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Integrated obstacle microstructures for gas-liquid separation and flow switching in microfluidic networks

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ABSTRACT

Split-flow is a fundamental manipulation method for liquid transport, which is challenging in microfluidics by simple structures, owing to the distinct flow mechanism in microchannels. Herein, we present a new strategy for fabricating switch-alternative fluid-splitters by reasonably embedding obstacle microstructures in microchannels. Precise confinement of triple-phase (gas, fluid front, obstacle microstructure) contact line of fluid fronts on the microstructures provides the device with advantage in controlling the flow motion of fluid in microchannels. The microstructures could act as a burst microvalve, and duration of fluid front flowing through the microvalve is essentially controlled by the quantity of the obstacles. Based on appropriate arrangement of the obstacles, we demonstrate that fluid-splitters with four and eight flow states of water and blood in microchannels could be obtained. In particular, implementation of the fluid splitters mostly relies on the regulation of the triple-phase contact line, which simplifies the complex equipments and enhances the compatibility of the devices. It is believed that the fabrication strategy of the switch-alternative fluid-splitters can be extensively used for disposable manipulation of fluid in microfluidic networks.

1. Introduction

Microfluidics has been recently applied in biomedicine, synthesis and analytical chemistry due to their advantages in sample amount, detection time and cost [1]. In microfluidics, components of fluid manipulation are essential constituent parts for many applications, such as organic reaction, cell culture, point of care diagnosis and so on [2–4]. Conventional manipulation and control approaches include electroosmosis control [5], valves [6], pumps [7,8], and mixing [9,10]. Superiorities in measuring liquid volume, guiding flow track, timekeeping reactions and reliability allow microvalves to act as an important part in microchips [11]. Ideal microvalves should possess straightforward fabrication methods, luggable structure, function friendly and be easy to be embedded in microchips [12]. A series of valves have been prepared [13–20], and one of the best is the Quake valve [13], which integrates double-deck PDMS structure to fabricate many microvalves for manipulating liquid transport in a single platform. Nonetheless, that microvalves can achieve disposable guidance of fluid in microfluidic networks and demand less auxiliary equipment remains a challenge [14–16].

Passive microvalves have been widely used as the appearance of early reports [21,22], which could guide flow motion of liquid in microchannels without intricate additional devices [14,23–26]. As one of the most classical passive valves, burst valves manipulate liquid by the variation of channel size, substrate structure, and sacrificial membrane [27–31]. Burst stop ability of the valves derives from suddenly enhanced energy barrier in microchannels [22]. Owing to simple structure, low-cost and little energy input, burst valves are highly desired for guiding microfluidics in permanent settings without closing the microchannels [6]. For example, an autonomous capillary system has been successfully presented using an uncomplicated fabrication process to control flow motion in multiple microchannels [23]. Furthermore, the combination of reasonable centrifugo-pneumatic valves can manage the fluid distribution in an integrated microfluidics platform [16,25]. Silicon stripes with anisotropic wettability have been bonded with a Y-shaped microchannel to realize fundamental split-flow of liquid in microchannels [32]. Though the fabrication method of the device is handy, the valve could not work any longer once fluid flows through them, and it is difficult to independently control the open/closed states of the two outlets. Despite these advancements, it is still chal-

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lenging to achieve independent and successive split-flow of fluid in microfluidic networks by a simple device.

Flow control devices not only possess the simplicity of burst microvalve but also can manipulate the flow motion of fluid in microfluidic networks independently, which own extensive application prospect. In this paper, a new strategy for fabricating switch-alternative fluid-splitter (SAFS) by reasonable arrangement of hydrophobic obstacle microstructures in microchannels is proposed. We found that the hydrophobic microstructures could act as a burst microvalve, and the duration that fluid front flowing through the microstructures is related to the quantity of the obstacles which is in accord with theoretical analysis. Inspired by this phenomenon, four and nine flow states of fluid have been gained in microchannels by corresponding SAFS, and operation procedure of the device in microchannels is established in detail. Most importantly, triple-phase contact line (TCL) of fluid fronts on the SAFS could be rebuilt, gaining and switching of these states can be conducted by changing the fluid pressure and short-time application of gas, which simplifies operation process and weakens the dependence for complex equipments. Especially, the device is easy to be redesigned and transformed into complicated microchips according to demand in microfluidic networks because of small bulk and straightforward fabrication method for the hydrophobicity of the microstructures We believe this kind of fluid-splitters could be extensively used in future microfluidics and taken as promising alternatives for fluid manipulation in organic reaction, cell culture, drug preparation and so on.

