

# AN ACTIVE MICRO MIXER USING ELECTROHYDRODYNAMIC (EHD) CONVECTION

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## ABSTRACT

This paper presents a new active micro mixer using electrohydrodynamic (EHD) convection for the application of microfluidic-based biochemical analysis systems and biochips. To understand the EHD convection mixing, analytical analyses on the micro mixer have been performed for two different liquid samples with different electric conductivities. Using the analytical results, a new active micro mixer has been designed, fabricated, and also characterized by flowing two liquid samples through the microchannel. DI water and saline water solution, which have less than the volume of 10  $\mu\text{l}$ , have been fully mixed in the mixing zone at 5 ~ 20 V of the applied voltage. Since the realized micro mixer has simple structure and no mechanical moving parts, it shows very reliable mixing performance. The active micro mixing device studied in this work also shows feasible mixing capabilities in nano- or pico-liter range of liquid volumes by applying a low voltage of 5 V across the microchannel.

## INTRODUCTION

In microfluidic-based biochemical analysis systems, mixing of the liquid samples is considered as one of the most challenging tasks to achieve an appropriate reaction in a short period of time. There are, however, some difficulties in realizing reliable micro mixing devices, because the fluid in microchannels behaves as a laminar flow in most case due to low Reynolds number in microchannels [1-2]. Mixing of the liquid samples in macro-scale systems is usually achieved by stirring or agitating of the liquid samples, but these methods are almost not applicable to micro-

scale devices due to its small size and fabrication compatibility. For these reasons, several micro mixing devices have been recently developed and reported [3-7]. Most of them are passive micro mixers [3-6], but few semi-active micro mixers with enough mixing capabilities have been reported [7]. Passive mixing devices can also be useful in micro total analysis systems ( $\mu\text{-TAS}$ ) and biochip applications, but they have limitation when the system requires precise control of mixing performances concerning mixing volume and time.

In this paper, we propose a new active micro mixer using electrohydrodynamic (EHD) convection phenomena [8] for the application of microfluidic-based biochemical analysis systems (Figure 1).

The electrohydrodynamic (EHD) and magnetohydrodynamic (MHD) phenomena have been explored since early 1960's and there have been studies to realize the EHD and MHD micropumps [9-13]. Both EHD and MHD phenomena are attractive as scales go down, specifically, for microfluidic control because of its simple structural advantage in micro- and nano-scale fluidic control. In addition, since these EHD and MHD devices include no mechanically moving parts, they provide more reliable mixing.

Figures 2 and 3 show schematic illustration and simple working principle of the proposed active micro mixer using EHD convection. From the electromagnetic theory, surface charges are induced and accumulated on the boundary of dielectric materials, which are the liquid samples in this case. When an external electric field is applied over the surface charges, the charges will be moved with liquids due to a shear stress generated at the

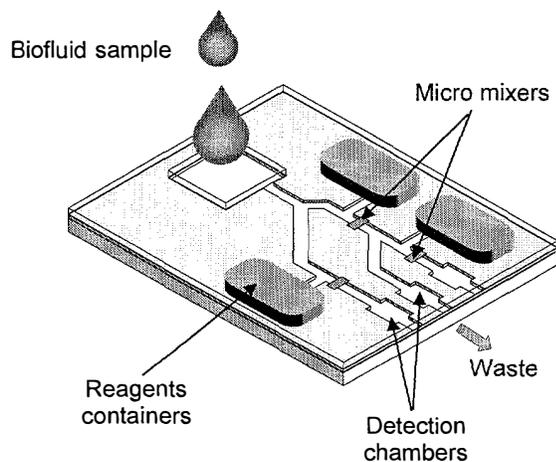


Figure 1. Schematic illustration of an on-chip microfluidic biochemical analysis system

