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The Design and Characterization of Capacitive Micromachined Ultrasonic Transducers (CMUTs) for Generating High-Intensity Ultrasound for Transmission of Directional Audio

Ira O. Wygant
National Semiconductor Labs
National Semiconductor
Santa Clara, California 95052-8090

Mario Kupnik,
and Butrus T. Khuri-Yakub
E. L. Ginzton Laboratory
Stanford University
Stanford, California 94305-4088

Mark S. Wochner, Wayne M. Wright,
and Mark F. Hamilton
Applied Research Laboratories
The University of Texas at Austin
Austin, Texas 78713-8029

***Abstract*—A directional source of audio sound created using a parametric array, sometimes called an audio spotlight, generates a sound beam that is much narrower than the sound beam generated by a conventional source. These directional sources require the transmission of a modulated high-intensity ultrasonic carrier wave. Capacitive transducers are well-suited for parametric array audio applications because they can efficiently generate high-intensity ultrasound with a relatively wide bandwidth. CMUTs with vacuum-sealed cavities are particularly advantageous because they lack squeeze-film damping, which increases bandwidth but reduces displacement, and because their sealed cavities and permanently attached membranes make them relatively robust. In this paper, we present the basic design constraints of CMUTs intended to generate low-frequency high-intensity airborne ultrasound. In addition, we describe a new method for fabricating these CMUTs that results in uniform cavity depths and a thick insulating oxide layer. Measurement of a fabricated device's input impedance and small-signal displacement demonstrates the success of the new fabrication method and shows good agreement with theory.**

I. Introduction

This paper presents a new method for making large-area capacitive micromachined ultrasonic transducers (CMUTs) for generating high-intensity ultrasound for directional audio applications. Compared to previously reported devices [1], [2], the new devices have thicker insulating oxide, deeper cavities, and more uniform cavity depths for increased maximum displacement. Here we present the fabrication method, the device design based on an equivalent mass-spring-damper system [3], and device characterization results.

We designed the CMUTs for transmitting highly directional audio. A conventional audio loudspeaker creates a wide beam of sound—the sound's beamwidth is inversely proportional to frequency and the source size. However, a relatively small source can create a narrow beam of sound by making use of the parametric effect [4].

Transmitting sound using the parametric array effect requires generating high-intensity modulated ultrasound. As the generated ultrasound propagates through air, nonlinear waveform distortion accumulates and demodulates the ultrasound into the audible range, creating a narrow beam of sound. For efficiently creating the ultrasound, micromachined ultrasonic transducers have the advantages of tightly controlled geometries, vacuum-sealed cavities that minimize losses due to squeeze film damping, and no dependence on potentially lossy and bandwidth-limited piezoelectric material.

TABLE I
CMUT Dimensions

Plate radius	2000 μm
Plate thickness	40 μm
Gap height	60 μm
Oxide thickness in cavity	5 μm
Oxide thickness at post	7 μm

TABLE II
CMUT Modeling Parameters

Linear spring constant, k_1	123 kN/m
Nonlinear spring constant, k_3	3.2×10^{14} N/m^3
Equivalent mass, m	2.2 μg
Equivalent damping, R_b	5.2×10^{-3} N·s/m
Capacitance, C_0	2.4 pF
Natural resonance frequency, f_0	48 kHz
Approximate quality factor, Q	125
Estimated max. sound pressure for Vac=Vdc=500 V	152 dB

II. Design

Generation of the ultrasonic carrier frequency requires a transducer with a center frequency equal to approximately 50 kHz, a bandwidth sufficient to create audio with frequencies up to 5 kHz, and the capability of generating sound pressure of approximately 140 dB (re 20 μPa) at the face of the transducer. For a circular CMUT cell, we choose the plate radius, plate thickness, gap height, and oxide thickness to meet these requirements (Fig. 1). Assuming the deflection of the CMUT plate is small relative to its thickness (the thin plate approximation), we can write the plate radius and plate thickness in terms of the center frequency and quality factor, Q [3]. The quality factor is roughly equal to the inverse of the

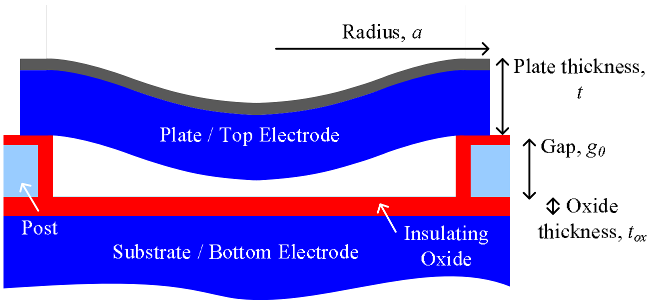

Fig. 1. A circular CMUT cell.

transducer's fractional bandwidth. Thus, the center frequency and bandwidth requirements dictate the dimensions of the CMUT plate.

