Design, Fabrication and Experimental-Numerical Study of PZT Sensors

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ABSTRACT

MEMS micropumps, based on PZT membranes have been designed and fabricated at the Microtechnology Laboratory of the University of Minnesota for use in fluid flow control, and as chemical and pressure sensors. Design, fabrication and numerical analyses of the PZT cantilever beams were presented at the MSM99, and are now extended to new MEMS devices; specifically reactive ion etched (RIE) bulk micromachined PZT membranes. Four major geometries including square, rectangular, circular and elliptic devices with different sizes have been successfully fabricated. The main advantage of the new devices is in providing more resonant points than the microcantilever beam, thus creating a larger working interval. Numerical studies have been carried out by using ANSYS Finite Element software. Numerical results compared well with the experimental findings.

Keywords: CAD, Finite element model, PZT Membrane, Atomic force microscope, Impedance analyzer.

INTRODUCTION

Simulation is of interest in designing efficient MEMS devices. During the last days of the twentieth century, it is critical to obtain cheap, easy, and optimum solutions for practical engineering applications and research. MEMS devices appear to have a promising future in many other applications including those in the automobile industry, biological sciences, and many engineering disciplines [1]. Since MEMS are a new research area and there is a notable lack of information related to the thin film properties of materials or applicable formulas, most of the fabrication has been done without any calculations, relying instead on trial and error. While this approach has lead to many successful developments, it is highly inefficient, and can often waste a large amount of time and resources.

PZT cantilever beams and membranes are commonly used in many MEMS applications such as; microvalves, transducers, and micropumps. PZT thin film membranes (see Fig. 1) are designed and fabricated by applying bulk micromachining techniques [2] and metal organic deposition (MOD) of PZT [3]. In this study, the Finite Element Method is used to characterize the structural behavior of the PZT membranes. A parallel experimental study has been carried out by using an atomic force microscope (AFM) and impedance analyzer to obtain resonant frequencies.

To obtain an optimum design Finite Element Analyses were performed for PZT thin film membranes. Both modal and harmonic analyses have been completed over the range of frequencies that the devices will be experiencing in the application. Later, MEMS devices were designed and fabricated. They were then tested by means of several experimental techniques to observe the resonant behavior of the devices.

FINITE ELEMENT ANALYSIS

To obtain an optimum design Finite Element Analysis was performed for PZT thin film membranes, such as shown in Fig. 1, before starting the fabrication stage of the sensors. ANSYS5.5 [4] was run on an IBM SP with 80 WinterHawk nodes. Each WinterHawk node has two 200 MHz Power3 processors sharing one GB of memory, with a total allocated memory of one Terra Byte. Shell elements were successfully used to model the membranes and each layer's thermophysical properties were introduced through the ANSYS material library. Zero displacements were applied in the x, y and z directions at the boundaries. In the harmonic analysis, pressure forces were applied on the nodes. Fine meshing was chosen for all of the devices and varied between 15000 and 35000 elements, for a membrane, 1600x1600 μm, and 2 μm thick (35000). With this meshing, it took about 1 minute per mode in the modal analyses and about 20 minutes in harmonic analyses for a range of 0 to 5 MHz in order to obtain the solution. The analysis of the PZT membranes began with a modal analysis that is used to determine the vibrational characteristics, including the natural frequencies and mode shapes of the membranes, which are important parameters in the design of a structure for dynamic loading conditions. It was also a starting point for the harmonic analyses. The best way of determining the vibrational excitation modes is determining the specified frequency at which the devices will display the range amplitudes of vibration.

