling reagent volume and efficiently handling tiny reagent plugs, it has been used in the design of high throughput microfluidic devices for various applications [9–15]. The most common approach of a plug microfluidics is based on the immiscibility between the oil and the reagent, where the reagent plug was sandwiched by oil plugs [13,15]. The oil was used as a carrier to transfer the reagent plug to the desired location, minimize the cross contamination from plug to plug, and improve the capability of controlling reagent plug due to its non-compressibility. Another type of plug microfluidics is the gas–liquid flow, where an inert gas was used as the carrier and separator between each reagent plug. Compared to liquid–liquid plug microfluidic system, a gas–liquid plug microfluidic system can be conveniently driven by a pipette or a pneumatic system which is more suitable for an on-site operation of a microfluidic system. The gas–liquid microfluidics has attracted lots of attention and applied in many fields like blood typing test [16], flow cytometer [17], and airway tree in the lung [18]. Basic movement of a gas–liquid microfluidic system has also been studied such as gas–liquid flow characterization [19–21], micromixer [22,23], and manipulation [24]. Prof. Suzuki's group demonstrated various

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manipulations of the reagent plugs like separation, merging, sorting, and etc. by carefully designing the gas–liquid microfluidic network and precise control of the pushing pressure [24]. Cross contamination between reagent plugs was observed in the experiments when a series of reagent plugs were flowed along the same microchannel, which came from the reagent deposition on the microchannel walls. By modifying the surface property of the microchannel walls, the cross contamination phenomenon was reduced due to the less reagent deposition. The motion of a liquid plug in a rectangular microchannel was studied empirically, which reported that the thickness of the deposited liquid layer in the microchannel depended on the capillary number, surface property, and the plug velocity [25,27], which reduced the resistance of the liquid plug motion in a microchannel and led to the instability in manipulating the gas–liquid microfluidic system especially when the microchannel wall was hydrophilic [26]. When the microchannel wall is hydrophobic, the thickness of the deposition layer was reduced and increased the stability in controlling the movement of a liquid plug [27].

The position accuracy and controlling reliability of a reagent plug is critical to the device performance in some applications like PCR [4,5], complicated microfluidic network [24], and microvalve [28]. Poly(methyl methacrylate) (PMMA) is a mainstream material in the disposable microfluidic devices for detection applications because of its excellent optical properties. The water contact angle of a PMMA substrate is roughly about 70° and is hydrophilic, which might cause difficulty in controlling a reagent plug in a gas–liquid microfluidic system. This study is aimed to quantify the difference of a reagent plug motion between the hydrophilic and hydrophobic microchannel by image recording and analysis. The experiments were carried out on the Poly(methyl methacrylate) (PMMA) microfluidic platforms which were micromilled and thermal bonded. The hydrophobic microchannel was realized via the static coating method with a commercial hydrophobic coating solution (anti-fouling, Industrial Technology Research Institute (ITRI) of Taiwan). A pneumatic system, including the hardware apparatus and the Labview programming, was developed to supply precise pulsed pressure to the reagent plug in the experiments.

2. Microfabrication

A micromilling machine was used to fabricate PMMA microfluidic devices, it has five major components including a laser non-contact tool setting system (NC4, Renishaw, United Kingdom), a micromilling spindle (E3000c, Nakanishi, Japan), a compressed air/oil coolant system, a numerical controller (M515i, LNC Technology Co. Ltd., Taiwan), and a milling bit holder for tool interchanging. The micromilling bit was a 2-flute endmill with a diameter of 400 μm (Taiwan Microdrill Co. Ltd., Taiwan). There had four steps required to fabricate a polymer microfluidic device, including (1) design drawing in a CAD software, (2) CAD file converted into G-code for the micromilling controller, (3) micromilling manufacturing, and (4) bonding. The overall fabrication process was less than 4 h to realize a ready-to-use chip for experiment. The dimension of a polymer device is 75 mm × 50 mm, which includes a single microchannel of 500 μm in width, 500 μm in height, and 4.5 cm in length, and four alignment holes, were manufactured on the polymer substrate. Fig. 1a shows the configuration of the microfluidic device which has the bottom substrate including the microchannel and alignment structures and the top substrate including the inlet/outlet and alignment structures. The micromilling parameters including the spindle speed, feed rate, and cut of depth achieved a roughness of 0.2 μm. To enclose the microchannel, thermal bonding was used at the operation parameters of 140 °C for 60 min with two paper clamps. Fig. 1b shows the cross section view of the microchannel: the microchannel was 507 μm × 484 μm before thermal bonding and 501 μm × 512 μm after thermal bonding.

3. Surface modification

Fig. 2 shows a reagent plug in an original PMMA microchannel with a scale attached to it. An original PMMA substrate is a hydrophilic material which has larger contact area and attraction force between the reagent plug and the microchannel walls and caused a thicker reagent deposition layer on the microchannel walls. The existing of the reagent deposition not only caused the problem of reagent loss, but also gained the difficulty of precisely controlling a reagent plug in a microchannel. To improve the position controlling of a reagent plug in a microchannel, a commercial hydrophobic solvent was used (anti-fouling, Industrial Technology Research Institute (ITRI) of Taiwan).

3.1. Process and characteristic of surface modification

To study the effect of the surface modification, twelve pieces of PMMA substrates of 1 cm in wide and 1 cm in length were cleaned with Isopropyl alcohol (IPA) and deioned (DI) water, dried with compressed air, and soaked in the hydrophobic solvent for 2 h. Water contact angle was measured as an indicator of the modification of the surface. The original water contact angle of a PMMA substrate was 70° (Fig. 3a) while a modified PMMA substrate

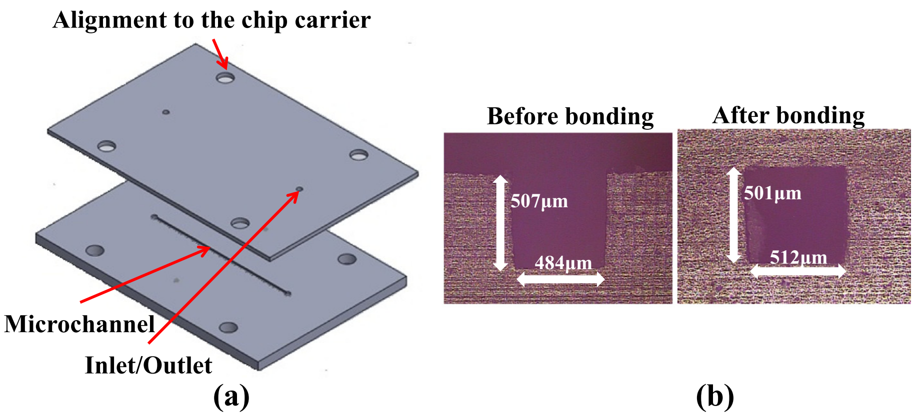

Fig. 1. (a) The layout of the polymer microfluidic device for experiments, including a single microchannel, inlet/outlet holes, and alignment structures to the chip carrier; (b) the cross section of a microchannel before and after thermal bonding.