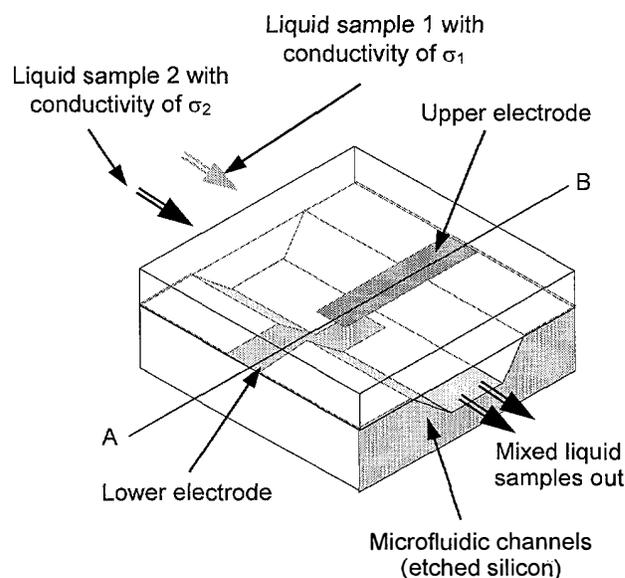
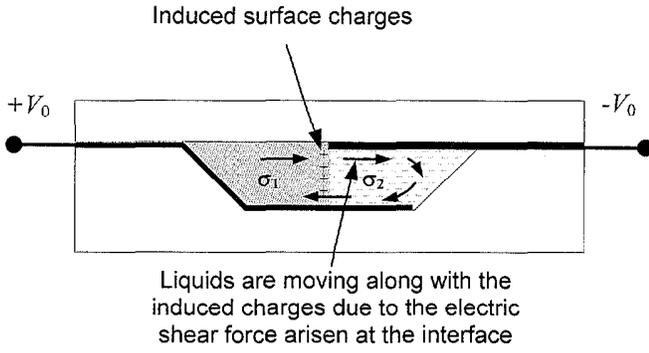


Figure 2. Schematic illustration of the active micro mixer



**Figure 3.** Cross sectional view of the active micro mixer (along the line A-B in Figure 2)

interface layer between the liquids to be mixed. These phenomena can continuously occurs and thus the convection of the liquid samples will continue until the liquid samples get fully mixed to eliminate the interfacial shear stress. The mixing speed is governed by the parameters of applied electric fields, electric properties like conductivity, and geometry of the electrodes. All these procedures can be understood analytically for the ideal case.

## THEORY

The parameters and geometry of the device are defined in Figure 4. Each region indicates two different liquid samples which have different conductivities.  $\sigma_I$  and  $\sigma_{II}$  denote the conductivities of liquid I and liquid II, respectively.

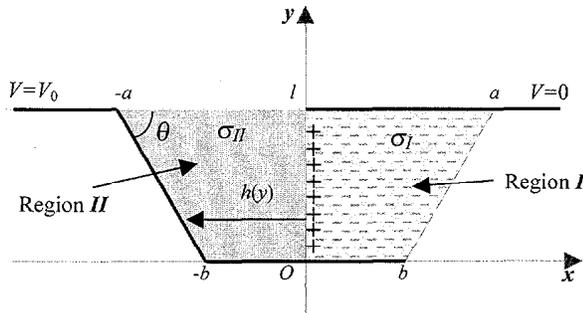
In the region I, we assume that  $y$ -directional electric fields can be described as

$$\mathbf{E}_y^I = \frac{V_0}{l} \hat{\mathbf{y}}, \quad (1)$$

where  $V_0$  is the applied voltage.

From continuity condition of the tangential component of electric fields at the boundary of the dielectric materials,  $y$ -directional electric fields near the interface in the region II can be written as

$$\mathbf{E}_y^{II} = \frac{V_0}{l} \hat{\mathbf{y}}. \quad (2)$$



**Figure 4.** Model and parameters for analytical calculation

The interface assumes a distribution in electrical potential that varies from  $V_0$  at the upper electrode to zero at the lower electrode. Because the lower electrode has zero potential, with a spacing  $h(y)$

that varies essentially linearly with  $y$ , there is a surface charge induced on the interface. Hence, the distribution of potential on the interface is

$$\Phi|_{x=0} = \frac{V_0}{l}(l-y), \quad (3)$$

and  $h(y)$ , the distance from electrode B to the interface, is

$$\begin{aligned} h(y) &= \cot \theta \cdot y + b \\ &= a - \cot \theta \cdot (l-y). \end{aligned} \quad (4)$$

