MICROMACHINED CAPACITIVE TRANSDUCER ARRAYS FOR MEDICAL ULTRASOUND IMAGING

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Abstract— **The fabrication and characterization of micromachined capacitive ultrasonic transducers are discussed with emphasis on the array operation. Several micromachined capacitive transducer arrays have been fabricated using CMOS compatible micromachining technology. Pulse echo experiments show around 100% bandwidth and the potential for phased array imaging. Radiation pattern and cross-coupling measurements are performed on the 1-D and 2-D arrays. Cross-coupling mechanisms due to Lamb and Stoneley type waves are identified by experiments and verified by theoretical calculations. Deep trench etching between array elements and wafer thinning are proposed to reduce the effects of these spurious waves for certain applications. Initial results on array imaging with 64 element 1D micromachined capacitive transducer arrays are also presented.**

Keywords— **Ultrasonic transducer, array imaging, micromachining, cross talk**

I. Introduction

Capacitive micromachined ultrasonic transducers (cMUT) have been recently emerging as an attractive alternative to conventional piezoelectric transducers [1]. They offer a larger set of parameters for optimization of transducer performance as well as ease of fabrication and electronics integration [2]. The fabrication process and theoretical modeling of single cMUT devices were reported earlier [3], [4], [2]. Many applications, especially immersion imaging applications, demand better understanding and improvement of cMUTs both in terms of individual device performance and array behavior. Cross coupling through the array structure and the fluid medium is one of the most important factors affecting the array operation [5]. The level of these disturbances can be quantified by radiation pattern measurements, electrical measurements on the array elements, and by detection of structural displacements using optical probes [5].

Several 1-D and 2-D cMUT arrays as well as test structures consisting of single isolated elements have been fabricated for experimental characterization. Radiation pattern measurements and optical probe measurements are performed using these structures. The results are related to Lamb waves propagating in the silicon wafer and to the Stoneley-type waves propagating at the fluid-silicon wafer interface. Images of radiating transducers and aluminum targets are also obtained using a 64 element 1-D array around 4 MHz to show the feasibility of array imaging by cMUTs.

In this paper, the fabrication process of 1-D and 2-D cMUT arrays is briefly explained. Then, the experimental and theoretical results on spurious mode excitation in the structure and their effects on cross coupling are discussed. Finally, the initial imaging results are presented.

II. CMUT Array Fabrication Process

One of the basic advantages of cMUT is the ease of fabrication. Once a single capacitor is optimized, it can be used as a building block of a more complex transducer geometry. This is achieved by simply defining the transducer by lithography, enabling the parallel fabrication of 1-D, 2-D arrays and individual cMUTs on a single wafer.

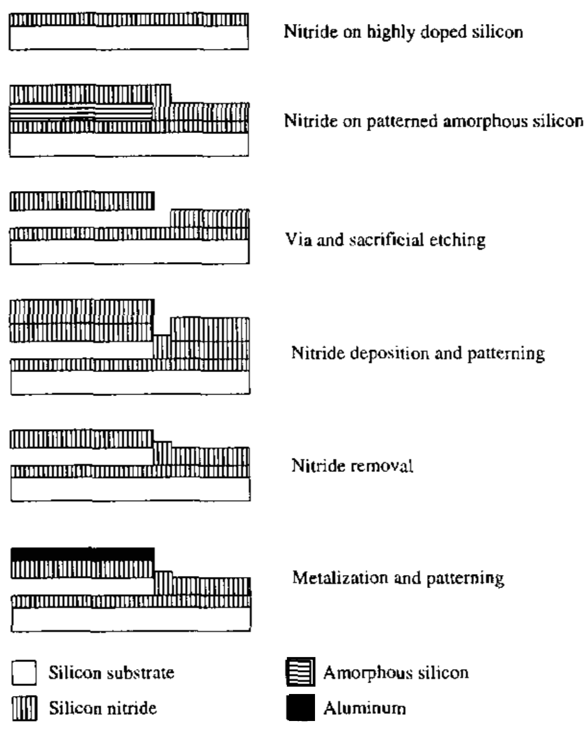

Fig. 1. Fabrication process of cMUTs array.

