Fabrication of Micromachined Piezoelectric Diaphragm Pumps Actuated by Interdigitated Transducer Electrodes

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ABSTRACT

Micromachined pump structures were fabricated using surface micromachining. The structures consisted of three or five connected chambers. Sequential actuation of the diaphragms on these chambers will yield peristaltic pumping. As the actuation material, lead zirconate titanate (PZT [53/47]) thin films were employed and actuated by interdigitated transducer (IDT) electrodes. First, chambers and channels on the 4" (100) silicon wafers were defined by reactive ion etching (RIE) and thermally oxidized. The etched structures were then filled with amorphous silicon. Low temperature (silicon) oxide (LTO) and PZT films were then deposited. The LTO and PZT layers act as passive and active layers in a piezoelectric unimorph, respectively. A ZrO_2 layer was employed to prevent reaction between SiO_2 and PZT layers. A Cr/Au electrode was evaporated on top of the PZT layer and patterned into ring-shaped IDT electrodes. Finally, a porthole at each end of the pump structures was defined by ion milling and the whole micropump structure was released by removing the sacrificial amorphous silicon using XeF_2. Completely released 500 μm diameter pump structures were fabricated. The remanent polarizations of the PZT films on released diaphragms were ~20 $\mu C/cm^2$ and their coercive fields were ~50 kV/cm. 500 μm diameter diaphragms were deflected as much as 2 μm with 120 V applied. The shape and behavior of the diaphragm deflection can be explained by considering both d_{31} and d_{33} piezoelectric coefficients of the PZT films.

INTRODUCTION

Microelectromechanical systems (MEMS) are micromachined devices that have sensors or actuators together with signal processors. These devices are usually fabricated using integrated circuit techniques, offering the possibility of order of magnitude decreases in the sizes and costs. This is a strong driving force to miniaturize many macroscopic devices using micromachining.

Mass spectrometers are universal gaseous chemical detectors. Conventional mass spectrometers are large, heavy, and expensive. In addition, a trained technical person is required to operate them [1]. Recently, several groups have successfully miniaturized chemical analysis systems for mass spectrometers [1], [2]. In order to miniaturize an entire mass spectrometer, a micromachined device to create a certain level of vacuum (~10 mTorr) in a detector chamber is an essential part [3].

In this study, peristaltic piezoelectric diaphragm pump structures were fabricated using surface micromachining. These pump structures consist of three or five connected chambers. Sequential actuations of the piezoelectric diaphragms on these chambers will perform pumping. To create the diaphragm structures, amorphous silicon was used as a sacrificial material and etched out in the final step by XeF_2 gas. For the released structures, dielectric and ferroelectric properties were characterized. In addition, mechanical resonance and electric deflections were measured to evaluate the piezoelectric diaphragms as actuators.

EXPERIMENTAL PROCEDURE

Figure 1 shows the process flow, showing half of a pump structure. First, chambers and channels were defined by reactive ion etching (RIE) using SF_6 (50 sccm) at 200 mTorr with a power of 200 W. The designed diameters of the chambers were either 500 or 800 µm. The depth of the chambers was ~ 4.0 µm. ~1.2 µm of thermal oxide was grown on the wells of chambers and channels. This layer acts as an etch stop layer during the XeF_2 release process. ~5 µm of amorphous silicon was sputtered on the wafer as the sacrificial material. It was then removed everywhere inside the chambers and channels by chemical mechanical polishing (CMP). A 0.7 µm thick low temperature silicon oxide was then deposited on top of the wafer as the passive layer for the piezoelectric unimorph structure. As the active material, a PZT film (~2.0 µm) was then deposited by 2-methoxyethanol (2-MOE) based sol-gel method [4]. To prevent reaction between the PZT and the silica layer, a ZrO_2 (~0.3 µm) layer was then deposited [4]. On top of the PZT layer, a Cr/Au blanket layer was evaporated. A porthole on each end of the serially connected chambers was then defined using ion milling. As the mask material, a 4 µm thick BCB4022 (Cyclotene resin, DOW inc.) layer was utilized. When the layer was baked on a hot plate for 2 hours at 200 ^{o}C, it provided enough resistance while the PZT, ZrO_2 and LTO were removed by ion milling. The mask layer was then removed by Nanostrip (Cyantek, Fremont, CA). Following this, the Cr/Au layer was then patterned into ring shaped IDT electrodes. Both the width and spacing of the IDT electrodes were ~7.5 µm and the IDTs covered 60% ~ 100% of the diaphragm area. Finally, pump structures were released by a process in a Xetch system (XACTIX Inc) using XeF_2. Standard Xetch etch parameters were used during the release. To characterize the electrical properties of the released PZT diaphragms, dielectric and hysteresis measurements were conducted using a HP4192A LF impedance analyzer and a RT-66A Ferroelectric Test system (Radiant Technology, Inc). In addition, mechanical resonance frequencies and electric deflections of piezoelectric diaphragms were measured by a HP4194A impedance gain analyzer and an interferometer (Zygo, Inc), respectively.

