2D CMUT Array Based Ultrasonic Micromanipulation Platform

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Abstract—**In this paper, we designed and simulated a multilayer planar resonator with target frequency of 2.5 MHz which is created over a row/column-addressed 2D CMUT array. We have shown through finite element modeling and simulations that a particle can be trapped and manipulated both in lateral and axial directions inside the fluid channel by activating CMUT elements; And calculated acoustic radiation force acting on a polystyrene particle of 10-μm radius. We fabricated a 32x32-element row/column-addressed 2D CMUT array on a glass substrate using anodic bonding technology. This approach provides a cost effective and easily implementable solution to micro-particle trapping and handling.**

Keywords—CMUT, planar resonator, acoustic tweezers, row/column-addressing, anodic bonding, microfluidics

I. INTRODUCTION

Acoustic tweezers have gained increased attention as they allow non-invasive trapping and handling of sub-micron sized particles which hold many promising applications in the field of biological sciences. Optical tweezers [1], which employ laser beams, emerged as a powerful tool for micro-particle trapping and manipulation. The use of optical tweezers, however, has been restricted particularly in applications that require longer holding time as the intense trapping light could damage the biological structure and could also damage the trapped specimen through a process known as photodamage [2]. Acoustic tweezers, on the other hand, use ultrasound for particle handling and have drawn particular attention as they allows separation of particles based on their mechanical characteristics, such as shape, size, compressibility, and density. Also, this approach is cost-effective and can easily be implemented in a lab environment.

A multilayer ultrasonic resonator can be used for acoustic tweezing, which simply utilizes an ultrasound transducer array and a reflector to generate acoustic standing waves along the fluid column. The generated wave creates fixed patterns of pressure nodes/antinodes, where the particles can be trapped. For half-wave resonator devices thickness of the fluid channel is kept at half wavelength of the operating frequency, so that the pressure minimum is close to the center of the fluid channel height.

So far, piezoelectric materials have been the core element in implementation of acoustic tweezers. The CMUT technology is an alternate to piezoelectric transducer technology which holds several potential benefits such as flexibility in the design parameters, fabrication using photolithography techniques and low self heating in continuous wave operation. As an attractive alternative of piezoelectric materials, CMUTs overcome the difficulties in miniaturization and provide a suitable environment for microfluidic applications that can be easily fabricated on chip without requiring a matching layer.

Building a channel on top of a 2D CMUT array will allow two dimensional manipulation of particles. We, therefore, developed row/column-addressed (RC) CMUT arrays that serve as a basis of the microfluidic platform. RC CMUT arrays have recently drawn attention as it reduces the number of connections from N^2 (where N corresponds to the number of elements on either side) to N+N. Early row/column-addressed CMUT arrays were lacking single element actuation which leads to edge effects in imaging applications [3] [4]. This issue has been addressed by using top orthogonal to bottom electrode (TOBE) arrays [5] [6], which address a single element by biasing column and exciting the corresponding row with pulse. The fabrication of TOBE arrays is done on SOI wafers that increases complexity of the overall process and also incurs parasitic effects due to silicon substrate. The issue has also been addressed by integrating apodization in the transducer array [7]. These devices are fabricated by bonding two silicon-on-insulator (SOI) wafers which is comparatively a simpler technique but the rows of these devices get coupled with the bottom SOI wafer and hence degrades the performance of the devices. We adapted our previously reported CMUT fabrication technique, using anodic bonding, to fabricate RC CMUT arrays [8]. This approach offers many advantages such as simpler fabrication, increased fill factor and effective membrane uniformity. Also,the use of borosilicate glass as the substrate prevents electrical coupling between the bottom electrodes and the substrate.

In following section the design of an ultrasonic planar resonator has been discussed along with details of a 3D FEM model. Optimization of the CMUT array parameters along with the resonator parameters are discussed and the proposed fabrication flow is given in the fabrication section.

