Finite Element Modeling of Capacitor Micromachined Ultrasonic Transducers

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Abstract - A finite element model of cMUTs is constructed using the commercial code ANSYS. The complex load impedance seen by individual cells is compared with the plane wave real impedance seen by a parallel combination of the cells to make a transducer. The result shows the origin and level of crosstalk between array elements, with evidence of coupling through Stoneley and Lamb waves. For reduction of the crosstalk level, the effects of various structural variations of the wafer are investigated, which includes change of wafer thickness, etched trenches in the wafer and the walls between array elements.

I. INTRODUCTION

Capacitor Micromachined Ultrasonic Transducers (cMUT) are gaining more and more acceptance as an alternative to piezoelectric transducers in many applications. A simple Mason type equivalent circuit model based on the theoretical model [1] has been used to predict the behavior of cMUTs. However, the equivalent circuit model lacks such important features as coupling into the substrate and the ability to predict crosstalk between elements of an array of transducers. Hence, in this paper, a finite element model of cMUTs is constructed using the commercial code ANSYS for multi-dimensional analysis of the crosstalk mechanism in cMUTs. Through various analyses with the FE model, we investigate the origin and level of crosstalk between array elements, with evidence of coupling through Stoneley waves propagating at the transducer-water interface and coupling through Lamb waves propagating in the wafer. For reduction of the crosstalk level, we investigate the effects of several structural schemes, which include the influence of etched trenches in the wafer on the crosstalk through Lamb waves as well as the influence of fences between elements on the crosstalk through Stoneley waves.

II. FINITE ELEMENT MODEL OF A SINGLE cMUT

As a first, a single cMUT transducer is modeled with the ANSYS. Figure 1 is the schematic view of the configuration.

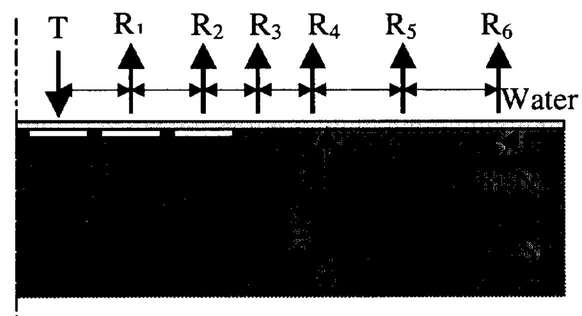


Fig. 1. Schematic view of an underwater single cMUT transducer on a Si wafer.

There is one cMUT transmitter and there are two cMUT receivers at the surface of a silicon wafer. Geometry of the three cMUTs is the same. Each cMUT consists of a Si_3N_4 membrane of 0.8 μm thickness and 35 μm diameter and a vacuum gap of 0.15 μm depth in the wafer. The whole solid structure is immersed in water. The transmitter cMUT is excited by a surface pressure distributed over only half of its membrane surface, and the crosstalk pressure and displacement in response to the excitation is measured at various points denoted R on the silicon surface. Figure 2 is the FE model of the structure in Fig. 1. The silicon wafer is 4 mm long. The circumference of the water is enforced by infinite boundary conditions in order to avoid the limit imposed by the finite dimensions in the model. The whole model consists of 26,500 nodes and 26,300 elements. With the model, various time domain and frequency domain responses of the structure can be obtained through transient and harmonic analyses. These responses of the receiver cMUTs in accordance to the excitation pressure allow the analysis of the crosstalk mechanism.

