Large Area Microfluidic Mixer Integrated with Linear Fluidic Transporters and Reservoirs

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ABSTRACT

This paper describes a large area (over 100 mm²) micromixer integrated with long-channel fluidic transporters and reservoirs on a same substrate. Both the micromixer and the linear fluid transporter are built on a PZT sheet with its electrodes patterned to produce self-focused acoustic beams for powerful in-plane liquid motion (through acoustic streaming effect). Self-focusing Acoustic Transducers (SFAT) are sectored and connected in various patterns for a variety of mixing and transport effects, and are set under a silicon, glass or plastic wafer that contains a large area, shallow, mixing chamber. Mixing in a 200 μ m deep, 100 mm² chamber can be done within 2 seconds.

INTRODUCTION

Lab-on-chip (LOC) with microfluidic processing capabilities has great potential for biomedical applications. Especially, microfluidic systems that can process liquids of tens of μ l are greatly needed for many biomedical processing systems. Microfluidic mixing has conventionally been done using heat, electrolysis and electromagnetic force. These methods, however, present some difficulties in any of the following requirements: compatibility with biomedical applications, easiness of integration with LOC system, mixing capability of relatively large volume liquid. It has been reported that focused acoustic waves are effective in generating fluidic motion [1], and a sectored Self-focusing Acoustic-wave Transducer can produce strong in-plane liquid motion for micromixing [2]. Thus, we have used several arrays of sectored SFATs to transport (over tens of mm length) and mix (over hundreds of mm²) fluids noninvasively. This paper describes the theory, design and experimental results of the fluid mixer integrated with fluidic transporters and reservoirs.

THEORY

SFAT with its electrodes on both faces of a piezoelectric film patterned as shown in Fig.1 focuses acoustic waves through constructive wave interference [3]. When RF power is applied between the electrodes (sandwiching the piezoelectric film) with its frequency corresponding to the thickness mode resonance of the piezoelectric film, strong acoustic waves are generated over the areas covered by the electrodes. With a proper design of the electrode patterns (e.g., a set of annular rings acting as half-wave-band sources), we can achieve wave-focusing effect without any acoustic lens due to the acoustic waves interfering with each other as they propagate in the fluid adjacent to the transducer.

With a set of complete annular rings, the acoustic field is radially symmetrical in the plane of the rings. But when the rings are broken into segments of various angles, the acoustic field becomes nonsymmetrical in the in-plane. The basic cell that we

employ for the SFAT fluid driver is a 90° sectored SFAT built on a PZT substrate shown in Fig. 2.

Fig. 1 The electrode pattern of annular rings on both faces of a piezoelectric plate for self-focusing of acoustic waves.

A high-intensity acoustic wave propagating in a medium is absorbed and scattered by the medium. The wave attenuation with a high intensity wave is nonlinear, and causes the medium itself to move. This nonlinear acoustic effect is called acoustic streaming.

In a sectored SFAT, the electrode patterns for the top and bottom electrodes are designed to produce large acoustic pressure gradient (especially in the in-plane direction) near the focal points. As the intensified acoustic waves travel in the liquid with accompanying acoustic loss, the acoustic streaming happens, and there exists steady body force in the liquid to drive fluid flow [4].

$$\vec{F}_b = \rho_0 \langle \vec{v}_1 \nabla \cdot \vec{v}_1 + (\vec{v}_1 \cdot \nabla) \vec{v}_1 \rangle$$

Fig. 2 A 90° sectored SFAT cell

FABRICATION

Figure 3 shows the fabrication process for the sectored-SFAT fluid driver. We use a 192 μm thick PZT sheet as the transducer substrate. With the front-to-backside alignment marks, 2.54 μm thick silver electrodes on both sides of the PZT sheet are patterned such that the top and bottom FASA electrodes overlap each other. The silver is etched with 3M HNO_3 in 35 seconds. The fluid chambers are micromachined in silicon substrate using HNA isotropic etching or KOH anisotropic etching. Two kinds of mixing chambers have been fabricated: one in a 400 μm thick silicon wafer, the other over a 170 μm thick glass or 100 μm thick plastic wafer with an etched-through silicon on its top (shown in Fig 4). The mixing chambers, built on a silicon wafer, are fabricated together with linear channels and rectangular reservoirs on a same substrate to produce an integrated microfluidic subsystem, which is then bonded (with about 10 μm thick epoxy) to the PZT transducer (Fig.3).

Fig. 3 Brief fabrication steps for two types of mixing chambers in Si wafer (top three) and Glass or plastic wafer (bottom three).

Fig. 4 Cross sectional views of the two types of mixing chambers.

Fig. 5 Cross-sectional photos of the completed mixers

EXPERIMENTAL METHOD

The fabricated devices are tested in an apparatus shown in Fig. 6, where a RF square wave (with the frequency around 12 MHz corresponding to the thickness of PZT sheet) is modulated with a sequence of pulses from a function generator before being amplified by an RF amplifier and applied to the device. The peak-to-peak voltage of the RF amplifier output is typically about 40 V, and the electrical field across the PZT substrate is about 10^5 V/m. When we apply a continuous square wave, the series resistance of the electrodes produce significant amount of heat. Thus, we use a pulsed square wave with 30 to 120 Hz pulse repetition frequency and on time of 40 to 100 μs (corresponding to a duty cycle of 0.12% to 1.2%). With this pulsed wave, heating is negligible.

