Electrokinetically-Driven Micro Mixer with a Novel Surface-Charge Pattern

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Abstract—An electrokinetically-driven micro mixer with a special surface-charge pattern was designed, fabricated and characterized using fluorescence video microscopy. Zeta potential of the working fluids was measured to facilitate the numerical simulation and optimization of the proposed mixer. The mixing flow of the electrolyte with and without microparticle was digitally recorded and analyzed in terms of concentration profile and mixing index. The experimental mixing enhancement is consistent with the simulation result.

I. INTRODUCTION

Microfluidics technologies play a key role in many applications such as analytical microsystems for genomics and proteomics, cell biology and chemical synthesis. The liquid handling in such a low Reynolds number regime creates many challenging problems. In particular, the liquid flow is typically laminar and stable, and flow phenomena such as turbulence or separation are not likely to develop; thus, mixing of liquids in the microsystems is one of the major challenges.

Electrokinetically-driven flow is a highly attractive alternative to pressure-driven flow in microchannels since a surface force is utilized. When an electrolyte fluid is in contact with a charged solid surface, an electric double layer is developed at the solid-liquid interface [1]. An external electric field then induces motion of the liquid, and the resulting relative velocity between the solid and fluid away from the surface leads to the well-known phenomenon of electro-osmosis. Since the driving mechanism is a surface force, it becomes more efficient as the system gets smaller.

We have successfully developed a surface-charge patterning technology that enables the generation of complex electrokinetic liquid flows even in a simple microchannel with a very low Reynolds number [2]. Basic flow patterns namely bi-directional shear flow, out-of-plane vortex and in-plane vortex have been experimentally realized in our research group [3, 4]. In this study, we experimentally demonstrated the application of our surface-charge patterning technology in mixing of liquids [5].

II. DEVICE DESIGN AND FABRICATION

The micromixer consists of a Y-shape microchannel with its $7\mu\text{m}$ height as the characteristic length scale. The main channel, having a mixing zone, is $400\mu\text{m}$ wide and two branch channels, leading to two inlet reservoirs respectively, are $200\mu\text{m}$ wide. The total length of the Y-shape channel is 34mm (Figure 1).

Figure 1. The photograph of a micromixer.

The fabrication of this micromixer is based on the bulk micro-machining technique and the surface-charge patterning technique [4]. The starting substrates were silicon and glass wafers both 100mm in diameter and 0.5mm in thickness. To fabricate the Y-shape microchannel, a $2000\text{\AA}$ thermal silicon dioxide was grown on the silicon wafer and patterned by photolithography to act as a mask for 25% TMAH silicon wet etching at 85°C . After wet etching, a channel grooves with depth of $7\mu\text{m}$ was formed on the silicon substrate. Afterwards, the silicon dioxide was stripped away as shown in Figure 2(a). A new silicon dioxide film, $1\mu\text{m}$ thick, was then thermally grown on the silicon substrate. The purpose of this oxide film is to provide negative surface charge as well as electrical insulation.

From this point forward, a glass wafer (Pyrex 7740, Corning, U.S.A.) was introduced into the fabrication process (Figure 2(b)). Surface-chemistry technology was next utilized to produce both positive and negative surface charges on both

the silicon dioxide and glass surfaces [2]. To enhance the negative charge, both the silicon and glass wafers (Pyrex 7740, Corning, U.S.A.) were treated with 1% (wt.) sodium hydroxide, at boiling temperature for 30min, to generate silanol-salt groups at the surface. The sodium ions were then replaced by hydrogen ions using 3% (vol.) hydrochloric acid to produce silanol groups. When these silanol groups are deprotonized in water, they carry negative charges.

The mixing zone in the main channel consists of a surface charge pattern whose design was based on the numerical simulation and analysis of an electrokinetic micro mixer with a special surface charge pattern [5]. Basically, the whole Y-shape channel is a positively-charged surface and, in the mixing zone, the 'z'-like patterns of negatively-charged surface was patterned as shown in Figure 3(a). To create such 'z'-like surface charge pattern, a lift-off technique combined with an electrostatic self-assembly (ESA) method was employed. photoresist (PR) was first spin-coated onto the silicon/glass wafer and photolithographically patterned. The silicon/glass wafers, with the PR pattern, were next submerged into a polyallylamine hydrochloride (PAH) solution in 0.01M NaCl at pH 6 for about 30min at room temperature. Then, the photoresist was removed in acetone and ethanol, leaving the PAH coated regions positively-charged (Figure 2(c)).

