Design, Simulation and Fabrication of a Bridge Structure Microtransducer

Ming Zang*, Shayne M. Zurn*, Dennis L. Polla*, Bradley J. Nelson**, and William P. Robbins*
*Department of Electrical and Computer Engineering, University of Minnesota, Minneapolis, MN 55455
**Department of Mechanical Engineering, University of Minnesota, MN 55455

ABSTRACT

ANSYS simulation of a variety of microtransducers was performed. The results indicate that a bridge structure is an optimal design for a microtransducer. Simulation of a bridge structure PZT thin film microtransducer was verified by fabricating the device on silicon wafers using reactive ion etching (RIE) and bulk micromachining techniques. The bridge of the microtransducer is released by back etching of the silicon wafer using an STS RIE system. One advantage of the STS RIE system is that is allows more than six wafers to be etched at one time, as opposed to deep trench RIE systems. The complexity of the fabrication process is also greatly reduced using this combination of processes. Analytical results of the frequency response closely agree with experimental results. Testing and simulation verified that the bridge structure PZT thin film transducer is more sensitive than other structures, such as membranes, cantilever beams and sandwich structures. The bridge transducer has a Q factor of 500.

Keywords: PZT thin film bridge, Microtransducer, PZT thin film, Microsensor, and Deep trench RIE.

1 INTRODUCTION

PZT($Pb[Zr_xTi_{1-x}]O_3$) thin films are a promising piezoelectric material for fabricating MEMS sensors and actuators on a silicon substrate. A variety of design structures have incorporated PZT, such as sandwiches, membranes, and cantilever beams [1][2]. However, development of microsensors and microactuators using PZT thin films on silicon is still a challenge. Research and development of PZT thin films, initially for acoustic emission microsensors on silicon wafers, has been pursued for several years at the University of Minnesota. As part of this endeavor, a bridge structure PZT thin film microtransducer on a silicon wafer has been fabricated. An optimal design of the proposed bridge structure is obtained by modeling the structure using finite element analysis (FEA) under ANSYS5.5.1. Testing and simulation demonstrate that the bridge structure PZT thin film transducer is more sensitive than other structures, such as membranes, cantilever beams or sandwich structures.

Bridge structure transducers have many potential applications. For example, one application being pursued is in micromanipulation and microassembly. The bridge structure is being used to produce micro fluidic flow for manipulating and assembling micrometer sized parts. The microactuator is driven at a high frequency, because bridge structures have a low power output, In a sensing mode, the bridge microtransducer can be used as an accelerometer for measuring high frequency vibrations, because the first of several natural frequencies of the bridge are in ultrasonic and megasonic frequency ranges. Compared with finger and cantilever beam array structures for capacitive accelerometers, the bridge structure PZT thin film microtransducer is a much simpler design.

2 FABRICATION

The bridge structure PZT thin film microtransducer is fabricated on a silicon wafer using reactive ion etching (RIE) and bulk micromachining techniques. Figure 1 shows a photograph of a PZT thin film bridge structure. The PZT thin film is prepared with a modified method of MOD (metallo-organic decomposition) [3]. The coating of PZT thin film onto the wafer is enhanced by carefully considering the effects of temperature and humidity. With these improvements, high quality PZT thin films are obtainable.

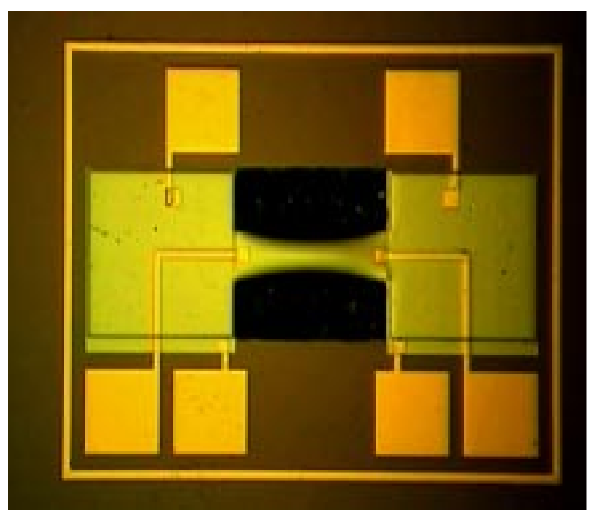

Figure 1: Photograph of a PZT thin film bridge structure. The dimensions of the bridge are: width 300μm, length 1000μm and thickness 2.5 μm.