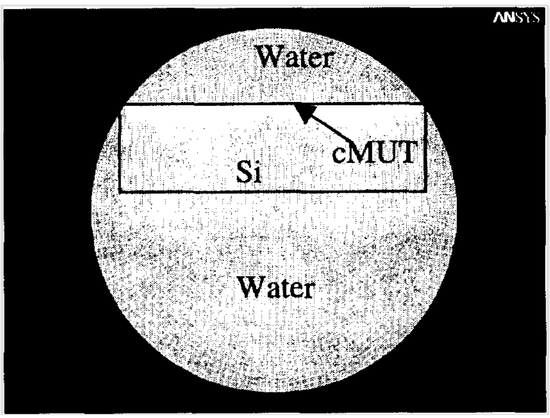
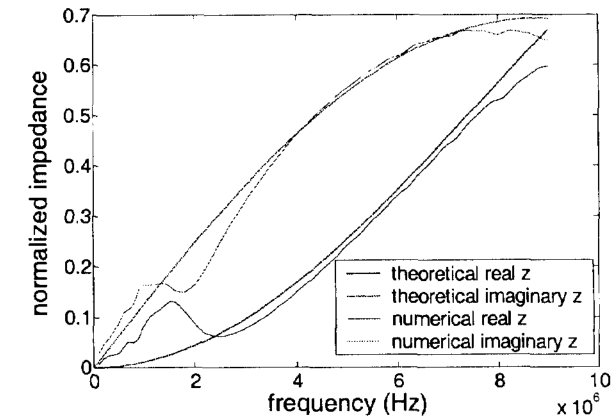
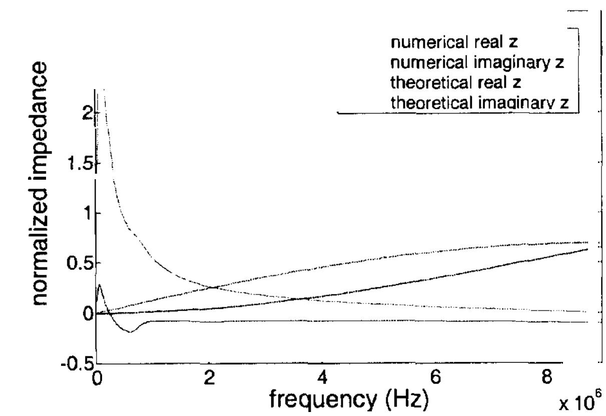


Fig. 2. Finite element model of the underwater single cMUT transducer on a Si wafer.

The load impedance of each cMUT in Fig. 1 can also be calculated from the frequency spectrum of displacement and pressure. Figure 3-(a) shows that the transmitter cMUT has the load impedance as a complex value (solid line). The theoretical complex impedance (dotted line) of a circular piston on an infinite baffle is also shown in the figure and is compared with the numerical data [2]. The agreement between the numerical and theoretical values verifies validity of the FE model. The complex load impedance means that the transmitter cMUT works almost like a point source due to its small dimension, and there is a direct relationship between the excitation pressure and the excited displacement. On the other hand, in Fig. 3-(b), the numerical complex impedance of the receiver cMUT does not show any agreement with the theoretical value, which means that the crosstalk pressure has no cause-and-effect relationship with the crosstalk displacement. This result says that the crosstalk pressure and the crosstalk displacement are not coupled with each other, and each field has its own means of energy transport. Therefore, with the experimental results reported earlier [3], the Stoneley wave propagating at the transducer-water crosstalk pressure, and the Lamb wave propagating in the Si wafer is considered to be responsible for the crosstalk membrane displacement.



(a) transmitter cMUT (T)



(b) receiver cMUT (R_1)

Fig. 3. Radiation impedance z of a single cMUT

III. FINITE ELEMENT MODEL OF A cMUT ARRAY

A similar finite element model is constructed for a cMUT array transducer. Figure 4 is the schematic diagram of the array transducer. Eight cMUTs are combined in parallel to make either a transmitter or a receiver. The responses of the receiver elements are analyzed in relation to the behavior of the transmitter elements. Similar analyses are performed as for the single cMUT, and the load impedance of the transmitter array is compared with the theoretical radiation impedance of a circular piston of the same radius on an infinite baffle in Fig. 5. Generally, the numerical

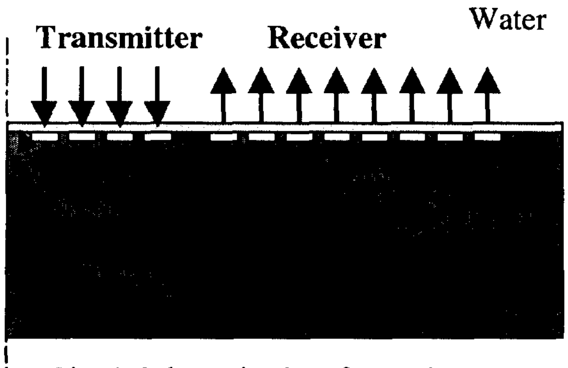


Fig. 4. Schematic vies of an underwater cMUT array transducer.