II. DEVICE DESIGN AND MODELLING

The working principle of a half-wavelength multilayer planar resonator is given in Fig. 1, that illustrates particle handling and consists of a 2D CMUT array for transduction mechanism, a microfluidic channel, and a glass reflector. Glass is chosen as a reflector because of its high acoustic impedance as compared to fluid, which makes it a great option for standing wave acoustofluidics. Borosilicate glass is chemically inert and hence is advantageous during the processes of microfabrication

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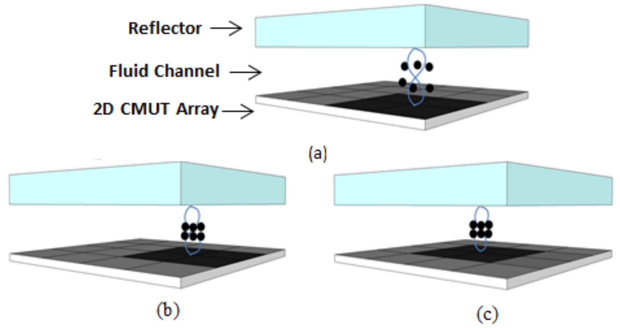

Figure 1: Acoustic tweezing through CMUT array-controlled multilayer resonator. (a) Ultrasonic standing wave is created that draws particles towards pressure nodal plane. (b) Lateral force traps particles on the center of active elements. (c) Driving a sub-set of elements allows 2D manipulation of the trapped particles

also, transparency of the material allows observing the particle behavior under a microscope.

Active CMUT elements generate a sound wave that reflects off the glass and creates an ultrasound standing wave within the fluid chamber. Height of the fluid column is kept close to half wavelength so that the pressure minimum is located in the center. The standing wave is responsible for creating potential and kinetic energy gradients that exert force on micro-particles [9], called acoustic radiation force. The main component is the axial component of radiation force which is given by (1) if the particle radius is very small as compared to the wavelength [10]. This force is responsible for driving the particle towards pressure node or antinode depending on acoustic characteristics of the particle.

$$F_{axial} = 4\pi E k \varphi \sin(2kx) R^3 \tag{1}$$

where k is wave number, R is the particle radius, x is the particle position in the direction of wave propagation and φ is the acoustic contrast factor which is given as:

$$\varphi = \frac{\rho_p + (2/3)(\rho_p - \rho_f)}{2\rho_p + \rho_f} - \frac{\rho_f c_f^2}{3\rho_p c_p^2} \tag{2}$$

E is the acoustic energy density which is given by the following equation:

$$E = \frac{P^2}{4\rho_f c_f^2} \tag{3}$$

P is the maximum pressure, ρ_f and ρ_p are the densities of fluid and the particle respectively. c_f and c_p are sonic velocities of fluid and of the particle.

Lateral component of the radiation force will trap particles above the center of active elements. Although it is much smaller than the axial force, yet it is required to agglomerate particles in the trapping site and to counteract the fluid drag force. An estimate of lateral trapping force on the particles is obtained from the Stoke's law which is valid because the Reynolds number of the flow is 2 x 10^{-4}.

$$F_L = 6\pi\mu c_p.R \tag{4}$$

where μ is the viscosity of water.

III. Finite Element Analysis

Finite element methods (FEM) are used to analyze the operation of the device. A quarter 3D model of the half-wave multilayer planar resonator with CMUT cells was created in ANSYS v16.0, (ANSYS Inc., Canonsburg, PA). Typically the design of a CMUT cell consists of a parallel plate capacitor, with the bottom electrode rigidly placed and the top electrode residing on a flexible plate. Silicon plate was modeled with SOLID45 element for structural and electrostatic analysis of the design. The electrodes were modeled by using electromechanical transducer elements, TRANS126. To model the fluid domain 3D acoustic elements (FLUID30) were used. The linear elastic and linear acoustic domains were coupled by defining a solid-fluid interface at the boundary.

For a mesh dependent study, a mesh of λ/30 was generated, where λ is the wavelength of sound wave in each material. The assigned material properties and layer dimensions are given in Table 1. Two elements comprising of 4x4 square CMUT cells with 2-µm thick membranes, 50-µm side length were modeled to generate pressure gradient in the fluid column. The transducers were biased at 64-V DC and were driven with a 12-V AC signal. The resonant frequency of a single CMUT cell was determined by performing a harmonic analysis, and was found to be 2.43 MHz. Simulation results clearly indicate the trapping position at pressure minima near the center of the fluid channel.

Table I: Model Dimensions and Layer Properties

Layer	Material	Density kg/m^3	Thickness µ	Sonic Velocity m/s
Fluid	Water	1000	300	1500
Reflector	Glass	2500	300	5640
Particle	Polystyrene	1055	Diameter 10	1958

Harmonic analysis was performed to obtain pressure field distribution and velocity of the particles in fluid medium. By activating adjacent 4 (2x2) transducer elements, a pressure node was created at the center of the fluid channel which shows trapping site of the particle, as can be seen in Fig. 2.

