Piezoelectrically Actuated Flextensional MUTs

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Abstract - This paper presents novel micromachined two-dimensional array piezoelectrically actuated flextensional transducers that can be used to generate sound in air or water. Micromachining techniques to fabricate these devices are also presented. Individual unimorph array elements consist of a thin piezoelectric annular disk and a thin, fully clamped, circular plate. We manufacture the transducer in two-dimensional arrays using planar silicon micromachining and demonstrate ultrasound transmission in air at 2.85 MHz with 0.15 µm/V peak displacement. The devices have a range of operating resonance frequencies starting from 450 kHz up to 4.5 MHz. Such an array could be combined with on-board driving and addressing circuitry for different applications. Classical thin plate theory and Mindlin plate theory are applied to derive two-dimensional plate equations for the transducer, and to calculate the coupled electromechanical field variables such as mechanical displacement and electrical input impedance. In these methods, the variations across the thickness direction vanish by using the bending moments per unit length or stress resultants. Thus, two-dimensional plate equations for a step-wise laminated circular plate are obtained as well as two different solutions to the corresponding systems. An equivalent circuit of the transducer is also obtained from these solutions.

I. Introduction

A schematic of the developed micromachined ultrasound transducer array is shown in Fig. 1. The individual cell design is based on a flextensional ultrasound transducer that excites the axisymmetric resonant modes of a clamped circular plate. It is constructed by depositing a thin piezoelectric annular plate onto a thin, edge clamped, circular plate. An ac voltage is applied across 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. The transducer array element is made of several cells.

The device is manufactured by silicon surface micromachining and implemented in the form of two-dimensional array. We have designed the fabrication process for micromachined piezoelectrically actuated flextensional ultrasound transducers in a two-dimensional array by combining conventional IC manufacturing process technology with zinc oxide (ZnO) deposition. Individual cells are made of thin silicon nitride membranes covered by a coating of piezoelectric zinc oxide in the form of annular plate that has optimized dimensions. The transducer array element is made of several cells attached in parallel. Materials are chosen in accordance with availability of micromachining and IC manufacturing processes. Other piezoelectric materials, carrier plate materials, electrode metals, and substrates can be used.

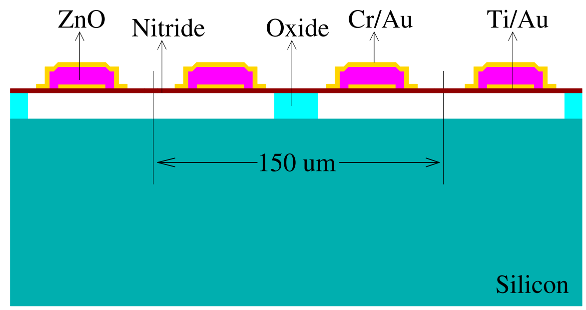


Figure 1: Side view of two adjacent cells of the developed micromachined two-dimensional array of transducers

II. Device Design

We have designed the individual cell to have a maximum volumetric displacement of the plate at the resonant frequency. We designed micromachined two-dimensional array transducers learning from the model of a one-element large scale prototype[1]. General information about designing unimorph and bimorph transducers, and review of theoretical models can be found in Germano[2] and Denkmann *et al.*[3]. Analyses of similar devices such as those of Allaverdiev *et al.*[4], Vassergiser *et al.*[5], Okada *et al.*[6], and Iula *et al.*[7] 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 or complex analytical models to determine the resonant frequencies of the structure, the input impedance of the transducer, and the normal displacement of the surface. Indeed, the complete analysis of the transducer is presented in Perçin *et al.*[10].

In the absence of analytical expressions for the equivalent circuit parameters of a flextensional transducer it is difficult to calculate its optimal parameters and dimensions, and to choose suitable materials. The influence of coupling between flexural and extensional deformation, and coupling between the structure and the acoustic volume on the dynamic response of piezoelectrically actuated flextensional transducer are rigorously analyzed using two analytical methods: classical thin (Kirchhoff) plate theory and Mindlin plate theory in Perçin *et al.*[8]-[10]. Classical thin plate theory and Mindlin plate theory are applied to derive rigorous two-dimensional plate equations for the transducer, and to calculate the coupled electromechanical field variables such as mechanical displacement and electrical input impedance. In these methods, the variations across the thickness direction vanish by using the bending moments per unit length or stress resultants. Thus, two-dimensional plate equations for a step-wise laminated circular plate are obtained as well as two different solutions to the corresponding systems. An equivalent circuit of the transducer is also obtained from these solutions. This approach has certain advantages compared to finite element modeling (FEM) analysis. For instance, a non-linear optimization routine can be developed based on the aforementioned methods.