The process flow for a single capacitor device is shown in Fig. 1. The fabrication process starts with 4 inch silicon wafers heavily doped with 4 hour phosphorus gas phase drive-in at 1000°C to achieve good conductivity at the wafer surface. A thin layer of LPCVD nitride is deposited at 800°C as an insulator and an etch stop in the sacrificial etch to be performed later. A sacrificial polysilicon layer is subsequently deposited and dry-etch patterned into octagonally shaped islands to define the active transducer regions.

Nitride as the membrane material is then deposited with desired stress control. Vias are dry-etched to allow sacrificial etch, followed by vacuum sealing and selective removal of sealing material to preserve the original membrane thickness.

Lastly, aluminum is sputtered and wet etch patterned to act as the top electrode. The same aluminum deposition also defines bonding contacts to the bottom electrode through a lithographically defined trench in silicon bulk.

For ultrasonic imaging applications in the frequency range of 2-5 MHz, both 1-D and 2-D arrays are designed and fabricated with 400 μm element pitch. The top view images of 64 element 1-D linear transducer arrays and a 25 element 2-D transducer array test structure are shown in Figs. 2 and 3, respectively. In addition, isolated single 1-D and 2-D array elements are also fabricated to be used in characterization experiments.

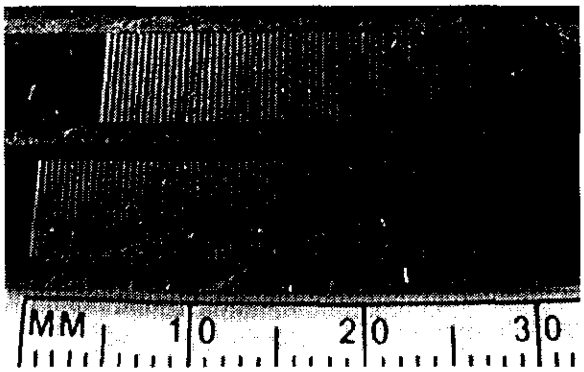

Fig. 2. Top view of 64 element 1-D array.

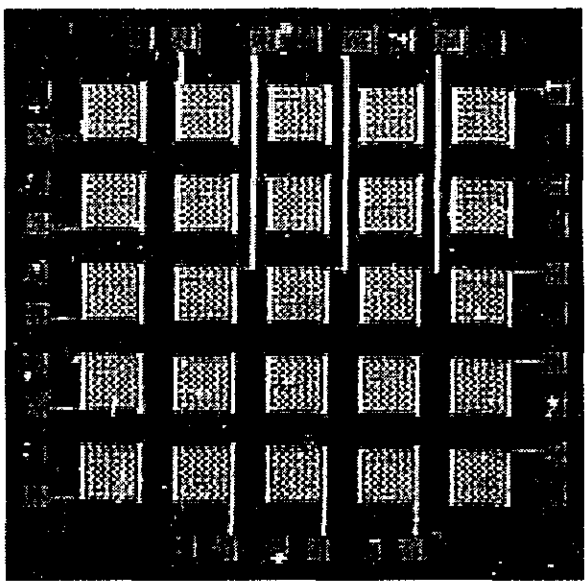

Fig. 3. Top view of 5x5 2-D test array.

III. Experimental Characterization

The transducers are characterized mainly by radiation pattern and optical displacement measurements. The radiation pattern measurements are performed in an oil bath using 50Ω off the shelf electronics. The transmitting cMUT is excited by 40 cycle tone burst signals while it is rotated around its axis. The waveforms received by another cMUT are digitized and in certain circumstances, data sample averaging is performed to obtain better signal-to-noise ratio.

