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BULK ACOUSTIC WAVE BASED MOCRFLUIDIC PARTICLE SORTING WITH CAPACITIVE MICROMACHINED ULTRASONIC TRANSDUCERS

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ABSTRACT

The main limitation of acoustic particle separation for microfluidic application is its low sorting efficiency. This is due to the weak coupling of surface acoustic waves (SAWs) into the microchannel. In this work, we demonstrate bulk acoustic wave (BAW) particle sorting using capacitive micromachined ultrasonic transducers (CMUTs) for the first time.

A collapsed mode CMUT was driven in air to generate acoustic pressure within the silicon substrate in the in-plane direction of the silicon die. This acoustic pressure was coupled into a water droplet, positioned at the side of the CMUT die, and measured with an optical hydrophone. By using a beam steering approach, the ultrasound generated from 32 CMUT elements were added in-phase to generate a maximum peak-to-peak pressure of 0.9 MPa. Using this pressure, 10 μm latex beads were sorted almost instantaneously.

KEYWORDS

CMUT, Microfluidic particle sorting, Acoustic particle sorting, bulk acoustic wave

INTRODUCTION

Acoustic particle sorting is a label-free, biocompatible method to sort particles within a microchannel. Such techniques are useful for manipulating micron-size cells or sub-micron size particles for clinical, biological, and chemical research. The two common method to achieve acoustic particle sorting is either to use bulk acoustic wave (BAW) or surface acoustic wave (SAW). BAW-based sorting devices use a single lead zirconate titanate (PZT) element attached to a microfluidic device fabricated from a high acoustic impedance material, such as silicon or glass [1]. The width of the microfluidic channel is designed to be an integer multiple of half of the acoustic wavelength, which creates a standing wave within the acoustic channel to sort particles. SAW-based sorting devices use an interdigitated transducer (IDT) fabricated through deposition and patterning of a thin piezoelectric layer. Due to this photopatternable fabrication process, the acoustic actuation area can be well controlled, therefore SAW-based devices are often preferred when they are integrated with other functionalities. However, SAW-based devices have a low throughput because the acoustic signal is weakly coupled into the microfluidic channel either through the top or bottom surface. Therefore, there is a need for a BAW-based sorting device which can allow high throughput particle sorting, while maintaining high control over the acoustic actuation area.

Over the last decade, in the field of ultrasound imaging, there has been great improvement in MEMS based ultrasonic transducers (i.e., piezoelectric micromachined ultrasonic transducers (PMUTs) and capacitive micromachined ultrasonic transducers (CMUTs)). These transducers are meant to couple ultrasound waves into the medium in contact with the transducers. However, during our preliminary investigations using CMUTs, it was noticed that acoustic energy can also couple into the silicon substrate and propagate laterally in-plane through the substrate. For ultrasound imaging, this would create an unwanted imaging artifact. On the other hand, for acoustic particle sorting, the in-plane ultrasound is another method to generate ultrasound within a microchannel on the same substrate. In addition, CMUTs are broadband devices which compared to PZT devices allow for an extra degree of freedom to manipulate particles within the microchannel. Furthermore, CMUT technology is highly compatible with silicon microfluidics; a growing field where silicon is used as the substrate to integrate complex functionalities such as cell manipulation, cancer detection, and DNA amplification [2], [3].

In this work, we propose a BAW-based particle sorting device using collapse-mode CMUTs. BAW generated in the in-plane direction of the silicon substrate will enable higher throughput particle sorting. CMUTs are fabricated through standard IC-based fabrication techniques and the acoustic actuation area can be well-controlled.

This paper is organized as follows. First, the concept of the device with CMUTs combined with a silicon embedded microchannel is explained. Then the sidewall acoustic pressure is measured from a CMUT die. Finally, the alignment of 10 μm particles is demonstrated.

DEVICE CONCEPT

The main components of a BAW-based microfluidic particle sorting device are the microfluidic channel and the CMUT. In this section, these two components will be explained.

CMUTs

A schematic cross-section of a CMUT is shown in Fig. 1a. A CMUT consists of a top and bottom circular membrane, each fabricated from an aluminum electrode which is passivated by a ceramic layer such as SiO_2 and Si_3N_4 [4]. At its non-biased state, the CMUT has a vacuum gap between its top and bottom membrane. The top membrane is brought into collapse-mode operation by applying a DC bias voltage beyond the pull-in voltage. Then an AC signal is superimposed to vibrate the donut-shaped region around the collapsed area. The ultrasound generated from this vibration couples into the substrate through the collapsed region. The ultrasound signal then propagates along the in-plane direction of the substrate.

