Microfabrication of Piezoelectric Composite Ultrasound Transducers (PC-MUT)

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Abstract—**In this paper a piezoelectric composite based micromachined ultrasound transducer (PC-MUT) fabrication technology is presented. PMN-PT single crystal posts with side length of 14 μm and height of > 60 μm were fabricated using a deep dry etching method. High frequency (20-50 MHz) PMN-PT single crystal/epoxy 1-3 composites were prepared and the electromechanical coupling coefficient of the composites was ~ 0.72. Prototype 40 MHz ultrasound transducers showed promising sensitivity and bandwidth.**

Keywords-piezoelectric composite; PC-MUT; PMN-PT single crystal; ultrasound; transducer; micromachining.

I. INTRODUCTION

High frequency ultrasound is needed for high resolution imaging applications in dermatology, ophthalmology, intravascular imaging, laproscopy and NDE [1]. In recent years a variety of methods have been investigated for constructing high frequency ultrasound transducers and arrays. Conventional transducers and arrays operated below 20 MHz are constructed by dicing piezoelectric ceramics and then backfilling the saw kerf with epoxy to form composite structures. Transducers based on this architecture exhibit high bandwidth, high sensitivity, good acoustic impedance matching to tissue, and good array properties (low inter-element cross talk, low side-lobe levels) [2]. However, this so-called dice-and-fill method of transducer fabrication cannot be used to make array transducers that operate much above 20 MHz. Alternative methods include use of PVDF piezoelectric polymer, $PbTiO_3$ ceramic, $LiNbO_3$ crystals, or ZnO and AlN thin films. All these approaches make use of materials with considerably lower properties than PZT-polymer composites (Table 1). Other reported composite fabrication methods include stacked plates or lamination techniques [3], tape casting technology [4], micromolding [5], laser micromachining [6], PZT fibres [7], and the interdigital bonding technique [8]. In general, these processes are experimental and have not been used in commercial production due problems with achieving the required uniformity and dimensional control needed for high frequency transducers and due to high fabrication costs.

Recent progress on PZT deep reactive ion etching (RIE) etching processes encouraged authors to develop micromachining techniques for the fabrication of high frequency single crystal piezocomposite ultrasound transducers [9-11].

Table 1. Film and bulk piezoelectric materials properties.

Piezoelectric materials	Piezoelectric coefficient (pC/N)	Young's Modulus (GPa)	Electro-mechanical coupling
AlN (film)	d_{31} ~-2	330	k_t ~0.24
ZnO (film)	d_{31} ~-5	210	k_t ~0.27
PZT (sol-gel, sputtering)	d_{31} ~-100	40	k_t~0.39
PZT (Bulk)	d_{33}, ~600 d_{31} ~-300	70	k_t~0.5 k_{33} ~0.7
Single crystal (bulk)	d_{33} ~2000 d_{31} ~-1000	12	k_t~0.6 k_{33}~0.93

Micromachining techniques were expected to be especially applicable to single crystal piezoelectrics by analogy with silicon micromachining. The development of single crystal piezoelectrics based on $(1\text{-}x)Pb(Mg_{1/3}Nb_{2/3})O_3\text{-}xPbTiO_3$(PMN-PT) provides a means of advancing the performance of high frequency transducers far beyond the capability of conventional ceramic devices [12].

Single crystal piezoelectrics have considerably higher piezoelectric coefficients and electromechanical coupling factors than PZT ceramics, and as a result they are being used to fabricate ultrasound transducers with unprecedented bandwidth (>100%) and sensitivity [13,14]. These materials are being investigated as a replacement for PZT in conventional ultrasound transducers, but the high cost of single crystals and difficulties in manufacturing large, uniform plates has limited penetration into the ultrasound market. However, high frequency clinical procedures can greatly benefit from the use of broad-bandwidth, high-sensitivity array transducers particularly because they provide a means of extending the depth of field over existing devices. Limited depth of field has been a severe trade-off against the increased resolution that, to date, is the price one must pay for operating at high frequency. Moreover, material cost is a much smaller percentage of the total transducer cost for small, complex high frequency devices than is the case for conventional transducers that operate below 20 MHz. All that is required to address high frequency transducer manufacturing with single crystals is a transducer fabrication process. In this paper, photolithography based micromachining of PMN-PT single crystal is reported for developing advanced single crystal/epoxy 1-3 composites for high frequency ultrasound transducers.

