TECHNICAL REPORT

Ultrasonic imaging using air-coupled P(VDF/TrFE) transducers with through-transmission method at 2 MHz

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(Received 11 December 2019, Accepted for publication 10 January 2020)

Abstract: Concave-type twin transducers with a center frequency of 1.93 MHz have been fabricated using polyvinylidene fluoride trifluoroethylene (P(VDF/TrFE)) resonators that have a transducer insertion loss of 100 dB (although this figure does not include the air absorption loss). A through-transmission acoustic imaging system was constructed using these twin (transmitting/receiving) P(VDF/TrFE) transducers. Burst waves composed of 50 cycles of sine-waves from a radio-frequency (RF) source were excited to approximately 600 V_{pp} by using a high-voltage power amplifier, and these high voltage burst waves were then input into the transmitting P(VDF/TrFE) transducer. Acquisition of the resulting small signal after it had passed through a sample object (a Rockwell 11229-12 logic integrated circuit) allowed the through-transmission image to be displayed on a personal computer monitor. The transverse resolution of this imaging system is approximately 0.5 mm. The results of this study demonstrate that these P(VDF/TrFE) piezoelectric films with their low acoustic impedances are applicable to through-transmission imaging in air in the MHz range.

Keywords: Air-coupled, P(VDF/TrFE) transducer, Through-transmission imaging, MHz-range

PACS number: 43.38.Fx, 43.58.—e, 43.60.Lq [doi:10.1250/ast.41.900]

1. INTRODUCTION

In recent years, research into ultrasonic inspection in air using air-coupled transducers has been reported frequently [1–6]. In the MHz-range ultrasonic imaging field, acoustic imaging using a lead zirconate titanate (PZT) transducer was first reported by Fox *et al.* in 1985 [7], and applications of air-coupled ultrasonics using PZT-5A disks were reported by Grandia and Fortunko in 1995 [8]. However, much of the research in ultrasonic imaging has used kHz-range transducers [6,9] because the attenuation of ultrasonic energy in air is approximately three orders of magnitude higher than that in water and is also proportional to the square of the operating frequency [10–12]. Detection of high-frequency ultrasonic waves that have passed through an object under study using an air-coupled transducer is more difficult than pulse-echo imaging from the object surface. It is therefore necessary to apply high-amplitude voltages to the transducer, which is excited in the MHz-range. In these cases, application of high voltages to transducers that are made from piezoelectric ceramics such as PZT could lead to dielectric

breakdown. In contrast, the piezoelectric copolymer polyvinylidene fluoride trifluoroethylene (P(VDF/TrFE)) has an electric coercive field (E_c) that is approximately 10 times as high as that of PZT, and it also offers the highest electromechanical coupling factor (k_t) among the piezoelectric polymers ($k_t \sim 0.3$) [13,14]. Piezoelectric polymer transducers have lower acoustic impedances and the impedance matching loss between this type of transducer and the air is much lower than that of piezoelectric ceramic transducers. While there is attenuation of 86 dB at the boundary between PZT and the air, the corresponding value between P(VDF/TrFE) and the air is only 68 dB [15]. Therefore, P(VDF/TrFE) transducers make it possible to transmit and receive signals in the air more efficiently than PZT transducers. The ultrasound wavelength distance is approximately 170 μm at 2 MHz in air. Therefore, it is possible to acquire high-resolution ultrasonic images using MHz-range ultrasound in the air. P(VDF/TrFE) transducers are also highly advantageous for object penetration during ultrasonic inspection because their low acoustic impedance allows more efficient transmission in the air than a PZT transducer. Thus far, the through-transmission imaging using P(VDF/TrFE) transducers has not ever been done in air.

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In this study, a transmission scanning acoustic imaging system has been constructed using concave-type twin (transmitting/receiving) P(VDF/TrFE) transducers with a center frequency of approximately 2 MHz ($f_c = 1.93$ MHz) that were fabricated using a casting method [16]. As a result, we have successfully displayed an acoustic image of a logic integrated circuit (IC; 11229-12, Rockwell) [17] acquired via through-transmission at 2 MHz in air.