Silicon embedded microchannels

To efficiently couple the ultrasound energy into a microfluidic channel, the channel must be fabricated on the same substrate, as shown in Fig. 1a. In our prior work, we developed techniques to fabricate silicon embedded microchannels with vertical walls through a standardized IC-based fabrication process [5]. In this work, these microchannels were not fabricated because the goal was to measure if sufficient sidewall acoustic pressure is generated. Yet CMUT technology and silicon embedded microchannels could be readily combined in future work.

Beam steering

Another benefit of using CMUTs is that the output pressure could be amplified by applying a beam steering approach. To explain this, in Fig. 1b several rows of CMUTs are aligned in parallel. Each row is referred to as a CMUT element and can be addressed with different driving voltages. Beam steering is achieved by incrementally delaying the same driving signal for each CMUT element with Δt, such that the ultrasound signal traveling through the substrate is added in phase. In this way, a higher output pressure can be achieved. The ultrasound waves will add in phase if the following equation is satisfied,

$$V = D/\Delta t \tag{1}$$

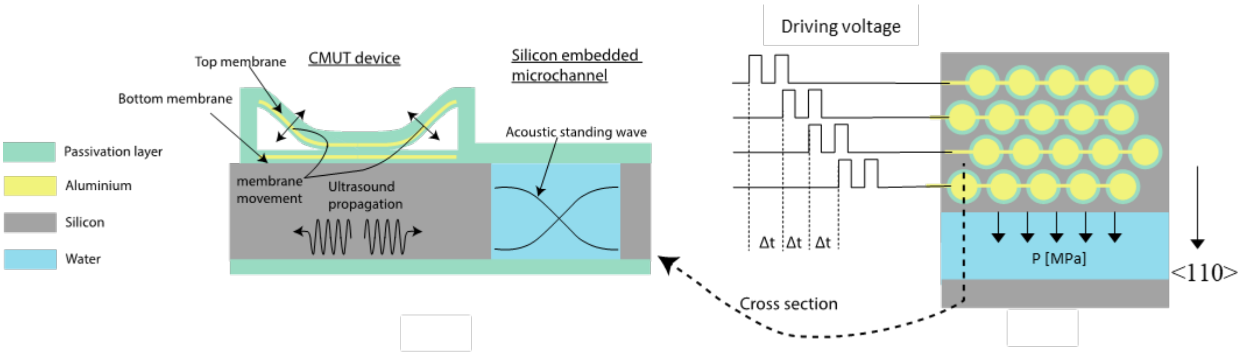
where D is the pitch between each element and V is the velocity of sound through the substrate. For silicon, V is dependent on the crystal orientation and the vibrational modes that are present. The CMUT devices used in this work have the <110> orientation perpendicular to the CMUT element, as shown in Fig. 1b. The vibrational mode is not clear and multiple vibrational modes could simultaneously exist. Therefore, in this work, Δt is swept to find the best beam steering condition.

RESULT

In this section, the results of acoustic pressure measurements from the side of a CMUT die are presented for a single element and 32 elements with and without beam steering. This is followed by a demonstration of 10 µm particle sorting.

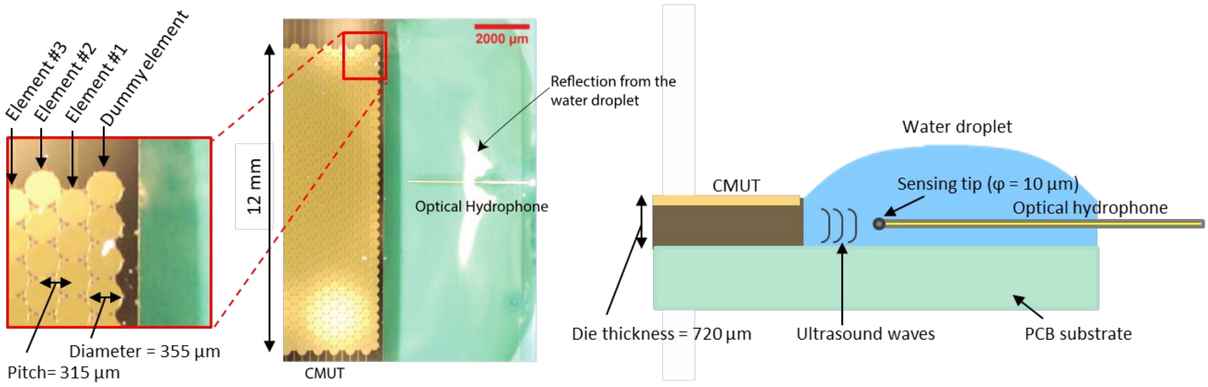
Single element acoustic pressure measurement

Fig. 2a shows the experimental setup used for the acoustic sidewall pressure measurement of the CMUT. A zoomed picture of the CMUT device is shown inside the red box. The diameter of the CMUT membrane used in this



(a) (b)

Figure 1: (a) The concept of combining ultrasound transducers with silicon embedded microchannels. (b) The concept of beam steering with a time delay of Δt and the <110> crystal orientation of the silicon substrate.