Table I: Physical dimensions of a typical cell

Dimension	Value
Radius of the silicon nitride carrier plate	57.5 µm
Inner radius of piezoelectric zinc oxide	15 µm
Outer radius of piezoelectric zinc oxide	40 µm
Thickness of piezoelectric zinc oxide	0.3 µm
Thickness of silicon nitride carrier plate	0.3 µm
Thickness of gold electrodes	0.1 µm

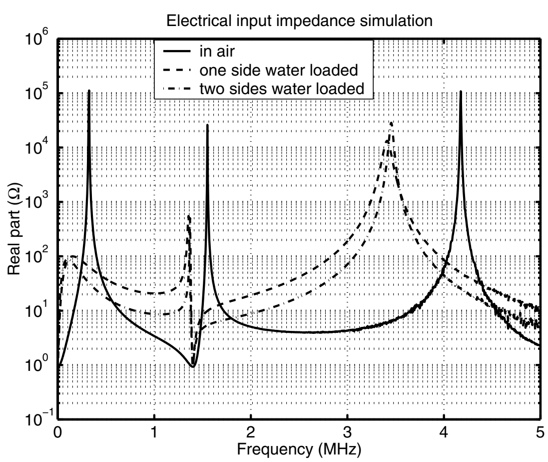


Figure 2: Electrical input impedance simulation of the single flexural mode transducer cell

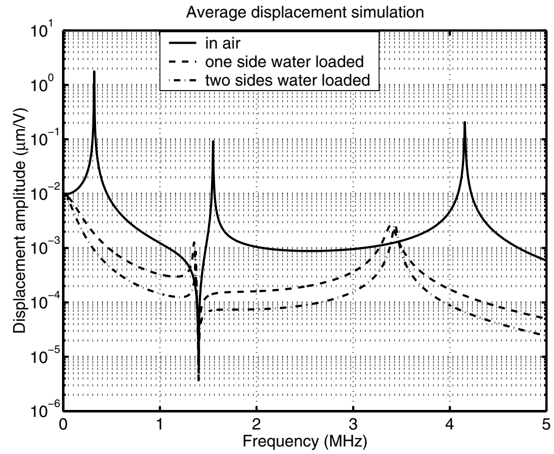


Figure 3: Average displacement simulation of the single flexural mode transducer cell

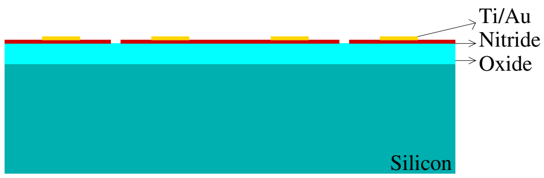
For an individual cell, by using the parameters of Table I, we obtain the first resonance frequency at 0.32 MHz, the second at 1.55 MHz, and the third at 4.17 MHz. The results of electrical input impedance and average displacement simulations are given in Figs. 2 and 3 for air, one side water loaded and two sides water loaded cases.

III. Device Fabrication

The fabrication process for micromachined two-dimensional flextensional transducer arrays is given in Fig. 4. The process starts with growing a sacrificial layer, chosen to be silicon oxide (LTO). A non-piezoelectric carrier plate layer of LPCVD silicon nitride is grown on top of the sacrificial layer. Holes for sacrificial layer etching are patterned in the silicon nitride carrier plate layer at the front surface of the wafer by plasma etching. The bottom Ti/Au electrode layer is deposited on the non-piezoelectric carrier plate by e-beam evaporation at relatively high temperature. The degree to which the ZnO c-axis, <0002>, is oriented normal to the substrate surface is very sensitive to the degree to which the Au film is <111> oriented. 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 sputtering from a zinc target. The deposition is made in an argon-oxygen ambient with a substrate at relatively high temperature. 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 developed devices.

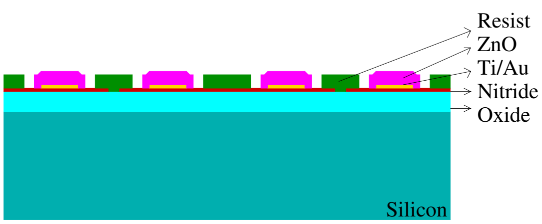
Growing 5 microns LTO.
Growing 0.3 microns LPCVD silicon nitride.
0.1 microns hot Ti/Au evaporation.

Patterning 8 microns holes in the Ti/Au layer with wet etch by using mask 1.
Etching 8 microns access holes in the nitride by dry etch.

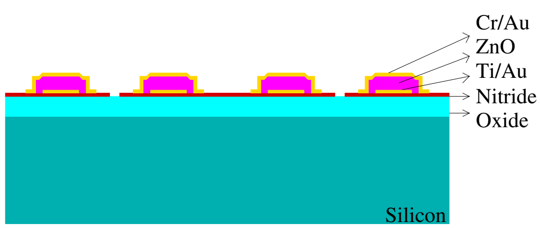


Patterning bottom electrodes in the Ti/Au layer with wet etch by using mask 2.

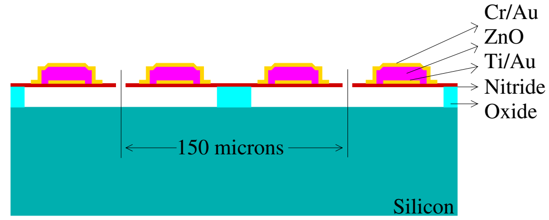
Magnetron sputtering of 0.3 microns ZnO as piezoelectric material.
Patterning the ZnO layer with wet etch by using mask 3.