In the region II, therefore,  $x$ -directional electric fields are

$$\mathbf{E}_x^{II} = -\nabla \Phi = \frac{V_0}{l} \cdot \frac{y}{a - \cot \theta \cdot (l-y)} \hat{\mathbf{x}}. \quad (5)$$

To obtain  $x$ -directional electric fields near the interface in the region I, the continuity condition of the normal current density at the interface

$$\hat{\mathbf{n}} \cdot (\sigma_{II} \mathbf{E}^{II} - \sigma_I \mathbf{E}^I) = 0 \quad (6)$$

is used. Then, the  $\mathbf{E}_x^I$  is described as

$$\mathbf{E}_x^I = \frac{\sigma_{II}}{\sigma_I} \mathbf{E}_x^{II} = \frac{\sigma_{II} V_0 y}{\sigma_I l [a - (l-y) \cot \theta]} \hat{\mathbf{x}}. \quad (7)$$

Maxwell stress tensor at the interface is given as

$$T_{ij} = \epsilon \left( E_i E_j - \frac{1}{2} \delta_{ij} E_k E_k \right), \quad (8)$$

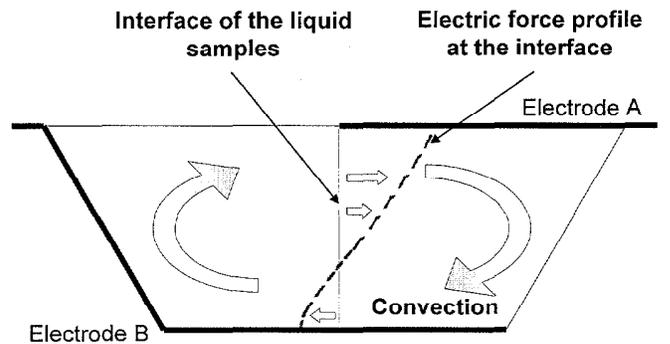
where  $\delta_{ij}$  is Kronecker delta.

With these equations, we can derive  $x$ -directional shear stress at the interface.

$$\begin{aligned} T_{xx} &= \frac{\epsilon}{2} \left( \frac{\sigma_{II} V_0^2 y^2}{\sigma_I l^2 [a - (l-y) \cot \theta]^2} - \frac{V_0^2}{l^2} \right) \\ &= \frac{\epsilon V_0^2}{2l^2} \left( \frac{\sigma_{II} y^2}{\sigma_I [a - (l-y) \cot \theta]^2} - 1 \right) \end{aligned} \quad (9)$$

The electric force on the interface can be obtained by surface integral of the shear stress. Although we only calculated that the  $x$ -directional shear stress,  $y$ -directional forces also exist along the interface of the liquids.

From Eq. (9), the force on the interface is determined by applied voltage ( $V_0$ ), depth of the channel ( $l$ ), width of the channel ( $a$ ), and the ratio of the conductivity of the liquid samples ( $\sigma_{II}/\sigma_I$ ). Looking into the term within the parenthesis in Eq. (9), the major parameter which effects on the force is the ratio of the conductivity. Figure 5 shows the plotted electric force profile on



**Figure 5.** The plotted electric force profile on the interface

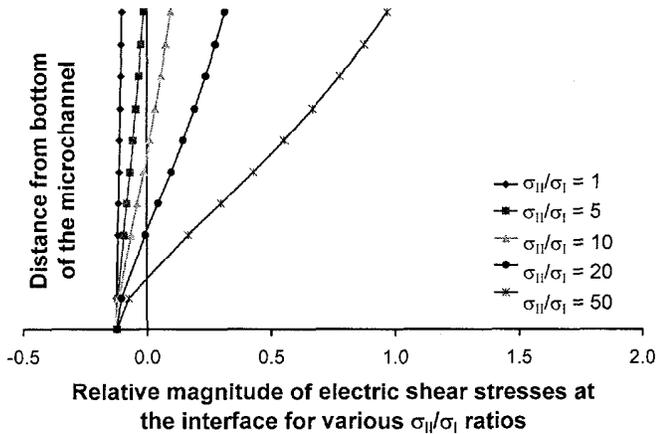


Figure 6. Relative magnitude of electric shear stresses at the interface for various conductivity ratios