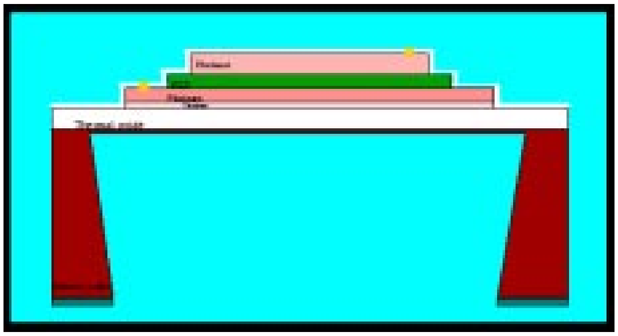

Figure 1: Cross section of a PZT membrane.

The basic equation solved in a typical undamped modal analysis is the classical eigenvalue relation:

$$[K]\{\phi_i\} = \omega_i^2[M]\{\phi_i\} \quad (1)$$

Where [K] is the stiffness matrix and $\{\phi_i\}$ is mode shape vector (eigenvector) of mode i, ω_i is the natural frequency of mode i (ω_i^2 is the eigenvalue), while [M] is defined as mass matrix [4]. The Block Lanczos method [4] was chosen to solve the eigenvalue problem as the most appropriate for the micropumps. This method applies the Lanczos recursion method. It is a highly accurate and fast method in comparison with other techniques. The first hundred modes have been extracted with the specified frequency range of 0 and 5 MHz. Figs. 2 and 3 show typical results of the analysis for the first and thirtieth modes.

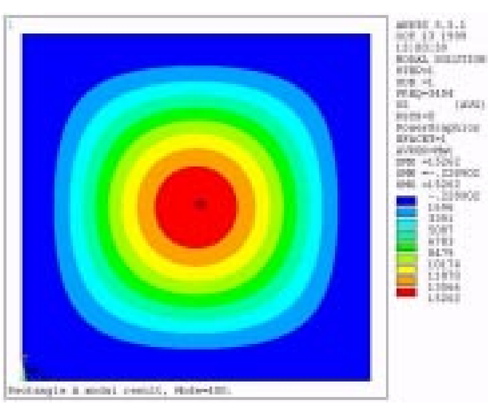

Figure 2. Modal result for square micropump at Mode=1.

The colored contours, with red a maximum and blue a minimum, show the deflections in the positive z-direction on the graphs. In Fig. 2, the maximum deflection is about 15. µm while the natural frequency is 3.4 kHz. The mode shape at the thirtieth mode shown in Fig. 3 is different than first mode. The natural frequency is obtained, as 30.86 kHz while the maximum deflection was 13 µm. When the devices are excited at higher frequencies, the membrane has many small sections, which vibrate independently of one another.

A sustained cyclic load will produce a sustained cyclic response, a harmonic response, in a structural system. Harmonic response analysis can predict the sustained dynamic behavior of structures that will allow one to verify whether or not the design will successfully overcome resonance, fatigue, and other harmful effects of forced vibrations. Transient effects are assumed as negligible in the harmonic analyses.

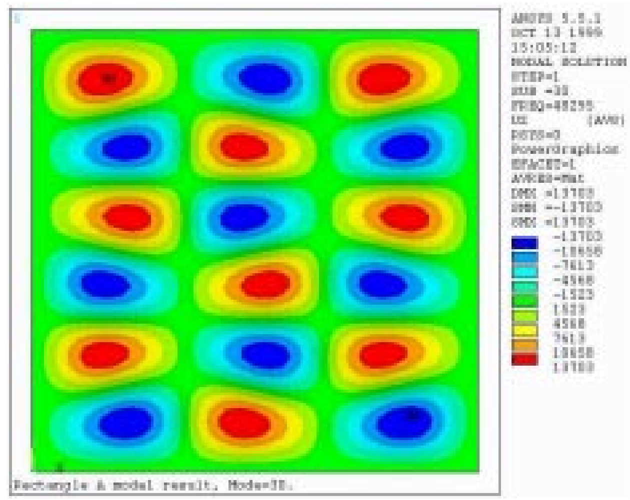

Figure 3. Modal result at Mode=30.