Finally, after mechanically drilling inlet/outlet holes to the microchannel, the fabrication process was completed by bonding the silicon and glass wafers together, and the attachment of three reservoirs using patterned UV cure epoxy, Figure 2(d).

Figure 2. The fabrication process flow of the micromixer.

III. EXPERIMENTAL SETUP AND RESULTS

A. The Zeta Potential Measurement

Prior to the mixing experiment, the zeta potential (or ζ -potential) of the PAH and the oxide surfaces have to be measured. However, in-situ measurement of the individual ζ -potentials of the PAH and the oxide surfaces in the mixing zone of the micromixer is impossible. What we can measure is only the "average" ζ -potential of the whole Y-shape channel. Therefore, some test devices were also fabricated on the same wafers of the micromixers. The test device has a straight microchannel measuring 7μm in height, 300μm in width and 34μm in length. They do not have a mixing zone but a homogenous surface of either the PAH or the oxide. A simple and reliable current-monitoring method devised by Huang *et al* was adopted to measure the ζ -potentials [6]. An acidic sodium phosphate buffer, with ionic strength $I=71\text{mM}$ and $\text{pH}2.4$, was used as a working fluid. The ζ -potentials of the PAH and the oxide from the test devices, as well as the average ζ -potential of the Y-shape channel in the micromixer device were used to estimate the ζ -potentials of the PAH and the oxide in the mixing zone. Finally, it was found that, along the channel, $\zeta_{\text{PAH}} = +3.5\text{mV}$ and the $\zeta_{\text{Oxide}} = -11.1\text{mV}$.

B. The Setup of the Mixing Experiment

The mixing experiment was performed under a optical microscope (Olympus, U.S.A.). Firstly, the inlet reservoir A was filled by the sodium phosphate buffer. Due to the capillary effect, the buffer flowed into and filled the whole Y-shape channel. Subsequently, the same buffer laden with polystyrene microparticles (microparticles GmbH, Germany), 1.8μm in diameter, was injected into the inlet reservoir B. This microparticle acted as flow tracer. Three platinum electrodes of diameter in 0.5mm were inserted into the inlet

and outlet reservoirs and were connected to a DC voltage supply (PS310, Stanford Research System, U.S.A.). The motion of the microparticles was captured by a CCD camera (JVC, Japan) connected to the light microscope and the video signal was sent to a DVD-harddisk recorder (DVD-510H, Pioneer, Japan). For image post-processing, the video in the recorder was sent to a Windows2000 platform computer through IEEE1394 connection. Using Premiere (Adobe, U.S.A.), the video data was converted into AVI file which is a frame-by-frame basis.

C. The Mixing Experiment

In the experiment, when the voltage supply was switched on, a 10kVm^{-1} electric field inside the microchannel was setup, driving the buffer in both reservoir A and B to flow into the main channel due to net mean flow driven by the PAH EOF as indicated in Figure 3(a). When the microparticles reached the mixing zone, the 'z'-like patterns

set the oxide EOF opposite to the main-stream, leading to a complicated 3-D flow field in the mixing zone. From the image in Figure 3(b), the microparticle stream was stirred up and down by the oxide EOF along the mixing zone. At the down stream, the microparticles were evenly distributed across the channel width.

To compare the effect from the 'z'-like surface-charge patterns in the mixing zone, a control experiment was also carried out. A Y-shape microchannel device was also fabricated without any surface-charge patterns. Instead, the whole Y-shape channel was uniformly coated with the PAH. Using the same buffer and experimental procedure, there was no any mixing phenomenon observed as seen in Figure 3(c). The boundary between the microparticle stream and the pure buffer was clear and straight. There was virtually no diffusion because of the relatively large size of the particle and, thus, the diffusivity is extremely low ($D=2.4\times 10^{-13}\text{m}^2\text{s}^{-1}$).