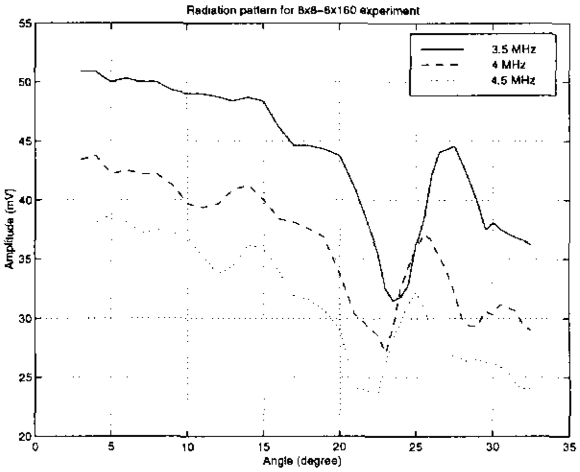

Fig. 4. Radiation pattern of an isolated 1-D array element.

The radiation patterns of an isolated single 1-D array element at 3.5, 4 and 4.5 MHz are shown in Fig. 4. The transmitting transducer element is 5.6 mm long and has a width of 0.28 mm, and the receiver element is a 0.28 mm square cMUT. There is a significant dip in the radiation pattern around 22 degrees at 4 MHz (f*d=2.0 MHz*mm), which is indicative of a spurious radiating mode in the structure. The angle of the dip varies with frequency, suggesting that the wave mode has a certain dispersive characteristics. Since the silicon wafer itself is an acoustic waveguide, it supports Lamb wave propagation when excited at its surface by the vibrating membranes [6]. In Fig. 5, the critical angle of Lamb waves in silicon wafer immersed in oil is plotted as a function of frequency thickness product. It is observed that both the critical angle and the phase velocity dispersion of the lowest order antisymmetric (A_0) mode match the measurements in Fig. 4. The lowest order symmetric (S_0) mode is also excited in the silicon, however, calculations indicate that its excitation efficiency is much lower. Nevertheless, it can be concluded that the A_0 and S_0 modes are significant factors in the cross coupling problems.

Figure 5 also indicates that a thinner silicon substrate will result in a higher critical angle for the A_0 mode. This is also verified by etching the silicon substrate down to 180 μm and measuring the radiation pattern at 4 MHz (f*d=0.72 MHz*mm). The result is compared to that of a 0.488 mm silicon substrate in Fig. 6, which shows that the beam pattern is smoother and the dip occurs around 32 de-

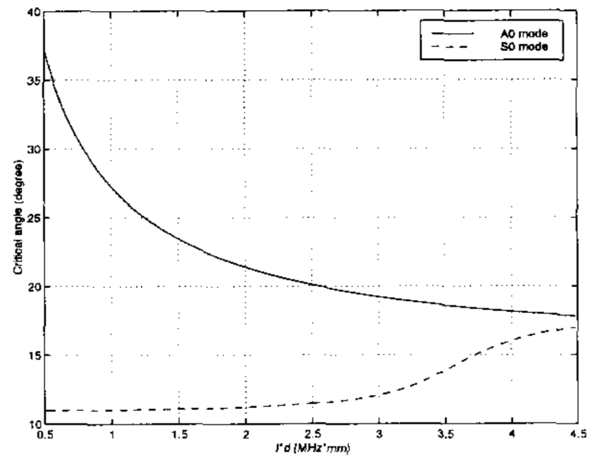

Fig. 5. Critical angle of Lamb waves in silicon immersed in oil.

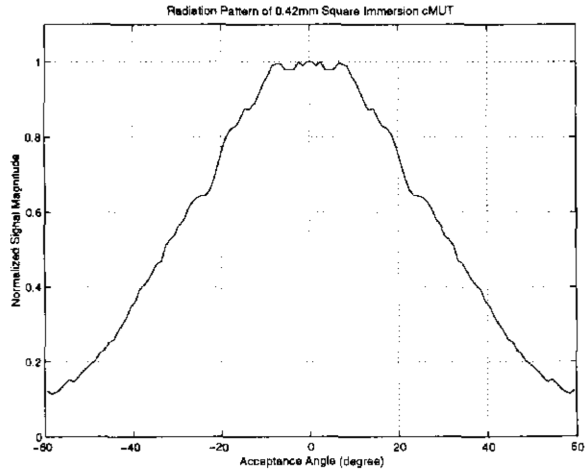

Fig. 7. Radiation pattern of 2D array element.

