Fabrication of Dome-Shaped Flexible Diaphragm Supported PZT Ultrasonic Transducers

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Abstract - This paper presents novel self-focused ultrasonic transducers batch produced by microfabrication. PZT film, tens of microns thick, can be deposited on an engineered flexible substrate composed of an F-number controllable parylene shaped diaphragm and heat resistant RTV material, with no fractures after thermal annealing. The strong residual stress of the piezoceramic film is released though the curvature change of the fabricated parylene/RTV, spherically shaped diaphragm. The experimental relationship between the designed and resultant F-number of the fabricated transducer is discussed. A Pulse-echo experiment is performed directly using the parylene/RTV curved diaphragm as the backing of the device. The outcome displays a central frequency of 50 MHz and a -6 dB bandwidth of 30%.

Keywords - PZT, ultrasonic transducer, acoustic beam, flexible diaphragm.

I. INTRODUCTION

High resolution ultrasonic transducers have many applications in noninvasive medical imaging and nondestructive evaluation. The axial resolution of a transducer is determined by its bandwidth and the lateral resolution is related to its wavelength and the ratio of the focal distance to the aperture size (F-number). The fabrication of thinner piezoelectric film to raise the operating frequency or formation of a spherically shaped active layer to focus the emitted and received ultrasonic can increase the resolution.

Existing research on high frequency (> 20 MHz) and focused spherical ultrasonic piezoelectric transducers was mainly conducted on P(VDF-TrFE) polymer and PZT ceramic film. Due to the flexibility and lower processing temperature of P(VDF-TrFE) material, spin-coating and vacumm sucking fabrication methods have been developed [1]. The lower acoustic impedance could be an advantage of piezopolymer films over their counterparts [2].

However, higher-impedance piezoceramics applied with matching layers makes the low impedance advantage not significant. A relatively low coupling constant of P(VDF-TrFE) (0.11 compared to 0.5 for PZT) and a high dielectric loss tangent (0.15–0.25 compared to 0.02 for PZT) display the piezoelectric polymer’s inherent weakness. Furthermore, a much smaller dielectric constant of pizeopolymer compared to piezoceramic could be a big drawback in making small sized ultrasonic transducers [3].

For a thickness mode piezoceramic transducer operating at a frequency larger than 20 MHz, a thickness less than 100 µm is usually required. Fabricating a spherically shaped piezoelectric ceramic film transducer is always challenging. Lockwood et al. [4] proposed a method of lapping a bulk PZT plate to a thickness of 25µm. Thin conductive epoxy was then cast onto the backside of the lapped PZT followed by ball pressing the PZT plate into a spherical well to form a focused ultrasonic transducer. Due to the extreme fragility of the thin PZT plate, careful handling is critical for successfully completing the fabrication. Lukacs et al. [5, 6] reported spin-coated sol gel PZT solution on an aluminum substrate. Although the aluminum substrate could serve as an electrode during the polarizing process and could be chemically etched to a thin layer, a thermal expansion mismatch with respect to PZT film, resulting in a large residual stress after the annealing process, was one of the major drawbacks. Q. Q. Zhang et al. [7] employed a similar fabrication process but replaced the aluminum substrate with silicon to raise the maximum annealing temperature. The porosity of the PZT thick film induced by the high annealing temperature was handled by a vacuum filling treatment. However, the induced residue stress during the process was not mentioned.

In this paper, a novel micromachining technique to fabricate spherically shaped ultrasonic transducers is demonstrated (Fig. 1). Rather than coating PZT sol gel onto a substrate, transferring the formed flat PZT film to a baking material, and then shaping with a ball, we directly fabricate a flexible spherically shaped diaphragm as a backing layer and coat it with PZT sol-gel solution. In this scheme, the novel diaphragm acts not only as a substrate, but as a material for releasing the residual stress through its geometric change after the annealing process. Details of the device fabrication and characterization are described below.

