ADVANCED PIEZOELECTRIC MATERIALS FOR MEDICAL ULTRASOUND TRANSDUCERS

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Abstract – A number of materials have recently been developed specifically for advanced ultrasound applications. These are high-density ceramics, fine grain ceramics, high dielectric constant ceramics, and single crystal piezoelectrics. Improvements in properties resulting from these materials range from greater strength and improved machinability to increased transducer element capacitance and coupling. The resulting transducer advances include high frequency arrays (>20MHz), high sensitivity 1.5 and 2-D phased arrays, and broadband (>100%) arrays.

I. INTRODUCTION

Many state-of-the-art ultrasound applications such as high frequency arrays (>20 MHz), 1.5 and 2-D phased arrays, and harmonic imaging arrays require advances in piezoelectric materials to fully achieve the anticipated performance benefits. Over the last several years TRS Ceramics, Inc. and the Pennsylvania State University have developed a number of piezoelectric materials to meet the challenges of these new transducer applications. This paper presents the results of property measurements and processing studies on these materials to quantify their merits for advanced transducer applications.

High Density Ceramics

High-density piezoceramics were developed in the early '70's using oxygen and vacuum-oxygen sintering [1,2]. Though very successful these methods still leave some residual porosity, which can be a source of failure during transducer manufacturing by dice and fill composite fabrication. To completely eliminate porosity, TRS has developed a high volume pressure densification process. As shown in figure 1, this process nearly eliminates all residual porosity leading to improved strength and machinability.

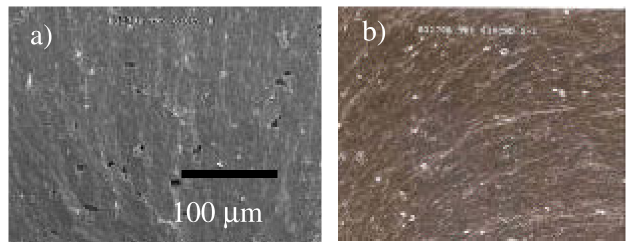

Figure 1: SEM micrographs for a) oxygen sintered and b) pressure densified Type VI peizoceramic. Nearly all residual porosity has been removed from the pressure-densified material.

Fine Grain Ceramics

An advance beyond high-density materials is the development of fine grain (< 1 to 2 μm) piezoelectric ceramics. These materials are prepared by a combination of fine particle formation during powder processing [3] and pressure densification. Fine grain materials are reformulated compared to conventional PZT ceramics to compensate the typical decrease in properties observed when grain sizes are reduced below 2 μm (see figure 2). The small grain size results in a > 30% strength increase as determined by 4-point bend tests [4]. As will be shown this results in dramatically improved machinability and is proving an advantage for the fabrication of high frequency transducers.

High Dielectric Constant Ceramics

Development of 1.5 and 2-D phased arrays for two-dimensional beam steering is currently a priority among many ultrasound companies. However, the small size and large aspect ratio of the array elements results in low capacitance compared to the drive electronics and cables. This in turn results in a reduced signal to noise ratio compared to 1-D phased or linear arrays with the same frequency [5]. In the past multilayer elements using stacked ceramic plates or tape casting and cofiring technology have been investigated as a way of increasing element capacitance. However, these methods have only met with limited success due to the great deal of complexity in fabricating and interconnecting multilayer elements in the form of 1-3 composites [5]. A simpler method is to use materials with increased dielectric constant. This can be done using relaxor-based piezoceramics with broad dielectric maxima and Curie temperatures below 200°C. TRS has developed such a material with a dielectric constant >6000. High density and fine grain processing have also been successfully applied to this material.

