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PMN–PT single crystal focusing transducer fabricated using a mechanical dimpling technique

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ABSTRACT

A ~5 MHz focusing PMN–PT single crystal ultrasound transducer has been fabricated utilizing a mechanical dimpling technique, where the dimpled crystal wafer was used as an active element of the focusing transducer. For the dimpled focusing transducer, the effective electromechanical coupling coefficient was enhanced significantly from 0.42 to 0.56. The dimpled transducer also yields a −6 dB bandwidth of 63.5% which is almost double the bandwidth of the plane transducer. An insertion loss of the dimpled transducer (−18.1 dB) is much lower than that of the plane transducer. Finite element simulation also reveals specific focused beam from concave crystal surface. These promising results show that the dimpling technique can be used to develop high-resolution focusing single crystal transducers.

1. Introduction

Piezoelectric ultrasound transducers have been designed for desired fields of application such as nondestructive testing [1–3] and medical imaging [4–6]. Because of the nature of the conventional plane transducers, lateral resolution and sound intensity in imaging are limited. In particular high-resolution imaging applications, focusing is utilized to improve the lateral resolution and performance [7–10]. Shaping the piezoelectric element or using a lens is a usual way to fabricate the focusing transducers. Among various transducer designs, transducers with shaped piezoelectric element have been proved to be more effective in producing high-sensitivity devices because the installation of extra lens would cause attenuation due to acoustic mismatching [11,12]. Generally, the piezoelectric transducer element is shaped by hard pressing [13,14] or pressure defection techniques [15]. For the polymer and composite materials, the concave surface can be easily fabricated using these techniques because of their flexibility. Degradation and short-circuit may occur for hard pressing the bulk ceramic or single crystal element since the element would be broken apart during the shaping process.

Lead magnesium niobate–lead titanate (PMN–PT) single crystal has ultra-high piezoelectric properties compared with conventional piezoelectric materials [16]. Recently, there is a trend towards the use of this single crystal to fabricate high-performance ultrasound transducers [17,18]. With the composition near the rhombohedral–tetragonal morphotrophic phase boundary (MPB), PMN–PT single crystal has extremely good dielectric and piezoelectric properties as a result of enhanced polarizability arising from the coupling between two equivalent energy states [19]. In this work, <0 0 1> oriented PMN–28%PT single crystal was used as the active element of ultrasound transducers. The single crystal thin plate was dimpled mechanically to form a curvature on its surface. A plane transducer with the same configuration was also fabricated for performance comparison.

2. Transducer elements

The PMN–28%PT crystal was grown in the Shanghai Institute of Ceramics by the modified Bridgman method [20]. Before poling, the crystal was polished to a proper dimension, and then a 3 mm thick conductive epoxy (E-solder 3022, 5.9 MRayl, supplied by Von Roll Isola, New Haven, CT) was casted on a plane face of the single crystal as a substrate and a backing layer of the transducer as well. The front-face surface of the single crystal was dimpled using a dimple grinder (Gatan, Model 656). As shown in Fig. 1, the grinding wheel moves downward with a controlled force. Meanwhile, the crystal is rotated so that a uniform dimple can be formed. The focal length (or curvature) of the sample depends on the radius of the grinding wheel, which is about 7.5 mm in the present work. The dimpled surface was finally polished using diamond lapping paste wheel with the same radius. Fig. 2 shows photographs of the dimpled single crystal plate with a backing material. It can be seen that the appearance of the dimple is obvious and round in shape.

After dicing into designated dimensions, chromium and gold electrodes were sputtered on the curved face of the single crystal.

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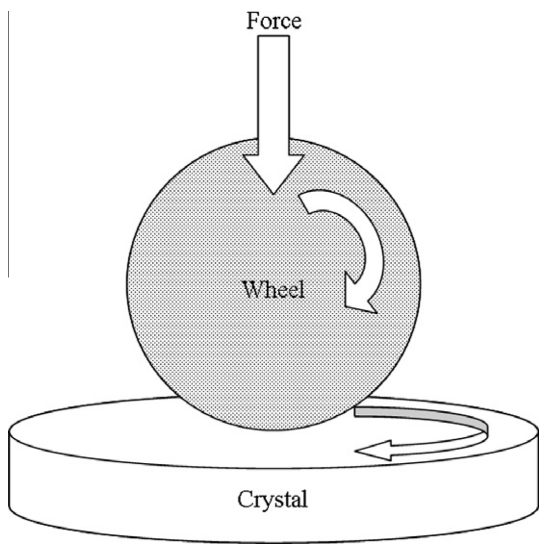

Fig. 1. A schematic diagram of the dimpling setup.