In the row/column-addressed approach, the column electrodes are biased with DC voltage whereas voltage pulses are applied to the rows. This scheme gives no electronic control over one single element and therefore to understand the effect of inactive elements, we simulated a 6x6 CMUT array with each element containing 3x3 CMUT cells. A transient analysis was performed for a time period of 400-ns to observe pressure field extending in the lateral and axial directions. The pressure field generated by the inactive elements is very low and therefore does not contribute in particle handling (Fig. 4)

The force acting on a 10-µm polystyrene sphere was calculated by using (1) and (4). The calculated maximum vertical force is 132 pN and lateral force is 3.31 pN.

Element isolation was simulated by applying DC on a single column and AC to the corresponding row. The pressure field generated by the non-active elements is very small as compared to the one generated by active elements, given in Fig. 4.

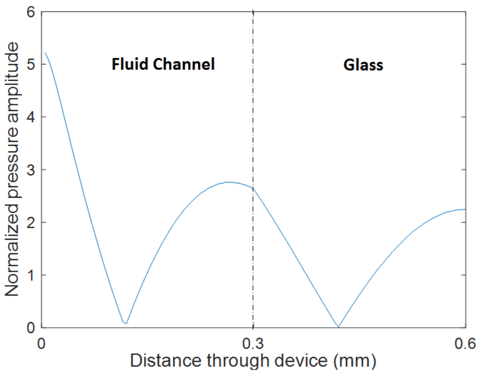

Figure 2: Normalized pressure distribution through thickness of the channel

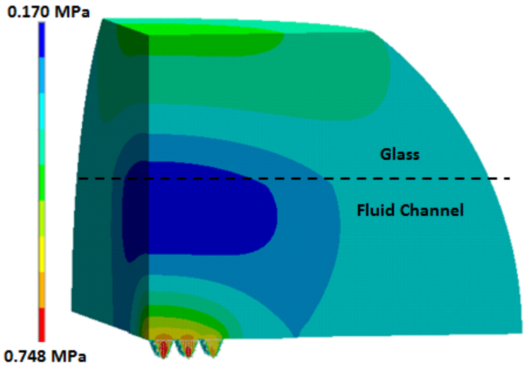

Figure 3: Pressure distribution in the FEM model

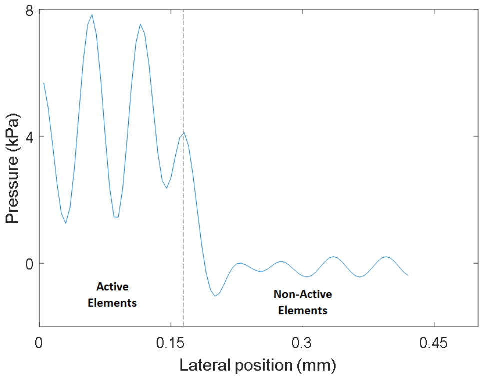

Figure 4: Lateral pressure distribution along the center line of fluid channel for 2x2 active elements

IV. FABRICATION

The row/column-addressed CMUT arrays are fabricated using anodic bonding [8]. A borosilicate wafer of 700-µm thickness was thoroughly cleaned for removal of impurities and was used as the starting substrate. First photolithography patterned the desired shape of cavities on the substrate by using a negative photoresist, Fig. 5(b). The wafer was hard baked at 125°C to improve adhesion between the wafer and the photoresist.

350-nm deep cavities were then created, Fig. 5(c), in 10:1 buffered oxide etch (BOE) solution as it results in less surface roughness and more uniform etching. 130-nm gold along with 20-nm chromium adhesion layer was deposited to obtain 150-nm bottom electrodes, Fig. 5(d).

An insulation layer of silicon nitride is incorporated between the top and bottom electrode to avoid any electrical shorting if the two electrodes come in contact with each other in case the CMUT cell collapses. To form the insulation layer a silicon nitride layer of 200-nm thickness was deposited on top of the device layer of the SOI wafer by plasma enhanced chemical vapor deposition (PECVD).

The borosilicate glass and the silicon nitride surfaces were bonded together at 350°C under 2.5-kN down force and 700-V bias voltage in vacuum, Fig. 5(e). The handle layer was then ground to 100- µm and the rest was removed by using heated tetramethyammonium hydroxide (TMAH) solution at 85°C. The membrane was released after removing the BOX layer by using 10:1 BOE solution, Fig. 5(f).