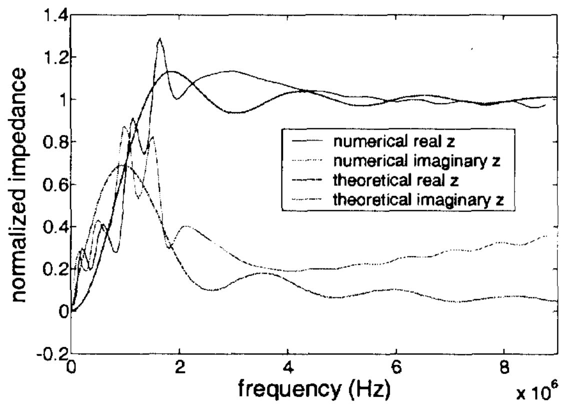


Fig. 5. Radiation impedance z of a cMUT array.

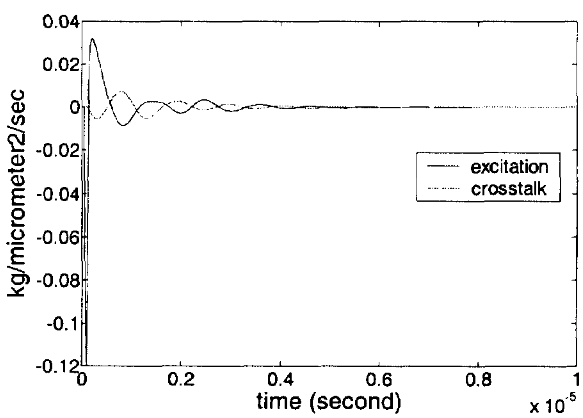
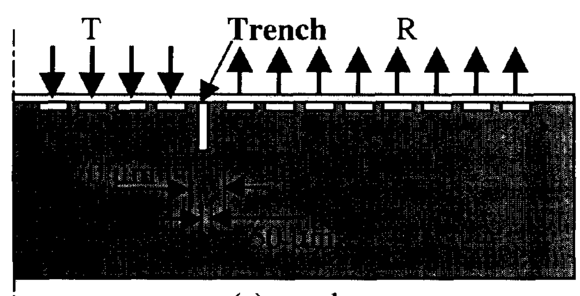


Fig. 6. Excitation pressure and crosstalk pressure for the cMUT array in Fig. 4.

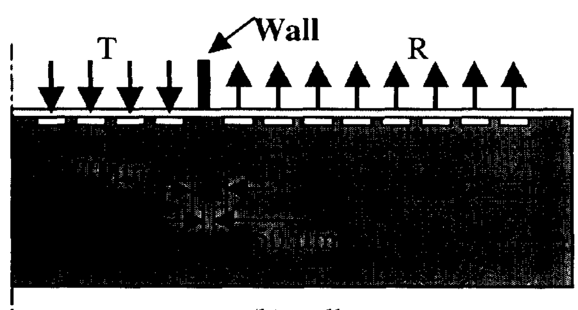
impedance shows fairly good agreement with the theory, which verifies the validity of the FE array model. The discrepancy in the comparison is due to the more complex structure of the cMUT array than a pure circular piston. The array transducer has much bigger radius than the single cMUT. Hence, the real part of the impedance is more dominant, which means that the wave form becomes more like a plane wave than that of a single cMUT. Figure 6 is the excitation and crosstalk pressure observed at the receiver array. The level of crosstalk is –21.2 dB.

