SILICON SUBSTRATE RINGING IN MICROFABRICATED ULTRASONIC TRANSDUCERS

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Abstract — Experimental and theoretical evidence of silicon substrate ringing in microfabricated ultrasonic transducers is presented. This ringing is clearly observed in immersion transducers with a 650 µm thick substrate at 7 MHz and harmonics. An analytical model of the ringing is introduced, and simulations based on the model are shown to agree with experimental observation. Experimental results are further compared to simulations carried out in time-domain, large-scale PZFlex models and qualitative agreement is demonstrated. The insights gained from the simulations and experiments are used to design and fabricate a device whose ringing mode is eliminated with a backing layer.

I. INTRODUCTION

Capacitive microfabricated ultrasonic transducers (MUTs) have generated interest recently because their low mechanical impedance enables both efficient air-coupled transduction and extremely broad-band immersion operation. Recent publications have concentrated on relatively narrow band air-coupled transducers and on immersion transducers with center frequencies below 5 MHz [1-7]. A sketch of the key elements of a MUT is found in figure 1.

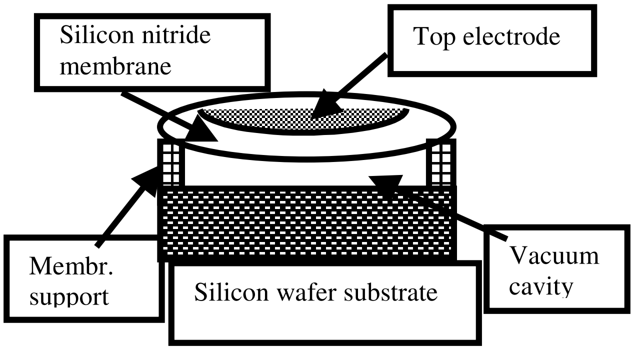

Figure 1: Sketch of MUT

In this paper, we present experimental and theoretical evidence of silicon substrate ringing. This ringing is clearly observed on immersion transducers at frequencies above 5 MHz, and is attributed to the thickness resonance of the silicon wafer. Indeed, MUTs do not repeal Newton's law; while the forces on the diaphragm electrode serve to launch acoustic waves efficiently in the medium of interest, equal forces are placed on the substrate electrode. To the extent that resonant modes exist in the substrate, these can be excited by the forces on the substrate electrode and by the reaction forces on the diaphragm's supporting structure. The net effect of such ringing is a significant decrease in the efficiency of the transducer at frequencies near the substrate resonance. Such ringing, if not controlled, can reduce the effective bandwidth of the transducer and lead to high levels of mechanical cross-coupling.

In this paper, we present quantitative data of 7 MHz ringing modes and harmonics generated in a 650 µm thick silicon substrate. We introduce an analytical model of the ringing. We compare the experimental results to simulations based on the analytical model and to simulations carried out in time-domain, large-scale PZFlex models of MUTs on silicon wafers. We conclude with an example of a single element device whose ringing mode is eliminated.

II. ANALYTICAL MODEL

An equivalent circuit model for a MUT adapted from Mason's work is described in [6]. The basic topology of such an equivalent circuit is found in figure 2. Underlying the equivalent circuit is the assumption that one of the electrodes (the substrate electrode) is infinitely stiff. If one allows for the motion of the lower electrode and the substrate, fully passive equivalent circuit models fail to capture the mechanical behavior of the device. The subtlety lies in the fact that usually the electrical dual of velocity is current, and the electrical dual of force is voltage, but force is a vector quantity and voltage is not. In order to accurately account for lower electrode and support forces and motion, we introduce the lumped

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mechanical model of figure 4 based on the physical sketch of figure 3. In this model, an effective spring constant and an effective mass are extracted from the model Zm. As is the case for the equivalent circuit derivation, the lumping of a distributed system into a mechanical model can be subtle. The derivation of the lumped mechanical model is beyond the scope of this paper. Rather, we present a heuristic description of the physics and the model, and then demonstrate results that simulations based on the model agree with experimental observation.

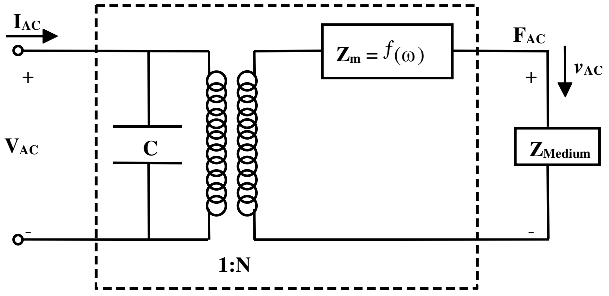

Figure 2: Equivalent circuit topology after [6]

As is sketched in figure 3, when an electrical potential is placed across the electrodes of a MUT, equal forces F_{Etop} and $F_{Ebottom}$ act on each of the electrodes. The dynamics of such a system are described accurately by the lumped model of figure 4. k_M is an effective spring constant,

$$k_M = (d \cdot \rho_N \cdot A_{memb} \cdot X_m) \div [\, c/d + R^2/8 - j \cdot R \cdot J_0(j \cdot R \cdot \sqrt{(d/c)}) \div (2 \cdot \sqrt{(d/c)} \cdot J_1(j \cdot R \cdot \sqrt{(d/c)}))\,]$$

where R is the diaphragm radius, A_{memb} is the area of the membrane, and other symbols are consistent with the referenced work [6]. k_M is the DC spring constant; the frequency dependent dynamics of the model are in M_{lump}, which we don't solve for analytically, but describe in the simulations as the subtraction of k_M from Zm of the equivalent electrical circuit model. Z_{SIL} is lumped by treating the silicon and the backing as transmission lines, the backing being a lossy transmission line.