2. EXPERIMENTS ON P(VDF/TrFE) PIEZOELECTRIC POLYMER

2.1. Fabrication and Evaluation of P(VDF/TrFE) Piezoelectric Film

P(VDF/TrFE) (with 75 mol% VDF, molecular weight 350,000 g/mol) was dissolved in dimethyl formamide (DMF) to produce an approximately 20 wt.% P(VDF/TrFE) solution. A film was then formed by casting the solution on a 0.6-mm-thick ($\lambda/4$) Cu plate substrate that also acted as a backing electrode [16]. The film was then annealed at 145°C for 2 h to enhance its crystallinity (β -form crystals), and an Au layer was subsequently deposited on the film using a vacuum evaporation process to form the front electrode. The P(VDF/TrFE) film, which was approximately 300 μm thick, was poled under an electric field E_p (± 75 MV m^{-1}) that was suitably higher than the coercive field E_c (~ 50 MV m^{-1}). The complex admittance of the resulting poled film resonator was then measured using a network analyzer (4395A, Agilent). Figure 1 shows the piezoelectric resonance behavior of the P(VDF/TrFE) resonator, which had an air/evaporated Au (0.2 μm)/P(VDF/TrFE) (300 μm)/Cu plate (600 μm) structure. The electromechanical coupling factor $k_t \sim 0.22$ was determined by fitting of the resonance behavior using Mason's equivalent circuit [18,19]. The parameter values that were determined are listed in Table 1.

Because the electromechanical coupling factor $k_t \sim 0.22$ is small, the crystal direction of P(VDF/TrFE) has

Fig. 1 Observed and simulated admittance-phase/frequency curves for P(VDF/TrFE) film with Cu plate fabricated by casting method. The area of the film was 380 mm².

Table 1 Electromechanical properties of P(VDF/TrFE) and air used in simulations.

active area of transducer	380 mm ²
density [P(VDF/TrFE)]	1.89 g cm ⁻³
sound speed [P(VDF/TrFE) longitudinal wave] ^a	2,400 m s ⁻¹
thickness [P(VDF/TrFE)]	298 μm
dielectric constant ϵ/ϵ_0 [P(VDF/TrFE)]	5.1
coupling factor k_t [P(VDF/TrFE)] ^a	0.22
dielectric loss tangent, $\tan \delta_e$ [P(VDF/TrFE)]	0.13
mechanical loss tangent, $\tan \delta_m$ [P(VDF/TrFE)]	0.06
backing-layer (Cu)	600 μm
forward-layer (Au)	0.2 μm
sound speed (Cu)	5,000 m s ⁻¹
sound speed (Au)	3,200 m s ⁻¹
sound speed (air)	340 m s ⁻¹
density (air)	0.0013 g cm ⁻³

^aFrom the fitting curve shown in Fig. 1.

a random orientation, which means that it is necessary to apply a higher voltage to the P(VDF/TrFE) film (thickness = 300 μm). However, poling was suspended because electrical breakdown occurred at voltages exceeding the field E_p (± 75 MV m^{-1}). Therefore, the electromechanical coupling factor of this P(VDF/TrFE) film is considered to have stagnated at $k_t \sim 0.22$.

2.2. Fabrication and Evaluation of P(VDF/TrFE) Transducers

The P(VDF/TrFE) transducer has an aperture angle of $2\theta = 83^\circ$ and a focal length of 15 mm, as shown in Fig. 2. The structure described in order from the front side is composed of the front Au evaporated electrode, the P(VDF/TrFE) film, the Cu backing plate and air (which act as the backing load). This concave-type transducer, which has a center frequency of 1.93 MHz, was fabricated using the P(VDF/TrFE) resonator shown in Fig. 1.

Fig. 2 Schematic showing configuration of 2 MHz P(VDF/TrFE) concave-type transducer.

Fig. 3 Block diagram of transducer insertion loss measurement system.

Fig. 4 The RF source signal voltage was $6.43 V_{pp}$ (sine burst waves 80 cycles), and the amplified signal voltage from receiving transducer was $3.75 mV_{pp}$ at 1.93 MHz in air (transducer focal length = 15 mm).