The applied force on the system can be represented as follows:

$$F = F_o Cos(\omega t + \phi) + F_o Sin(\omega t + \phi) \quad (2)$$

F_o is amplitude of the applied force, while ωt is the phase angle. F_o is calculated by using the analytical correlations and it is applied to the numerical model [5]. Fig. 4 shows the results obtained from the FEM analysis and presents the maximum and the minimum deflections of the membrane as a function of the driving frequency.

The capability of the ANSYS5.5 [4] has been successfully used to obtain a simulation model for PZT micropumps. Although ANSYS could provide a level of understanding for the current MEMS devices, it could not provide results with higher accuracy as a result of the material properties of the devices. Especially PZT layer properties were introduced as of bulk properties. Further studies with ANSYS will be accomplished by introducing related piezoelectric effect matrices into the ANSYS batch model. Next section will include the design, fabrication and experimental studies of the MEMS devices.

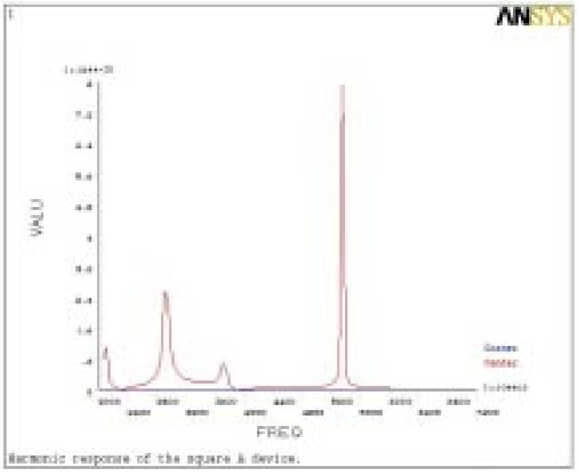

Figure 4. Result of the harmonic analysis for PZT sensor.

DESIGN AND MICROFABRICATION

The devices were formed by using an aqueous, metallo-organic precursor for PZT [2]. Fig. 1 shows a schematic diagram of the cross sectional view of a PZT MEMS micropumps. About 15 fabrication steps were followed during the micorfabrication of the devices but only the main steps will be presented. The first step is to deposit and planarize a layer of thermal silicon dioxide. Next step is depositing the bottom electrode. The bottom electrode is composed of a very thin layer of Titanium and a thicker layer of Platinum. The third step is to deposit the PZT material. Next step is depositing the top electrode, Pt. The following three steps are: etching the top electrode, PZT, and bottom electrodes. The seventh step is depositing a layer of silicon dioxide that will electrically isolate the top and bottom electrodes when the bonding pads are deposited. Etching the holes [6] in the silicon dioxide to reach the bottom and top electrodes was completed during the eighth steps. Last step on the top surfaces of the wafers is depositing and etching the gold bonding pads.

A layer of chromium was deposited as a protective mask for Silicon on the backside of the wafers. After that, the Chromium was patterned and etched. That was followed by etching of the Silicon wafer by using DRIE to free the membranes. Figs. 5 through 8 present the snapshot images of the devices at the end of the fabrication.

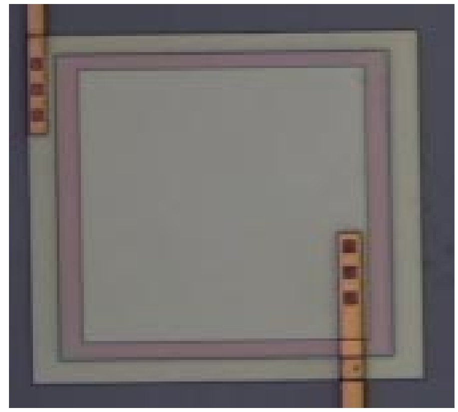

Figure 5. Schematic diagram of the square micropump.

Successful development of the design and fabrication was completed, and twenty devices were chosen for the experimental studies. While searching for an optimum design with a maximum efficiency micropump, different geometries were sought. Masks were designed for four different geometries with three different sizes each. Fig. 6 shows a single circular PZT device.