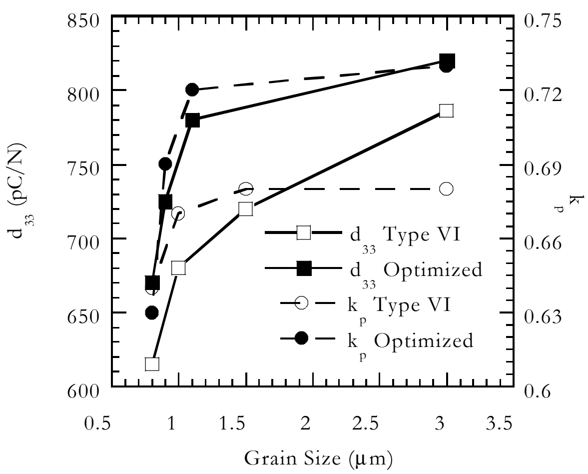

Figure 2: Piezoelectric (d_{33}) and planar coupling coefficient vs. grain size for a standard Type VI material compared to a composition that has been chemically re-optimized for reduced grain size

Single Crystal Piezoelectrics

The development of single crystals based on relaxor-lead titante solid solutions is a revolutionary advance in high performance piezoelectrics [6]. These materials exhibit extremely high piezoelectric coefficients and electromechanical coupling constants with the potential to provide very broadband transducer performance at equivalent or better sensitivity than PZT ceramic transducers [7]. Crystals based on $Pb(Mg_{1/3}Nb_{2/3})_{1-x}Ti_xO_3$ (PMN-PT) are currently being grown in sizes of > 2.54 cm in diameter by > 7cm in length (figure 3). Broadband transducers have been demonstrated from these materials [7] and process improvements are in progress to increase crystal yields and reduce costs.

Figure 3: PMN-PT single crystal boule.

II. Property Measurements

Piezoelectric and elastic properties of each of the materials discussed above were measured using standard IEEE resonance methods. Results are shown in Table I. HD refers to high-density ceramics and FG refers to fine grain materials. TRS610 and 600 are Type VI equivalent materials, TRS200 is a Type II ceramic, and TRSHK1 is the high dielectric constant material. Grain sizes were determined from scanning electron micrographs of fracture surfaces. The ranges listed in Table I correspond to average grain sizes observed in several material batches and ceramic firing trials. The crystal properties were measured by Prof. Cao of the Pennsylvania State University [8] and properties were calculated assuming tetragonal 4mm crystallographic symmetry.

Important results to note are the large coupling coefficients for the high density Type VI ceramics (including the fine grain version) and the single crystals. Also of importance are the very high elastic compliances and therefore low frequency constants of the single crystal materials. This results in thinner transducers for a given frequency and can lead to lateral clamping in filled composites and bonded structures. Successful methods for alleviating the lateral clamping issue have been presented in [7], and the availability of higher stiffness PMN-PT crystals (compared to PZN-PT) addresses the thickness issue to some extent. PMN-PT crystals also have very high clamped permittivity values; low clamped permittivity in PZN-PT resulted in lower than expected sensitivity in early crystal transducer development efforts.

Table I: Properties of Advanced Piezoelectric Ceramics and Crystals

Property	3203HD	TRS610HD	TRS600FGHD	TRS200FG HD	TRSHK1	PMN-33%PT [8]
Free K_3	3550	3900	3650	2050	6000	8000
Clamped K_3	1310	1250	1350	875	2500	3000
Loss	0.020	0.018	0.021	0.018	0.017	<0.01
k_{33}	0.79	0.80	0.79	0.73	0.74	0.91
k_{31}	-0.43	-0.46	-0.44	-0.37	-0.39	-0.51
k_p	0.72	0.73	0.68	0.66	0.64	N/A
k_t	---	0.56	0.54	0.49	0.50	0.62
d_{33} (pC/N)	660	690	670	400	750	2250
d_{31} (pC/N)	-297	-340	-310	-190	-360	-1050
Free s_{33} (10^{-11} m^2/N)	2.20	2.11	2.20	1.59	1.75	8.65
Free s_{11} (10^{-11} m^2/N)	1.55	1.65	1.48	1.48	1.54	5.97
T_c (°C)	215	210	190	340	150	166
Density (g/cm^3)	7.90	7.95	7.95	7.95	7.95	8.0
Grain Size (μm)	3 - 5	3 - 5	1	<1 - 2	3 -7	N/A

