Fabrication of Micromixers Utilizing Shedding Effect Induced by Electrokinetic Instability

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This paper proposes a T-shaped micromixer featuring 45° parallelogram barriers within the mixing channel. The proposed device obtains a rapid mixing of two sample fluids by means of the electrokinetic instability induced by shedding effect which is produced as an appropriate intensity of DC electric field of is applied. The proposed device uses a single high-voltage power source to simultaneously drive and mix the sample fluids. The effectiveness of the mixer is characterized experimentally as a function of the applied electrical field intensity and the extent to which the parallelogram barriers obstruct the mixing channel. The experimental results indicate that the mixing performance reaches 91.2% at a cross-section located 2.3 mm downstream of the T-junction when the barriers obstruct four-fifths of the channel width and an electrical field of 300V/cm is applied. The micromixing method presented in this study provides a simple low-cost solution to mixing problems in lab-on-a-chip systems.
1. Introduction

Microfluidic devices have many key advantages over conventional large-scale analytical techniques, including shorter detection times, a higher resolution, reduced sample consumption, ease of portability, and disposability. However, the Reynolds number of the liquid flow in microfluidic devices tends to be very small (typically less than 10). Therefore, the homogenization of two different solutions within the microchannel is achieved by diffusion mechanisms alone and therefore mixing takes place very slowly. However, the poor mixing efficiency of diffusion-based microfluidic devices limits their practicality for real world applications. Consequently, improving the mixing performance of microfluidic structures is an important step in realizing μ–TAS systems.

The micromixer is a crucial element in many microfluidic systems (or Lab-on-a-Chip devices), and its characteristics determine the overall quality of the reaction which can be achieved. Microfluidic mixers have conventionally performed the mixing operation by bringing the separate fluid streams together within a single channel. However, this mixing technique tends to be slow and therefore requires the use of extended mixing channels. In macroscale systems, stirrers or special geometry designs have been used to generate turbulent flow to enhance the mixing effect.

Microfluidic mixers can broadly be categorized as either active mixers or passive mixers. Typically, active mixers use pressure perturbation, magnetic, electrokinetic, thermal, or acoustic/ultrasonic techniques to improve the mixing performance.

Various passive microfluidic mixers have been developed. For example, Liu et al. fabricated passive microfluidic mixers with three-dimensional serpentine microchannels on silicon and glass substrates. The mixing performance of micromixers is enhanced at higher Reynolds numbers. This suggests that chaotic advection occurs predominantly at high Reynolds numbers (i.e. Re= 25-70). Various other forms of three-dimensional passive microfluidic mixer structures have been proposed. Several studies have indicated that grooves on the channel wall can generate chaotic advection, which enhances the mixing efficiency. Researchers have proposed a number of alternative passive microfluidic devices and mixing techniques, including the zigzag-type and curved-square micromixing devices. Furthermore, some researchers have presented the use of a heterogeneous surface charge distribution along the microchannel walls to induce separation vortexes in order to enhance the mixing efficiency.

The use of electrokinetic instability (EKI) as a mixing technique in electrokinetically-driven microfluidic flows with conductivity gradients has received considerable attention in the recent literature. Many researchers have attempted to develop accurate models for predicting the onset of instability and its flow features, including its coherent wave structures and associated mixing rate. The results of these studies provide a fundamental insight into electrokinetic instabilities and identify the key factors and conditions governing its onset.

In an attempt to improve the mixing performance of microfluidic mixers, this paper develops a T-shaped micromixer incorporating two pairs of 45° parallelogram barriers (PB) within the mixing channel. Figures 1(a) and 1(b) present optical microscopy (OM)

Fig.1. OM images of microfluidic mixer with parallelogram barriers in mixing channel: PB =4/5 W.
images of the proposed microfluidic mixer with the inclined parallelogram barriers extending to a distance of 4/5 W (where W is the channel width). As shown in Figure 2, the samples are driven through the micromixer by an externally applied DC field.

2. Experimental Section

The current microfluidic chips were fabricated on commercially available microscope glass slides of dimensions 76x26x1 mm³ supplied by Marienfeld (Germany). Figure 3 presents an overview of the microfabrication process. Prior to fabrication, the slides were annealed at 400°C for 4 hours in order to release any internal residual stresses. Photomasks were then designed using layout software (AutoCAD) and printed on a 10000dpi high-resolution printer. The annealed glass slides were cleaned in a boiling piranha solution (H₂SO₄:H₂O₂=3:1) for 10 min and then rinsed with deionized (DI) water and blown dry with nitrogen gas. Residual water molecules were removed by baking the slides on a 100°C hot plate for 3 min. The slides were then coated with a layer of AZ4620 positive photoresist (PR) using a spin coater and baked for a further 3 min at 100°C. After the soft baking process, the thickness of the PR layer was measured and found to be approximately 3 µm. UV lithography was performed using a mask aligner (OAI Corp.) with an exposure dosage of 180 mJ·cm⁻² and PR development was accomplished by immersing the exposed substrates in a developer solution (AZ400k:DI water=1:3) for 70 sec. The resulting photoresist patterns were then hard-baked at 150°C for 10 min. The baked PR layer was etched in a BOE (6:1) solution over a period of 40 min. During the etching process, the substrates were removed from the BOE solution every 5 min and dipped in a 1 M HCl solution for 10 sec in order to remove precipitated particles. After being dipped in the HCl solution, the substrates were rinsed in DI water and then re-immersed in the BOE etchant. The final depth of the etched microchannels was found to be 29.95 µm and the surface roughness was 30 Å. Having prepared the etched lower substrate, via holes were drilled in a second glass slide of identical dimensions to form the inlet and outlet ports of the micromixer. This slide was cleaned in a boiling Piranha solution and then carefully aligned with the etched substrate in DI water to form a weak bond between the two plates. The two plates were then fusion bonded in a furnace at 580 °C for 20 min.

