AIP Applied Physics Letters

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Citation: Appl. Phys. Lett. **72**, 1397 (1998); doi: 10.1063/1.121067

View online: http://dx.doi.org/10.1063/1.121067

View Table of Contents: http://apl.aip.org/resource/1/APPLAB/v72/i11

Published by the American Institute of Physics.

Micromachined two-dimensional array piezoelectrically actuated transducers

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(Received 16 December 1997; accepted for publication 20 January 1998)

This letter 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 modeling. We manufacture the transducer in two-dimensional arrays using planar silicon micromachining and demonstrate ultrasound transmission in air at 2.85 MHz. Such an array could be combined with on-board driving and an addressing circuitry for different applications. © *1998 American Institute of Physics.* [S0003-6951(98)03911-4]

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 by 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.

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 at the center is large.

We design the individual array element to have a maximum displacement at the center of the membrane at the resonant frequency (Perçin *et al.*[1,2]). Analyses of similiar devices such as those of Allaverdiev,[3] Vassergiser *et al.*,[4] Okada *et al.*,[5] and Iulo *et al.*,[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]

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

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

$$\omega = \frac{\lambda^2}{a^2 \sqrt{\rho/D}}, \tag{2}$$

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

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

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 of the 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 a reasonable approximation to 2.8–3.0 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

$$f_w = \frac{f_a}{\sqrt{1+\beta\Gamma}}, \tag{4}$$

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 mem-

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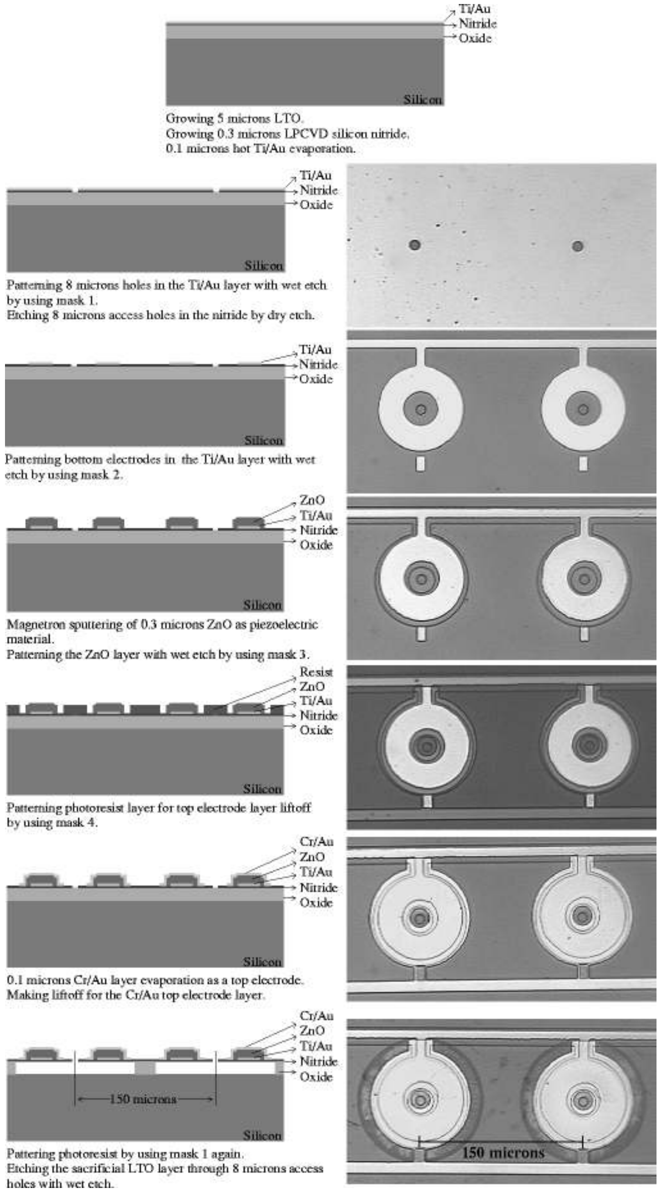

FIG. 1. Realized micromachined device process flow.

brane, Γ is 0.75. Assuming the composite will behave similarly to the single membrane, we expect the resonant frequency to shift down by 63% for one of our devices.

