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Micromachined PMN-PT Single Crystal Composite Transducers -- 15-75 MHz PC-MUT

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***Abstract*—In this paper a piezoelectric composite based micromachined ultrasound transducer (PC-MUT) technology is presented for fabrication of PMN-PT single crystal piezoelectric composite transducers. Micromachined PMN-PT single crystal 1-3 composites with resonance frequencies of 15 MHz – 75 MHz were fabricated and characterized with coupling coefficient of 0.67 – 0.79. Transducers with a frequency of 75 MHz were prototyped and characterized.**

Keywords-piezoelectric composite; PC-MUT; PMN-PT single crystal; 1-3 composite; ultrasound transducer; micromachining of piezoelectrics.

Introduction

Ultrasound transducers with short wavelength (high frequency) and short pulse-width length (high frequency, broadband) are desired for ultrasound imaging with high axial and lateral resolutions in applications including dermatology, ophthalmology, intravascular imaging, laparoscopy and NDE imaging [1-3]. TRS recently developed a process capable of micro-machining PMN-PT single crystal into < 20 – > 100 MHz composites using Deep Reactive Ion Etching (DRIE). Micromachined PMN-PT single crystal composite structures with feature sizes appropriate for operation between 25 MHz – 40 MHz were fabricated for high frequency transducers and transducer arrays [4-6].

The micromachined 1-3 single crystal piezoelectric composite transducer technology (PC-MUT) takes the advantage of high electromechanical coupling coefficients of advanced single crystal piezoelectrics, fine patterning features of photolithography and DRIE for fabrication of both composite structures and array electrode interconnections. Further development on PC-MUT with higher frequency will be of interest for HF ultrasound NDE and molecular imaging applications. Conversely, considering the fact that the majority of ultrasound medical imaging applications lie in the frequency range of 3 MHz-15 MHz, demonstration of < 15 MHz PC-MUT may be of interest to decrease the fabrication cost and time for medical ultrasound transducers and arrays. In this paper, high frequency (HF) 1-3 composites with operational frequencies from < 15 MHz and to 75 MHz will be designed, fabricated and characterized for ultrasound applications. PC-MUT transducer with frequency of 75 MHz was prototyped and tested.

I. Experimental design

A. 1-3 Composite Design, Fabrication and Characterization

Composite piezoelectric materials have high electromechanical coupling coefficients, low acoustic impedance, and are relatively easy to conform, which are desired for many ultrasound applications. However, the conventional 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. As an example, in order to obtain 40 MHz 1-3 composite, a kerf width < 6 μm, volume fraction of 56-70% was designed referring to the reported works [15]. Table summarized the designed kerf width of 15 MHz-75 MHz 1-3 composite. On the other hand, dicing of ceramics is a slow process, and PMN-PT single crystal dicing is even more difficult [4].

The PCMUT fabrication process developed recently took the advantage of high precision and batch fabrication capability of microfabrication of semiconductors, holding the promise to further advance the high frequency ultrasound transducer fabrication [4-6]. The PC-MUT fabrication process details can be found in [4]. 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 as wafers 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 2000 A Ni as electroplating seed layer at the polished side. Ni coated PMN-PT wafers were next coated with photoresist using a spin coater. The photoresist was baked at elevated temperature for a few minutes to prepare for UV exposure. UV exposure could be conducted using contact aligner, laser writing or stepper. After UV exposure, the wafers were developed using photoresist developer and then a patterned photoresist structure was formed. A through-wafer Ni electroplating process was then used to form Ni etching mask out of the photoresist pattern. After plating, photoresist was stripped using solvent. The PMN-PT wafer with Ni etching mask was then put into a dry etching chamber for deep etching. The kerfs of etched PMN-PT single crystal post arrays were next filled with epoxy. The wafer was then lapped on one side until PMN-PT posts were exposed. The wafer was then flipped over for the second side lapping until the final thickness (~ 40 μm) was achieved. The 1-3 single crystal/epoxy composite is then formed, both sides of the composite wafer were coated with 500 Å Cr and 2000 Å Au as electrodes.

The composite with Cr/Au electrodes was first poled under 10 kV/cm at room temperature for a minute. The dielectric constant and dielectric loss of PMN-PT/epoxy 1-3 composites were directly measured using an HP impedance analyzer. Effective electromechanical coupling of PMN-PT/epoxy 1-3 composites were measured and calculated using standard IEEE resonant method [9].

B. *PC-MUT Transducer Prototyping and Characterization*

Figure 1 shows the schematic cross view of a PC-MUT transducer. A backing layer was cast to one side of the electroded composite wafer and was lapped to obtain a flat surface. Small squares were then diced from the wafer with a backing layer, and a 0.5-0.6 mm square was used to fabricate the device. After potting into the brass housing, the face was designed to be coated with a thin parylene matching layer and was sputtered with Cr/Au to achieve the ground connection. A SMA connector was attached for the interconnection. The transducer was poled at 12 kV/cm at room temperature. The pulse-echo response of the 75 MHz transducer was tested using a Panametrics/Olympus 5900PR pulser-receiver and a steel plate echo source. The pulse-echo result obtained from the 75 MHz PC-MUT was compared with the one from a commercial 75 MHz focused transducer .