the interface for the case that the ratio of the conductivity is larger than 1. The electric force profile varies along the interface and the liquids in the microchannel are assumed incompressible, so the unbalance between top and bottom of the channel along the interface causes clockwise convection in the channel and the two liquid samples will be mixed. Figure 6 shows the relative magnitude of the electric shear stress profiles at the interface for the various conductivity ratios. For the higher conductivity ratio, the electric shear stress has much larger unbalance along the interface and causes much faster convection than for the lower conductivity ratio. If the two liquids have same conductivity, then convection is hardly occurred. Further simulations using CFD are now under development.

## FABRICATION AND EXPERIMENTS

Based on the analytical study, an active micro mixer has been designed fabricated using simple micromachining techniques. The (100) silicon wafer was patterned and unisotropically etched in potassium hydroxide solution for the microchannel of the device. The width and depth of the microchannel are 200  $\mu\text{m}$  and 60  $\mu\text{m}$ , respectively. After etching process, silicon wafer was oxidized and the electrodes (Cr/Au) were deposited and patterned on both

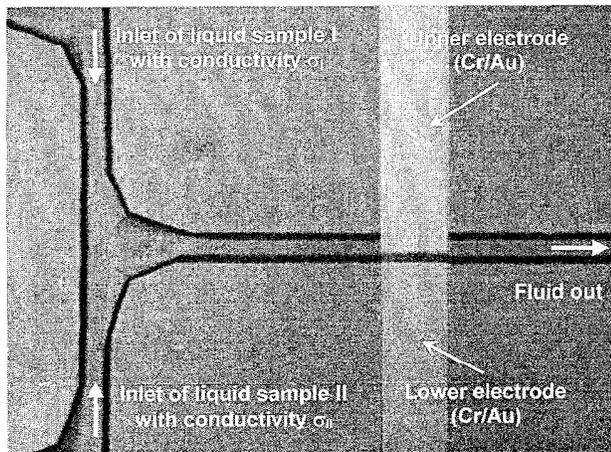
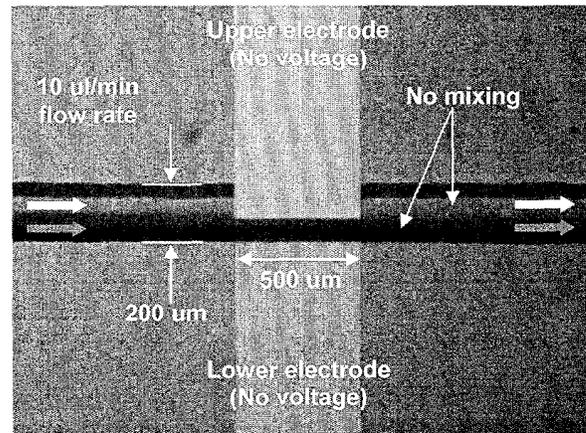


Figure 7. Microphotograph of the fabricated active micro mixer (upper electrode are shown from back side through the glass wafer)

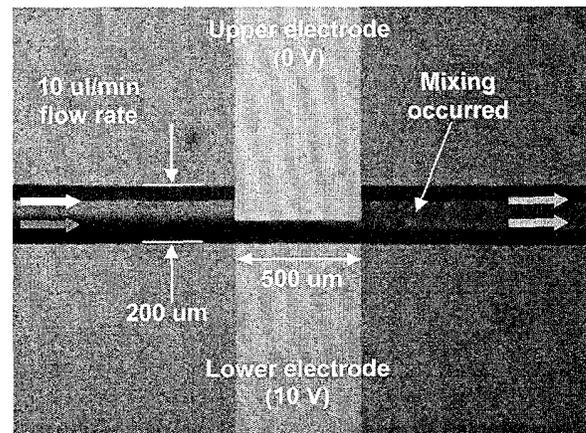
silicon and glass wafer. Finally, those two wafers have been properly bonded using fluoropolymer [14]. The fabricated device is shown in Figure 7.