III. Dicing Studies

To determine the merits of increased density and reduced grain size for transducer fabrication, a dicing study was conducted on the ceramic materials to quantify the minimum post width that can be machined. The materials studied were 3203HD, 610HD, 600FGHD, 200FGHD, and a version of HK1 with grain size < 3 μm. Crystals were not included in this study because their dicing parameters are known to be considerably different from ceramics [7]. All samples were machined with an H405RM-T3 Asahi Diamond, Inc. 12 μm x 330 μm nickel bonded diamond blade. One mm thick samples were lapped with 3 μm alumina powder, electroded with sputtered Cr/Au electrodes, and poled. Four cuts were made 250 μm deep for each of 10 index settings resulting in diced beam aspect ratios from 1:1 to 10:1. The blade height was reset before starting a new sample and after every 12 cuts. Failure was defined at the index level for which 50% of the diced beam length was broken.

The maximum diced aspect ratios for each material compared to CTS 3203HD are shown in Table II, and photomicrographs of the diced ceramics are shown in Figure 4. The advantage of fine grain size is readily apparent. A much larger aspect ratio beam can be diced without breakage in the fine grain ceramics than in the more conventional materials. Of course, dicing parameters can be optimized to successfully dice finer features in the conventional samples than was achieved in this study, but even after optimization, fine grain materials are expected to exhibit improved machinability.

Table II: Maximum Aspect Ratio of Diced Beams Achieved for Various Ceramic Materials

3203HD	610HD	600FGHD	200FGHD	HK1
5:1	6:1	8:1	10:1	7:1

V. Implications for Transducers

The improved machinability of fine grain, high density ceramics compared to conventional materials has enabled the development of high frequency array transducers [9]. A micrograph of a 50 MHz array made by stacking lapped plates of TRS600FGHD is shown in figure 5. Such structures are not feasible with conventional grain sized materials.

The development of high dielectric constant ceramics is proving to be an enabling technology for 1.5 and 2-D phased arrays. The increased permittivity of these materials leads to improved signal to noise ratios compared to standard Type VI compositions [10]. In addition versions of these ceramics with grain sizes < 3 μm will enable phased arrays to be developed at higher frequencies than is currently practical.

Finally, single crystal materials are leading to the development of very broad bandwidth transducers. This is expected to enable advanced applications such as harmonic imaging and lead to the replacement of as many as three transducers with a single probe.

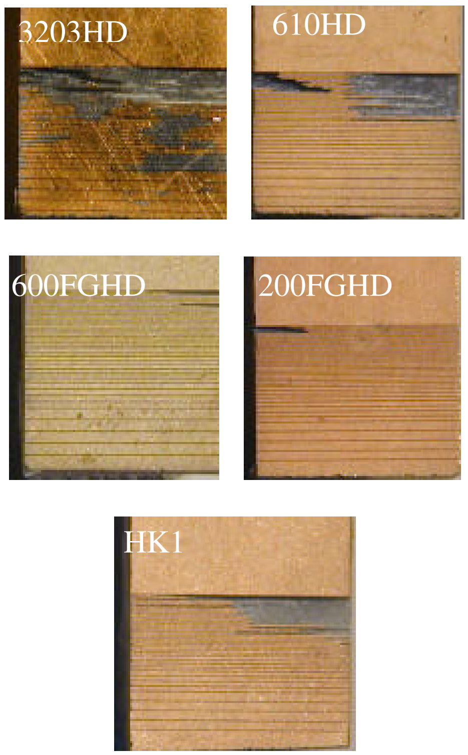

Figure 4: Photomicrographs of materials used in the dicing study summarized in Table II.

Acknowledgements

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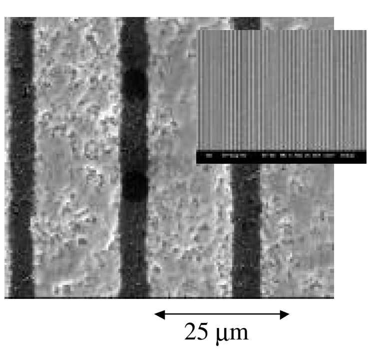

Figure 5: 50MHz composite constructed from stacked TRS600FG plates [9].

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