Figure 3. The plan view of (a) the schematic of the mixing zone with 'z'-like surface-charge patterns, (b) the mixing zone of the mixing experiment, (c) the control experiment without the surface-charge patterns, and (d) the mixing zone of the simulation.

IV. SIMULATION

A numerical model was constructed and simulated for the mixing process by using a commercial CFD package (CFD-ACE+, ESI CFD, Inc. AL, USA) that contains graphical user interface and simulation code. Three modules were selected to simulate the mixing process, namely “Flow”, “Electric”, and “Chemistry”.

The “Flow” and “Electric” modulus together could simulate the EOF. Instead of resolving the details of electrical double layer (EDL), the Helmholtz-Smoluchowski equation was used to simplify the calculation. To save processing power, the model was a partial one that includes the Y-shape junction and the mixing zone only. The size of the model was $7\mu\text{m}$ in height, $400\mu\text{m}$ in width and 5.6mm in length. The $\zeta_{\text{PAH}} = +3.5\text{mV}$ and the $\zeta_{\text{Oxide}} = -11.1\text{mV}$, which were estimated based on measurements, were input as the boundary conditions. The physical properties of the water were used in the simulation. The “Chemistry” module, coupled with the other two modules, was used to simulate the microparticle concentration governed by diffusion, convection and migration. In fact, the microparticle was treated as a continuum phase having concentration in the working fluid (the water) rather than a discrete and solid sphere.

The result from simulation was shown in Figure 3(d). At a first glance, the wave-like pattern of the microparticle concentration distribution looks very similar to that in Figure 3(b). The ‘z’-like negative surface-charge patterns set an electro-osmotic motion opposite to the main stream, leading to a complex 3-D flow field in the mixing zone. The streamlines were stretched, enhancing the mixing locally, as indicated by the trajectory of fluid particle in Figure 3(d). To quantitatively study the mixing performance, the time-averaged and the area-averaged particle concentration over a rectangular area as shown in Figure 3(b) were extracted from the video frames. In Figure 4, the normalized particle concentration profiles across the channel width (z -direction) at three different locations along the mixing zone (x -direction) were plotted. It shows that the particles were gradually spread over the channel width. At $x=2.4\text{mm}$, the particles occupied nearly 90% of the channel width. The profiles represented by the continuous lines showed consistent trend of particle concentration.

If the normalized concentration of the pure buffer is represented by C_A and that of the buffer laden with microparticles is represented by C_B . Then, it follows that

$$C_A + C_B = 1 \quad (1)$$

Specifically, we defined a mixing index with the range of 0-to-1 corresponding to zero and complete mixing [5].

$$I(x, z) \equiv \begin{cases} \frac{C_A}{C_B} & \text{if } C_A \leq C_B \\ \frac{C_B}{C_A} & \text{if } C_A \geq C_B \end{cases} = \begin{cases} 0 & \text{is no mixing} \\ 1 & \text{is complete mixing} \end{cases} \quad (2)$$

Measured and computed mixing index profiles across the microchannel, at $x=0\text{mm}$ and $x=2.4\text{mm}$, are shown in Figure 5. The mixing of the pure buffer and the buffer laden with microparticles was significantly enhanced, with an average index of 0.62 obtained over a very short distance. Though the simulation result over-estimated the mixing performance, it showed a very consistent trend of uniformity improvement.

Figure 4. The normalized particle concentration profiles across the channel width at three different locations along the mixing zone.

Figure 5. The mixing index profiles across the channel width of two different locations in the mixing zone.

V. CONCLUSIONS

In conclusion, micromixers were fabricated with the integration of surface-charge patterning technique to make the mixing zone. The effect of these surface-charge patterns

on mixing enhancement was experimentally demonstrated. The normalized particle concentration profiles were plotted and, based on this, the mixing index profiles were also obtained. The result from simulation also showed a consistent trend of improvement of the uniformity of the mixing index.

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