To demonstrate the proposed mixing concepts, two different liquid samples have been chosen: one is water (low conductivity) and the other is saline water (high conductivity) which was dyed for the optical monitoring.

Two liquid samples have been injected through the fabricated device as shown in Figure 8 (a). With no applied electric fields, the two injected liquid samples were not mixed in the microfluidic channel as clearly showing two separate liquid streams along the microchannel. By applying electric fields to the electrodes, however, the flowing liquid samples were fully mixed after passing the electrodes due to the electric shear force generated on the interface between the liquid samples. Figure 8 (b) obviously shows the function of the proposed active micro mixer, demonstrating two separate liquid streams before reaching the electrodes and one liquid stream after passing the mixing zone.



(a) No potential applied (no mixing)



(b) 10 V applied with the flow rate of 10  $\mu\text{l}/\text{min}$  (Liquid samples are mixed passing electric fields)

Figure 8. Microphotograph for the mixing capability tests

## RESULTS AND DISCUSSION

At a given geometry of the device and with the selected liquid samples, the mixing speed and capability of the mixer depends on the strength of the applied electric fields and the flow rate of the

samples. Figure 9 shows the characteristics of the micro mixer by measuring the voltage at which the flowing liquid samples get mixed. At a flow rate of 10  $\mu\text{l}/\text{min}$ , two fluids are immediately mixed with a low mixing voltage of 7 V.

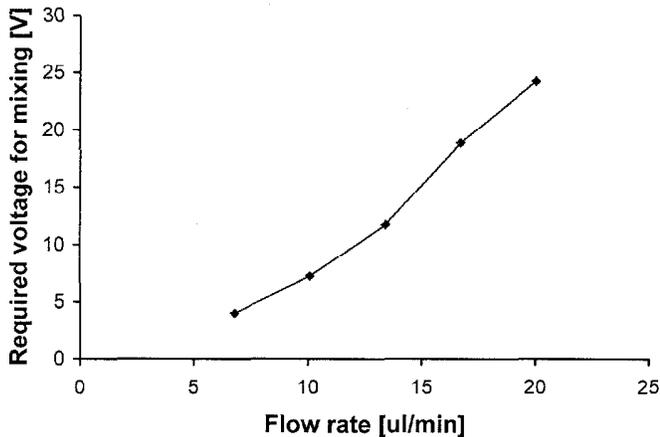


Figure 9. Minimum voltage required for mixing of the flowing DI water and saline water

The excellent mixing performance of the proposed active micro mixer has been demonstrated using saline water solution and DI water. However, the mixing of the solutions, which have very similar low conductivities, was not successfully achieved with such as DI water-methanol and DI water-isopropyl alcohol sets. When we use very high conductive aqueous solutions or operate the mixing device at very low flow rate, we could see the electrodes to be occasionally electrolyzed because the electrodes are exposed to the relatively high electric current once mixing begins. So further research on the dynamic characteristics related to conductivity of the solutions and voltage levels is now undergoing in addition to the structural optimization of the device.

## CONCLUSION

A new active micro mixer using electrohydrodynamic convection has been proposed, fabricated, and characterized in this work. Basic analytical analyses have been studied to describe mixing mechanism. The surface charges are induced at the interface of the liquid samples which have different conductivities, and these surface charges react with the applied electric fields to generate electric shear forces. Mixing capability has been clearly shown with DI water and saline water solution, which have less than 10 pl of the volume. By applying electric fields, the separate flow streams get mixed passing the electrodes. The micro mixing device realized in this work has simple structure and no mechanical moving part, which can provide a reliable mixing function on biochips.

With the demonstrated device, active mixing control of electrolytes can be envisaged toward microfluidic-based biochemical analysis systems and biochip applications.

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