Figure 2 shows the fabrication process. There are five main steps in fabricating the device. The first step is the deposition of the thin films. Silicon dioxide is first deposited on the silicon wafer substrate using thermal oxidation at 1000 ^{o}C. Silicon nitride is then deposited using LPCVD. Titanium and platinum thin films that serve as the bottom electrode are sputtered on the insulation layers using DC sputtering or e-beam. The PZT thin film is coated on the bottom electrode using the MOD process, and then the top electrode of platinum is deposited. The thickness of each thin film is given in Table 1.

The second step entails patterning the bridge on the PZT film using RIE and wet etching. This step is followed by the deposition of aluminum bonding pads. An insulation or protection layer of silicon dioxide is deposited on the patterned bridge using PECVD. The bonding pad is deposited using e-beam on the insulation layer in which there are holes etched by STS RIE for contacting the top and bottom electrodes.

The fourth step entails back etching the wafer for releasing the bridge. The back etching of the wafer can be done using deep trench RIE or STS RIE. The main advantage of using the STS RIE system is that more than six wafers can be etched at one time. Finally, the last fabrication step is to wire bond and package the microtransducer.

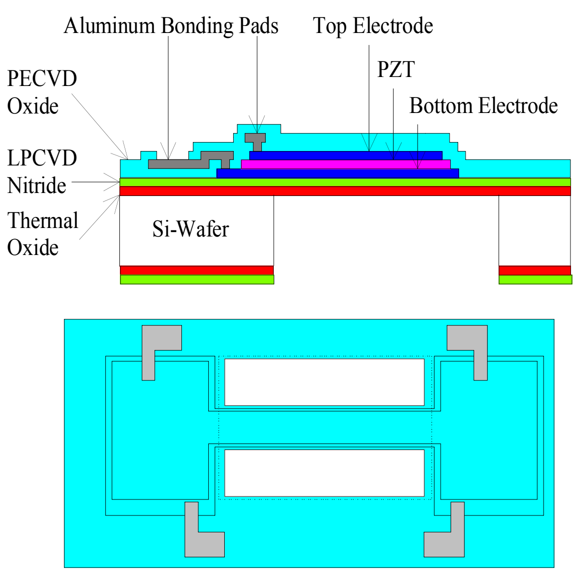

Figure 2: Schematic of a PZT thin film bridge structure.

Materials	Thickness (μ)
Silicon wafer	450-475
Silicon dioxide	1.5
Silicon nitride	0.5
Titanium	0.02
Platinum	0.1
PZT	0.5
Platinum	0.1
Silicon dioxide	0.5

Table 1: Thickness of each thin film of the bridge structure.

3 MODELING

The design of the microtransducer bridge structure has been analyzed and optimized by finite element analysis (FEA) using ANSYS5.5.1. For applications of acoustic emission detectors and accelerometers in high frequency domains as well as micromanipulation applications using low power actuators, the bridge transducer is designed with a high natural frequency in ultrasonic and megasonic frequency ranges. The frequency response of the bridge under the force of gravity is modeled by the harmonic analysis in ANSYS. In simulating the frequency response, the influence of damping on the bridge in air is taken into account to determine the stiffness matrix multiplier β for the harmonic analysis. The viscosity of air is assumed to be 0.181×10^{-4}Pa-s. The constant damping ratio is set to 2% and the mass matrix multiplier α is not considered. For comparisons, a cantilever beam that has the same size as the bridge was also analyzed.

