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Design and Experimental Characterization of a Silicon-Based Acoustic Microfluidic Resonator for Particle Focusing

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***Abstract* - Acoustophoresis provides an efficient and non-contact approach for manipulating suspended particles in microfluidic systems without affecting their physical or functional properties. In this work, a silicon-based acoustic microfluidic resonator is designed and experimentally demonstrated for the spatial localization of microparticles within a microchannel. Acoustic radiation is generated using a piezoelectric ceramic transducer attached beneath the microfluidic chip. The fabricated device is capable of focusing particles of different sizes toward the center of the microchannel under resonant acoustic excitation. Polystyrene microspheres with diameters of 3.5, 4.5, 6, 12, and 25 microns were experimentally evaluated. Results show that larger particles can be focused more efficiently, while smaller particles require higher excitation voltage for effective localization. The measured resonant frequencies remained close to the theoretical resonance frequency of the acoustic cavity. The proposed device demonstrates the feasibility of acoustic particle manipulation for potential applications in particle sorting, cell handling, and lab-on-chip systems.**

Keywords - Acoustophoresis, Microfluidics, Acoustic Resonator, Piezoelectric Transducer, Particle Focusing

I. INTRODUCTION

Microfluidic technologies have emerged as an important platform for biomedical analysis, chemical processing, and particle manipulation due to their ability to precisely control fluid flow at the microscale. One of the major challenges in microfluidic systems is the controlled positioning, concentration, and separation of suspended particles or biological cells without affecting their viability or physical properties. Conventional particle manipulation techniques based on electric, magnetic, or optical forces often require complex device integration and may introduce unwanted effects on sensitive biological samples.

Acoustophoresis has attracted significant interest as a non-contact and label-free particle manipulation technique. In acoustophoretic systems, acoustic standing waves generated inside a microchannel produce acoustic radiation force that drive suspended particles toward pressure nodes or antinodes, depending on their acoustic properties. Acoustic manipulation methods provide several advantages, including low power consumption, biocompatibility, and compatibility with continuous-flow microfluidic systems [1]-[3]. Due to these advantages, acoustic microfluidic devices have been investigated for applications such as cell separation, particle focusing, blood component isolation, and sample preparation for lab-on-chip systems [4], [5].

The efficiency of acoustic particle focusing depends on several parameters, including acoustic frequency, channel geometry, acoustic pressure amplitude, and particle size. Larger particles generally experience stronger acoustic radiation forces, thereby improving focusing efficiency. The design of an efficient acoustic resonator is therefore essential for achieving stable standing-wave patterns within the microchannel.

Materials used in fabrication also play an important role in the performance of acoustic devices. Although polydimethylsiloxane (PDMS) is widely used in microfluidics due to its ease of fabrication, its relatively low acoustic impedance and mechanical softness reduce acoustic energy confinement. Silicon offers improved acoustic transmission characteristics, higher rigidity, and compatibility with standard microfabrication processes, making it a suitable material for acoustic microfluidic resonators [6].

In this work, a silicon-based acoustic microfluidic resonator is designed, fabricated, and experimentally demonstrated for spatial localization of microparticles. Acoustic excitation is generated using a piezoelectric ceramic actuator attached beneath the silicon substrate. The fabricated device consists of multiple inlets and outlets, enabling future implementation for continuous particle focusing and sorting applications. Experimental characterization was performed using polystyrene microspheres with diameters ranging from 3.5 µm to 25 µm.

II. DEVICE DESIGN

A. *Device Configuration*

The proposed microfluidic device consists of three inlet channels connected to a central microfluidic resonator channel, which in turn connects to three outlet channels. The design enables both particle focusing and particle separation applications. Fig 1 illustrates the schematic configuration of the device.

The microchannel is fabricated on a silicon substrate and sealed using a borosilicate glass cover. The channel width is 740 µm, with a depth of 100 µm. The inlet and outlet channels are connected to the main channel at approximately 34°. The borosilicate glass cover not only seals the microfluidic channel but also allows optical visualization during experimental testing.

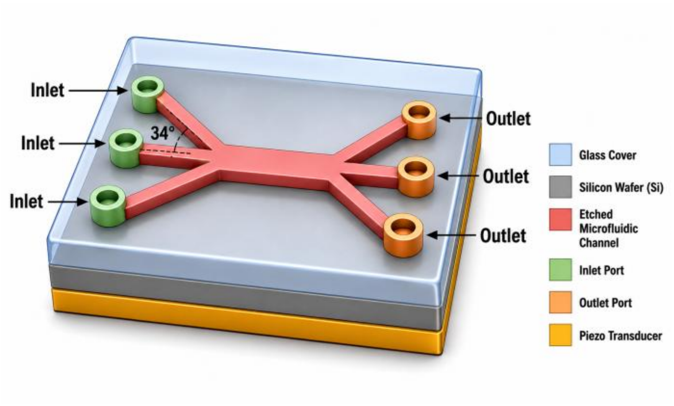


Fig. 1. Schematic illustration of the acoustic microfluidic device configuration.

A piezoelectric ceramic transducer (PZT-20) is attached beneath the silicon substrate to generate acoustic excitation. The microchannel acts as an acoustic resonator, with standing acoustic waves established during operation.

