Innovations in Piezoelectric Materials for Ultrasound Transducers

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Abstract — Piezoelectric materials lie at the heart of ultrasonic transducers. For transducers used in medical imaging (3–7 MHz), PZT-5H ceramics offer high electromechanical coupling ($k_{33} \geq 75\%$), resulting in good bandwidth and sensitivity. As transducer arrays become smaller with increasing frequency, the development of high permittivity (ε_R^T > 7,000 vs. 3,400 for PZT-5H), piezoelectrics based on polycrystalline PMN-PT, provide improved electrical impedance matching. Advanced medical diagnostic techniques, including contrast and harmonic imaging, have taken advantage of the recent development in single crystal Relaxor-PTs that offer coupling k_{33}'s > 90% and subsequently, significant increases in bandwidth. For small animal, ophthalmology and cellular imaging, higher resolution is demanded, thus requiring transducers operational in the range of 20–100 MHz. Advancements in ceramic processing include pore-free and fine-grain (≤1 micron) piezoelectric ceramics of PT and PZT, being an "enabling" technology, allowing the fabrication of high frequency single element and annular arrays. Innovations in the fabrication of high frequency arrays (≥ 30 MHz) include tape casting and sol-gel molding techniques. Of particular significance, DRIE (deep reaction ion etching), has demonstrated the ability to mill out ultrafine features, allowing 1–3 crystal-polymer composites operational at frequencies ≥ 60 MHz, far beyond that achieved by current state-of-the-art dicing.

INTRODUCTION

Innovations in piezoelectric materials are driven by the need for high performance transducers. Electromechanical coupling (k_{ij}), dielectric permittivity (ε_r) and acoustic impedance (Z) are the most important parameters which determine the performance of ultrasonic transducers [1,2]. Piezoelectric ceramics have been the material of choice, offering high coupling, and a range of permittivies. These merits translate into transducer performance in the form of high sensitivity and broad bandwidth. To efficiently couple the acoustic energy from high impedance piezoelectric ceramics (Z~30 -36Mrayls) to the human body (Z~ 1.5Mrays), quarter wavelenth matching layers and/or low impedance composites comprised of piezoelectric ceramics with a passive polymer may be used. In addition, improved impedance matching composites offer geometries that ultilize high coupling coefficient elements as depicted in Fig. 1.

The selection of the appropriate piezoelectric material is also based upon the frequency of operation.

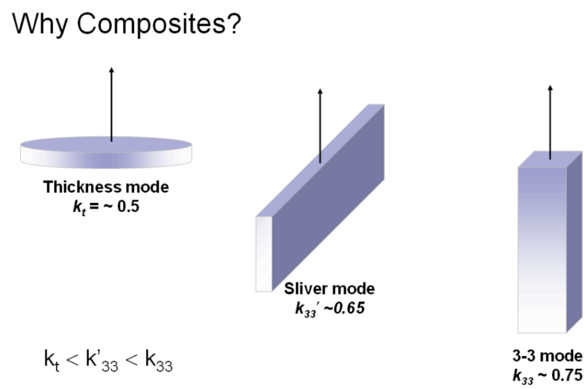


Fig. 1 Piezoelectric geometries and associated electromechanical coupling coefficients for single element transducers, 2-2 arrays and 1-3 composite transducers.

For ultrasonic imaging in the 3-7MHz regime, PZT-5H type ceramics have been the mainstay for array transducers offering electromechanical coupling k_{33}s ≥ 75% and large dielectric permittivities ($\varepsilon_r \geq 3400$). As transducer arrays become smaller with increasing frequency, piezoelectrics with higher permittivities are desired to maintain electrical impedance matching to the electronics. For very high frequency transducers >>20MHz, as used in ophthalmic eye imaging, catheter – based intravascular imaging (IVUS) and small animal imaging, the ability to fabricate the associated fine scale features of the transducer elements becomes the critical issue.

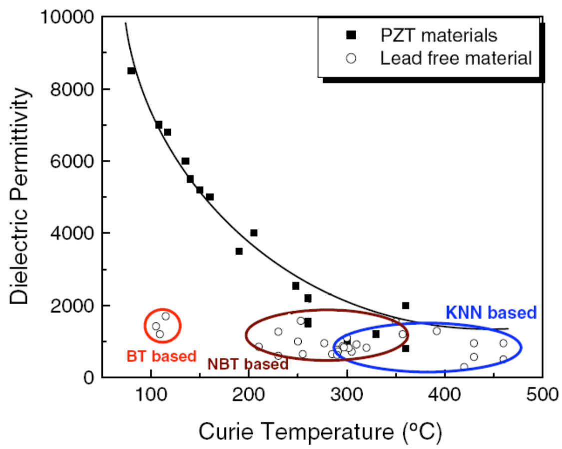
In this review, recent developments in piezoelectrics as related to transducer requirements are presented including high permittivity ceramics, high coupling single crystals and novel fabrication methods.