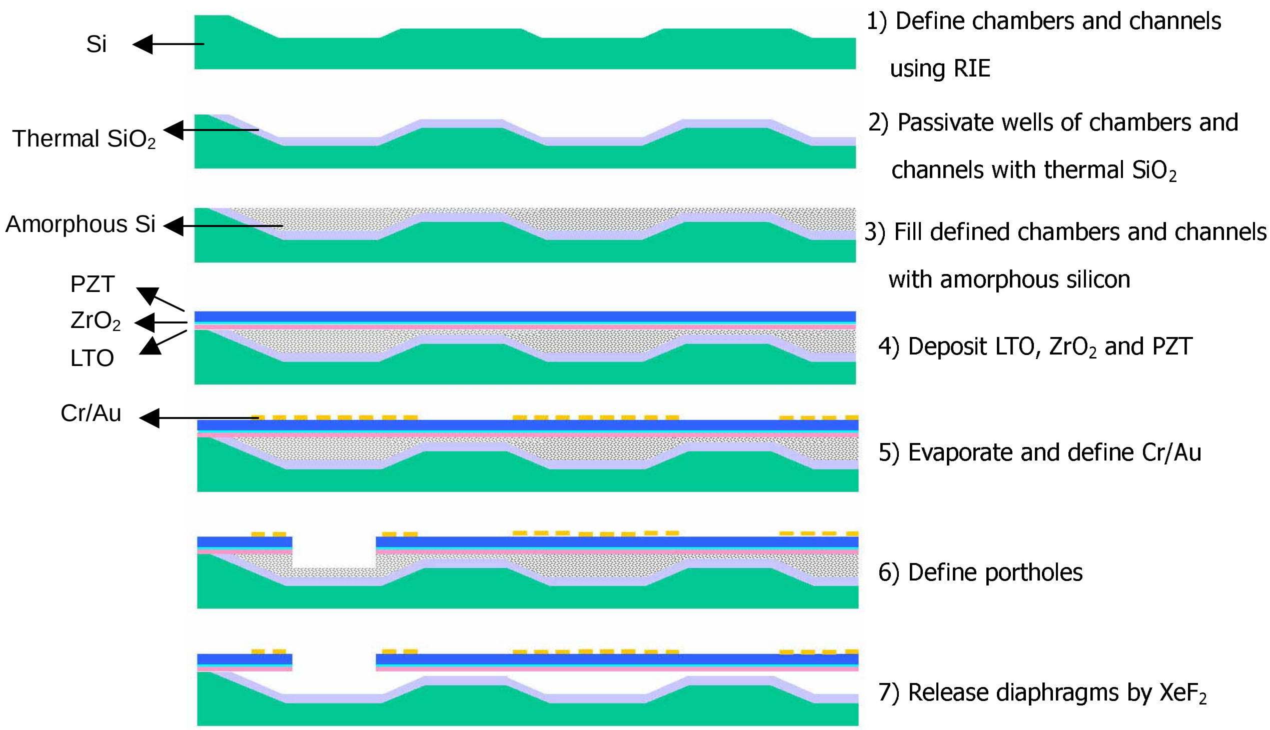


Figure 1. Process flow of micromachined pumps.