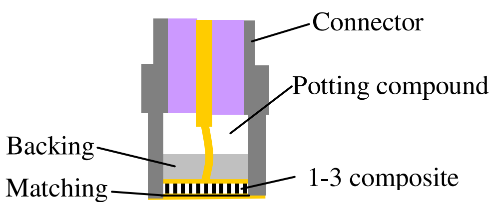


Figure 1. PMN-PT 1-3 composite transducer assembly.

II. Experimental Results and Discussion

A. *Piezoelectric 1-3 composite*

Micromachined PMN-PT single crystal 1-3 composite wafers with diameter of 15 mm and Cr/Au electrode on both sides were prepared using the PC-MUT technique. The etched post height for the 15 MHz ad 75 MHz design was about 125 μm, and 45 μm, respectively. Figure 2 shows the photographic pictures of PC-MUT composites (75 MHz) with electrode. All composites were then poled and characterized before transducer prototyping. Table I summarizes the PC-MUT composite poling voltages and measured composite properties. Figure 3 shows the impedance and phase spectrum of the prepared 1-3 composites. All PC-MUT composites tested showed high electromechanical coupling coefficients, and the PC-MUT frequency range was extended from previous 25-40 MHz to the current 15-75 MHz. For the first time, < 20 MHz 1-3 PMN-PT single crystal composite was successfully fabricated using PC-MUT technique, indicating that in addition to high frequency ultrasound, PC-MUT will also play an important role for ultrasound with frequency < 15 MHz.

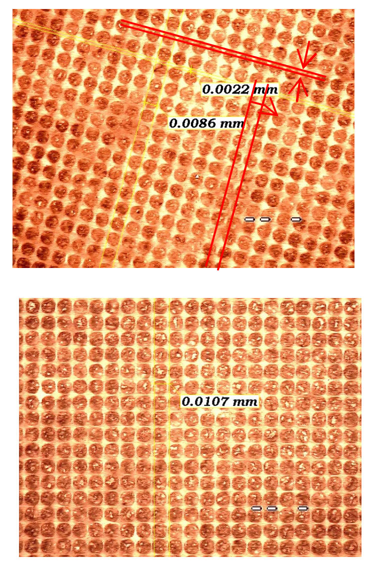
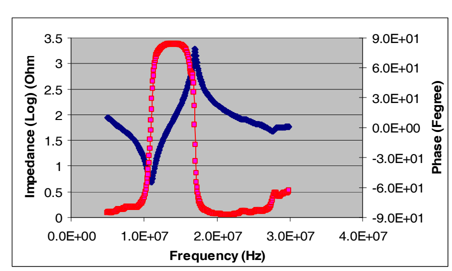


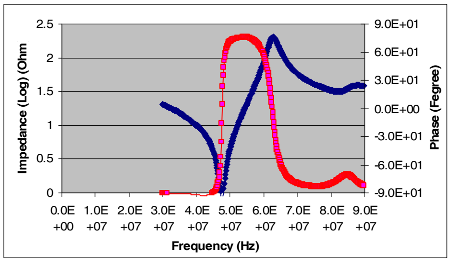
Figure 2. Photograph pictures of PC-MUT composites (both top (left) and bottom (right) surfaces) (75 MHz) with kerf < 3 μm.

Table I. PC-MUT composite properties

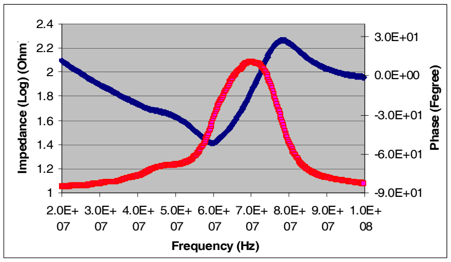
Frequency (MHz)	Kerf (μm)	Thickness (μm)	Poling voltage (V)	Coupling coefficient
15	<15	104	100	0.79
40	<6	40	40	0.75
60	<4	27	30	0.69
75	<3	18	20	0.67



(a)



(b)



(c)

Figure 3. Impedance sweep for PC-MUT composites. (a) 15 MHz; (b) 60 MHz, and (c) 75 MHz.