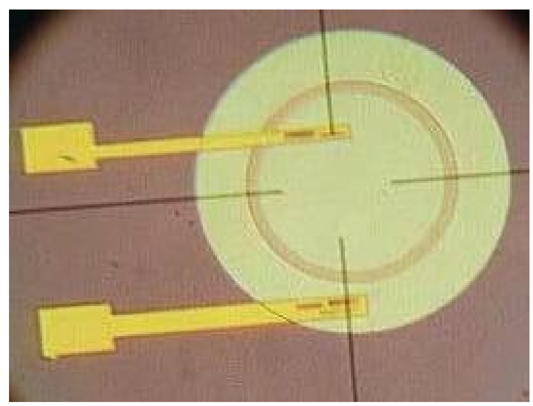

Figure 6. Schematic diagram of the circular micropump.

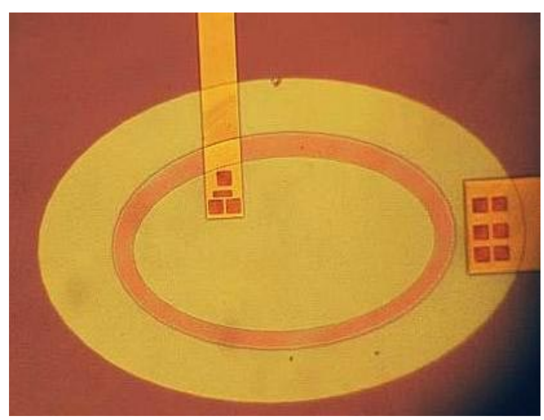

Figure 7. Elliptic micropump.

Each wafer had single devices and rows of devices.

Devices at the same rows had the same geometry while single devices were prepared in different sizes for experimental purposes. Fig. 8 shows a part of a rectangular row. The system is designed as having more than one row and each row can be actuated from a single bonding pad.

After completion of the fabrication, devices have been tested by using two different test set-ups. Test procedures and results will be discussed in the following section.

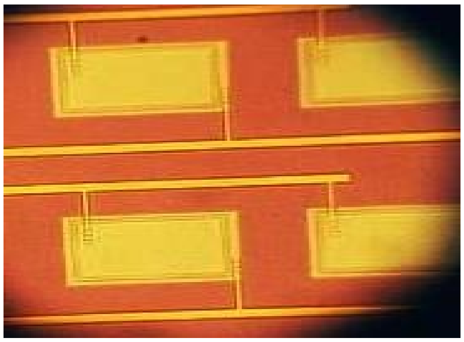

Figure 8. Rectangular PZT pump array.

EXPERIMENTAL STUDY

The experimental study consisted of two different tests: atomic force microscope and impedance analyzer tests. The first set of experiments was run on a Digital Instruments Dimension 3000 atomic force microscope. A function generator was used to actuate the membranes, and the photodetector of the AFM was used to measure the displacement of the center of the devices. Before the test was started, the system was calibrated carefully to decrease the measurement uncertainty. The function generator was swept from 100 Hz to 5 MHz to determine the resonance points of the microcantilever. Frequency swept interval was decreased following experiments as low as 25 kHz to observe the resonance points with a higher accuracy. Fig. 9 presents a typical response of the square PZT membrane.

The next set of experiments was run on a HP 4194A Impedance phase analyzer. The output is a constant voltage, and it measures the current necessary to maintain this constant voltage. As the impedance analyzer sweeps the frequency of the constant voltage source, the devices appeared to go through resonance at the same frequencies as seen on the AFM results. At each of the resonance frequencies the membrane will move much more than all of the other frequencies, and this motion will create a large stress in the PZT thin film. This stress will produce an excess charge on the electrodes, and then this excess charge can be detected by measuring the current flowing into the device. The impedance analyzer was swept from 0 Hz to 5 MHz to determine the major resonance points of the sensor. Fig. 10 shows a typical result from the impedance analyzer. Following the standard uncertainty analysis techniques [7], the measurements were found to be within $\pm$ 0.01% in a range of 1mΩ to 10 MΩ, with a 95% confidence level.

