Microfabricated Ultrasonic Transducers: Towards Robust Models and Immersion Devices

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Abstract— **The successful fabrication of ultrasonic immersion transducers is reported. Transducers are observed to operate from 1 MHz to 20 MHz in water, with the frequency range limited by electronics, not the transducers. Transmission results are included which show that a single pair of transducers is able to operate in water at 4, 6, and 8 MHz with a signal to noise ratio of at least 48 dB. The same transducer pair is shown to operate in air at 6 MHz. A model is introduced which highlights the significant parameters of transducer design. The model enables the design of optimized transducers.**

I. Introduction

Ultrasound is now used in a wide variety of applications which can be characterized as either sensing modalities or actuating modalities. Sensing applications include medical imaging, non-destructive evaluation (NDE), and ranging. Practical uses of ultrasound as an actuating mechanism include industrial cleaning, soldering, and therapeutic ultrasound (heating, lithotripsy, tissue ablation, etc.). Current theoretical understanding indicates, however, that many fruitful applications of ultrasound remain unrealized. It is often a lack of adequate transducers that precludes theoretically interesting ultrasonic systems from materializing. Air-coupled ultrasonic inspections motivate the development of air transducers [1], [2], [3], [4], [5] and the advantages of limited diffraction beams motivate the realization of 2-dimensional transducer matrices [6], [7], [8].

Although piezoelectric ceramics and engineering cleverness have enabled a significant number of ultrasonic devices and systems, many modern applications would benefit from transducers based on a different principle of actuation and detection. Analyses of capacitive acoustic transducers have existed for many decades [9]. The use of capacitive transducers for air-borne ultrasonics dates back to the 1950's [10], [11], and the first immersion version appeared in 1979 [12]. Microfabricated ultrasonic transducers (MUTs) are an advanced configuration of capacitive ultrasonic transducers. MUTs have been shown to be superior air transducers [13], [14]. In this paper, we show that micromachined ultrasonic transducers (MUTs) are viable as immersion transducers.

II. Device Description and Fabrication

A MUT consists of metalized silicon nitride membranes suspended above heavily doped silicon bulk. A schematic of one element of the device is shown in Figure 1. A transducer consists of many such elements. When a voltage is placed between the metalized membrane and the bulk, coulomb forces attract the membrane toward the bulk and stress within the membrane resists the attraction. If the membrane is driven by an alternating voltage, significant ultrasound generation results. Conversely, if the membrane is biased appropriately and subjected to ultrasonic waves, significant detection currents are generated.

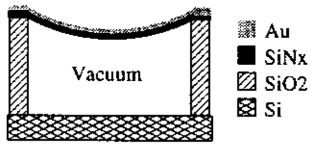

Fig. 1. Schematic of one element of a MUT

MUTs are fabricated by using techniques pioneered by the integrated circuits industry. The fabrication scheme of the MUTs used to generate the results herein reported is found in Figure 2. A p-type (100) 4 inch silicon wafer

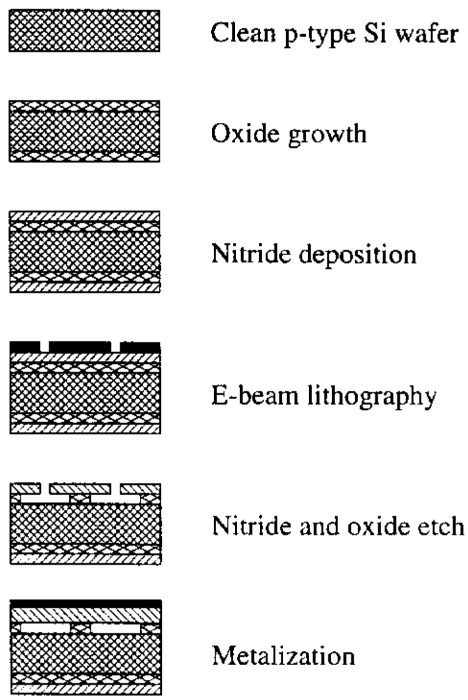

Fig. 2. Major steps of MUT fabrication

is cleaned and a 1 μm oxide layer is grown with a wet

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oxidation process. A 3500 Ålayer of LPCVD nitride is then deposited. The residual stress of the nitride can be varied by changing the proportion of silane to ammonia during the deposition process. A pattern of etchant holes is then transferred to the wafer with a lithography process. The nitride is plasma etched and the sacrificial oxide is removed with HF. A second 2500 Ålayer of LPCVD nitride is then deposited on the released membranes, vacuum sealing the etchant holes. A chrome adhesion layer and a 500 Å film of gold are evaporated onto the wafer.

III. Results

A single pair of MUTs was used to generate figures 3 - 6. Furthermore, transmission was observed from 1 MHz to 20 MHz, with electronics limiting the frequency range, not the transducers. The figures were digitized with an 8 bit oscilloscope. A full scale signal contains undetectable noise, so the signal to noise ratio (SNR) is at least 48 dB. It is important to note that the MUTs were designed as air transducers. This accounts for the poor matching evidenced by multiple echos. The optimization parameters recommended in the following model would result in better matching, yielding a greater overall system budget.