$$t \approx \frac{Z_0 Q}{1.84 \rho \omega_0} \quad (1)$$

$$a = 1.72 \sqrt{\frac{t}{\omega_0} \sqrt{\frac{E}{\rho(1-\nu^2)}}} \quad (2)$$

The desired sound pressure at the face of the transducer or the magnitude of the dc bias voltage and ac excitation voltage determine the size of the gap and thickness of the insulating oxide. To generate 140-dB 50-kHz sound at the face of the transducer, the CMUT plate must have an average displacement of 2.2 μm. For a circular plate, the peak displacement equals about three times the average displacement. Thus, the peak ac CMUT plate displacement needs to be at least 6.5 μm. The gap size must accommadate the CMUT plate's static deflection resulting from atmospheric pressure and a dc bias voltage as well as the 6.5 μm transient displacement. We can estimate the large-signal transient plate deflection by multiplying the magnitude of the applied ac voltage by the CMUT's small-signal transmit sensitivity [3]. In (3), $w_{ac,avg}$ equals the ac plate displacement, $V_{\rm ac}$ equals the applied ac voltage, $V_{\rm dc}$ equals the dc bias voltage, Z_0 equals the characteristic impedance of air, w_0 equals the CMUT's resonance frequency, and C is the CMUT's capacitance.

$$w_{ac,avg} = \frac{V_{ac} n}{Z_0 \omega_0 \pi a^2} = \frac{V_{ac} V_{dc} \frac{dC}{dw_{dc,avg}}}{Z_0 \omega_0 \pi a^2} \quad (3)$$

To obtain a simple equation, we assume the derivative of the capacitance equals that for a parallel-plate capacitor.

$$w_{ac,avg} \approx \frac{V_{ac} V_{dc}}{Z_0 \omega_0 \pi a^2} \frac{\varepsilon_0 A}{(g_0 - w_{dc})^2} \quad (4)$$

This equation shows that if we pick a gap, we can solve for the product of the ac and dc voltages that will create ac plate displacement equal to the full extent of the gap. By solving this equation for different gaps, we can see how maximum sound pressure level varies with the product of the ac and dc excitation voltages. The equation must be solved numerically because the derivative of the capacitance is a function of $V_{\rm dc}$. However, for increasingly high Q, the plate displacement due to $V_{\rm dc}$ approaches zero; thus, the maximum sound pressure for a given Q is independent of Q when Q is higher than about 10. For devices with lower Q, the pull-in voltage is often lower than the dc voltage needed to cause the CMUT plate to displace the full extent of the gap. For this analysis, we assume that the plate can dynamically displace to the top of the oxide without pull-in. Large-signal simulations show that the plate can at least dynamically displace a large fraction of the gap before pull-in.

For high Q, the maximum sound pressure level is independent of Q. The only drawback of reducing the Q is that for a vacuum-sealed device, the static plate deflection increases for lower Q. When the static plate deflection becomes significant relative to its thickness, forces in the plate's midplane becomes significant relative to the bending forces of the plate. A cubic spring constant is often used to capture this affect [2]. Based on our previous results, we know that a 40-μm-thick plate provides sufficient bandwidth for this application. For this thickness of plate, nonlinear displacement affects are significant but not dominant. Table I and Table II summarize the design of the device presented in this work.

III. Fabrication

We modified the device fabrication method (Fig. 2) described in [2] for improved cavity depth uniformity and for a thicker insulating oxide layer. We use a combination of isotropic and anisotropc DRIE to create the cavities in an SOI wafer. Isotropic etching undercuts any small particles or spots of photoresist left in the cavity regions. However, it also increases the cavity diameter which changes the CMUT's frequency response and reduces the length of the post region between CMUT cells. As a result, we limit the isotropic etching to about 40 μm. We use additional anisotropic etching to create deeper cavities.

Thermal oxidation of the substrate wafer creates a uniform 3 μm-thick oxide layer in the post regions and adds 1 μm of oxide to the exposed BOX layer of the SOI wafer. As a result, the total insulating oxide thickness in the post region is 7 μm; in the cavity regions, the oxide is 5 μm-thick. The remaining processing steps illustrated in Fig. 2 are described in detail in [2].

IV. Results

Fig. 3 shows a complete device. Each wafer contains four large-area devices for transmitting audio over signiciant distances. The large-area devices are surrounded by numerous single-membrane test devices.

Fig. 4 shows the measured input impedance for a 500-V dc bias. The device withstood bias voltages as large as 600-V, which demonstrates the insulating capability of the thick oxide layer.

Fig. 5 shows the ac plate displacement measured with a laser interferometer.