II. EXPERIMENATL DESIGN

A. 1-3 Composite Design

Composite piezoelectric materials have high electromechanical coupling factors, low acoustic impedance, and are relatively easy to conform. However, as stated above the diced feature sizes are very difficult to achieve in high frequency transducers. The frequency limitation comes from the frequency of the lateral mode resonance, which is determined by the shear wave velocity of the filler material and the width of the dicing cut. The frequency of the first lateral mode in a 1-3 composite can be empirically expressed as

$$f_l = \frac{V_T}{2\sqrt{2}d_p}$$

where f_l is the frequency of the first lateral mode, V_T is the shear wave velocity of filler and d_p is the kerf width. For example, if the kerf width is 10 µm, which is the present state of the art for dicing, the frequency of the first lateral mode is about 39MHz, limiting the operating frequency of this composite to about 20MHz. Composites with kerf width < 6 µm and volume fraction of 56-70% were designed for 40 MHz PC-MUT fabrication.

B. Fabrication of PMN-PT Single Crystal/Epoxy 1-3 Composite

A Photolithography based deep dry etching of PMN-PT single crystal was developed for high frequency 1-3 composite fabrication (As shown in Figure 1). Photolithography based micromachining has several advantages compared with conventional ultrasound transducer and transducer arrays fabrication, including submicron machining precision, batch fabrication, a low-stress mechanical environment for fragile, fine structures, and the possibility for integrated array design.

For high frequency composite fabrication, PMN-PT single crystal plates with d_{33} of 1800-2200 pC/N, dielectric constant of 5000-7500, and dielectric loss < 0.01 were prepared with dimensions of 15 mm in diameter and 0.5 mm in thickness. PMN-PT wafers were lapped on both sides and polished on one side. The crystal wafers were then coated with Ni as an electroplating seed layer on the polished side. Ni coated PMN-PT wafers were next coated with photoresist using a spin coater. Photoresist was baked at elevated temperature for minutes and then exposed to UV light. UV exposure could be conducted using a contact aligner, laser writer, or stepper. After UV exposure, the wafers were developed using photoresist developer and then a patterned photoresist structure was formed. A through-wafer Ni electro-plating process was then used to form the Ni etching mask out of the photoresist pattern. After plating, photoresist was stripped using a solvent. The PMN-PT wafer with Ni etching mask was then put into the dry etching chamber for deep ion etching. The kerfs of etched PMN-PT single crystal post arrays were next filled with epoxy. Epoxy was cured at 60 °C over night. The wafer was then lapped on one side until the PMN-PT posts were exposed. The wafer was then flipped over for the second side lapping until the final thickness was achieved. Both sides of the resulting 1-3 single crystal/epoxy composites were then electroded with Cr and Au.

Composites with Cr/Au electrodes were poled under 10 KV/cm at room temperature for minutes prior to characterization. Dielectric constant and dielectric loss of the PMN-PT/epoxy 1-3 composites were measured using an HP impedance analyzer at 1 KHz. Effective electromechanical coupling coefficients of PMN-PT/epoxy 1-3 composites were calculated from the measured resonant and anti-resonant frequencies using the standard IEEE resonant method.

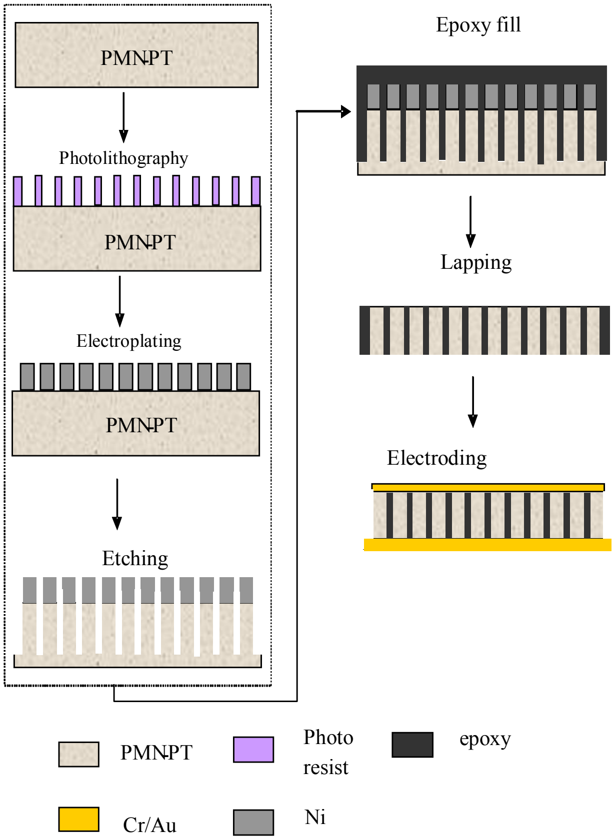


Figure 1. Schematic process flow for micromachined PMN-PT/epoxy 1-3 composites.