IV. CROSSTALK CONTROL STRUCTURES

Cross-coupling between elements is one of the most important factors affecting the performance of an array transducer. Hence, several structural schemes are devised to reduce the crosstalk level: (1) change of Si wafer thickness, (2) placement of an etched trench between the elements, and (3) placement of a wall between the elements. Figure 7 shows the trench and the wall. The first two schemes are to reduce the effects of a Lamb wave because the Lamb wave propagates inside the solid wafer, while the third scheme is to reduce the effects of a Stoneley wave because most of its energy resides in water. The influences of these structural variations are shown in Fig. 8. The crosstalk level increases with the thickness of the wafer, although the effect is not much. As the



(a) trench



(b) wall

Fig. 7. Schematic view of the crosstalk control structures.

wafer is thickened, the Lamb wave leaks more energy into water due to the change of its velocity that corresponds to the change of its critical angle. Hence, a thinner wafer is more desirable for crosstalk reduction. However, there is a certain limitation in reducing the wafer thickness, and this method can not be a very efficient way. The trench is shown to have almost no effect in reducing the crosstalk level. Since only a small portion of the wafer thickness is etched, the Lamb wave propagates as well as without the trench, and thus no reduction in the level. For the wall placed to prevent the propagation of a Stoneley wave, we can observe the crosstalk level to increase up to some height of the wall but to decreases after that. Careful analysis of the wall motion shows that a higher wall is likely to have its own vibration and thus generate its own pressure field. The effect of the wall motion results in worse crosstalk level as noted in Fig. 8-(c). However, with further increase of the height, the role of the acoustic fence becomes more prominent, and the resultant crosstalk level decreases. Hence, this result says that a well designed wall can be an efficient tool to prevent the crosstalk between the arrays by a Stoneley wave, but it requires more elaborate design for optimal performance.

V. CONCLUSION

In this paper, with a finite element model of cMUTs, we analyzed the origin and level of crosstalk between single elements as well as array elements, with evidence of coupling through Stoneley waves and Lamb waves. Based on the analyzed mechanism, several structural variations of the Si wafer were tried to reduce the crosstalk level, and their effects were investigated. Further work to elaborate the results in this paper lead to optimal design of cMUT structures robust to crosstalk.

ACKNOWLEDGEMENT

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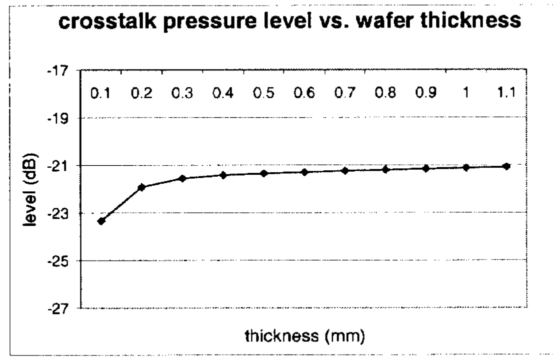
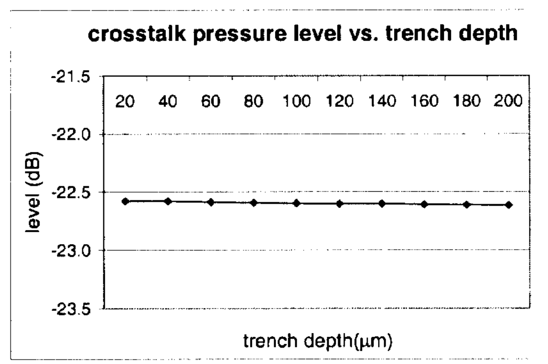
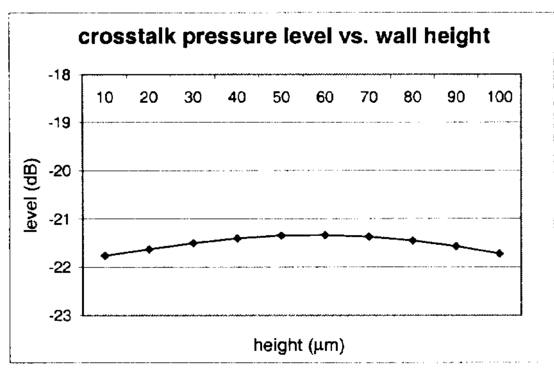


(a) change of wafer thickness



(b) change of trench depth



(c) change of wall height

Fig. 8. Effects of crosstalk control structures.