Micromachined 2-D Array Piezoelectricallly Actuated Flextensional Transducers

Gökhan Perçin and Butrus T. Khuri-Yakub

Edward L. Ginzton Laboratory, Stanford University, Stanford CA 94305-4085.

Abstract— **This paper presents micromachined two dimensional array flextensional transducers that can be used to generate sound in air or water. Individual array elements consist of a thin piezoelectric ring and a thin, fully supported, circular membrane. We report on an optimum design for an individual array element based on finite element modelling (FEM). We manufacture the transducer in two dimensional arrays using planar silicon micromachining. Such an array could be combined with an on-board driving and an addressing circuitry.**

I. Introduction

TWO dimensional arrays of ultrasound transducers are desirable for imaging applications in the fields of medicine, nondestructive evaluation, and underwater exploration. Making arrays of transducers by dicing and connecting individual piezoelectric elements is fraught with difficulty and expense, not to mention the large input impedance mismatch problem that such elements present to transmit/receiving electronics. Our approach is to use micromachined flextensional piezoelectric transducers. Individual elements are made of thin silicon nitride membranes covered by a coating of piezoelectric zinc oxide (ZnO). The arrays are made using silicon micromachining techniques, and are capable of operation at high frequencies. Inherently, this approach offers the advantage of integrating transducers with transmitter and receiver electronics. Thus, we present arrays where elements can be individually addressed for ease of scanning and focusing by using on board electronics.

II. Micromachined Device

We fabricated micromachined piezoelectrically actuated flextensional transducers in a 2-D array by combining conventional IC manufacturing process technology with ZnO deposition. Individual array elements consist mainly of a circular membrane attached to a circular ring of piezoelectric material which has optimized dimensions. An AC voltage is applied accross the piezoelectric material to set the compound membrane into vibration. At the resonant frequencies of the compound membrane, the displacement in the center is large.

III. Design Parameters

We designed the individual array element to have a maximum displacement at the center of the membrane at the resonant frequency (Perçin [1], [2]). Analyses of similiar devices such as those of Allaverdiev [3], Vassergiser [4], Okada [5], and Iulo [6], are helpful in identifying the important parameters of the device. However, the complexity of the structure and the fact that the piezoelectric we use is a ring rather than a full disk necessitate the use of finite element analysis to determine the resonant frequencies of the structure, the input impedance of the transducer, and the normal displacement of the surface.

It is well known that the transverse displacement ξ of a simple membrane of uniform thickness, in vacuum, obeys the following differential equation [7]:

$$\nabla^4\xi + \frac{\rho}{D}\frac{\partial^2\xi}{\partial t^2} = 0 \qquad (1)$$

The axisymmetric free vibration frequencies for an edge-clamped circular membrane are given by

$$\omega = \frac{\lambda^2}{a^2\sqrt{\frac{\rho}{D}}} \qquad (2)$$

where λ represents the eigenvalues of Equation (1), a is the radius of the membrane, ρ is the mass per unit area of the membrane, and

$$D = \frac{Eh^3}{12(1-\nu^2)} \qquad (3)$$

where E is Young's modulus, h is the membrane thickness, and ν is Poisson's ratio.

By substituting typical dimensions for the individual array element at above equations and by using average values for h, E, ν, and ρ, we obtain the first resonance frequency at 2.62 MHz, which is reasonable approximation to 2.8 MHz - 3.0 MHz that was measured in our experiments. The above equations suggest that the resonant frequency is directly proportional to the thickness of the membrane and inversely proportional to the square of the radius. However, it is also known that the resonant frequency will be decreased by fluid loading on one or both sides of the membrane. The shift in the fluid loaded resonant frequency of a simple membrane is shown by Kwak [8] to be

$$f_w = \frac{f_a}{\sqrt{1+\beta\Gamma}} \qquad (4)$$

where $\beta = \rho_w a/\rho_m h$ is a thickness correction factor, ρ_w is the density of the liquid, ρ_m is the mass density of the circular membrane, and Γ is the non-dimensional added virtual mass incremental (NAVMI) factor, which is determined by boundary conditions and mode shape. For the first order axisymmetric mode and for water loading on one side of the membrane, Γ is 0.746313. Assuming the composite will behave similarly to the single membrane,