We designed micromachined two dimensional array transducers by modeling one element large scale prototype (Perçin *et al.*[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. The dc displacement is 2.27 A^o/V. The resonance

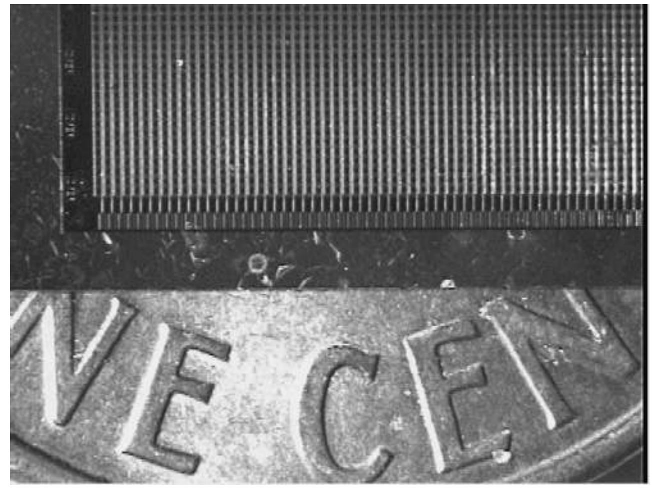

FIG. 2. Realized micromachined device.

frequency 3.46 MHz obtained from ANSYS simulation in vacuum is a good approximation to 3.07 MHz that was measured in vacuum with one of our devices.

The fabrication process for micromachined two-dimensional array flextensional transducers is given in Fig. 1. At the right side of the figure, actual pictures of two adjacent elements from a two-dimensional array are given along with the process flow. The process starts with growing a sacrificial layer, chosen to be silicon oxide (8% phosphorus doped densified LTO). A membrane layer of low-pressure chemical vapor deposition (LPCVD) silicon nitride is grown on top of the sacrificial layer. The bottom Ti/Au electrode layer is deposited on the membrane by e-beam evaporation at 228 °C. The degree to which the ZnO *c*-axis, $\langle 0002 \rangle$, is oriented normal to the substrate surface is very sensitive to the degree to which the Au film is $\langle 111 \rangle$ oriented. The quality of the ZnO is measured by an x-ray rocking curve scan. The ZnO had a 5.5°-wide rocking curve above Au with a 5°-wide rocking curve. The bottom metal layer is patterned by wet etch, and access holes for sacrificial layer etching are drilled in the membrane layer by plasma etch. Later, the bottom electrode layer is patterned by wet etch, and a piezoelectric ZnO layer is deposited on top of the bottom electrode. The ZnO is deposited by dc planar magnetron reactive sputtering from a 127-mm-wide target consisting of 99.99% Zn. The deposition is made in an 20%–80% argon-oxygen ambient with a flow rate of 26.6 sccm, a pressure of 7 mTorr, a substrate temperature of 145 °C, and a dc power of 350 W. The separation between the substrate and the target is 51 mm. The depositon rate is 9.0 A^o/s. The top Cr/Au electrode layer is formed by e-beam evaporation at room temperature and patterned by liftoff. The last step is etching the sacrificial layer by wet etch, and this concludes the front surface micromachining of the devices. Figure 2 shows final 60×60 two-dimensional array devices. The die size is 1 cm$\times$1 cm.

Figure 3 shows the real part of the electrical input impedance of only one row of 60 elements of devices shown in Fig. 2. Operating in air, the transducers have a resonant frequency of 3.0 MHz and a fractional bandwidth of about 1.5%. The real part of the electrical input impedance has a 280 Ω base value, and it was determined by SPICE simulation that this base value is caused by the bias lines connect-

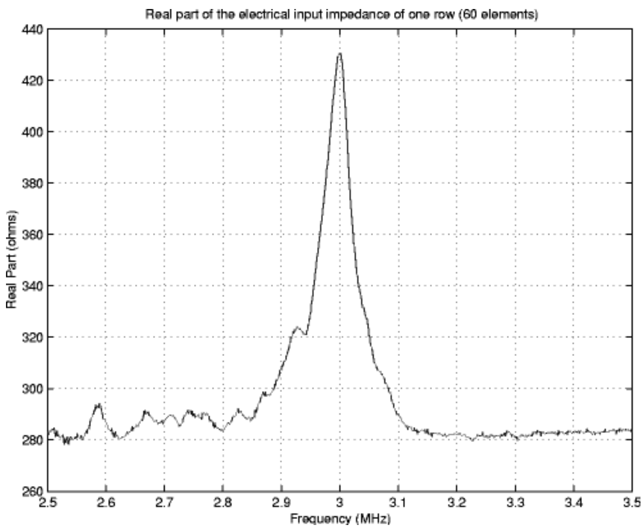

FIG. 3. Electrical input impedance real part of the realized micromachined device.