Shell99, a 100-layer structural shell element with isotropic properties, is used for a structural analysis in ANSYS5.5.1. The Block Lanczos method is chosen in modal analysis for finding the natural frequencies. The Jacobi Cojugate Gradient (JCG) solution is selected for the harmonic analysis. The boundary conditions used in the modeling are shown in Figure 3. By symmetry, half of the bridge is modeled to reduce meshing elements and save computation time. The mechanical properties used for each of the layers are shown in Table 2[4].

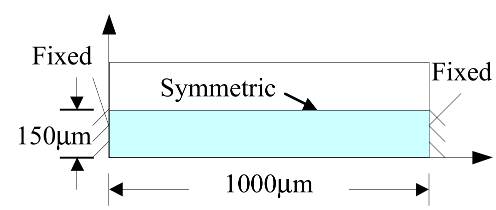

Figure 3: Schematic of boundary conditions on half of the bridge in the modeling.

Properties / Materials	Young's modulus Y(GPa)	Poisson's ratio σ	Density ρ(kg/m^3)
Silicon dioxide	72	0.17	2200
Silicon nitride	222	0.28	3440
Titanium	110	0.34	4506.3
Platinum	170	0.39	21450
PZT	75	0.31	7550
Platinum	170	0.34	21450
Silicon dioxide	57	0.17	2200

Table 2: Properties of materials for each layered thin film.

4 RESULTS AND COMPARISONS

Table 3 shows that the bridge transducer has very high natural frequencies with the frequency of the first mode at 8.226kHz. This is useful for an accelerometer for high frequency vibration measurements. There are very rich natural frequencies in the range from 100k to 1MHz, a typical frequency range of acoustic emission (AE) induced by fatigue cracks. The first natural frequency of the cantilever beam, the same size as of the bridge, is 1.7405kHz as shown in Table 4, far smaller than that of the bridge.

Natural Frequencies of the Micro Bridge					
Mode	**Freq. (kHz)**	**Mode**	**Freq. (kHz)**	**Mode**	**Freq. (kHz)**
1	8.2265	8	182.84	15	381.6
2	24.329	9	197.27	16	434.31
3	49.92	10	244.13	17	449.09
4	85.032	11	244.37	18	513.23
5	129.38	12	299.65	19	513.81
6	133.87	13	311.57	20	582.77
7	159.45	14	362.92		

Table 3: Natural frequencies of the bridge microtransducer obtained with using the Shell element with the modal analysis of ANSYS 5.5.1.

Natural Frequencies of the Micro Beam					
Mode	**Freq. (kHz)**	**Mode**	**Freq. (kHz)**	**Mode**	**Freq. (kHz)**
1	1.7405	8	180.34	15	412.95
2	11.643	9	217.76	16	481.55
3	33.843	10	242.76	17	508.17
4	67.990	11	269.17	18	571.75
5	114.13	12	32308	19	603.58
6	157.24	13	330.62	20	672.20
7	171.81	14	401.26		

Table 4: Natural frequencies of the cantilever beam micro-transducer obtained using the Shell element with the modal analysis of ANSYS 5.5.1.

Figure 4 shows the frequency response of the bridge under acceleration at one g (9.8 m/s^2), simulated by harmonic analysis of ANSYS. The displacement at the center of the bridge in the direction vertical to the surface is about 19 nm at the natural frequency of 129.38kHz. This agrees with experimental results obtained with an HP 4194A impedance phase analyzer shown in Figure 5. The resonant frequency of the bridge is measured at about 130kHz, 1% greater than that of the modeling, and has a Q_e factor of approximately 500. The mechanical quality factor Q_m calculated from the simulation is greater than 3000. The difference between the two factors indicates that the electrical gain response is not precisely linear with the mechanical displacement in the region of the resonant frequency. This seems reasonable because the electrical response may saturate at the resonant frequency. The lower resonant peaks are not detected in the measurements. This may be because the available power from the HP analyzer for the driver is much smaller at these frequencies.