RESULTS AND DISCUSSION

Released pump structures

Figure 2 shows a 500 μm diaphragm pump structure. Holes at both ends of the structure are portholes for the XeF_2 release process. To release this structure completely, the total etch time by XeF_2 was several hours. Considering that the etch rate of silicon by XeF_2 is usually 0.3~ 1 μm/min for (100) silicon [5] and modest amount of amorphous silicon was etched, this etch time is long. It is believed that the extra time was necessitated by in-diffusion of XeF_2 gas and out-diffusion of by-product through the narrow channels and thin gaps. It is possible that the amorphous silicon was also partially oxidized. In addition, a considerable amount of XeF_2 gas was consumed to etch unwanted parts such as the edge of the wafer. Using a focused ion beam, a diaphragm was bisected. The thicknesses of the Cr/Au, PZT, ZrO_2, SiO_2 (LTO), Gap and SiO_2 (thermal oxide) were approximately 0.25, 2.0, 0.3, 0.25, 4.8 and 0.8 μm, respectively (see Fig. 3).

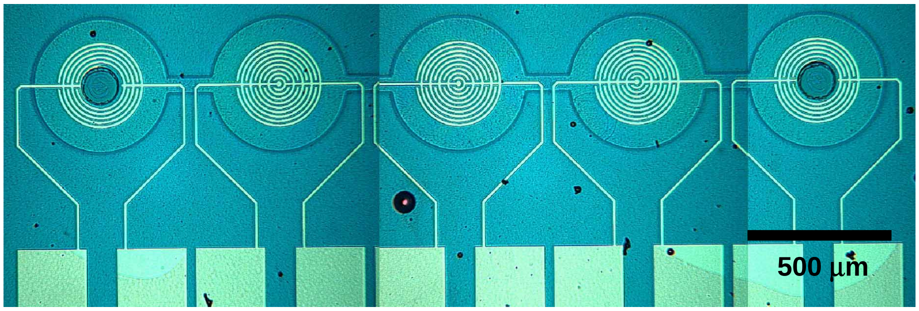


Figure 2. Released 500 µm pump structure.

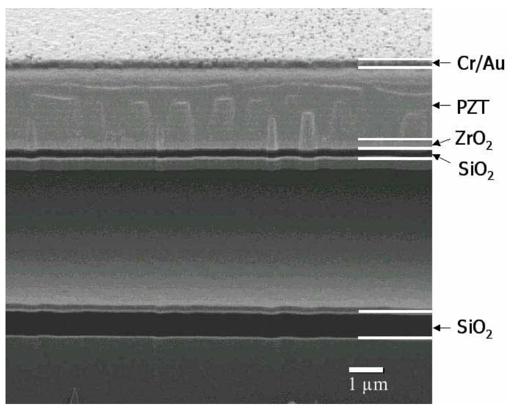


Figure 3. Cross-sectional view of a released diaphragm.

The layers beneath the LTO and on top of the thermal oxide in Figure 3 were re-deposited during the focused ion beam cutting. Considering the original thicknesses of the LTO and thermal silicon oxide, these oxide layers were significantly etched out during the XeF_2 release process. Especially, the thickness of the LTO beneath the ZrO_2 layer was reduced from 0.7 µm to 0.25 µm. Because this layer acts as the passive layer in the piezoelectric unimorph structure, reduction of its thickness will make the unimorph structure weaker. Therefore, this problem should be solved in subsequent process runs either by using a protective layer under the LTO or a significantly thicker LTO layer.

Electrical Properties

The electrical properties of released diaphragms are important, since they are directly related to performance of the diaphragm actuators. The values of their capacitances for 500 µm diameter diaphragm ranged from 7 pC to 12 pC at 100 kHz with an oscillation of 1 V, depending on the size of the IDT electrodes. The dielectric losses were maintained below 0.02. Figure 4 shows hysteresis loops from a piezoelectric diaphragm. The polarizations were calculated by dividing the charge outputs by the effective areas and the electric fields were obtained by dividing the applied voltage by the IDT spacing [6]. This figure shows good ferroelectric characteristics.