B. *Device Fabrication*

The device was fabricated using standard silicon micromachining techniques. Silicon was selected as the substrate material because of its high mechanical rigidity and favorable acoustic properties.

Initially, the silicon wafer was diced and cleaned using acetone, isopropyl alcohol, methanol, and deionized water. Plasma ashing was then performed to remove residual organic contaminants from the wafer surface.

A silicon dioxide (SiO2) layer was thermally grown on the silicon substrate to serve as an etching mask. Standard photolithography was used to pattern the microfluidic channel structure on the oxidized wafer surface. The patterned wafer was then etched using potassium hydroxide (KOH) solution at 80 °C to form the microchannels. The average etching rate achieved was approximately 1 µm/min, and the etching process was continued for 100 minutes to obtain a channel depth of 100 µm.

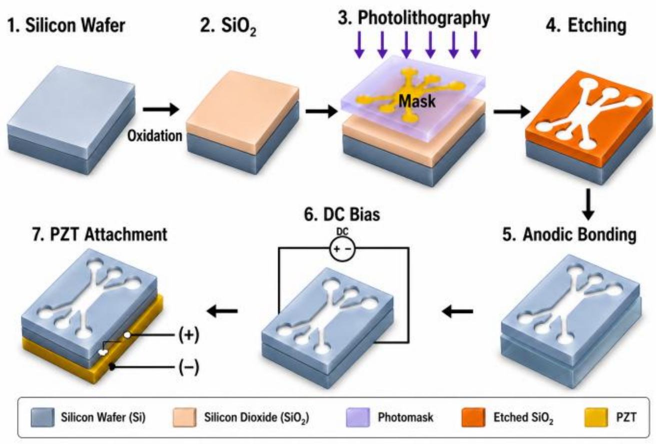


Fig. 2. Fabrication flow of the silicon acoustic microfluidic resonator.

Fig. 3. Fabricated acoustic microfluidic chip with integrated piezoelectric actuator.

After completion of the etching process, the wafer was thoroughly cleaned to prepare it for anodic bonding. Borosilicate glass was used as the sealing layer due to its optical transparency and compatibility with anodic bonding. Inlet and outlet holes were manually drilled into the glass slide.

Anodic bonding between silicon and glass was performed at 430 °C using a DC power supply at 730 V. This process created a permanent hermetic seal between the silicon substrate and the glass cover.

Fluidic connectors were attached to the glass surface using epoxy adhesive to facilitate tubing connections. Finally, electrical wires were soldered to the piezoelectric ceramic actuator, which was attached to the silicon substrate with adhesive. The fabrication method is depicted in Fig 2, and the final device is shown in Fig 3.

C. *Testing Setup*

The fabricated device was experimentally evaluated using polystyrene microspheres of different diameters. Pluronic surfactant was introduced into two side inlets to minimize particle adhesion to the channel walls and prevent particle aggregation.

Microspheres with diameters of 3.5 µm, 4.5 µm, 6 µm, 12 µm, and 25 µm were diluted in pluronic solution and injected through the center inlet using a syringe pump. The flow rate for each inlet was maintained at 500 µL/h.

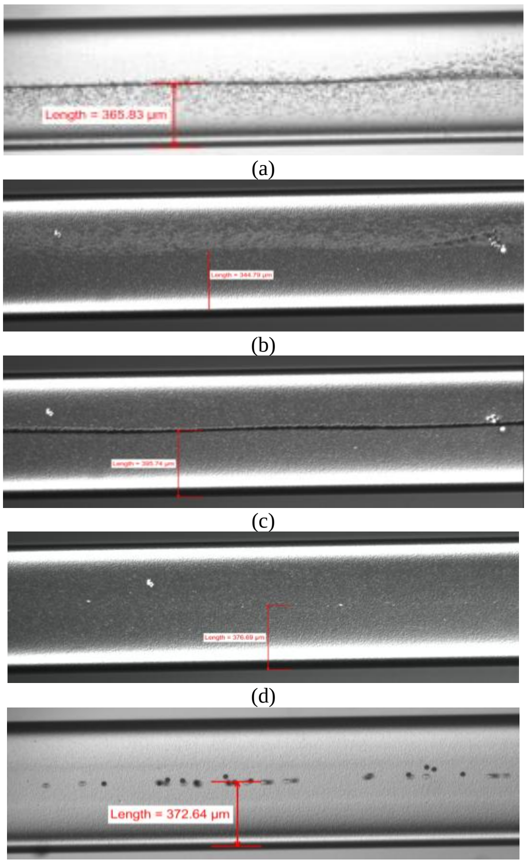
The piezoelectric actuator was driven using an arbitrary waveform generator connected to a power amplifier. The acoustic excitation frequency and voltage were adjusted to achieve optimal particle focusing conditions.

The device was placed under an optical microscope connected to a high-speed camera for real-time visualization of particle motion. Care was taken to ensure that the piezoelectric actuator could vibrate freely during testing.

After each experiment, the channel was flushed with Pluronic surfactant, followed by methanol to remove residual particles and contaminants.