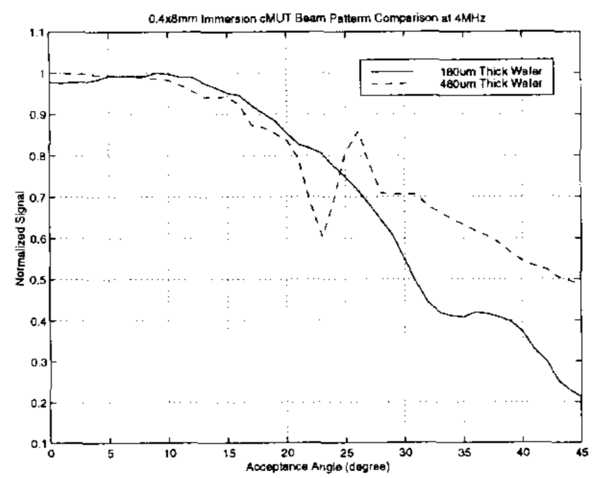

Fig. 6. Radiation pattern for different substrate thickness.

grees as predicted by calculations. For certain applications such as ultrasonic cameras, where the array is used only for reception with a limited acceptance angle, this method can be used to eliminate spurious effects due to the A_0 mode.

The radiation pattern of a 0.42 mm square 2-D array element shown in Fig. 7 indicates that the A_0 mode has much less effect in this case. This is mainly due to the fact that the Lamb waves generated by the small 2-D array element are diffracted cylindrically as opposed to the collimated beam generated by the 1-D array element.

An optical displacement probe is also used to investigate the ultrasonic waves excited in the silicon wafer that can cause cross coupling problems in cMUT arrays. A laser beam is focused on the surface of the silicon wafer approximately 1.5 mm away from a 1-D array element and the displacement signal is recorded. Figure 8 shows signal at this first point in the upper trace. When the measurement point is displaced 1 mm, the recorded signal is essentially unchanged except for a time delay of 0.7 μsec, corresponding to a non-dispersive phase velocity of 1470 m/sec. This is verified by propagating the first signal with that phase velocity, which results in the signal with dashed lines. A theoretical calculation of possible modes in silicon wafer facing a fluid shows that a Stoneley-type wave can propagate at the oil-silicon interface [7]. The phase velocity of this wave in a 0.5 mm silicon wafer is plotted as a function of frequency in Fig. 9. The phase velocity rapidly increases with frequency and in the limit approaches to the speed of sound in the fluid. This is consistent with the optical measurements where the signal has frequency components between 1-9 MHz. The energy flow of the wave is concentrated at the surface of the silicon wafer, suggesting that etching trenches between array elements can significantly reduce the cross coupling due to these interface waves.

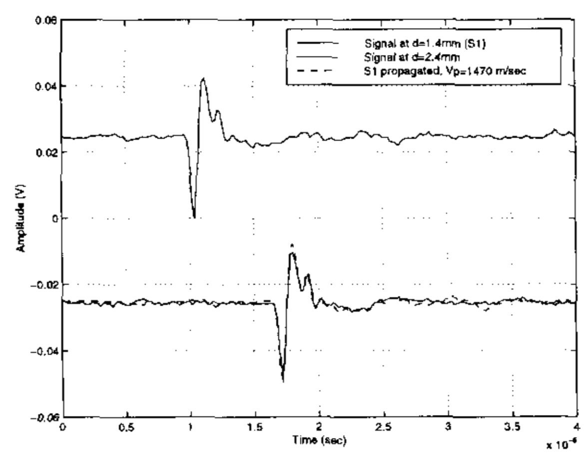

Fig. 8. Optical displacement signals due to Stoneley wave.