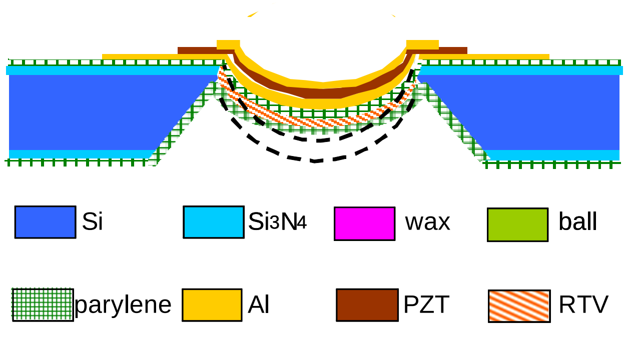

Fig. 1. Schematic diagram of micromachined flexible diaphragm backed PZT ultrasonic transducers. The region between two dashed lines represents the original profile of the device supported parylene/RTV diaphragm before PZT deposition. The resulting spherical shaped profile (color layers) decreases the curvature due to releasing residual stress after PZT deposition.

II. DEVICE FABRICATION

Figure 2 shows the fabrication process flow. We began with silicon bulk-machining to make square thru-holes on a silicon wafer, and thereby defined the active region of the transducers. According to the designed F-number of the ultrasonic transducers, selected balls were placed onto the thru-holes of the silicon wafer. This was followed by forming spherically shaped wax molds underneath the processed wafer. The wax was removed after the parylene was conformally coated, and concave diaphragms were then shaped on the wafer [8, 9].

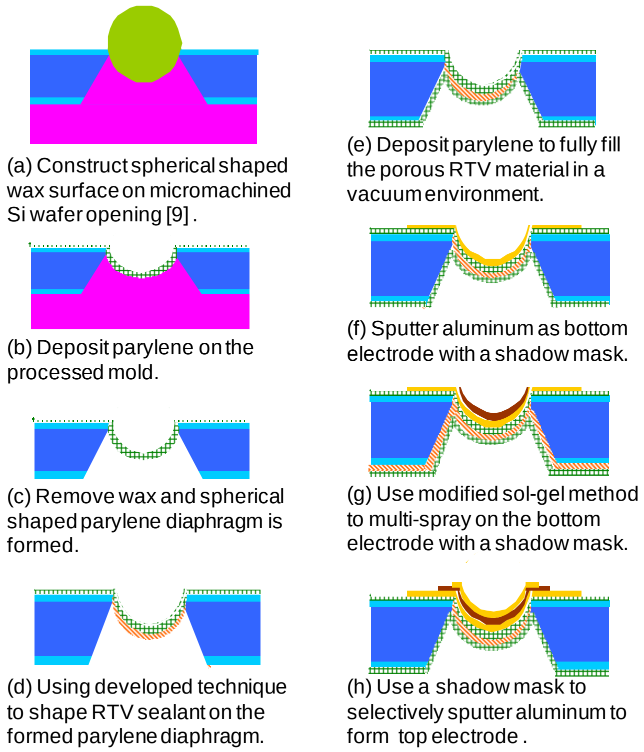

Fig. 2. Fabrication process flow of micromachined flexible diaphragm backed PZT ultrasonic transducers.

One novelty of this work was to fabricate a flexible diaphragm-type substrate so that a piezoelectric material PZT with a high electromechanical coupling coefficient could be deposited, and the resulting high residual stress after annealing could be released through the proper geometrical rearrangement of the transducer's substrate.

To construct a flexible diaphragm substrate capable of sustaining high temperature, RTV silicone rubber (Dow corning 736 Heat resistant sealant) was chosen. The application of the RTV uniformly onto the spherically shaped parylene diaphragm was implemented with a technique similar to imprinting [10].

Using this method a ~200 μm thick RTV layer could be attached to the backside of the spherical parylene surface and became stiffer after heating at 80℃ for 4 hours. Moreover, extra parylene coating was useful to fully fill the porous RTV material in a vacuum environment. This was followed by PZT film formation after the aluminum lower electrode deposition. Modified sol gel method was prepared for fabricating PZT film, and included four chemicals: lead acetate trihydrate, zirconium n-propoxide, titanium n-butoxide, and 2-methoxyethanol. Spray coating with a two-step heating process was used to make a 40 μm thick PZT layer [11]. A change in curvature of the spherically shaped diaphragm device was observed after annealing. Subsequently, parylene and aluminum were deposited for making the insulting layer and top electrode, respectively.