III. RESULTS AND DISCUSSION

The acoustic microfluidic resonator was experimentally evaluated using polystyrene microspheres with diameters of 3.5µm, 4.5 µm, 6 µm, 12 µm, and 25 µm. The experiments demonstrated successful acoustic focusing of suspended particles toward the pressure node located near the center of the microchannel.



(a)

(b)

(c)

(d)

(e)

Fig. 4. Particle focusing results for different particle sizes. (a) the particles of 3.5µm; (b) the particles of 4.5µm; (c) the particles of 6µm; (d) the particles of 12µm; (e) the particles of 25µm.

Fig 4 illustrates the optimal focusing condition obtained for each particle size. During device operation, acoustic standing waves generated within the resonator channel exerted radiation forces on the suspended particles. The balance between acoustic radiation force and hydrodynamic drag determined the particles' focusing efficiency. Experimental observations showed that larger particles experienced stronger acoustic radiation forces and therefore exhibited more stable focusing behavior than smaller particles.

For particle diameters of 12 µm and 25 µm, nearly all particles were concentrated along the center of the microchannel with minimal dispersion. The focusing performance for 6 µm particles was also satisfactory, although a small amount of spreading was observed under certain operating conditions. In contrast, particles with diameters of 3.5 µm and 4.5 µm required significantly higher excitation voltages to achieve partial focusing, and a fraction of these particles remained distributed near the channel walls.

The experimentally measured resonant frequencies and corresponding excitation voltages required for optimal focusing are summarized in Table I.

TABLE I. MEASURED FREQUENCY AND VOLTAGE

Particles/ µm	**Frequency/kHz**	**Voltage/mV**
3.5	987.6	100
4.5	956.9	95
6	1013	43
12	959.6	50
25	1066	38

The resonant frequency of the acoustic cavity can be estimated using the half-wavelength resonator relationship.

$$f = v/2w \qquad (1)$$

where f is the resonant frequency, v is the acoustic wave velocity in the fluid medium, and w is the width of the microchannel. For the present device, the acoustic velocity in the pluronic solution was 1500 m/s and the channel width was 740 µm. Based on these parameters, the theoretical resonant frequency was calculated to be approximately 1.013 MHz. The experimentally measured resonance frequencies remained close to this theoretical value across all particle sizes.

The small variation in resonant frequency observed during experiments can be attributed to several factors, including temperature fluctuations, minor fabrication nonuniformities, and changes in the electromechanical response of the piezoelectric transducer during prolonged operation. Similar variations have also been reported in previously published acoustofluidic resonator studies [3], [7].

The relationship between required excitation voltage and particle diameter is shown in Fig 5. Experimental results indicate that the required driving voltage decreased with increasing particle size. This behavior is expected because the acoustic radiation force acting on a particle is strongly dependent on particle volume. Larger particles, therefore, experience stronger acoustic forces and can be focused efficiently even at lower acoustic excitation amplitudes.

The 3.5 µm particles required the highest excitation voltage of 100 mV and still exhibited incomplete focusing. This indicates that acoustic radiation forces acting on smaller particles become comparable to competing effects such as viscous drag and Brownian motion. In contrast, the 25 µm particles achieved highly stable focusing behavior at a significantly lower voltage of 38 mV.

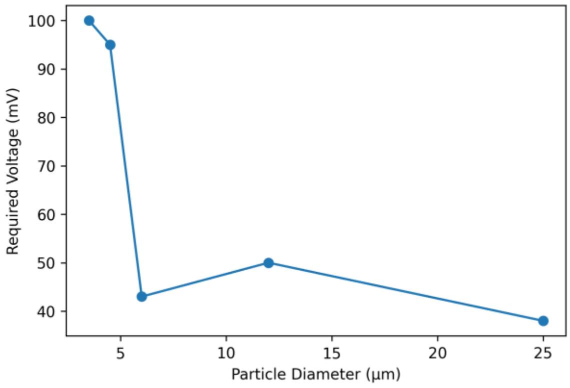


Fig. 5. Required voltage versus particle size.

The experimental results confirm that the proposed silicon-based acoustic resonator can effectively manipulate microparticles over a wide particle size range. The device architecture also provides flexibility for future implementation in applications such as continuous particle sorting, cell concentration, and biomedical sample preparation.

Future improvements may include optimizing channel geometry, integrating temperature control mechanisms, and implementing automated image-processing methods to quantitatively evaluate focusing efficiency.

IV. CONCLUSION

A silicon-based acoustic microfluidic resonator for spatial localization of microparticles has been successfully designed, fabricated, and experimentally demonstrated. The device utilized a piezoelectric transducer to generate acoustic standing waves inside a microfluidic channel.

Experimental results demonstrated successful focusing of particles ranging from 3.5 µm to 25 µm. Larger particles exhibited improved focusing efficiency and required lower excitation voltages. The measured resonant frequencies were found to be in close agreement with theoretical predictions.

The proposed device demonstrates the potential of acoustic particle manipulation for applications in particle sorting, cell separation, and lab-on-chip systems. Future work may include optimizing channel geometry, stabilizing temperature, and integrating with automated particle analysis systems.

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