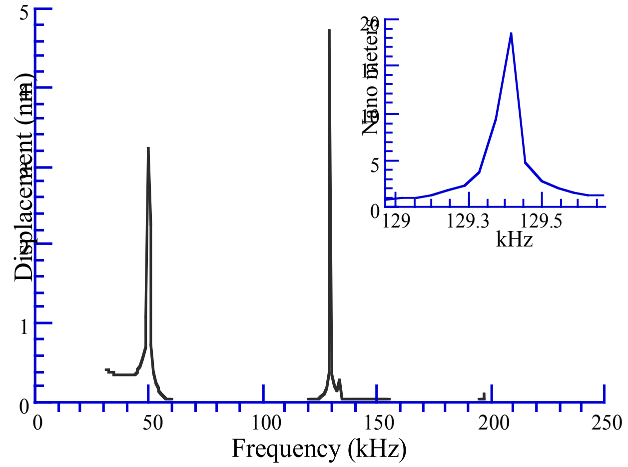

Figure 4: Vibration amplitude of the bridge accelerated gravitationally at one g (9.8m/s^2) given by harmonic analysis of ANSYS.

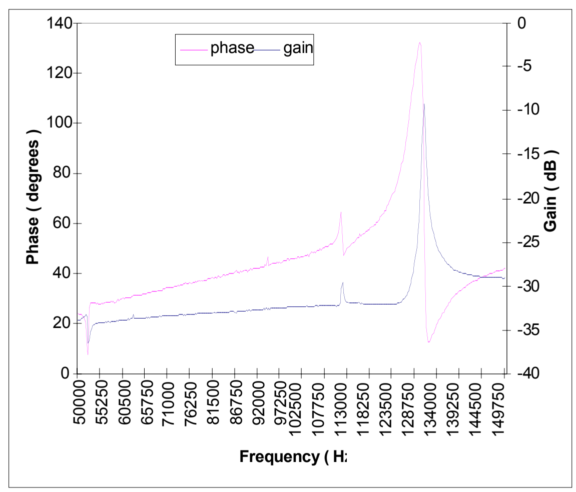

Figure 5: Experimental Impedance Analyzer results for the bridge structure.

Using the same measurement conditions as the bridge, the resonant frequency of a PZT thin film cantilever beam, occurs at 113kHz and has a Q_e factor about 100, as shown in Figure 6. This agreed with the modeling results in Figure 7, which show that the resonant frequency is at about 114.13kHz, 1.01% greater than measured, and has a Q_m factor about 2282. Compared with experimental results for the beam, the bridge structure has a higher resonant frequency and a Q factor five times greater than the beam.

Figure 8 shows a comparison of the low frequency response of the bridge and cantilever beam accelerated gravitationally at one g. The amplitude of vibration in the

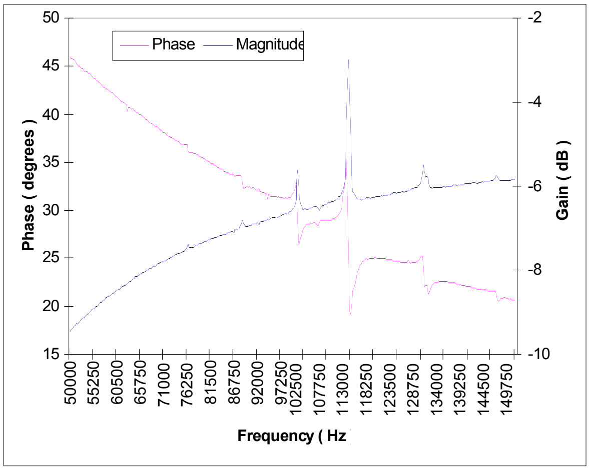

Figure 6: Experimental Impedance Analyzer results for the cantilever beam structure.