PIEZOELECTRIC MATERIALS

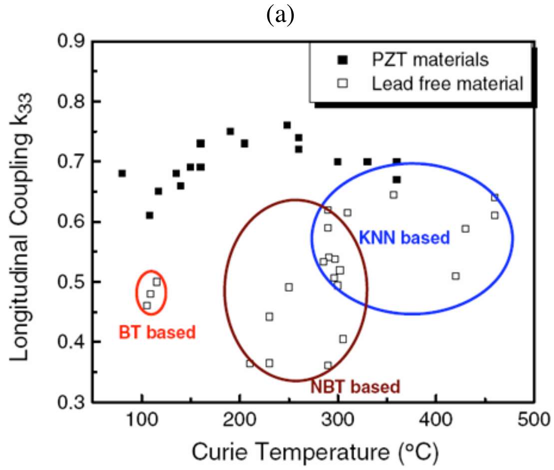
The parameters of a few piezoelectric materials used in 1-3 composites and array transducers are presented in Table 1 and contrasted in figures 2 a &b. Developed more than 30 years ago, optimal PZT-5H ceramics possess a combination of high coupling and high permittivity while exhibiting a transition temperature T_C ≥ 200°C, which leads to improved temperature stability and minimal depolarization during fabrication. Furthermore, these materials are microstructurally pore free, a key aspect in transducer fabrication.

From figure 2a, higher permittivity piezoelectrics are readily available, but one must sacrifice T_C. Listed in Table I, PMN-PT and/or Relaxor-PZTs, e.g., $Pb(Ni_{0.5}Nb_{0.5})O_3$ based systems, offer permittivities nearly twice that of the 5H materials, but exhibit T_Cs ≤150ºC. A fine grain version of the PMN-PT material (1-2 microns vs 5-10 microns) has been developed allowing ease of fabricating fine scale arrays by dicing [3]. Fine grain versions of $PbTiO_3$ (PT) have also been shown to be an enabling technology for the fabrication of 20-100MHz single elements and annular array transducers [4].

New MPB piezoelectrics in the $Bi(Me)O_3$-PT system have recently been found, offering good coupling, while exhibit T_Cs >400ºC, which have potential in transducers operational in harsh environments, e.g. NDE [5,6].



(a)



(b)

Fig. 2 Room temperature dielectric permittivity (a) and coupling coefficient (k_{33}) (b) as a function of Curie temperature for various PZT- based ceramics and lead free piezoceramics (BT-$BaTiO_3$, KNN-K,$NaNbO_3$, NBT-Na,$BiTiO_3$).

LEAD FREE PIEZOELECTRIC CERAMICS

With regislations of RoHS and WEEE to be enforced in Europe, enormous activities in the development of lead free ceramics to replace PZTs are ongoing. Shown in figures 2 a &b, data for various families of lead free piezoelectric ceramics clearly reflect that these materials exhibit far lower dielectric permittivities and electromechanical coupling than their lead based counterparts, thus limiting their usefulness in ultrasonic imaging to perhaps single element transducer(s) [8].

Table I. Properties of selected piezoelectric materials[7].

Property	PZT-5H	PMN-PT polycrystalline	PMN-32PT crystal
ε_r^T	3900	6000	8000
d_{33} (pC/N)	690	750	2250
k_{33}	0.80	0.74	0.91
N_3^T (Hz.m)	1300	1400	600
Curie Temperature (ºC)	210	150	166

Note: Piezoelectrics for high frequency (20-100MHz) single element transducers may include the low permittivity (≤100) materials PVDF, $PbTiO_3$, $LiNbO_3$ and $KNbO_3$ crystals.

RELAXOR-PT SINGLE CRYSTALS

Advancements in medical diagnostic technologies including contrast and harmonic imaging, have taken advantage of the recent development of single crystal Relaxor-PTs that offer ultra high electromechanical coupling coefficients (k_{33} ≥ 90%) and thus high bandwidth. Advances in crystal growth and subsequent transducer fabrication have lead to the commercialization of these novel crystals by Philips, Ibule and others, primarily ~5MHz cardiac imaging [9,10].