The deposited PZT film was polarized by applying a DC electric field of 1 kV/mm. 40 V was applied across the top and bottom electrodes for 30min at room temperature to establish the permanent polarization. After that, the transducer was complete and ready for testing. Figure 3 shows the batch processed ultrasonic transducers made on a silicon wafer.

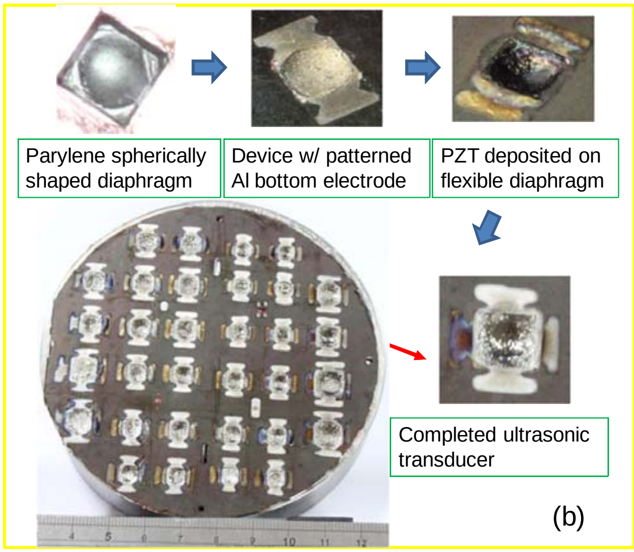

Fig. 3. Photographs of the flexible diaphragm backed ultrasonic device after different fabrication steps.

III. EXPERIMENTAL SETUP FOR DEVICE CHARACTERIZATION

To quantitatively investigate the geometry deformation of the spherically shaped diaphragm transducers releasing residual stresses after the annealing process, five sets with different ball diameters (10, 12.5, 14, 15.5 mm) and square hole sizes (5, 6, 6.5, 7, 8.5 mm) on the silicon wafer were fabricated and studied. The focal ratios were selected to be in the range of 0.91 to 1.04 and larger F-number values were expected to be yielded after the PZT film released the thermally induced stress.

To characterize the geometric changes of the transducers, a molding transfer technique was applied. Liquid PDMS was filled with the concave portion of the spherically shaped device described in the fabrication steps (f) and (g), respectively (Fig. 2).

Since both PDMS and parylene have strong molecular cohesion, the formed PDMS molds could be easily peeled from the device with parylene interface after being solidified. The profile images of the molds were acquired with a microscope and high resolution CCD camera for further analysis (Fig. 4). In the following experiments, the transducer with sample #1 specification was used (diameter = 5mm, designed radius of curvature = 5 mm, and resulting radius of curvature = 6.3 mm after deposited PZT film releasing residual stress).

To evaluate the performance of the transducer we started by examining its electric impedance characteristic using a Hewlett-Packard 4921B RF Impedance Analyzer. Once the series and parallel resonant frequencies had been determined, the effective electromechanical coupling coefficient keff2 could be calculated from their relative interval. A pulse echo experiment was executed using a PANAMETRICS 75MHz manually controlled pulser-receivers (model: 5073PR). A quartz slide was used as the reflector and was placed at the focal region of the fabricated transducer in a water tank at room temperature.

The echo signal from the receiver was monitored and recorded on a 100 MHz bandwidth Tektronix DPO2014 digital oscilloscope. The resulting signal was used to find the frequency spectrum and bandwidth by Matlab software.

The testing system for finding the lateral beam width of the transducer in liquid was also set up [12-14]. A 10 μm wire used as the target was mounted onto a platform of an x-y-z three axis moving stage (x, y axes were horizontally driven by computer controlled motors; z-axis was manually adjusted in the vertical direction; 10μm displacement resolution for three axes). Both the wire and transducer were immersed in a water tank. The transducer was excited with a RF signal generator and the amplifier set at its central frequency.