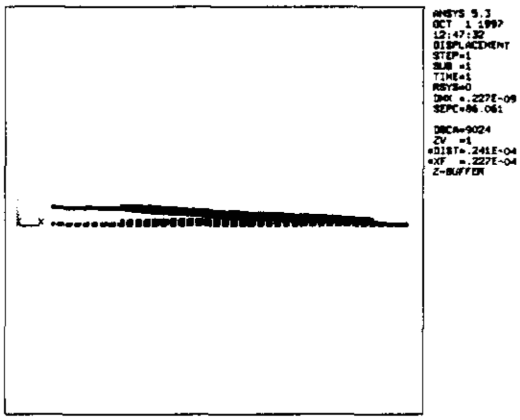

Fig. 1. ANSYS simulation for the DC placement of an array element.

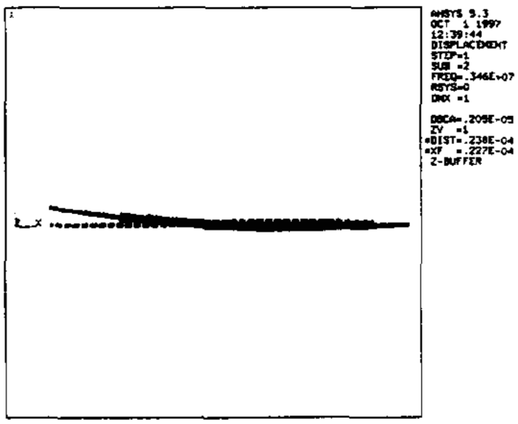

Fig. 2. ANSYS simulation for resonance frequency of an array element in vacuum.

we expect the resonant frequency to shift down by 63% for one of our devices.

We designed micromachined two dimensional array transducers by modelling one element large scale prototype (Perçin [1], [2]). However, the two dimensional array nature of the device is accomodated by a suitable micromachining process. Materials are chosen in accordance with availability of micromachining and IC manufacturing processes. Other piezoelectric materials, membrane materials, electrode metals, and substrates can be used.

We used ANSYS to optimize an individual array element made with piezoelectric ZnO on a silicon nitride membrane. Several iterations were run to maximize the displacement of the membrane as a function of the dimensions of the piezoelectric ring. Maximum displacement was obtained when the piezoelectric ring had an inner diameter of 30 μm and outer diameter of 80 μm with a thickness of 0.3 μm, and the silicon nitride had a diameter of 100 μm with a thickness of 0.3 μm. Figures 1 and 2 show typical results of such an analysis. The DC placement is $2.27 A^o/V$. The resonance frequency 3.46 MHz obtained from ANSYS simulation in vacuum is a good approximation to 3.07 MHz that was measured in vacuum.