III. FINITE ELEMENT MODELING

There are a number of numerical modeling difficulties associated with MUT devices. Foremost is the need for two distinct resolution scales, due to the thickness disparity between MUT structure (2-3 microns) and the silicon wafer (around 600 microns). Second is nonlinearity in both the electrical and mechanical fields.

Weidlinger Associates have developed a time-domain finite element model that treats near-surface structure as a constrained boundary layer and includes all electromechanical coupling between individual membranes. It permits global 3D models, i.e., "many" neighboring membranes over a significant piece of silicon real estate. This boundary layer model relies on a high-resolution, local model of MUT response for calibration of the membrane approximation[8].

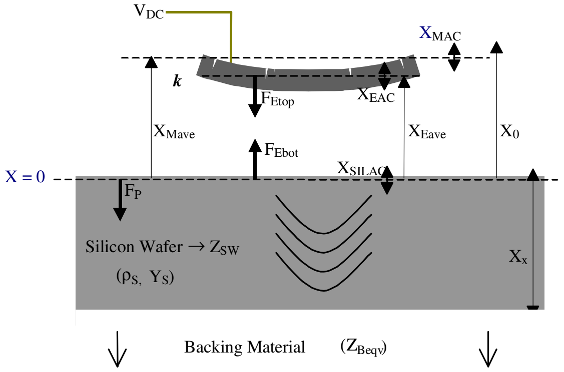

Figure 3: Sketch of substrate ringing concepts.

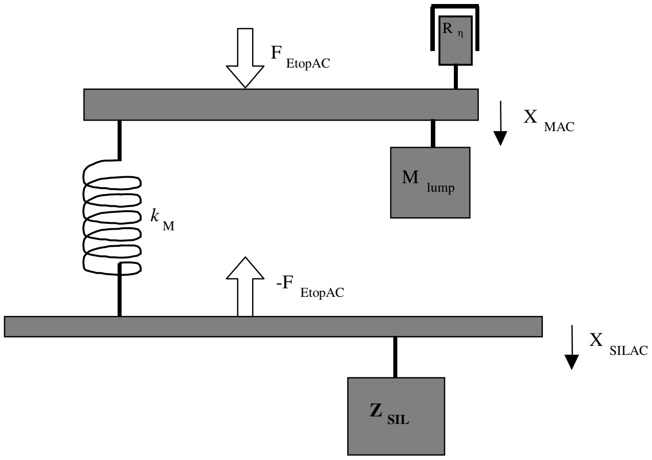

Figure 4: Sketch of equivalent mechanical model.

IV. RESULTS AND DISCUSSION

Both transmission (pitch catch) and pulse echo experiments were performed to first discover the ringing mode and then to verify that application of a judiciously designed backing material eliminates the ringing mode. Here we include only transmission results, which are taken with a 2 mm diameter single element MUT with a 10 MHz center frequency. A 10V 30 ns pulse is applied on the transmitter, which is biased to 90 V. Frequency responses are obtained by taking the FFT of the time-domain impulse response.

The first transmission experiment demonstrated a long ringing tail in the time domain. It was the observation of this tail in the experiment that lead us to develop the mechanical model in order to explain the reasons we observed such ringing. Figure 5 shows the experimental and simulated results. Of course, such a tail would preclude the generation of good images with the device.

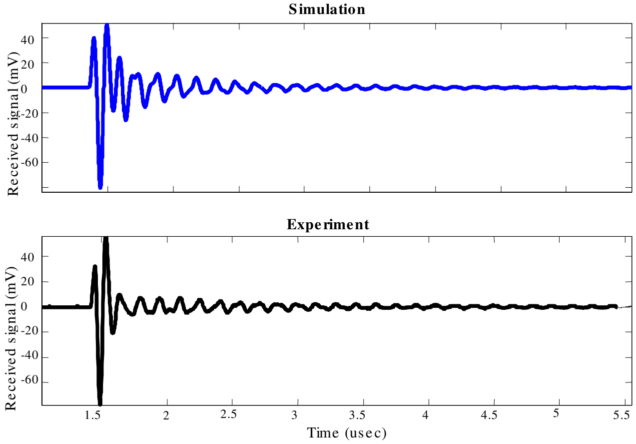

Figure 5: Simulated and experimental ringing

The frequency spectrum of these results indicates that there are distinct frequencies at which the ringing occurs. Figure 6 demonstrates the results obtained from Weidlinger Associates' time domain FEM [8] both with and without a backing material. The backing material properties are chosen such that its acoustic impedance matches that of silicon and that it be very lossy. With these constraints, any acoustic energy reaching the back of the substrate would be dissipated, so longitudinal ringing modes would be eliminated. Figure 6 verifies that such a backing material greatly improves transducer performance.