The fluidic subsystem includes a mixer, two linear transporters and rectangular reservoirs. In the rectangular reservoirs, we first place red ink and DI water along with microspheres of 10 μm in diameter to facilitate the observation of the liquid flow and mixing trace. Those liquids are transported from the reservoirs to the circular mixing chamber through the connecting fluidic channels by the microfluidic driver [5], and then are mixed together in the mixing chamber by the micromixer.

Fig. 6 Schematic of the test set-up.

EXPERIMENTAL RESULTS

The top-view photo of the fabricated microfluidic subsystem (with two rectangular reservoirs of 9.4 x 3.4 mm² each, 1 mm wide and 8.4 mm long channels, and a circular mixing

chamber of 7.4mm in diameter) is shown in Fig. 7. The micromixer can mix liquids (about 0.2 to 0.4 mm tall) over 100mm² area within 2 seconds. To demonstrate the mixing capability, two kinds of liquids (red ink and DI water) with microspheres are stored in the two rectangular reservoirs (on the right-hand side of Fig. 7), driven along the two narrow and long channels (on the middle of Fig. 7) by linear arrays of the sector SFATs, and mixed in the circular chamber (on the left-hand side of Fig. 7) by the micromixer.

Fig. 7 Top view photo of the fabricated microfluidic subsystem made in a silicon wafer with PZT sheet.

The fluids in the subsystem are driven by the sector SFATs, and their flows are captured at the four regions indicated with elliptical circles in Fig. 7 at different points of time (a-h) as follows:

(a) 0.5 sec after electrical pulses are applied to the PZT drivers, the liquids begin to be driven from the rectangular reservoirs at the right hand side (Fig. 7);

(b) 1.2 sec after the turn on of the pulses, the liquids arrive at the channel midpoint;

(c) the liquids being continuously transported by two sets of linear array of sector SFATs attached to the microfluidic subsystem;

(d) the liquids being continuously delivered to the mixing chamber by the linear array of sector SFATs.

(e) 1.7 sec after the turn on of the pulses, the liquids arrive at the mixing chamber;

(f) start of the mixing;

(h) 3.2 sec after the power on (it shows the effective mixing of the two liquids).

The mixing speed can easily be controlled by adjusting the pulse duty cycle or the peak voltage level. And different electrode patterns on the SFAT can produce different fluid mixing traces as shown in Fig. 8: in (a) there are 3 “eyes” producing almost random mixing, while in (b) there is only one “eye” in fluid mixing flow which would be good for a directional mixing.

Fig. 8 Mixing patterns and the electrode patterns on the SFATs that produce the mixing traces.

In the experiment, we find the ‘eye’ point is not good for mixing liquids with particles, because the particles come and tend to stay there without moving around. To solve this problem, we adjust the RF frequency so that the liquid mixing trace may be changed. When the frequency is changed a little, such as $\pm 0.1\text{MHz}$, there is still good mixing effect in the chamber, although the mixing speed is slowed down a little, and at same

time, the liquid mixing trace is changed. The reason for such trace change is that when the frequency is varied, the interference between the waves varies, resulting in a variation in the acoustic wave distribution in the liquid, which changes the body force distribution in the liquid. When we change the liquid traces by changing the RF frequency, we can force all particles to mixing and avoid the nodal effect by the 'eye' (Fig.9).

Fig. 9 Liquid trace changes when the RF frequency is changed by a small amount.

When the PZT SFAT is glued to a silicon wafer that contains microfluidic channels and chambers, the S11 parameter of the SFAT (without any liquid) is as shown in Fig. 10. There are two peaks in the S11 (due to the micromachined silicon attached to the PZT sheet), which broaden the resonance characteristic. From the S11, we see that there is still at least 30% of the peak power at the frequency ± 0.1 MHz off from the center frequency. With liquid in the mixing chamber, the drop in the available power (from the peak power as the frequency is varied) would be less due to the mass loading effect by the liquid. Thus, we would still have significant amount of acoustic power available for mixing, even when we vary the RF frequency to change the liquid traces.

Fig. 10 S11 parameter of the sector SFAT attached to a silicon wafer with microfluidic channels and chambers.

In addition to silicon wafer, glass and plastic wafers also have been used as the chamber/channel/reservoir substrate. We get almost same mixing effect on these wafers, although the mixing speeds are slowed down, especially on the plastic wafer, due to more acoustic absorption in the plastic or glass wafer than in a silicon wafer. Figure 11 shows the time sequence of the mixing effect on a plastic wafer.

Fig 11 Time procession of the mixing: (a) Right after red ink is dropped in the water, (b) 2.4 sec later, (c) 8.6 sec later.

SUMMARY

In this paper, we describe a large area (over 100 mm²) micromixer integrated with long-channel fluidic transporters and large reservoirs on a same substrate. The three major microfluidic components are integrated in a micromachined silicon substrate with sector SFATs built on a PZT sheet. The micromixers and linear fluid transporters built on the PZT SFATs produce strong in-plane fluid motion without heat. And we demonstrate a powerful mixing effect over a large surface area. In addition, we demonstrate the integrated microfluidic subsystem over a glass or plastic wafer with silicon sidewalls. The microfluidic subsystem described in this paper integrates three major fluidic components (i.e., micromixer, liquid transporter, and reservoir), and is ready for a stand-alone microfluidic system, once one-way valves are integrated.

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