CMOS COMPATIBLE GHZ ULTRASONIC FRESNEL MICROFLUIDIC ACTUATOR

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ABSTRACT

We report on an aluminum nitride based gigahertz frequency ultrasonic transducer to realize a microfluidic actuator using acoustic radiation force and acoustic streaming. The transducer uses focusing transducers placed in a Fresnel lens configuration, which generates bulk acoustic waves through the silicon substrate adding in phase at the focus. The transducer is planar and is fabricated with a CMOS compatible process, with no thin-film release steps. Peak displacement of 250pm was achieved at the focus with 1.06GHz and 5V amplitude input. Acoustic vortices were formed with microfluidic streaming velocity >2.6mm/s in water droplets placed on top of the transducer.

INTRODUCTION

Micro-particle manipulation in liquid is useful in many chemical, bio-medical, and biological applications [1]. Among the contactless manipulation mechanisms, optical and acoustic techniques are the most common. The laser based optical technique can produce a few pico-Newtons of trapping forces but cannot control larger biological objects and operate in a medium of high optical opacity [2]. On the other hand, acoustic devices can be more easily integrated with the microfluidic channel and have been shown to handle biological particles better because of longer wavelengths and higher radiation forces [1-3].

An acoustic wave propagating through a medium carries energy and momentum. Wave energy is dissipated into the liquid due to absorption and diffraction, and leads to momentum transfer to the liquid. When the wave encounters an object, scattering and net radiation forces can move the object [3, 4, 7]. These forces can result in particle trapping, streaming, and atomization [3, 4, 6]. As the acoustic radiation and streaming forces increase inversely with the acoustic wavelength in the medium, recent works have increasingly utilized higher frequencies for microparticle actuation [4]. The gradient force, resulting from the radiation force can further be enhanced by having a larger intensity difference between the center of the beam and the peripheral region [3].

Acoustic beam based manipulators such as acoustic tweezers that use high frequency focused ultrasonic beams have recently been explored [3, 5, 10]. Most of the high frequency ultrasonic beam manipulators reported so far use surface acoustic wave (SAW) transducers on non-CMOS compatible substrates such as lithium niobate, lithium tantalate or lead zirconate titanate (PZT) [3, 8, 9]. Further, their actuation requires >10V drive voltage.

Micro-particle actuators based on bulk acoustic wave (BAW) have also been reported for driving circulatory motion in microfluidic chambers and micro droplet ejection [3, 4, 6]. These millimeter scale devices have used PZT transducers, operate below 200 MHz frequencies [4, 6], and typically require a drive voltage of a few 10s-100s of volts.

Despite the advantages of using high frequency focused ultrasonic beams for manipulation of fluid-laden particles, several challenges in the implementation prevents easy adoption. The expense of fabrication, and generation and amplification of high voltages at these frequencies are two reasons often mentioned [3]. Another technological impediment is that considerable chip area is required to isolate the electrical interconnects of the transducers from the fluidic sample; as the fluid is placed on the same surface as the transducer.

Figure 1: a. Cross sectional schematic of the structure of the AlN-Si stack; b. image of the circular transducer on the receive side after fabrication; c. image of the Fresnel lens transmit transducer after fabrication.

In this paper, we present a microscale GHz focused-beam bulk acoustic wave microparticle manipulator which decouples the fluidic side from the actuator side. The device is fabricated without any thin-film release steps, using CMOS compatible materials such as aluminum nitride (AlN) solidly mounted to silicon substrate. Microfluidic streaming action was observed near the vicinity of the focus and the streaming velocity in water with 2μm diameter polystyrene microspheres was measured to be about 2.6mm/s for a 5V amplitude, 1.06GHz frequency continuous wave (CW) input.

FRESNEL MICROFLUIDIC ACTUATOR DESIGN

Planar AlN based transducer stack for GHz ultrasonics, similar to the one previously reported by our group [11], was used here. The AlN transducers were fabricated at the Institute of Microelectronics (IME) in Singapore under the IARPA - Trusted Integrated Chips (TIC) program. Resonant frequency of the transducer was 1.06GHz. The transducer consisted of 200nm molybdenum as electrode layers, 2μm thin film piezoelectric AlN, and 1.3μm thick insulating silicon dioxide layer, on a 725μm thick silicon wafer.

The electrodes on one (transmit) side of the silicon substrate were patterned in Fresnel zone plate (FZP) configuration in order to focus the emanating acoustic field through the substrate onto the opposing receive side. The receive electrodes were patterned to form a circular transducer of 2μm radius. Figure 1 shows the cross-sectional sketch of the simplified GHz transducer stack with planar FZP shaped AlN transducer on the transmit side and a small circular AlN transducer on the receive side. AlN in the regions without transduction are not shown here for simplicity.