IV. Imaging Results

Ultrasonic images of several different structures are obtained using the 64 element 1-D linear array. Figure 10 shows the image of a 0.28 mm square cMUT source emitting pulses with a center frequency of 4 MHz. The signal

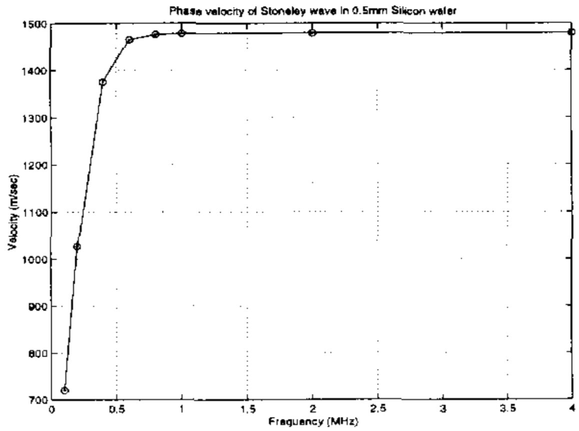

Fig. 9. Calculated Stoneley wave phase velocity.

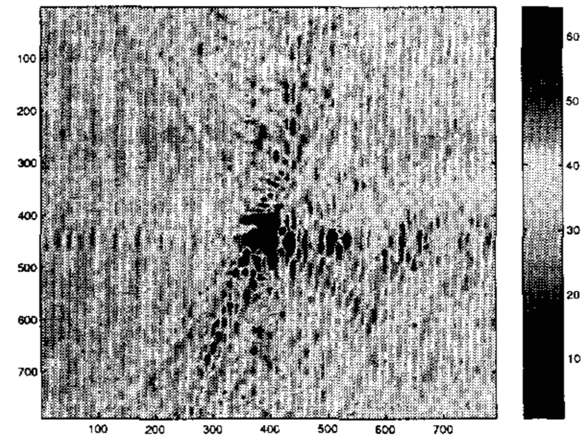

Fig. 11. Aluminum rod image reconstruction.

level of the image indicates that the system has more than 20 dB signal-to-noise ratio. An image of a 2 mm diameter aluminum rod is also reconstructed with the same 1-D array in pulse echo mode as shown in Fig. 11. The ghost images of the rod are due to the creeping waves circulating around the rod and received by the transducer array at a later time.

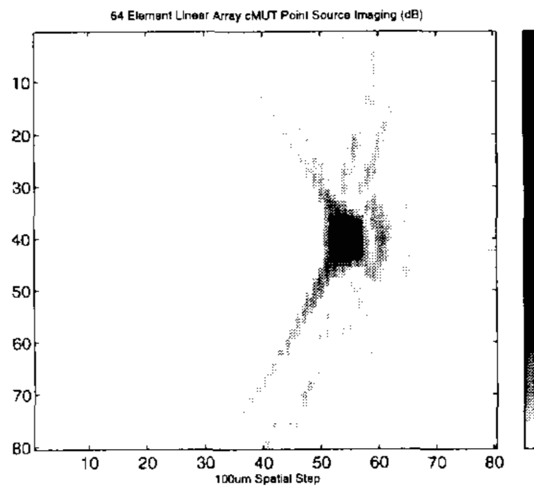

Fig. 10. Point source image reconstruction.

V. Conclusion

Several micromachined capacitive transducer arrays have been fabricated in this paper. Initial results on array imaging with 64 element 1-D cMUT arrays are presented. The radiation pattern and crosstalk measurements on 1-D and 2-D test arrays indicate that A_0 mode Lamb wave in the substrate and Stoneley type waves at the solid-liquid interface are important cross coupling sources. Several solutions to reduce the cross coupling have been suggested and tested. Further quantitative analysis has also been conducted, and it will be the subject of another paper. The fabrication techniques and results reported herein indicate that cMUT arrays are an attractive alternative to piezoelectric array transducers in immersion ultrasonic imaging applications.

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