III. EXPERIMENTAL RESULTS AND DISCUSSION

Thick photoresist lithography was achieved by using laser direct writing exposure. Figure 2(a) shows Ni plating through a well-defined photoresist pattern, and Figure 2(b) shows the Ni mask after stripping the photoresist. The Ni posts were very straight indicating an excellent photoresist pattern from the lithography. A straight and thick Ni etching mask is critical to achieving straight PMN-PT deep etching.

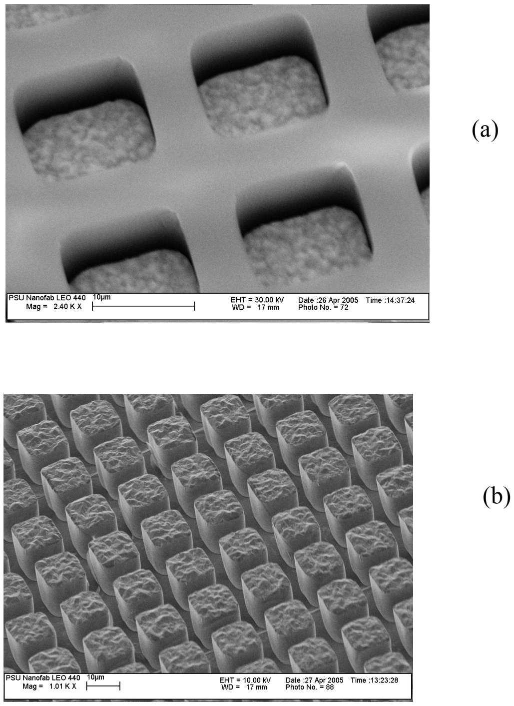


Figure 2. Photoresist and Ni pattern. (a) a photoresist pattern and plated Ni posts during plating. (b) the Ni post array after stripping the photoresist.

Etching rate, selectivity ratio and profile angle are important parameters in deep etching of PMN-PT. The etching rate ranged from 2 μm/hour to 8 μm/hour depending on the pattern, exposed area, and etching conditions [9-11]. The etching rate ratio (selectivity) of PMN-PT crystal to Ni was about 4 - 5 in this study. Figure 3 shows an etched PMN-PT wafer with posts ~67 μm high, and a post height/width aspect ratio is >4. A high aspect ratio is important to ensure high electromechanical coupling and minimize the lateral mode effect in transducers. It was also noticed that the angle of etched side wall profile is >87°, which allows precise and deep etching of closely packed arrays of PMN-PT single crystal posts compared to the PZT etching results published by other groups [9-11], where the profile angles were mostly < 80 °.

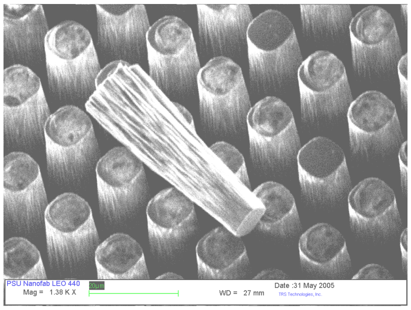


Figure 3. SEM picture of an etched PMN-PT single crystal micro-array.

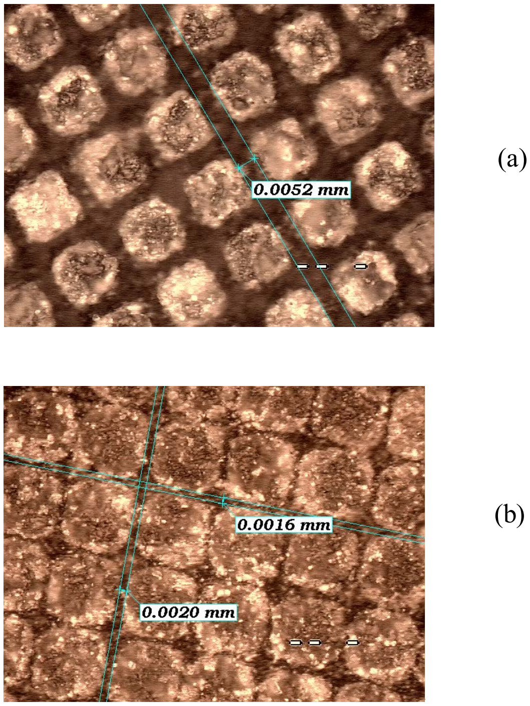
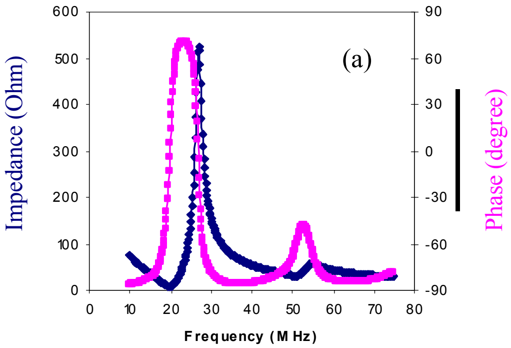