FABRICATION METHODS

An overview of various fabrication methods is given in figure 3 as a function of achievable scale and normalized acoustic frequency. The most common method used to fabricate 2-2 arrays and 1-3 composites is the "dice and fill" technique where a mechanical dicing saw is used to machine kerfs into a bulk piezoelectric and subquently backfilled with an epoxy. The use of pore and defect free bulk materials insures the highest possible piezoelectric performance. The "dice and fill" technique, however, is limited in frequency when considering the small feature sizes of the piezoelectric elements and kerfs, the later to minimize unwanted lateral mode coupling.

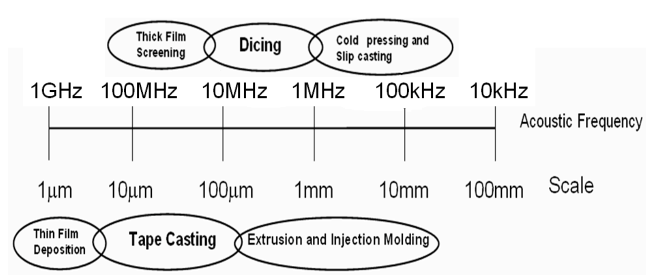


Fig. 3 Fabrication Methods and normalized frequency as a function of feature scale. Note: A frequency constant of N_{33} = 1000Hz.m was assumed

For 2-2 composites, alternative methods to dice & fill have been used to create high frequency transducers (20-40MHz), including "tape-casting", "stack and bond" and "interdigital phase bonding", however, these techniques are not amenable for high volume manufacturing [11-13]. As for 1-3 composites, the "lost mold" technique and related micro injection molding have been shown to produce composite transducers for frequencies >20MHz [14,15]. These techniques utilize powder processes and mixtures generally comprised of relatively large amounts of organic phase(s) which must be removed prior to densification. The subsequent polycrystalline ceramics are found to possess less than ideal microstructures and thus degraded performance, with coupling coefficients $k_{eff} \leq 40\%$.

Thin and thick film techniques include sputtering, chemical vapor deposition, sol-gel spin coating, inorganic/organic thick paste, etc., as well as polymer piezoelectrics such as PVDF, which offer features <10 microns and thus very high frequencies of operation. All these techniques suffer from low dielectric and electromechanical coupling (k_t <30%), due to clamping and defects as well as the inability to fabricate structures with high aspect ratios [16-18].

To overcome defficiencies of energetic and powder processes, micromaching of bulk materials has been recently developed to fabricate high frequency composite transducers (>40MHz). Figure 4 shows an SEM photo micrograph of a 1-3 compoiste PMN-PT single crystal prepared by deep reaction ion etching (DRIE). This repeatable and manufacturable process offers the transducers with coupling coefficient >70% [19-20].

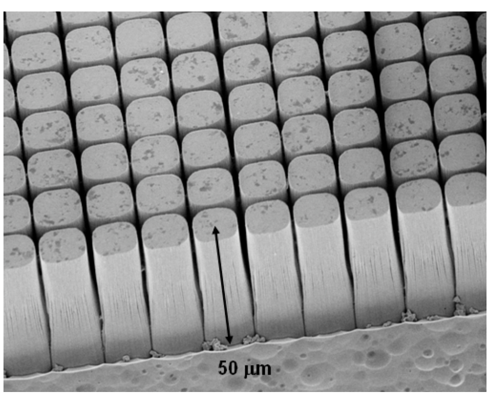


Fig. 4 SEM photo micrograph of a high frequency 1-3 single crystal composite fabricated by DRIE
Note- Kerf ~5µm

SUMMARY

Innovations in piezoelectric materials and fabrication methods for ultrasonic transducers have been primarily driven by the need for resolution in medical imaging. The development of Relaxor-PT single crsytals with electromechanical coupling coefficients k_{33}s> 90%, significantly higher than current state of the art PZT-5H ceramic (k_{33} ~75%), have made a significant impact, particularly in the area of cardiac harmonic imaging (~5MHz). As transducer arrays become smaller with increasing frequency, the development of higher

frequency (>20MHz) ultrasound transducers," *Proc. Ultrason. Symp.,* pp.1253-1256, 2002.

permittivity ceramics, $\varepsilon_{33} > 7000$ vs 3,400 for PZT-5H provides improved electrical impedance matching and thus performance. Advancements in ceramic processing including pore free and fine grain ($\leq$ 2 microns) piezoelectrics, such as PT and PMN-PT, being an "enabling" technique for fabricating high frequency single element transducers and annular arrays

Innovations in fabricating high frequency 2-2 arrays and 1-3 composites include tape casting and sol-gel lost mold techniques. Of particularly significance, DRIE (Deep reactive ion etching) has demonstrated the ability to mill out ultra fine features, allowing composites to be fabricated from bulk ceramics and single crsytals for high frequency transducers.

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