Figure 3 shows the measurement system that was used to measure the efficiency of the 2 MHz concave-type transducers (30-mm-long one-way signal path in air). The RF source signal voltage (33500B, keysight) input to transmitting transducer was $6.43 V_{pp}$ (sine burst waves 80 cycles), and the amplified signal voltage from receiving transducer of same structure with transmitting transducer (Fig. 2) was $3.75 mV_{pp}$ as shown in the below of Fig. 4. As shown in Fig. 4, is defined as the ratio of the output acoustic power in air to the input electric power, which is given by $-20 \log(V_{out}/V_{in})$ and consists of the transmitting and receiving transducer loss ($2TL$) and the one-way absorption loss in air (AL). The obtained the $2TL + 53$ dB (low noise amplifier LA110, R&K) + AL characteristic was 117 dB. The value of AL , i.e., the air absorption loss, is 1.6×10^{-12} (frequency)² (dB/cm), according to [16]. The concave-type P(VDF/TrFE) transducer insertion loss [$2TL = (\text{transducer observed loss}) + (\text{amplifier gain } 53 \text{ dB}) - (\text{air absorption loss } 17 \text{ dB})$] was 100 dB at 1.93 MHz.

Fig. 5 Block diagram of air-coupled through-transmission imaging system.

3. ULTRASONIC IMAGING SYSTEM OF THROUGH-TRANSMISSION METHOD USING AIR-COUPLED P(VDF/TrFE) TRANSDUCERS

A block diagram of the through-transmission acoustic imaging system, which is controlled via a computer program, is shown in Fig. 5. The burst waves, which were composed of 50 cycles of sine waves from a radio-frequency (RF) source (33500B, Keysight), were excited up to approximately $600 V_{pp}$ using a high-voltage power amplifier, and the resulting high-voltage bursts were input to the transmitting P(VDF/TrFE) transducer. Because impedance matching with a low-noise amplifier (LA110, R&K; impedance: 50 ohm) was required, a radial leaded inductor was added to the receiving P(VDF/TrFE) transducer. After the small transmitted waves that passed through the sample object were detected using the twin receiving P(VDF/TrFE) transducer, the signal waves were then amplified using the low-noise amplifier (gain: 53 dB) and the cascading small signal amplifiers, and sent to a digital oscilloscope (DSOX3012T, Keysight). Figure 6(a) shows a photograph of a Rockwell 11229-12 logic IC [17] mounted on an acrylic plate that was used as the sample object and Fig. 6(b) shows the P(VDF/TrFE) twin transducer arrangement. The dimensions of this IC are 24 mm × 24 mm with a thickness of 1.5 mm. Figure 7 shows the averaged receiving signals (16, 32, 64, 128, 256, 512 and 1,024 times) of passed through in the central area (Si-chip) of Rockwell 11229-12 logic IC, respectively. In this study, the signal detected from the receiving P(VDF/TrFE) transducer was averaged 512 times using the digital oscilloscope for noise reduction.

Fig. 6 (a) Photograph of Rockwell 11229-12 logic IC that was used as a sample object (24 mm × 24 mm × 1.5 mm (thickness)). (b) Photograph showing arrangement of twin transmitting/receiving P(VDF/TrFE) transducers and sample object shown in Fig. 6(a).

Fig. 7 The averaged receiving signals (16, 32, 64, 128, 256, 512 and 1,024 times) of passed through in the central area (Si-chip) of Rockwell 11229-12 logic IC (displays are 1 V/div : 50 μs/div on arb.units).

4. THROUGH-TRANSMISSION SCANNING ACOUSTIC IMAGING OF INTEGRATED CIRCUIT

Figure 8(a) shows a through-transmission acoustic image of the same IC acquired in air at 2 MHz (using the concave-type P(VDF/TrFE) twin transducers shown in Fig. 2 and the ultrasonic imaging system shown in Fig. 5. Figure 8(b) shows an X-ray image of the same IC for comparison with the acoustic image. In this study, the mechanical scanning X-Y stage that was driven using a pulse motor to display the through-transmission acoustic image (two-dimensional) showed a width displacement of 40 μm/step [21]. The mechanical scanning was driven using pulse motors that were controlled by a personal

Fig. 8 (a) Through-transmission acoustic image of Rockwell 11229-12 logic IC shown in Fig. 6(a). (b) X-ray image of the same IC.