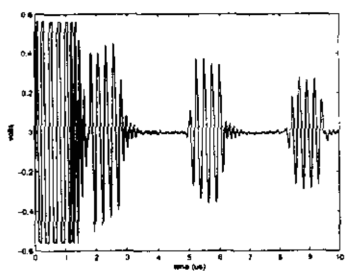

Fig. 3. Transmission with 4 cycles at 4 MHz.

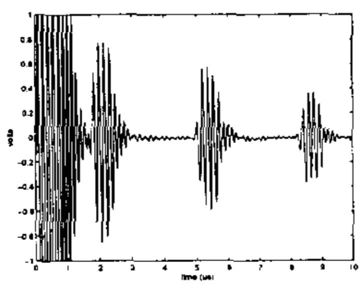

Fig. 4. Transmission with 4 cycles at 6 MHz.

IV. Device Modeling and Optimization

In order to facilitate the design of systems enabled by MUTs, the goal of the theory is to arrive at an equivalent circuit model of the transducer. The approach, as first suggested by Mason [9], is to find the mechanical impedance of the membrane in vacuum and then to insert it in a transformer equivalent circuit.

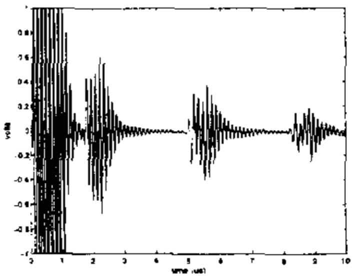

Fig. 5. Transmission with 4 cycles at 8 MHz.

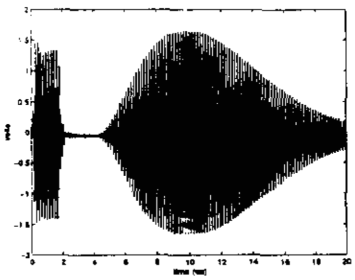

Fig. 6. Toneburst transmission in air at 6 MHz.

We consider a circular membrane of radius a operating in vacuum. The membrane has a Young's modulus of Y_0 and a Possion's ratio of σ . In addition, the membrane is in tension T in units of N/m^2. The differential equation governing the normal displacement $x(r)$ of the membrane can be written as [15], [9]

$$\frac{(Y_0+T)l_t^3}{12(1-\sigma^2)}\nabla^4 x(r) - l_t T\nabla^2 x(r) - P - l_t\rho\frac{d^2x(r)}{dt^2} = 0 \quad (1)$$

where l_t is the membrane thickness, and P is the external uniform pressure applied to the membrane. The equation is derived from an energy formulation and the critical assumption is that the tension generated by a displacement x is small compared to the tension T. Assuming a harmonic excitation at an angular frequency ω, equation 1 is known to have a solution of the form

$$x(r) = AJ_0(k_1 r) + BJ_0(k_2 r) - P/(\omega^2\rho l_t) \quad (2)$$

where A and B are arbitrary constants and $J_0()$ is the zeroth order Bessel function of the first kind. If we use equation 2 to substitute for $x(r)$ in equation 1 we find that k_1 and k_2 must satisfy the characteristic equations:

$$\frac{(Y_0+T)l_t^2}{12(1-\sigma^2)}k_1^4 + \frac{T}{\sigma}k_1^2 - \omega^2 = 0 \quad (3)$$

$$\frac{(Y_0+T)l_t^2}{12(1-\sigma^2)}k_2^4 + \frac{T}{\sigma}k_2^2 - \omega^2 = 0 \quad (4)$$

Following Mason's notation we define

$$c = \frac{(Y_0+T)l_t^2}{12(1-\sigma^2)} \qquad \text{and} \qquad d = \frac{T}{\rho} \quad (5)$$

The quadratic formula then gives the solutions

$$k_1 = \sqrt{\frac{\sqrt{d^2 + 4c\omega^2} - d}{2c}} \quad (6)$$

$$k_2 = j\sqrt{\frac{\sqrt{d^2 + 4c\omega^2} + d}{2c}} \quad (7)$$

In order to determine the constants A and B, two boundary conditions are necessary. Physically resonable boundary conditions at $r = a$ are that $x = 0$, which implies that the membrane undergoes no displacement at it's periphery, and $\frac{d}{dx}x = 0$, which implies that the membrane is perfectly flat (i.e. does not bend) at it's periphery. Both conditions amount to stating that the membrane is perfectly bonded to an infinitely rigid substrate. Using these conditions we determine the constants A and B and find the displacement of the membrane as

$$x(r) = \frac{P}{\omega^2 \rho l_t}\left[\frac{k_2 J_0(k_1 r) J_1(k_2 a) + k_1 J_0(k_2 r) J_1(k_1 a)}{k_2 J_0(k_1 a) J_1(k_2 a) + k_1 J_1(k_1 a) J_0(k_2 a)} - 1\right] \quad (8)$$

Fig. 7 is a calculated plot of the displacement of a typical membrane various frequencies. For the simulation, values used were $a = 25 \times 10^{-6}$, $l_t = 0.6 \times 10^{-6}$, $P = 1$, $Y_0 = 3.2 \times 10^{11}$, $\sigma = 0.263$, $T = 280 \times 10^6$, and $\rho = 3270$ (all in MKS units).