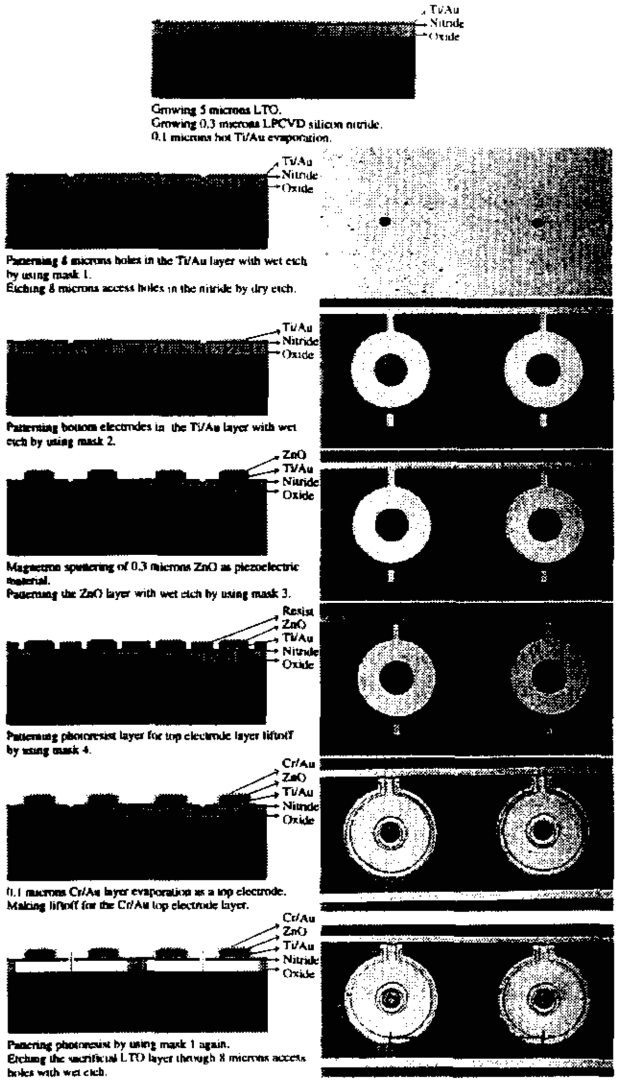

Fig. 3. Realized micromachined device process flow.

IV. Device Fabrication

The fabrication process for micromachined two dimensional array flextensional transducers is given in Fig. 3. At the right side of the figure, actual pictures of two elements from two dimensional array are given along the process flow. The process starts with growing a sacrificial layer, chosen to be silicon oxide for now, yet which can be grown of other compatible materials, such as aluminium, ZnO, polysilicon. A membrane layer is grown on top of the sacrificial layer. We used silicon nitride as a membrane; however, other materials such as polysilicon, aluminium can be used by using a compatible sacrificial layer material. The bottom metal electrode layer is put on the membrane, and later this metal layer is patterned and access holes for sacrificial layer etching are drillled in the membrane layer. After this step, the bottom electrode layer is patterned and the piezoelectric layer is deposited on top of the bottom electrode. ZnO was used as a piezoelectric material, but other thin film piezoelectric materials can be used, such as sputtered PZT films, and $PVDF$. The top metal electrode layer is patterned by the liftoff method. The last step is etching the sacrificial layer, and this concludes the front surface micromachining of the devices. Fig. 4 shows the cross-sectional view of the final individual array element. Fig. 5 shows final 60 x 60 two dimensional array devices. The die size is 1 cm x 1 cm.

Fig. 4. Cross-sectional view of an array element.

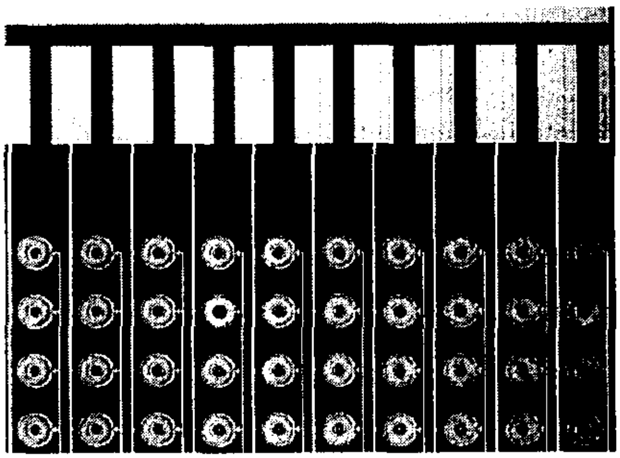

Fig. 5. Realized micromachined device.

V. Experiments and Results

Fig. 6 shows the real part of the electrical input impedance of only two rows of 120 elements of devices shown in Fig. 5. Operating in air, the transducers have a resonant frequency of 2.78 MHz and a fractional bandwidth of about 2.9 %. The real part of the electrical input impedance has 148 Ω base value, and we determined by SPICE simulation that this base value of real part is caused by bias lines connecting individual array elements. Using electroplating to increase the thickness of bias lines will solve this problem. Fig. 6 also shows the existence of acoustic activity in the device. and R_a equals to 52 Ω in air. In Fig. 7 presents change of the electrical input impedance in vacuum of a device consisting of one row of 60 elements. Resonance frequency is 3.00 MHz in air, and 3.07 MHz in vacuum. This result is in accordance with our expectations, since resonant frequency and the real part of the electrical input impedance at resonance should go up. In addition to that, we conducted this vacuum experiment to estimate how much energy is coupled to the structure. This issues is a present topic of research in our group. And finally, Fig. 8 demonstrates air transmission experiment. We see that a received signal follows electromagnetic feedthrough. The insertion loss is 112 dB. In the transmit/receive experiment, the receiver had only one row of 60 elements and the transmitter had two rows of 120 elements.