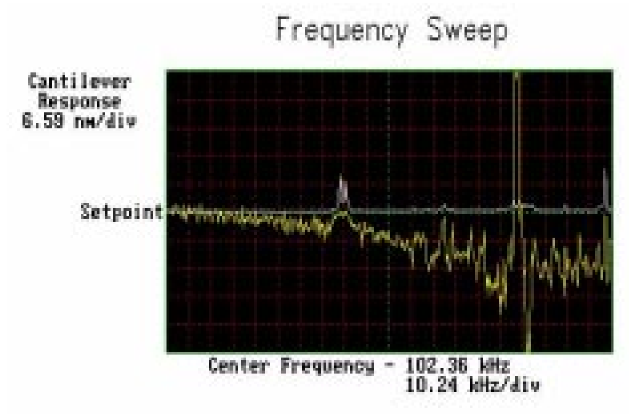

Figure 9: AFM result for square device.

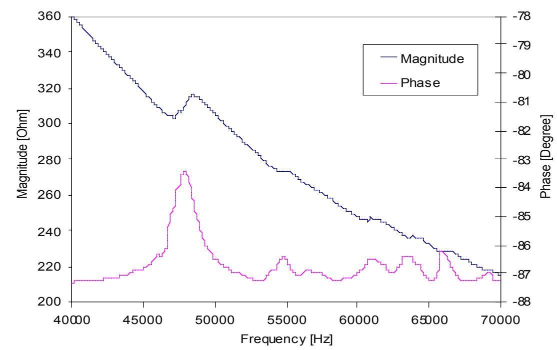

Figure 10: Impedance magnitude measurement.

RESULTS AND DISCUSSIONS

The ANSYS simulation provided CAD verification results for a large number of modes, although two selected modes are presented in this paper. By comparing the frequency responses obtained in AFM and impedance analyzer experiments, it is observed that the two methods experimentally produce the same resonant frequencies within 1.27 % deviation. Fig. 4 shows the results obtained from harmonic analysis. A typical force is applied to the physical system and its response over a wide range of frequency is studied. When the membrane reaches the resonance frequency, it has a peak displacement as seen on the Figs. 4, 9 and 10. A similar behavior of the natural frequencies to the experimental findings was observed. However, as a result of the difficulty in determining the exact force in z-direction on the Piezoelectric layer, it is hard to obtain precise agreement.

This study focused on the effect of the geometry and sizes of the sensors on the resonant frequencies with corresponding deflections. Experimental and numerical numerical and experimental results suggest that the bigger the device, the lower the first resonance frequency and the greater the resonance points. Also, square and rectangular devices showed similar behavior in terms of first resonant and number of resonances, while elliptic devices give more resonant points than circular devices. For a specified frequency range, square devices showed more resonant points than circular devices. Numerical method was able to catch the sensor behavior with high accuracy even with the bulk material properties for the thin films.

SUMMARY AND FUTURE WORK

The numerical and experimental analyses of the membrane devices has been presented. A CAD model has been developed before starting the design and fabrication of the MEMS devices, and successful design, and fabrication was accomplished. A brief description of the fabrication process and experimental results are presented and they have been compared with the numerical results. After modal analyses has been completed, numerical solution of the devices are extended to the resonance frequencies by applying a harmonic driving force on the beams. The frequency range is chosen between 0 and 5 MHz and results showed similar behavior as experimental results obtained by using an atomic force microscope and impedance analyzer. Future work will consist of applying piezoelectric matrices into ANSYS code and obtaining results with a higher accuracy with a dielectric liquid medium.

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