In a Fresnel lens design, the distance from each annular zone to the point of focus is an integral multiple of the wavelength. As a result, the acoustic waves reach the focal point in phase, interfering constructively. If the wavelength of the wave in the medium is λ_{Si} , the focal length is F , then the radius of each annular zone is given

by [12]

$$r_n = \sqrt{\frac{n\lambda_{si}}{2} \left(F + \frac{n\lambda_{si}}{8}\right)} \quad (1)$$

The longitudinal speed of sound in silicon being $c_{si} = 7963\text{m/s}$, the AlN Fresnel lens radii were optimized to achieve a focal length of $\sim 725\mu\text{m}$ in silicon for 1.06GHz using PZFlex simulation software. Five Fresnel rings were used, and the radius of the outermost ring was $165\mu\text{m}$. The 2D PZFlex simulation result for normalized acoustic pressure in silicon showed a maximum pressure around $725\mu\text{m}$ (Figure 2).

Figure 2: PZFlex simulation results showing the focal length to be around $725\mu\text{m}$ in silicon.

ACOUSTIC STREAMING IN FLUIDS

Propagation of an acoustic wave results in acoustic radiation forces on particles and acoustic streaming of fluids. These are second order effects that are caused by nonlinearities in governing physics [3]. When the particle size is very small compared to the acoustic wavelength of the incident wave, i.e., $ka \ll 1$ where, k is the propagation constant in the fluid and 'a' is the radius of the particle, the acoustic force on the particle is determined by the spatial gradient of the force potential field U , with the particle movement from the region of high force potential to low force potential. The acoustic radiation force is given by [3, 4]

$$F_R = -\nabla U \quad (2)$$

and the force potential field is

$$U = \frac{4\pi}{3} a^3 \left[f_1 \frac{1}{2} \kappa_0 \langle |p_l|^2 \rangle - f_2 \frac{3}{4} \rho_0 \langle |v_l|^2 \rangle \right] \quad (3)$$

$$f_1 = 1 - \frac{\kappa_p}{\kappa_l} \text{ and } f_2 = \frac{2\left(\frac{\rho_p}{\rho_l} - 1\right)}{\frac{2\rho_p}{\rho_l} + 1} \quad (4)$$

$$\kappa = \frac{1}{\rho c^2} \quad (5)$$

In the above equations, $f_{1,2}$ parameters represent the monopole and dipole scattering coefficients, $\langle |p_l|^2 \rangle$ is the mean squared pressure, $\langle |v_l|^2 \rangle$ is the mean squared particle velocity in the fluid, ρ is the density and κ is the compressibility. The subscripts l denote the fluid and p denote the particle in the fluid medium.

In the Rayleigh regime, where $ka \ll 1$, scattering force due

to the reflection of propagating waves from the particle is small and is often neglected [3]. Whereas, in Mie scattering regime, where the particle size is comparable or larger than the acoustic wavelength, i.e. $ka > 1$, scattering becomes important. The force acting on the particle is now [4]

$$-F = \left\langle \int_S p_2 n dS \right\rangle + \left\langle \int_S \rho_l (n \cdot v_l) v_l dS \right\rangle \quad (6)$$

The integration is over an arbitrary surface, S that encloses the particle, and $\vec{n}$ is the vector normal to the surface. The second order pressure p_{2l} for an inviscid fluid can be obtained from first order terms

$$p_{2l} = \frac{1}{2} \kappa_0 \langle |p_l|^2 \rangle - \frac{1}{2} \rho_0 \langle |v_l|^2 \rangle \quad (7)$$

As the force potential is proportional to the cube of the particle radius, i.e., $F \propto a^3$, larger particles are displaced further away from the center of the ultrasonic beam compared to smaller particles [3]. Further, as the force gradient scales inversely with the acoustic wavelength, high frequency ultrasonic waves increase both radiation and streaming forces. It is observed that with increasing frequency, the radiation force increases much faster than the force due to streaming [5].

At higher frequencies, attenuation in fluids also play a key role as the attenuation coefficient, $\alpha(f) = \alpha_0 f^2$, is a strong function of frequency. In pure water, the characteristic attenuation length, α^{-1} , is below $100\mu\text{m}$ for frequencies above 500MHz at room temperature (Figure 3). This indicates that the force fields can be highly localized at GHz frequencies. This can be used in applications such as particle and cell separation, concentration, droplet production, encapsulation, active sorting, controlled heating, nanotube alignment, viscosity measurement, and aerosol production [4].

In harmonic systems, the particle velocity in fluid, v_l , is given by $v_l = \omega u_l$, where ω is the angular frequency of the acoustic wave and u_l is the displacement of the fluid due to the propagation of the ultrasonic wave. For fluids with low Mach numbers, $M = \frac{v_l}{c} \ll 1$, where c is the acoustic velocity in the fluid, the second order streaming velocity is related to the first order velocity in fluid by $v_{2s} \propto v_l^2$ [4]. As the displacement u_l is proportional to the applied voltage, it can be inferred that the second order streaming velocity increases as the square of the applied voltage, i.e., $v_{2s} \propto V_{in}^2$.

Figure 3: Characteristic attenuation length in water [13].