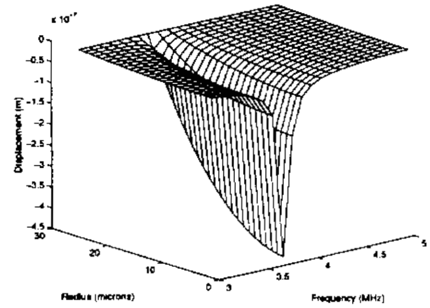

Fig. 7. Calculated displacement as a function of frequency for a 25 μ membrane excited by uniform pressure.

Mechanical impedance is defined as the ratio of force to velocity. Hence, the mechanical impedance of the membrane per unit area, Z_m, can be written as

$$Z_m = \frac{P}{\overline{v}} \quad (9)$$

$$= j\omega\rho l_t \frac{j\omega\rho l_t a k_1 k_2 (k_2 J_0(k_1 a) J_1(k_2 a) + \cdots}{a k_1 k_2 (k_2 J_0(k_1 a) J_1(k_2 a) + k_1 J_1(k_1 a) J_0(k_2 a)) - \cdots}$$

$$\frac{\cdots j\omega\rho l_t k_1 J_1(k_1 a) J_0(k_2 a))}{\cdots 2(k_1^2 + k_2^2) J_1(k_1 a) J_1(k_2 a)}$$

The electrical part of the analysis remains. Approximating the MUT as a parallel plate capacitor, it's capacitance is given by

$$C = \frac{\epsilon_0 \epsilon S}{\epsilon_0 l_t + \epsilon l_a} \quad (10)$$

where l_a is the gap thickness, ϵ is the dielectric constant of the membrane material, and S is the area of the membrane.

Let the total voltage across the capacitor be $V_T = V_{DC} + V$, where V_{DC} is the bias voltage and $V \ll V_{DC}$ is the small signal AC voltage. Then, the current flowing through the device is

$$I = \frac{d}{dt}Q = \frac{d}{dt}CV_T = C\frac{d}{dt}V + V_{DC}\frac{d}{dt}C \quad (11)$$

Since

$$\frac{d}{dt}C = -\frac{\epsilon_0 \epsilon^2 S}{(\epsilon_0 l_t + \epsilon l_a)^2}\frac{d}{dt}l_a \quad (12)$$

and the derivative of the air gap thickness is equal to membrane velocity $(d/dt)l_a = \overline{v}$, we have

$$I = C\frac{d}{dt}V - V_{DC}\frac{\epsilon_0 \epsilon^2 S}{(\epsilon_0 l_t + \epsilon l_a)^2}\overline{v} \quad (13)$$

To arrive at an electrical equivalent circuit we can define a transformer ratio

$$n = \frac{V_{DC}\epsilon_0 \epsilon^2 S}{(\epsilon_0 l_t + \epsilon l_a)^2} \quad (14)$$

and write the current as sum of electrical and mechanical components

$$I = C\frac{d}{dt}V - n\overline{v} \quad (15)$$

It is clear that n can be made larger by increasing the applied voltage or by decreasing the membrane and air gap thickness. Now we can draw the small signal equivalent circuit shown in Fig. 8.

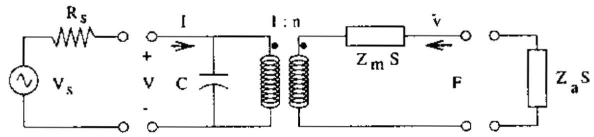

Fig. 8. Electrical equivalent circuit of MUT

The electrical equivalent circuit allows analysis and optimization of the MUT structure. Parameters in the model can be varied to generate desired values in the equivalent circuit. Furthermore, electrical matching circuits can be included.

Thus, it is clear that the structural control offered by microfabrication coupled with the insight from the equivalent circuit model can yield optimized transducers.

V. Conclusion

We have demonstrated that a pair of immersion MUTs can transmit ultrasound in water from 1 to 20 MHz. These transducers were also able to send and receive airborne ultrasound at 6 MHz. An equivalent circuit model has been presented which can be used to optimize MUT design. Optimized MUTs should challenge piezoelectrics in many applications due to their numerous advantages. MUT advantages include high temperature operation, ease of fabrication of two dimensional arrays, and most importantly, the ability to realize matched transducers by varying accessible parameters of the transducer.

VI. Acknowledgment

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