The echo signal was received by PANAMETRICS 5073PR. The signal was also monitored and recorded using a Tektronix DPO2014 oscilloscope.

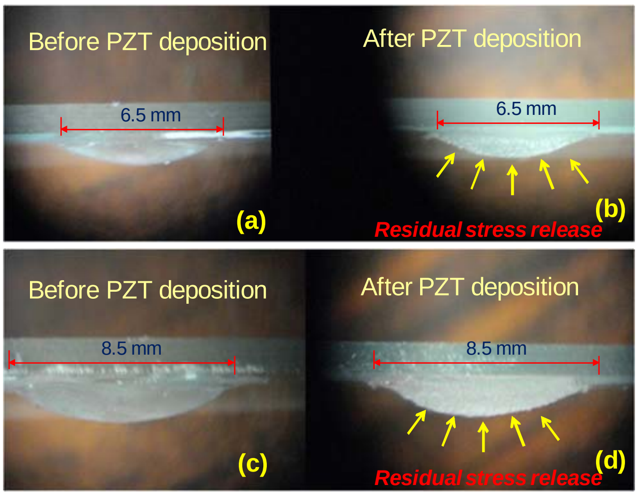

Fig. 4. Photographs of the casted PDMS molds to display the deformation of the spherically shaped diaphragm device beofore and after PZT deposition.

IV. RESULTS AND DISCUSSION

A. F-Number Variation Due to Releasing Residue Stress

Table 1 shows five different parameter sets used for fabricating spherically shaped diaphragm transducers in this study. The resulting F-numbers of the finished transducers are in the range of 1.25 to 1.84. To find the relationship between the experimental parameters among these devices, we try to normalize the F-numbers by dividing them by the ratios of the radiuses to the opening sizes for the correspondingly designed transducers. Therefore, all normalized F-numbers of the designed transducers have a value of 1 (Fig. 5). The normalized F-numbers of these transducers after annealing to release thermal stresses exhibit a nonlinear trend. An approximate parabolic relation is obtained in the experimental range.

TABLE I
FIVE DIFFERENT PARAMETER SETS USED FOR FABRICATING SPHERICALLY SHAPED DIAPHRAGM TRANSDUCERS

Designed sample no.	1	2	3	4	5
Radius of transducer (mm)	5	6.25	6.25	7	7.75
Opening size (mm)	5	6	6.5	7	8.5
F-number	1	1.04	0.96	1	0.91

Further investigation was performed to compare the effect of the transducer before/after PZT deposition. Figure 5(a) shows that the inscribed angle of interest that intercepts the larger arc between two anchored points of the spherically shaped diaphragm. If we calculate the normalized inscribed angle, defined as the measured inscribed angle divided by the ball radius divided by the opening size for each designed transducer, the results and trend curves for the original designed and completed transducers are shown in Fig. 5(b). Both trends are very close to parabolic distribution and can be estimated by least square method with correlation coefficients greater than 0.99 as: $y = 0.1357x^2 - 2.3611x + 11.389$ (designed device), $y = 0.1184x^2 - 2.1394x + 10.843$ (finished device), where y is the normalized inscribed angle (degree) and x is the opening size (mm). The difference in the normalized inscribed angles means that considering a ball of unit length radius and a frame of unit length opening formed a spherically shaped diaphragm transducer (i.e. F-number equals one), the inscribed angle of the finished transducer is always larger than that of the designed transducer and the difference is a function of the opening size.

B. Pulse-echo Response

The operational settings of the pulser/receiver are as follows: pulse repetition rate: 1 kHz; input energy: 2 μJ; damping: 50 ohms; gain: 39 dB; High pass filter: 1 kHz; low pass filter: 75 MHz. The quartz reflector is placed 6mm away from the transducer.

Figure 6(a) and (b) show the time domain and frequency domain responses of the transducer (sample #1: diameter of 5mm with the resulting F-number of 1.25).