Fig. 2 Schematic of experimental setup for mixing performance evaluation.
3. Results and Discussion

To qualify the degree of mixing within the channel, the following mixing ratio parameter is introduced

\[
\sigma = \left(1 - \frac{\int_0^W |C - C_\infty|\,dy}{\int_0^W |C_\alpha - C_\infty|\,dy}\right) \times 100\%
\]  

(1)

Figure 4 shows the experimental concentration distribution images obtained in a micromixer with PB=4/5W for a 10:1 conductivity ratio and electrical field intensities of 150 V/cm, 300 V/cm and 500 V/cm. The critical threshold value of the field intensity, i.e. the electrical field intensity at which the stable flow transits into unstable flow, is found to be 243 V/cm. For a driving voltage of 150 V/cm (Figure 4(a)), stable flow is observed, and the mixing ratio is low (60.2%) since mixing is achieved as a result of diffusion effects only. However, when the electrical driving voltage is increased to 300 V/cm (Figure 4(b)) or to 500 V/cm (Figure 4(c)), the flow becomes electrokinetically unstable, and the shedding phenomenon which commences in the region over the first parallelogram barrier generates a chaotic flow along the length of the mixing channel, thereby enhancing the mixing effect.

Figure 5 compares the normalized concentration intensities across the width of the micromixer channel (PB=4/5W) at a location 2.3 mm downstream of the T-junction for electrical intensities of 150 V/cm, 300 V/cm and 500 V/cm, respectively. As shown, the normalized concentration intensity profiles are very close to 0.5 (i.e. full mixing) at applied electrical fields of 300 V/cm and 500 V/cm. It is found that the mixing ratios are 91.2 % and 80.8 %, respectively, for these two electrical fields.

Figure 6 presents the optimal operating conditions for the proposed electrokinetic instability micromixer with different PB values. The average value of the mixing ratio is calculated at cross-sections from 2.3 mm to 2.5 mm (three (2.3 mm, 2.4 mm and 2.5 mm) cross-sections average) downstream of the T-junction. For the micromixer with PB = 4/5W, the optimal mixing ratio is greater than 90% when the applied electrical field is specified in the range 300V/cm to 400V/cm. For micromixers with PB=1/2W or PB=2/3W, a mixing ratio of 74% or 83%, respectively, can be achieved. Therefore, it is clear that the proposed electrokinetic instability micromixer is capable of obtaining a high mixing performance.

Fig. 4 Experimental concentration distribution images in microchannel with PB = 4/5 W for 10:1 conductivity ratio and electrical field intensities of: (a) 150V/cm, (b) 300V/cm and (c) 500V/cm.

Fig. 5 Variation in normalized concentration intensity across channel width at microchannel cross-section located 2.3mm downstream from T-junction with PB = 4/5 W and applied electrical fields of 150 V/cm, 300 V/cm and 500 V/cm.
Fig. 6 Experimental evaluations of mixing ratio for different driving electric fields and different PB values at cross sections located 2.3 mm to 2.5 mm (three (2.3 mm, 2.4 mm and 2.5 mm) cross-sections average) downstream from T-junction.

4. Conclusions

This study has presented a T-shaped microfluidic mixer featuring embedded 45° parallelogram barriers. The barriers, which partially obstruct the mixing channel width, are designed to generate a shedding flow as a result of electrokinetic instability and to increase the mixing performance as a result. The electrokinetic driving force established in the microchannel not only drives the sample flows along the microchannel, but also produces a natural flow shedding effect. Therefore, the requirement for additional driving forces to induce perturbations within the flow field is removed. The microfluidic mixer has the form of a two-layered glass structure and can be fabricated using simple and reliable fabrication techniques. The experimental results have shown that a natural flow shedding effect is induced in a micromixer channel with parallelogram barriers obstructing 4/5 of the channel width when an electrical field with an intensity of greater than 243 V/cm is applied. When a shedding effect is not induced in this microchannel, the mixing performance is approximately 60% at a cross section located 2.3 mm downstream of the T-junction. However, when a shedding flow is established, the mixing ratio increases to 91.2%. The simple microfluidic mixer presented in this study provides a valuable contribution to the ongoing development of micro-total-analysis-systems.

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