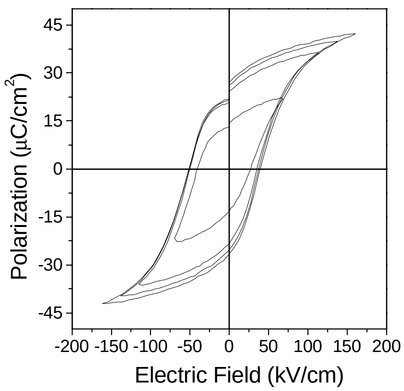
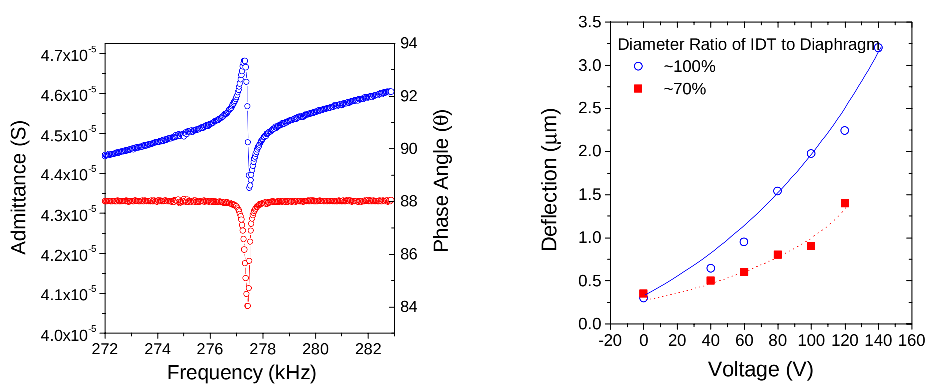


Figure 4. Hysteresis Loops from a released piezoelectric diaphragm.

Mechanical Resonance & Electric Deflection

Figure 5 (a) shows the first mechanical resonance for a 500 μm piezoelectric diaphragm with 100% IDT electrode coverage. The three lowest resonance frequencies were 277, 735 KHz and 2.22 MHz. Electric field induced deflections of 500 μm piezoelectric diaphragms of with 70% or 100% IDT coverage were measured using an interferometer (Zygo, Inc) (see Fig. 5 (b)). ~2.2 μm center deflections were generated at 120 V applied for a piezoelectric diaphragm with 100% IDT coverage. With applied voltage, the piezoelectric diaphragms flex downwards in a funnel-shape. To explain these observations, both the d_{33} and d_{31} piezoelectric constants of the PZT film must be considered. In the case of ring-shaped IDT electrodes, when an electric field is applied, tension is induced in the radial direction of the diaphragm by the d_{33} piezoelectric constant. Simultaneously, compression is induced in the tangential direction by d_{31}. This combination causes the diaphragm center to deflect down [6].



(a) **(b)**

Figure 5. (a) The 1st resonance of a 500 μm piezoelectric diaphragm and (b) electric deflections of a piezoelectric diaphragm as a function of applied voltages.

CONCLUSIONS

Micromachined pump structures were fabricated using surface micromaching. As a sacrificial material, amorphous silicon was employed. 500 μm pump structures were completely released by a XeF_2 process. However, the thickness of the LTO layer was significantly reduced during this etching process. The released piezoelectric diaphragms showed good ferroelectric properties. ~2.2 μm deflections were generated at 120 V for piezoelectric diaphragms of which IDT electrodes cover 100% of the diaphragms.

ACKNOWLEGEMENTS

The authors would like to acknowledge Robert L. Smith for his contributions in the resonant frequency measurements using mechanical excitation and discussions on the implications of the differences with the electrically excited results. The research reported in this document was performed in connection with Cooperative Agreement number DAAD17-00-2-1001 with the U.S. Army Research Laboratory.

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