ing individual array elements. This can be avoided by using electroplating to increase the thickness of the bias lines. Figure 3 also shows the existence of acoustical activity in the device, and an acoustic radiation resistance R_a of 150 Ω. Figure 4 presents the change of the electrical input impedance in vacuum of a device consisting of one row of 60 elements. The resonance frequency is 3.00 MHz in air and 3.07 MHz in vacuum (at 50 mTorr). This result is in accordance with our expectations, since the resonant frequency and the real part of electrical input impedance at resonance should increase in vacuum. The acoustic activity in vacuum reflects energy coupling to the structure. This is a major

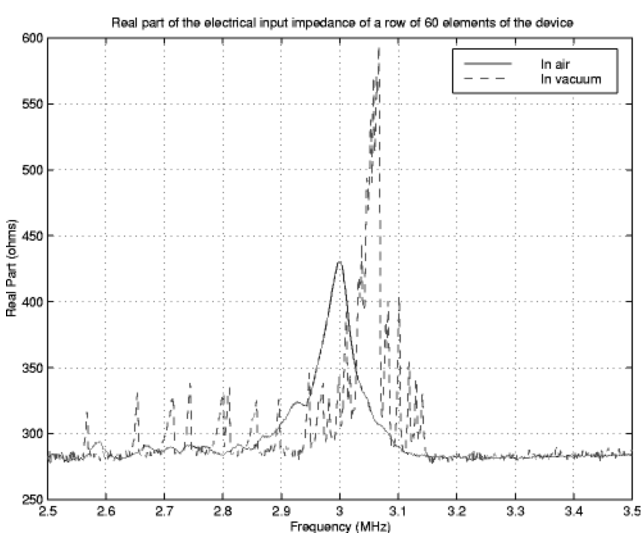

FIG. 4. Electrical input impedance real part change of the device in vacuum and air.

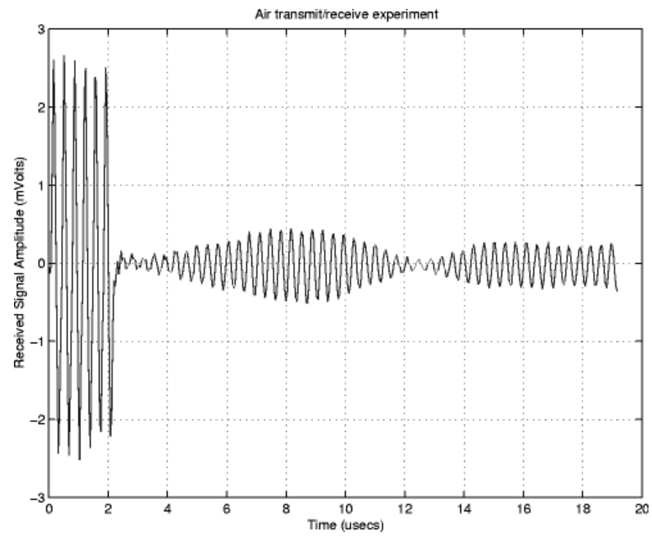

FIG. 5. Air transmission/receive experiment of the realized micromachined device.

source of loss in the device and is a present topic of research in our group. Figure 5 shows the result of an air transmission experiment where an acoustic signal is received following the electromagnetic feedthrough. The insertion loss is 112 dBs. In the transmit/receive experiment, the receiver had one row of 60 elements, and the transmitter had two rows of 120 elements. Loss due to eletrical mismatches is 34.6 dBs. Other important loss sources are alignment of receiver and transmitter, and structural losses.

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

This research was supported by the Defense Advanced Research Projects Agency of the Department of Defense and was monitored by the Air Force Office of Scientific Research under Grant No. F49620-95-1-0525.

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