In order to access bottom electrodes, silicon/silicon nitride layer on the location of pads was etched by reactive ion etching (RIE) with SF6, Fig. 5(g); Gas that got trapped in the cavities during bonding was also evacuated in this step. This step also separated rows and created dicing lines that separate arrays of different geometries. The photoresist was removed by oxygen plasma. To seal the cavities a conformal PECVD silicon nitride layer was deposited, Fig. 5(h), the thickness of which was chosen to be three times the cavity height for a proper sealing [8]. This layer also serves as an insulation between the transducers and the microfluidic channel.

By using the final mask, silicon nitride was removed by RIE at locations where contact pads would be made, Fig. 5(i). Finally, 180-nm gold and 20-nm chromium was deposited to ensure a good electrical contact, Fig. 5(j). Fig. 6 shows the fabricated RC array (left) and the close-up view shows the array elements (right).

V. CONCLUSION

In this paper we designed and simulated electronically controlled trapping and manipulation of micro-particles in a microfluidic chamber. In simulations, a 2D CMUT array has been integrated into a multilayer ultrasonic planar resonator to trap the particles along the center of the channel and manipulate them in horizontal or vertical directions by switching elements.

We also presented a simple fabrication process for creating 2D row/column-addressed CMUT arrays that can be easily integrated with an electronic circuit and also incorporates microfluidic channel very conveniently. The use of an insulator as a substrate considerably reduces the parasitic capacitance and thus improves sensitivity of the devices. This fabrication process can therefore be further extended for imaging applications as well.

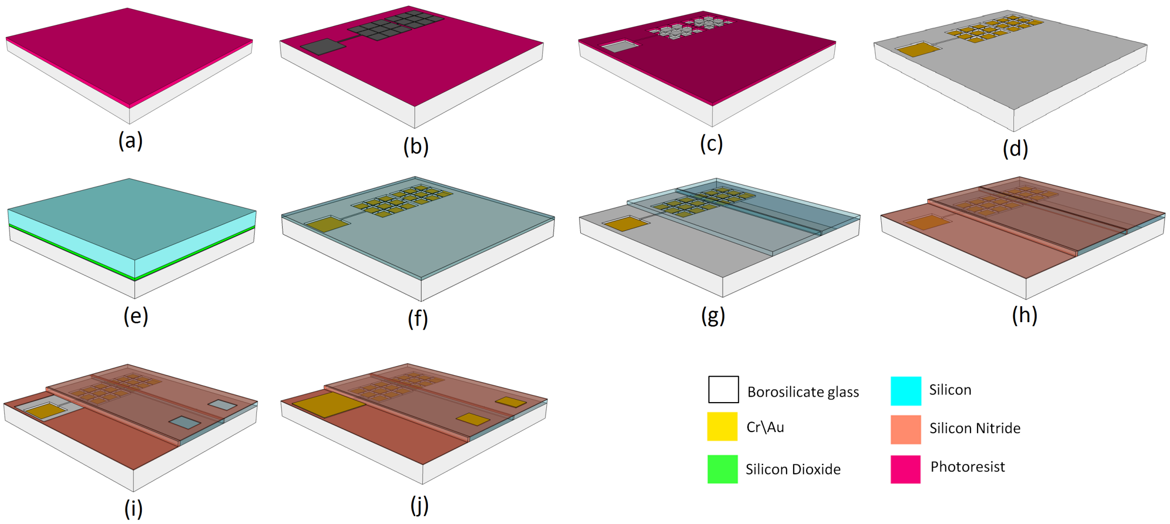

Figure 5: Fabrication Flow: (a) Photoresist coated on top of the substrate. (b) Cavity pattern through photolithography. (c) Cavities through BOE etch. (d) Metal deposition and lift-off. (e) Anodic bonding. (f) Handle and Box Removal. (g) Silicon/silicon nitride etching for addressing rows. (h) Silicon nitride deposition. (i) Reaching pads through silicon nitride etching. (j) Metal deposition and lift-off.

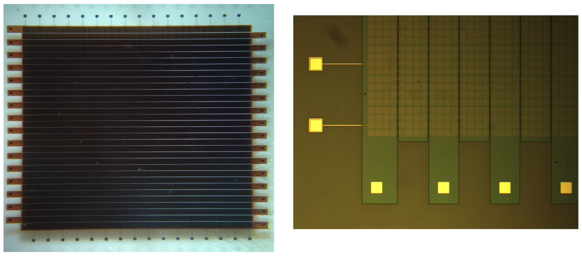

Figure 6: Fabricated RC CMUT array

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