B. 75 MHz PC-MUT transducer

PC-MUT transducers with frequency of 40 MHz –75 MHz were prototyped and characterized. The 15 MHz PC-MUT transducer characterization results will be reported later. The 40 MHz transducer results were reported in [5]. The 60 MHz PC-MUT is reported by Yuan, et al. in this proceeding [7]. The pulse-echo responses of 75 MHz transducers were tested using a Panametrics/Olympus 5900PR pulser-receiver, with 15 dB total gain and the lowest energy setting. The echo target was a stainless steel plate placed in DI water at room temperature. A Tektronix 644B oscilloscope was used to digitize the echo signal, and spectral analysis was done with MATLAB™. A commercial 75 MHz transducer (1/4” aperture, ½” focal length) was tested to compare the performance with the single crystal device. The commercial transducer used a quartz delay line for focusing the acoustic beam. All testing conditions were maintained between the two transducers. The comparison in acoustic signals is shown in Figure 4. The most noticeable difference in signals is the amplitude, the PMN-PT composite transducer produces a much stronger signal than the commercial device. As can be seen in the spectrum, which is normalized to the PMN-PT transducer, the commercial device is 40 dB lower in signal intensity. It must also be noted that the commercial device was focused, and the composite transducer was not, implying that even more contrast could be gained for the TRS transducer. There are also no matching layers currently on the PC-MUT device.

The center frequency of both signals is lower than the expected 75 MHz, though this could be due to a number of factors, including the frequency dependent attenuation in water [8]. This accounts for approximately 6 dB of signal intensity. Electrical mismatch could also be a factor, as the impedance drops at higher frequencies, and more electrical transmission losses could occur. This is currently being studied. The bandwidth of both transducers is near 90%, and the -20 dB pulse lengths are 60 ns and 55 ns for the commercial and composite transducers, respectively. Pulse-echo experiments for 75 MHz PC-MUT were then conducted with water path decreased from ~ 5 mm to ~ 0.4 mm between the transducer front and the target surface (Figure 4, Figure 5). The center frequency is increased to 62 MHz comparing with ~ 45 MHz in Figure 4), the bandwidth is about 80%, and the sensitivity increasing is also noticed. The commercial transducer was not tested at shorter water path since it is a focused transducer and the response decreased drastically as the target is away from its focal point.

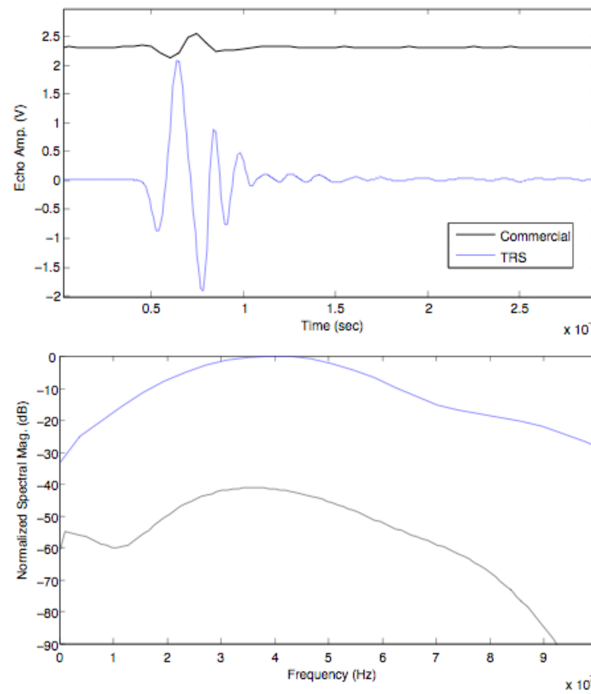
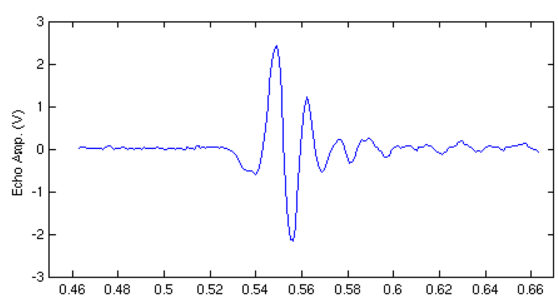


Figure 4. Time domain and spectral magnitude of echo signals for 75 MHz transducers. Comparison of a commercial device (focused) and TRS composite device show the composite gives much greater signal strength with comparable bandwidth.



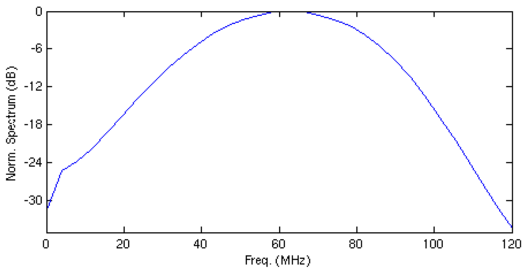


Figure 5. Time domain and spectral magnitude of echo response from TRS 75 MHz transducer at distance of approximately 0.4 mm from the echo target.

III. CONCLUSIONS

PMN-PT single crystal 1-3 composite with frequency of 15 MHz – 75 MHz was fabricated successfully using the PC-MUT technique. The measured electromechanical coupling coefficient for 15 MHz, 60 MHz ad 75 MHz composite was 0.79, 0.69, 0.67, respectively. The prototyped 75 MHz PC-MUT transducer showed significantly higher sensitivity that that of a commercial 75 MHz focused transducer, and the broad bandwidth was achieved (80-90%). Future work will focus on the transducer performance optimization and PC-MUT array fabrication.

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