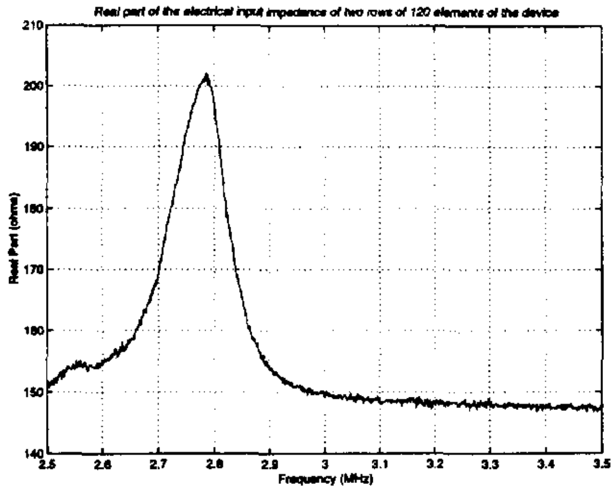

Fig. 6. Electrical input impedance real part of the realized micromachined device.

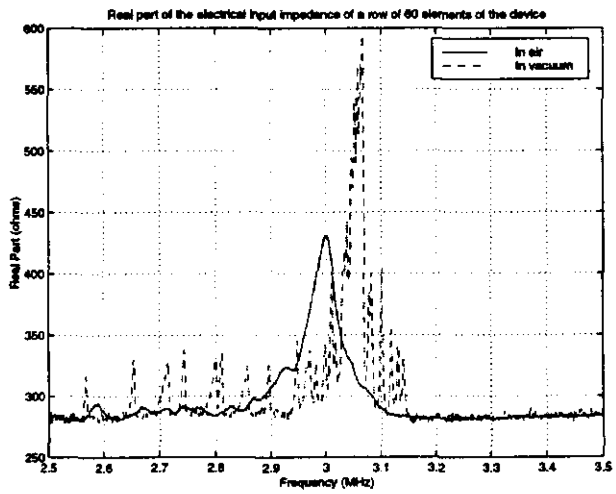

Fig. 7. Electrical input impedance real part change of the device in vacuum and air.

VI. Conclusions

In summary, we have developed a novel ultrasonic transducer which is silicon micromachined into two-dimensional arrays. The individual array element is based on a variation

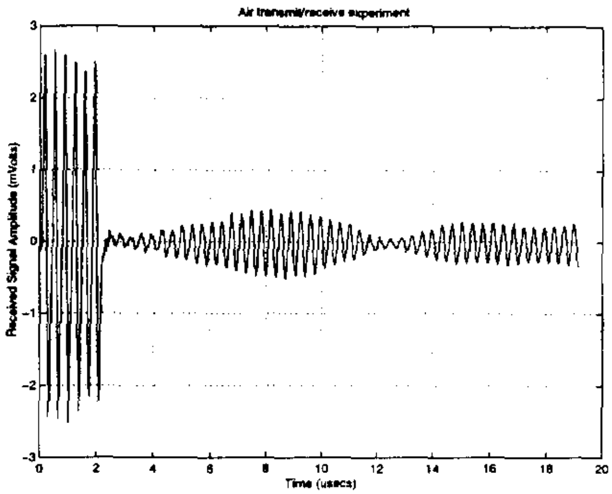

Fig. 8. Air transmit/receive experiment of the realized micromachined device.

of a flextensional transducer. The transducer design was optimized using finite element analysis, and the transducer was demonstrated in air.

Acknowledgments

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