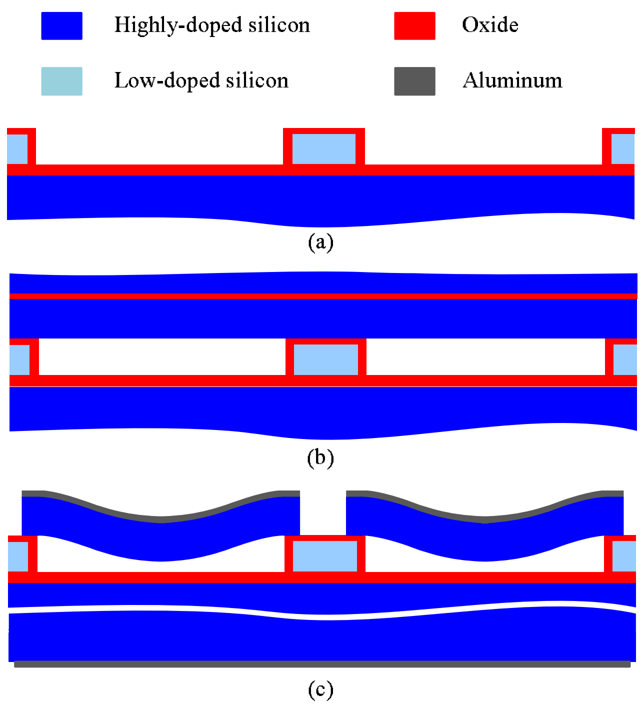

Fig. 2. Process flow diagram. (a) DRIE creates cavities in an SOI wafer. Thermal oxidation creates a 3-m-thick oxide layer in the post region. (b) The wafer is bonded to an SOI wafer with a device thickness equal to the desired membrane thickness. (c) The handle wafer is removed using wafer grinding and etching in TMAH. DRIE removes silicon in the post region. Aluminum electrodes are deposited.

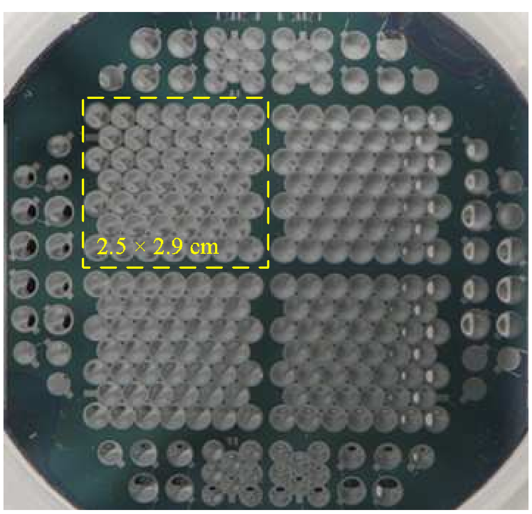

Fig. 3. Photograph of the finished device.

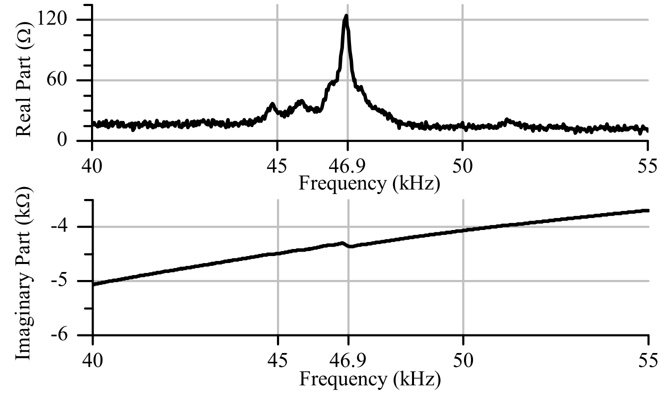

Fig. 4. Measured input impedance of a 46-membrane device with a 500-V DC bias. The device exhibits resonance close to the theoretical resonance of 48 kHz.

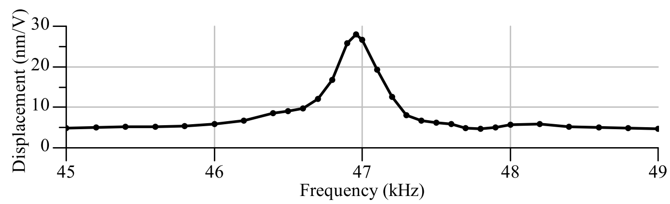

Fig. 5. Displacement per volt at the center of a membrane as a function of frequency for a 300-V DC bias. The peak sensitivity of 28 nm/V is close to the theoretical value of 34 nm/V. With a 600-V DC bias we measured a peak displacement of 53 nm/V. The peak displacement is about one-third of the average membrane displacement.

V. Conclusion

The methodology described for designing transmit-only airborne CMUTs results a in few simple design rules and equations. Initial testing of devices designed according to this methodology show good agreement with theory. Furthermore, the newly fabricated devices demonstrate the success of an improved method for fabricating low-frequency CMUTs.

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References

[1] I. O. Wygant, *et al.*, "50-khz capacitive micromachined ultrasonic transducers for generating highly directional sound with parametric arrays," in *2007 IEEE Ultrasonics Symposium*, 2007, pp. 519–522.

[2] ——, "50-khz capacitive micromachined ultrasonic transducers for generating highly directional sound with parametric arrays," *accepted for publication in IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control*, pp. 519–522, 2008.

[3] I. O. Wygant, M. Kupnik, and B. T. Khuri-Yakub, "Analytically calculating membrane displacement and the equivalent circuit model of a circular cmut cell," in *2008 IEEE Ultrasonics Symposium*, 2008, pp. 519–522.

[4] P. J. Westervelt, "Parametric acoustic array," *Journal of the Acoustical Society of America*, vol. 35, no. 4, pp. 535–537, 1963.