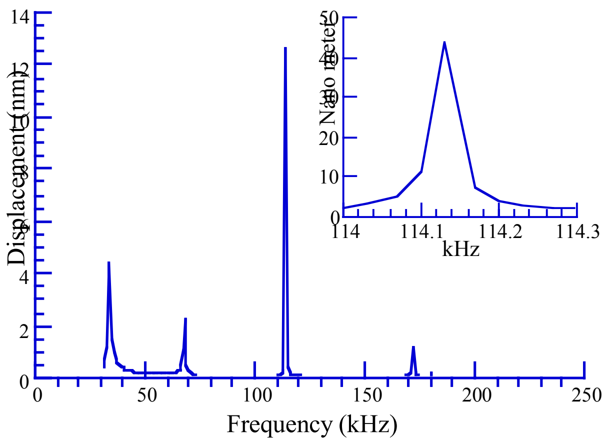

Figure 7: Vibration amplitude of the beam accelerated gravitationally at one g ($9.8 m/s^2$) given by harmonic analysis of ANSYS.

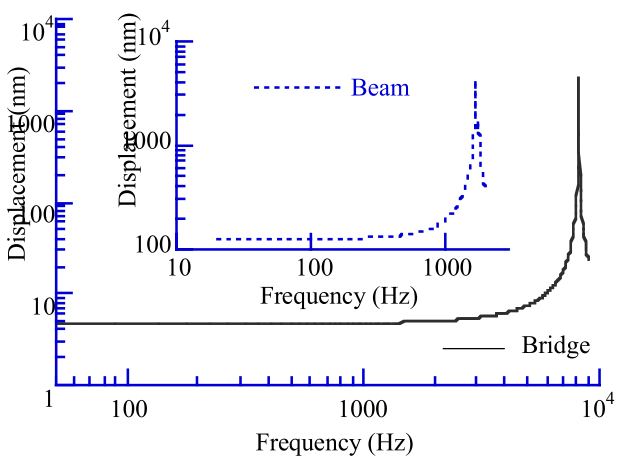

Figure 8: Comparison between the bridge and cantilever beam in low frequency response.

bridge is quite a flat up to 4 kHz. The beam has a much higher response in the low frequency range than the bridge, but the bridge has a wider range. This is useful for fabricating an accelerometer for high frequency vibrations.

5 CONCLUSIONS AND FUTURE WORK

A bridge structure PZT thin film transducer was fabricated based on the optimization of a finite element analysis using ANSYS. Analytical results of the frequency response agree very well with what was obtained from tests of the transducers. Testing and simulation show that the bridge structure PZT thin film transducer is more sensitive than a cantilever beam. The bridge transducer has a Q factor of 500, five times that of the beam.

In future work, mass loading on the central area of the bridge will be considered to enhance the sensitivity of the bridge transducer. The design of the bridge with mass loading will be modeled and optimized using ANSYS.

ACKNOWLEDGMENT

The authors would like to thank the Office of Naval Research for supporting this work (under ONR grant N000014-95-1-0539 for the project of Integrated Diagnostics).

REFERENCES

[1] C. Lee, T. Itoh, and T. Suga, “ Micromachined Piezoelectric Force Sensors Based on PZT Thin Films”, IEEE Trans. Ultrason., Ferroelect., Freq. Contr., vol. 43, pp. 553-9, 1996.

[2] D.L. Polla, SPIE, Int. Soc. Opt. Eng., vol. 3064, pp. 24-7, 1997.

[3] M. Klee, R. Eusemann, R. Waser, W. Brand, and H. van Hal, “Processing and electrical properties of Pb $(Zr_xTi_{1-x})O_3$ (x=0.2-0.75) films: Comparison of metallo-organic decomposition and sol-gel processes”, J. Appl. Phys. 72, pp. 1566-76, 1992.

[4] M. Zang, D. L. Polla, S. Zurn, and T. Cui, “Stress and Deformation of PZT Thin Film on Silicon Wafer due to Thermal Expansion”, in Multicomponent Oxide Films for Electronics, Proc. MRS, vol. 574, Spring Meeting, San Francisco, CA, April 5-9, pp. 107-10, 1999.