Figure 4. Photgraph pictures of top and bottom surfaces of PMN-PT/epoxy 1-3 composites.

Epotek 301 epoxy was used to fill the kerfs between etched PMN-PT posts. A precise lapping process was developed with thickness control variation of +/- 2 μm. Figure 4 shows photograph pictures of a typical 40 MHz composite (Figure 4 (a) is the front side and 4 (b) is the back). The kerf variation between the top and bottom surfaces of the composites were caused by the tapered etching profile. But this profile angle is acceptable according to the modeling results reported in [15].

The prepared 1-3 composites were then coated with Cr/Au electrodes, followed by poling and characterization. A HP impedance analyzer was used to record the impedance and phase vs. frequency of the composites, Figure 5 (a) shows an impedance and phase spectrum of a 60 μm thick micromachined 1-3 composite, and Figure 5 (b) shows an impedance and phase spectrum of a 40 μm thick 1-3 composite.



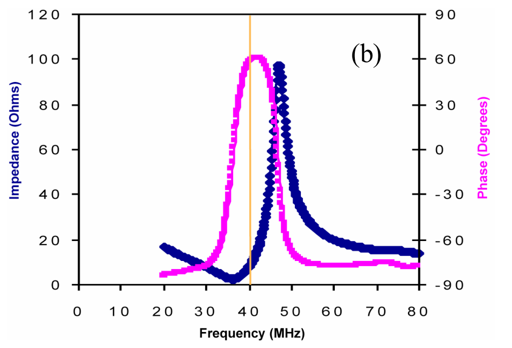


Figure 5. Resonant mode of the PMN-PT single crystal micro-array. (a) Impedance and phase vs. frequency of a 60 µm thick 1-3 composite. (b) Impedance and phase vs. frequency of a 40 µm thick 1-3 composite.

Table 2. Measured results for fabricated 1-3 composites.

	Thickness(µm)	fr (MHz)	fa (MHz)	k
Average	39.9	33.5	45.3	0.7
Stdev	1.29	1.76	3.42	0.04

The effective electromechanical coupling coefficients of the composites were calculated to be ~0.72 from the resonant modes shown in Figure 5, which is very promising for advanced high frequency transducers with high sensitivity and broad bandwidth.

More than 20 pieces of micromachined 40 MHz 1-3 composites have been prepared and tested. Table 2 shows the average and standard deviation of the key parameters measured for the fabricated composites. The dielectric loss of the fabricated 40 MHz 1-3 composites is about 0.04-0.06 and free dielectric constant is about 2000. Ultrasound transducers using 40 MHz 1-3 composites were prototyped and characterized by Boston Scientific. The transducer characterization results, reported in another paper in this proceeding, showed significantly improved sensitivity (30% increase) and bandwidth (~ 100% increase) compared with PZT transducers (thickness mode) [15].

IV. CONCLUSIONS

A novel photolithography based micromachining process was successfully developed to fabricate piezoelectric composite ultrasound transducers (PC-MUT). A deep etching process with profile angle >87° was developed for PMN-PT single crystal. PMN-PT single crystal/epoxy 1-3 piezoelectric composites were successfully produced at TRS with consistent results. Composites with resonant frequency ranging from 20 MHz to >45 MHz showed electromechanical coupling coefficients of ~0.72, which is promising for high frequency ultrasound transducers for medical and NDE/NDT imaging applications.

ACKNOWLEDGMENT

Authors would like to acknowledge the processing helps from Matt Corbin, Hua Lei, Dr. Seongtae Kwon and Dr. Jun Luo at TRS. Helpful discussions from Rick Bautista, Alain Sadaka (BSC) are also greatly acknowledged.

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