Fig. 9 (a) Photograph (rear view) of a Rockwell 11229-12 logic IC with the epoxy over-mold removed. (b) Photograph of the structure of the same IC, which has a silicon substrate (chip dimensions of 6 × 6 mm, with thickness of 350 μm) on a copper frame (8 × 8 mm), for inspection after the chip was dismantled by heating and removal of the epoxy over-mold; the fixing tape (width of 1.2 mm) on the lead frame is also shown. (c) Structure of a Rockwell 11229-12 logic IC showing the Si chip, the bonding wire and the fixing tape; the image also shows the attenuations of (1) the Si chip: 39 dB; (2) the area around the Si chip: 64 dB; (3) the outer lead: 36 dB; and (4) the fixing tape (including the outer lead): 41 dB.

computer program. Figure 9(a) shows a photograph (rear view) of a Rockwell 11229-12 logic IC with the epoxy over-mold removed. The photograph confirms the bonding wire distance (width) with of approximately 0.5 mm at the four corners in the IC. Figure 9(b) shows a photograph of

the structure of the same type of IC, which has a silicon substrate (chip dimensions 6×6 mm, thickness of $350 \mu\text{m}$) on a copper frame (8×8 mm), intended for inspection after being dismantled by heating and removing the epoxy overmold, and also shows the fixing tape (width: 1.2 mm) on the lead frame. The locations of Si chip, the bonding wire and the fixing tape are confirmed using the acoustic image shown in Fig. 9(c). In this displayed image, the ultrasonic energy transmission is divided into 16 color (monochrome) values, which were converted into image data after detection by the receiving P(VDF/TrFE) transducer (the lighter colors indicate higher transmission and the dark colors indicate lower transmission for the ultrasonic energy transmission processes.). In addition, several partial attenuation values of parts of this logic IC at 2 MHz are shown in the figure, including: 1. Si chip: 39 dB; 2. surrounding area of the Si chip: 64 dB; 3. outer lead: 36 dB; and 4. fixing tape (including the outer lead): 41 dB. Figure 10(a) shows a through-transmission acoustic image of the Si chip and

surrounding area with outer lead (monochrome), and Fig. 10(b) shows the same area that is divided into 16 color (Z axis = 0 mm). Figure 10(c) also shows an acoustic image of the Si chip and its surrounding area produced by adjusting the focus position (Z axis = -0.3 mm) to be near the Si chip. As a result, this acoustic image can be used to confirm the bonding of the wire and Si chip, along with the frame of Si chip [20]. A three-dimensional image in the form of a graph in Microsoft Excel® of the same area shown in Fig. 10(b) (two-dimensional image) is shown in Fig. 10(d). The transverse resolution of the proposed imaging system is approximately 0.5 mm, based on the bonding wire distance shown in Fig. 10(a) and Fig. 10(b).

5. CONCLUSION

Ultrasonic through-imaging techniques play an important role in nondestructive testing of various substances. Because the P(VDF/TrFE) piezoelectric polymer has a much lower acoustic impedance than PZT, it provides a better match for the low acoustic impedance of the air. Therefore, this study has focused on enhancing the display of ultrasonic through-transmission images of an IC by improving on the research on P(VDF/TrFE) transducers to date [21,22]. While the electromechanical coupling factor k_t remains small at this initial development stage, it is still possible to reinforce the difference in efficiency (k_t) for a P(VDF/TrFE) transducer that is excited using a high voltage. As a result, we have successfully displayed a through-transmission acoustic image of an IC that was acquired at 2 MHz in air. The insertion losses of the transducers that were used in this study are still quite large (100 dB) at present. Additionally, to improve the through-transmission acoustic image by providing high transverse resolution, it will be necessary for the transducer with the P(VDF/TrFE) piezoelectric resonant film to have a high electromechanical coupling factor k_t , which will be addressed in future work.

ACKNOWLEDGMENTS

The author is grateful to Dr. H. Ohigashi for his valuable advice on this study. This work was supported by JSPS KAKENHI [grant Number JP16K06378].

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Fig. 10 (a) The through-transmission acoustic image of the Si chip and surrounding area with outer lead (16 color monochrome). (b) Acoustic image of the IC chip and its surrounding area (16 color). (c) Acoustic image when adjusted onto a focusing position near the bonding wires (outer lead). (d) Three-dimensional acoustic image formed by plotting a graph in Microsoft Excel® of the same area that is shown in Fig. 10(b) (as a two-dimensional image).

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