The maximum amplitude of the echo signal is 2.83 V.

FFT analysis shows that the spectrum has a central frequency of 50 MHz and a -6 dB bandwidth of 30%. Figure 6(c) shows a lateral resolution of 40 μm at -6 dB is observed.

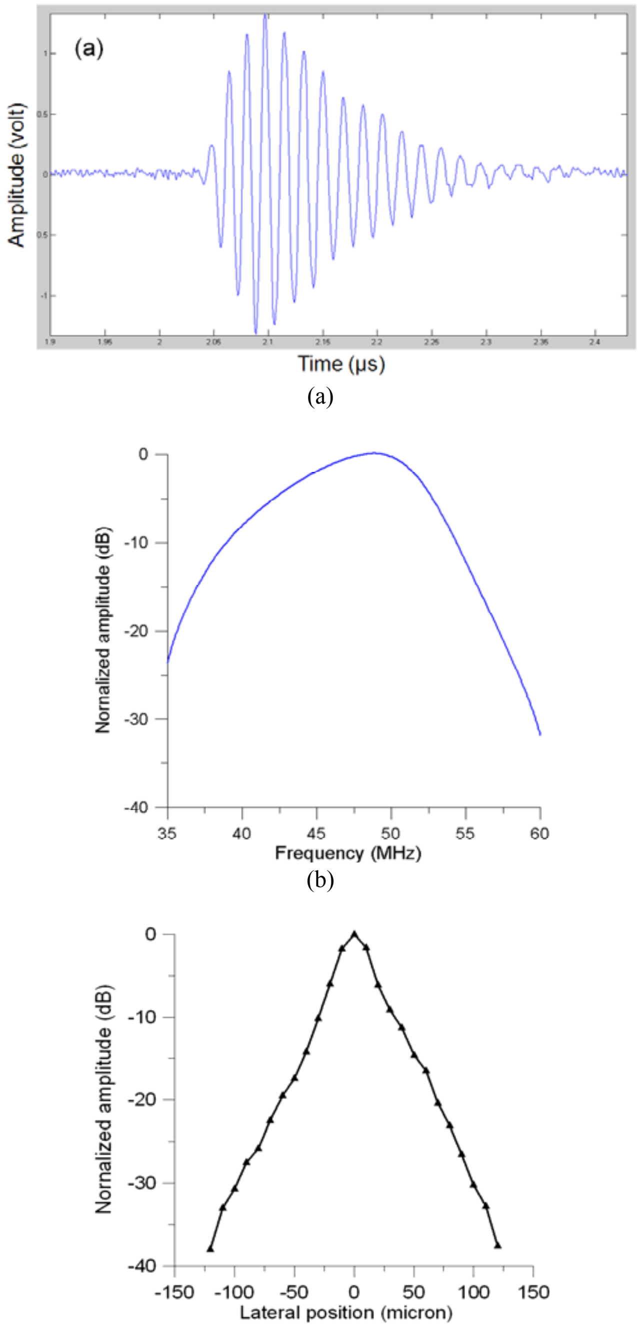

Fig. 6. (a) Pulse-echo response of the fabricated ultrasonic transducer. (b) Fourier transform spectrum. (c) Lateral line response of the transducer.

V. CONCLSION

A self-focused spherically shaped diaphragm PZT ultrasonic transducer is developed. A novel micromachining technique is proposed for the first time and successfully demonstrated. Flexible thermally-resistive spherically shaped diaphragms, with transducer substrates composed of RTV and parylene, are developed. PZT sol-gel solution can be deposited on the diaphragm to form a 40 μm thick film by a two-step thermal process. The residual stress after depositing ten-micron-thick PZT film caused by thermal annealing can be successfully released via the curvature change of the fabricated device.

The completed transducers possess have F-numbers compared to the originally designed transducers after releasing the thermal stress. The fabricated transducer exhibits a central frequency of 50 MHz. According to the pulse-echo experiment, a lateral resolution of 40 μm is obtained and a 30% bandwidth at -6 dB.

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