(a) (b)

Figure 2: (a) Acoustic pressure measurement setup seen from above. An optical hydrophone is positioned at the side of the CMUT die and a zoomed in image of the CMUT devices are shown in the red box. (b) Side view of the acoustic pressure measurement setup. The drawing is not to scale.

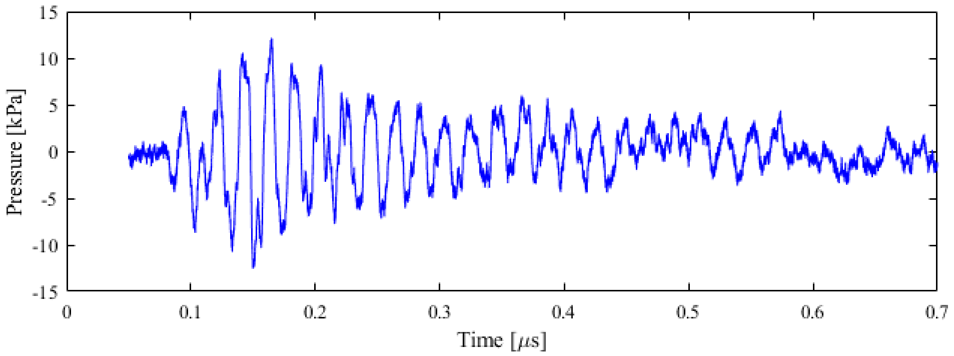


Figure 3: Transient waveform of the pressure from the side of the silicon die. Time = 0 µs is when the ultrasound signal was transmitted.

work is 355 µm. Each CMUT element has a length of 12 mm, with 33 CMUT devices in each element. These CMUT elements were positioned in a row with a pitch of 315 µm along the 2 cm width of the die. The first element at the very edge of the die is a dummy element and cannot be used.

Fig. 2b schematically shows the side view of the experimental setup. The thickness of the silicon die was 720 µm. A droplet of water was placed at the die's right side, and the surface tension kept the water in place. The acoustic pressure coupled from the silicon substrate into the water was measured with a fiber optic hydrophone (Precision Acoustics, UK) with a tip size of 10 µm diameter. The hydrophone was carefully positioned with a motorized 3D axis stage. The distance between the hydrophone and the silicon sidewall was approximately 0.9 mm. In the vertical direction, the hydrophone was positioned near half the height of the CMUT. The output pressure was relatively insensitive to the vertical position of the hydrophone.

Fig. 3 shows a transient response when the 2nd CMUT element closest to the sidewall (element #2 in Fig. 1a) was driven with one cycle of sine wave at 4.5 MHz with 15 V amplitude and a bias voltage of 150 V. The response showed a ringing behavior because the CMUT membrane was in resonance at this frequency. The maximum peak-to-peak output pressure was 25 kPa.

To further increase the acoustic pressure, beam steering was applied using the first 32 CMUT elements closest to the water droplet. The in-house-built ultrasound driver system was based on the HV7351 pulser chip (Microchip Technology, USA). The driving signal was a unipolar square wave with 15 V amplitude, 15 cycles, 4.5 MHz frequency, a pulse repetition frequency (PRF) of 1 kHz and a bias voltage of 150 V. The acoustic pressure was measured as the Δt was increased from 5 ns to 150 ns in 5ns steps. From Fig. 4, the output pressure constructively interfered when $\Delta t = 40$ ns and 65 ns. This corresponds to a sound velocity within silicon at 7875 m/s and 4846 m/s respectively based on equation (1). The maximum peak-to-peak pressure was 0.9 MPa. For comparison, the output pressure of 32 CMUT elements without beam steering is shown in Fig. 4 with a dashed line ($\Delta t = 0$ ns). The peak-to-peak output pressure was 140 kPa which was 6.4 times lower than when beam steering was applied.