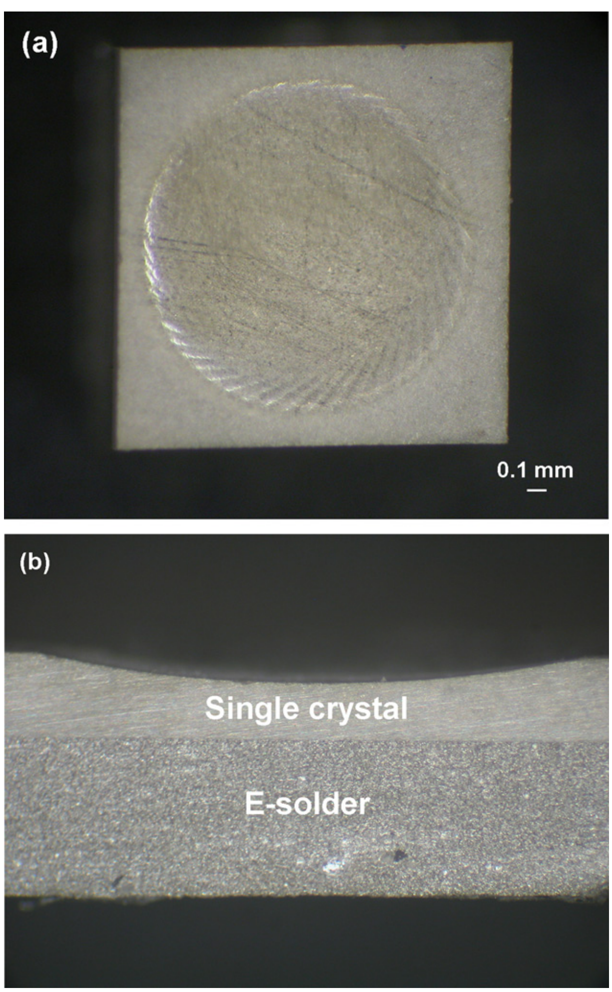

Fig. 2. Photographs of the (a) top view and (b) enlarged cross-sectional view of the dimpled single crystal.

The sample was then placed in a silicone oil bath and poled with a DC field of 1 kV/mm across its thickness at 130 °C. After being poled for 10 min, the heater of the oil bath was switched off and the electric field was maintained until the sample was cooled to 50 °C. After poling, the single crystal was short-circuit at room temperature to remove the injected charges. As a comparison, a plane plate transducer with the same single crystal and similar dimension was also fabricated. The properties of the PMN–PT single crystal used for modeling are shown in Table 1.

3. Experimental

The single crystal transducer was designed using the one-dimensional Krimholtz–Leedom–Matthae (KLM) model software PiezoCAD (Version 3.03 for Windows, Sonic concepts, Woodinville, WA). Four main components are involved including matching layer, active element, backing layer and metal tube. The PMN–28%PT single crystal with an active area of $2.0 \times 2.0\,\text{mm}^2$ and a thickness of 0.4 mm was used as the active element of the transducer. Parylene C (supplied by Specialist Coating System) was evaporated onto the front-face surface of the transducers by a Parylene deposition system (Specialist Coating System, model PDS 2010). The basic parameters of the Parylene C are shown in Table 2. Since this layer acts as a matching layer and a protecting layer as well, the thickness was calculated using PiezoCAD prior to the evaporation. The calculated optimized thickness of the matching layer is approximately quarter wavelength at the design resonance frequency. The experimental matching layer thickness was found to be ~148 μm. The entire configuration is the same for both plane and focusing transducers. Fig. 3 shows a photograph of the focusing ultrasound transducer.

To evaluate the electrical performance of the transducers, the impedance and phase of the transducers were measured using a precision impedance analyzer (Agilent 4294A). The effective electromechanical coupling coefficient, k_{eff}, was determined by [21]:

$$k_{eff} = \sqrt{\frac{f_p^2 - f_s^2}{f_p^2}} \qquad (1)$$

where f_s and f_p are the series and parallel resonant frequencies of the fundamental mode of the transducer, respectively. The square of the coupling coefficient describes the conversion efficiency of energy from electrical to mechanical form or vice versa.

Besides the resonance characterization, the performance of the transducer was also evaluated using a conventional pulse-echo response method. Both theoretical simulation and experiments have been used to compare the performance of the plane and focusing transducers. The theoretical analysis of imaging performance was evaluated by simulating the on-focus beamplots using finite element modeling software Field II [22]. The plane transducer is modeled as a square aperture with dimensions of 2.0 mm × 2.0 mm with an element size of 0.1 mm. The focusing transducer is modeled in the same way but with a concave aperture placed at the center. The radius and focal radius of the concave aperture are 1.8 mm and 7.5 mm, respectively. In the simulation, a Gaussian pulse with a center frequency of 5 MHz is used to excite the apertures. Each aperture is used in both pulse transmission and reception. The focal point of the beam emitted by an aperture can be obtained where the intensity is the maximum intensity along the central axis of the aperture.

Table 1
Basic material parameters of the PMN–PT single crystal.

Parameters	
Density, ρ	8000 kg/m^3
Longitudinal velocity, υ	3490 m/s
Clamped dielectric constant, ε_{33}	1032
Electromechanical coupling coefficient, k_t	0.63
Acoustic impedance, Z_a	28 MRayl