Figure 4: Experimental setup with Polytec UHF-120 vibrometer

EXPERIMENTS AND RESULTS

The GHz FZP actuator displacement profile was characterized using a Polytec UHF-120 vibrometer (Figure 4). Continuous wave (CW) signal from the vector signal generator (VSG) was applied to the Fresnel lens type transducer. Keeping the amplitude at 5V, frequency of the VSG was varied from 1.01GHz to 1.1GHz to determine the resonant frequency of the device. Figure 5a shows the plot of surface displacement on the receive side of the device under test (DUT) for various frequencies. Peak displacement profile was observed at 1.06GHz, which closely matches with the PZFlex simulation. Figure 5b shows the surface displacement profile of the DUT with peak displacement occurring at the location of the circular receive transducer. These two results confirm focusing of the acoustic wave emanating from the planar Fresnel lens transmit transducer.

Figure 5: a. Plot of surface displacement at point of focus vs. input frequency; b. scan profile showing surface displacement on the receive side.

The peak surface displacements at the center of the receive transducer as a function of applied voltages for a CW signal of 1.06GHz is shown in figure 6. The expected linear behavior of the displacement with applied voltage is observed.

From the displacement data for 5V amplitude input, the average acoustic intensity I_{avg} ,

$$I_{avg} = \frac{1}{2} p v_l, \quad (8)$$

with ultrasonic pressure $p = \rho c v$, was calculated to be 1.7 KW/cm^2 on the silicon dioxide surface located on the receive side. Thus, a very high intensity ultrasonic beam was realized from the GHz FZP microfluidic actuator.

A metal washer/cylinder was adhesively attached on the receive transducer side such that the receive transducer was centered within the washer. The inner diameter of the cylinder was 3.25mm and the height was 0.8mm. This formed a fluid capacity of $6.6 \mu\text{l}$. The well formed by the cylinder was filled with a mixture of deionized water, polystyrene (PS) microspheres of $2 \mu\text{m}$ diameter, and soap solution for reducing surface tension between spheres and water. Figure 7a shows the 3D model of the microfluidic actuator with the well and liquid mixture.

Figure 6: Box plot of surface displacement at the point of focus with different applied voltages. Twenty data points are plotted for each voltage.

The test setup was slightly modified for the microfluidic experiments; the input to the DUT came from the same VSG, but the DUT was now placed under a Keyence VW-9000 high speed microscope. Upon application of an input signal from the VSG to the transmit transducer, streaming vortices around the receive transducer, or the region of focus was observed. Figure 7c shows an image of the streaming patterns observed around the region of focus.

The amplitude of the input signal was varied from 1 – 5V, and the videos of the micro particle streaming movements were recorded. From these videos, the streaming velocity of the particles were estimated. The quadratic behavior of streaming velocity with applied voltage is shown in Figure 8. Average streaming velocity of about $2636 \mu\text{m/s}$ was observed for an applied voltage of 5V. Such high streaming velocities were observed because of the enhanced radiation and streaming forces arising due to GHz frequency acoustic waves, and highly localized microbeam from the Fresnel lens configuration.

CONCLUSION

In this paper, a GHz ultrasonic microfluidic actuator is presented. The device employs a thickness mode AlN piezoelectric transducer stack, which is in principle CMOS compatible. The thickness mode resonance of the FZP transducer generates bulk waves into the silicon substrate that focus constructively at the intended focal point, which is on the opposite side of the wafer. Although a smaller receive transducer was used here to measure the received signals electrically, the receive transducer is not required for microfluidic actuation. The focused ultrasonic wave displaces the silicon dioxide surface on the receive side which then propagates through the fluid.

Owing to high dissipation of the GHz ultrasonic field in water,

Figure 7: a. 3D sketch of the microparticle actuator assembly; b. cross sectional sketch showing the streaming vortices in liquid around the receive transducer; c. streaming patterns observed around the circular transducer in the receive side.

Figure 8: Box plot of streaming velocity versus applied voltage. Ten data points are plotted for each voltage.

a strong acoustic streaming force is generated; which pushes the fluid out and recirculates forming spherical vortex shell around the focal point. The highly defined focal point is an opportunity to create microfluidic systems with distributed fluidic sources controlled from the transmit transducer side.

The ability to change the frequency of the ultrasound and amplitude can also be used to spread the spatial extent of the force and its amplitude. Since the voltages required are CMOS compatible, and the fabrication process is also CMOS compatible, microfluidic samples placed on the receive side of the silicon die can be enabled easily with the ultrasonic actuator presented here. Further work is required to investigate the effect of microfluidic channel boundary conditions to contain the field and generate flow in channels.

In summary, a GHz actuator was designed, fabricated and tested for microparticle actuation. This can find applications in microparticle capturing, and biological assays requiring localized mixing and pumping. The device when integrated with CMOS can

not only reduce the size and cost of the test setting drastically, but also enable digital control and automation of particle manipulation in a closed lab-on-chip environment.

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