Patterning photoresist layer for top electrode layer liftoff by using mask 4.



0.1 microns Cr/Au layer evaporation as a top electrode.
Making liftoff for the Cr/Au top electrode layer.



Pattering photoresist by using mask 1 again.
Etching the sacrificial LTO layer through 8 microns access holes with wet etch.

Figure 4: Developed micromachined device process flow

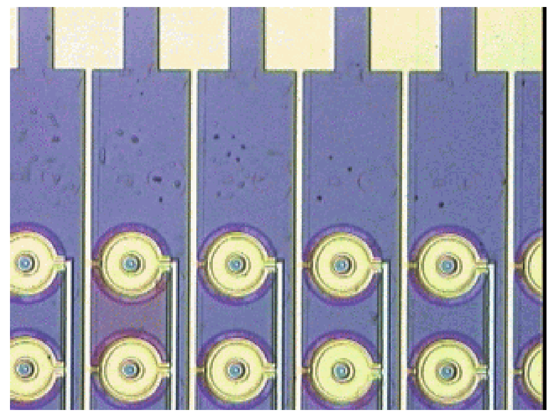


Figure 5: Realized micromachined device: individual cells are 100 μm in diameter

IV. Experiments

Fig. 5 shows realized micromachined device and individual cells are 100 μm in diameter. By using the fabricated device, shown in Fig. 4, which has 4 cells connected in parallel, 100 μm-diameter thru-wafer backside access holes were filled with water, and a conventional longitudinal thickness mode transducer was used to excite ultrasound waves in air at 4 MHz. The longitudinal mode transducer was driven with a sinusoidal tone burst with 4 cycles at 4 MHz. In Fig. 6, the received signal at the transducer is shown. As seen in Fig. 6, the device has a fractional bandwidth of 10% when loaded with water. Fig. 6 demonstrates the acoustical or, equivalently, electromechanical activity in the devices when they are loaded with fluid. In the experiments, a low noise amplifier with a gain of 25 (28 dB) was used to amplify the received signal at the device. Figs. 7 presents the real part of the electrical input impedance measurements of the device loaded with water. As shown in Fig. 7, the resonances shift down in frequency and become relatively broadband (25%) when the device is loaded with water. Another important point in Fig. 7 is the fact that the quality factor for the third resonance for water loaded case is still relatively high, and this is because of the fact that the third mode has relatively small coupling to the surrounding medium. As a result, one can say that some resonant modes are suitable for ultrasound transducer applications, such as imaging, NDA, etc., and some resonant modes are suitable for fluid ejection applications due to reduced acoustic coupling to the surrounding medium, but still large displacement.

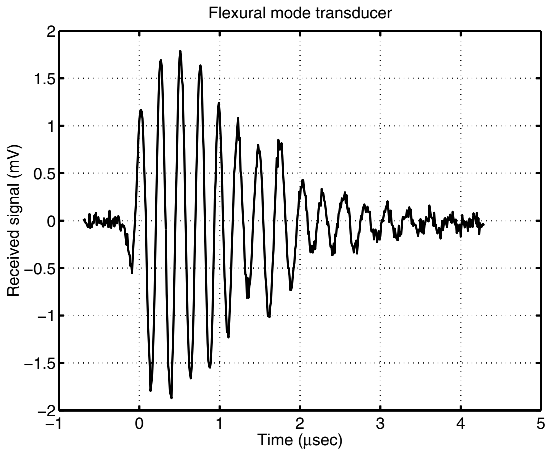


Figure 6: Received signal at the flextensional transducer element

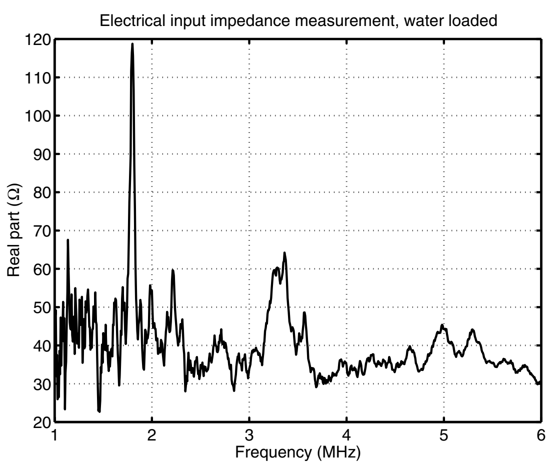


Figure 7: Electrical input impedance of the flextensional transducer element (4 cells connected in parallel) when loaded with water

V. Conclusion

In summary, we have developed a novel ultrasonic transducer, which is silicon micromachined into two-dimensional arrays. The individual cell design is based on a variation of a flextensional transducer. The transducer design was optimized initially using finite element analysis, but later using the model developed in Perçin *et al.*[8], and the ultrasonic transmission was demonstrated in air and water.

VI. References

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