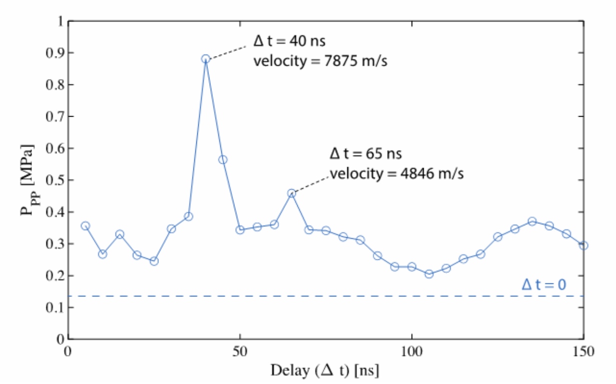


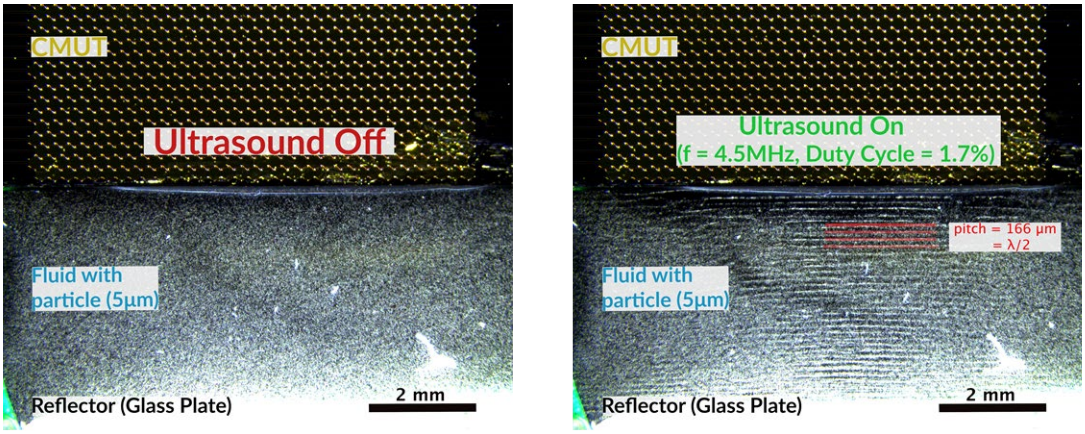
Figure 4: Peak-to-peak pressure when beam steering was applied with a time delay from $\Delta t = 5$ ns to 150 ns in 5 ns steps. $\Delta t = 0$ ns is the peak-to-peak pressure without beam steering.

Particle sorting

Fig. 5a, is the microscope view of the experimental setup used to demonstrate particle sorting. A droplet of water with 10 µm latex beads was positioned next to the CMUT with a glass reflector at a 4 mm distance from the sidewall of the CMUT. To increase the contrast of the latex beads a thin silicon wafer with a thickness of 280 µm was positioned beneath the water droplet. In the beginning, the particles were mixed, and there were no distinct patterns. The ultrasound was then turned on for a few seconds, using the same beam steering conditions found to generate the maximum output pressure (f = 4.5 MHz, $\Delta t = 40$ ns, Vp = 15 V, Vbias = 150V, 15 cycles). The PRF was increased to 5 kHz for a slightly higher output power resulting in a duty cycle of 1.7 %. The effect of the ultrasound field on the particles is shown in Figure 5b. The particles aligned in stripes of 166 µm pitch, which corresponds to half of the wavelength of 4.5 MHz ultrasound in water. The video recording of particle alignment can be seen in the link in the footnote[1]. The video is not fast-forwarded. In the video, interesting streaming effects are also visible, but the study of this phenomenon was beyond the scope of this work.

DISCUSSION AND CONCLUSION

In this work, particle sorting using collapse-mode CMUTs was demonstrated for the first time. A beam steering approach was used to increase the output pressure.



(a) (b)

Figure 5: Ultrasound 10 µm latex beads sorting, (a) before the ultrasound and (b) after the ultrasound. The ultrasound parameter used: f = 4.5 MHz, PRF = 5 kHz, Vp = 15 V, Vbias = 150 V, Duty Cycle = 1.7%, Δt *= 40 ns, 32 elements, and cycle number = 15. The video can be seen in the link in the footonote*[1].

This improved the output pressure by 6.4 times compared to when no beam steering was applied. The maximum output peak-to-peak pressure of 0.9 MPa is much higher compared to prior work on acoustofluidic separation [6] and would allow higher throughput particle sorting.

However, there are still many unanswered questions regarding the mechanism of this sidewall acoustics. The time delay used for beam steering provided some insight on the velocity of the ultrasound wave travelling through silicon (i.e., 7875 m/s and 4846 m/s). According to [7] the ultrasound propagation along the <110> crystal orientation for longitudinal and transversal velocity is 9138 (m/s) and 4675 (m/s) respectively. The fact that there are two distinct peaks in Fig. 4 may be related to the two different velocity seen in literature, but the exact values do not match. Thus, it is difficult to make concrete statements whether we are using BAW or SAW. However, the hydrophone was vertically positioned near half the height of the die and there were no large changes when the hydrophone was moved vertically. Therefore, we expect that the ultrasound is transmitted from the entire sidewall which confirms that this is a BAW-based sorting device.

There are several other factors that also play a role in this work. For example, i) the ultrasound wave generated from the collapse-mode CMUT will propagate vertically within the substrate, ii) ultrasound waves will reflect internally at the boundary of the silicon substrate and may add coherently, iii) the acoustic driving parameters such as PRF and acoustic frequency may also have an influence. Thus, deepening our understanding of these mechanisms require a more detailed model and should be considered for future work.

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