2. Experimental section

2.1. Materials

Si substrates were cleaned by immersion in piranha solution (7:3 concentrated H2SO4/30% H2O2) for 2 h at 120 °C to create a hydrophilic surface. A photoresist (BP212–37 s positive photoresist) was purchased from Kempur Microelectronics. Borosilicate glass (SG-2506; with a 145-nm-thick chrome film and a 570-nm-thick S-1805-type positive photoresist, Changsha Shaoguang Chrome Blank Co. Ltd.) was applied as the initial wafer for mold fabrication. A Sylgard 184 elastomer base and a curing agent for poly(dimethylsiloxane) (PDMS) were purchased from Dow Corning (Midland, MI). Trichloro(octyl)silane (OTS), 3-aminopropyltrimethoxysilane (APTMS) and Trichloro(1H,1H,2H,2H-perfluorooctyl)silane (PFS) were purchased from Aldrich. Anticoagulation newborn bovine blood was purchased from Solarbio, and the experimental blood sample was originated from the same bovine. Dichloromethane, triethylamine, absolute ethanol, and methanol were used as received.

2.2. Device fabrication and characterization

Fabrication of the obstacles embedded photoresist surfaces and silicon (Si) surfaces were performed as earlier [32]. The Si substrates with advancing contact angle (θ_V) varied from $3.8 \pm 0.2^\circ$ (contact angle) to $117.8 \pm 2.3^\circ$ (the figure '2.3′ indicates the standard deviation of the result, same below) were fabricated using oxygen plasma treatment, chemical vapor deposition of APTMS, OTS and PFS to the entire Si surfaces. Morphology of the Si-obstacles was characterized by fluorescence microscopy (Olympus BX51 microscope), electron microscope (JEOL FESEM 6700F) and atomic force microscopy (AFM). Contact-angle measurements (Dataphysics OCA20) were performed to study the wetting properties of fluids on these surfaces and the surface tension of the whole blood.

Glass molds and trapeziform PDMS microchannels were fabricated by conventional photolithography and wet etching [33,34]. After being detached from the glass mold, the PDMS channel was compressed onto the obstacles-embedded surfaces and connected to a microfluidic flow control system (MFCS and FLOWELL, FLUIGENT) using a poly(tetrafluoroethylene) pipe. The fluids in the microchannels were pressure-driven, and the applied pressure in the inlets of the microchips was controlled by the MFCS. The applied pressure of the gas was controlled by the MFCS, and the volume of the compressed gas was 5 ml. The flow behavior of fluids was recorded by an Olympus fluorescence microscope. The flow speed of fluids was acquired according to the recording video, and the flow rate was calculated on the basis of the flow speed and size of the microchannels.

3. Results and discussion

3.1. Flow motion of fluid upon single Si-Obstacle in microchannels

In this study, a single PFS-modified Si-obstacle (SPSO) of 1500 nm in height, 10 μm in width was prepared (Fig. 1a) and coupled with a trapeziform microchannel (200 μm in bottom width, 146 μm in top width, 25 μm in height, Fig. 1b). Flow motions of water in the device were investigated under different hydrodynamic pressures, and P_{maxS} is defined as the maximum hydrodynamic pressure that the SPSO can withstand in microchannels. Table 1 shows that both the flow speed and flow rate increase with the augment of the hydrodynamic pressure, and until the applied pressure of water increases to 44.0 ± 0.7 mbar, water stops at the initial region of the SPSO (Fig. 1c,d, the duration of water front on the SPSO is more than 1 min). Once the applied pressure is higher than 44.0 ± 0.7 mbar, water will flow through the SPSO, and the pressure applied to flow of water can be decreased. Applied pressure of water that below and above 44.0 ± 0.7 mbar corresponding to the closed and open states of the outlet, respectively, and the P_{maxS} is 44.0 ± 0.7 mbar (The actual applied pressure to the SPSO is attenuated compared to the pump pressure owing to the pressure drop in the inlet microchannels, and we ignore the difference in our results and discussions for describing the flow motion more compactly). When the applied pressure is larger than P_{maxS}, there is little difference on flow speed and flow rate between before and after water flows through the SPSO. The results demonstrate that stopping ability of the SPSO is rapidly weakened once water passes the structure, which conforms to essential feature of burst microvalves. Interestingly, the SPSO possesses considerable delay ability for fluid though the applied pressure is larger than the P_{maxS}. The durations that water front needs to flow through the SPSO are almost consistent at same hydrodynamic pressure, which could be a potential application for controllable split-flow of fluid in microfluidic networks. Then we conducted the same measurements on the microchannels without Si-obstacle (Fig. 1e), and water passed through the whole microchannels without visible pause at different applied pressures (Fig. 1f). By contrast, the SPSO is found to smartly guide flow motion of fluid in microchannels, and the guidance performance is strict. There is no water that flows through the SPSO in microchannels as long as the applied pressure is less than the P_{maxS}. It is worth mentioning that the SPSO guides the flow motion of fluid by manipulating the TCL, and the manipulation ability of the SPSO will be weak for a long time period control of fluid.

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