Often in ultrasound theoretically desirable material properties are impossible to find or realize in nature. Fortunately, we were able to design a custom backing material with an acoustic impedance that does indeed match that of silicon and loss which is sufficient to eliminate the ringing mode. Figure 7 shows the experimental results obtained when a 1 mm thick dampening layer is placed on the back side of the silicon substrate.

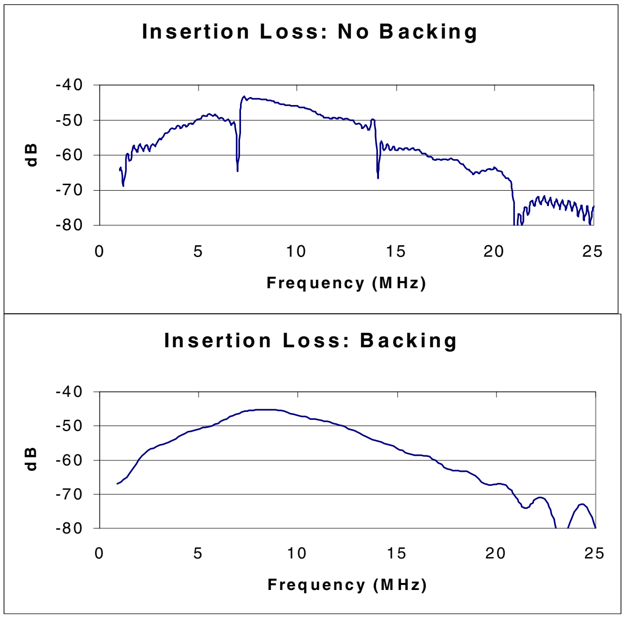

Figure 6: FEM simulation results

It is clear from Figure 7 that the ringing mode and harmonics have been successfully eliminated. Figure 8 shows the experimental time domain impulse response with backing and the simulated response using the lumped model. Excellent agreement is obtained between FEM simulations, lumped model simulations, and experimental observation.

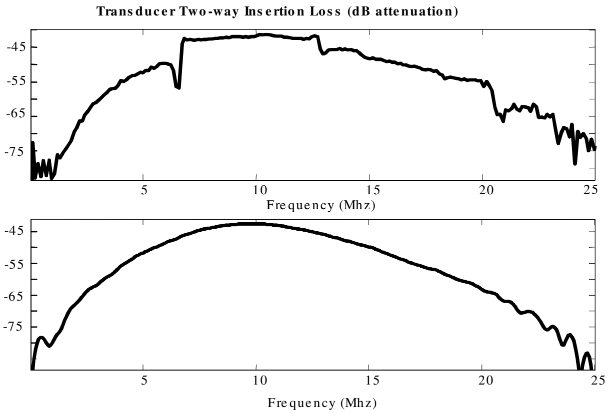

Figure 7: Experimental results confirming that backing material eliminates ringing modes.

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V. CONCLUSIONS

In this paper we have demonstrated that longitudinal substrate ringing modes exists in the silicon substrate of MUTs. These ringing modes would preclude obtaining good images from MUT devices if the ringing occurs within the frequency band of interest. Thus, eliminating such ringing modes is desired if MUTs are to replace piezoelectric elements in certain applications. This paper has demonstrated that both a lumped model and Weidlinger Associates' FEM model correctly describe the physics and can be used as predictive models. Finally, we have experimentally demonstrated that the substrate ringing mode can be eliminated by placing a judiciously designed (matched and lossy) backing material in contact with the silicon substrate. This work brings the state of the art of MUT technology much closer to the point where good images can be obtained, and future work will concentrate on the generation of such favorable images.

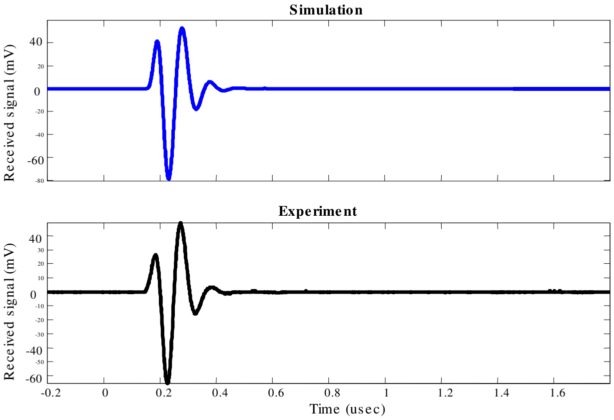

Figure 8: Lumped simulation and experimental results demonstrating effectiveness of backing layer.

VI. REFERENCES

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