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# Monolithic Integration of P(VDF-TrFE) Thin Film on CMOS for Wide-band Ultrasonic Transducer Arrays

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***Abstract*— We developed a novel ultrasonic transducer with a P(VDF-TrFE) thin film monolithically integrated on a CMOS LSI. Its higher sensitivity and wider bandwidth in the 20 MHz range compared to a conventional PZT transducer is demonstrated. The P(VDF-TrFE) is an attractive piezoelectric sensor material with an excellent piezoelectric constant and low acoustic impedance matched to human tissue. However, it is difficult to miniaturize the device like a 2D array, and due to its low dielectric constant, the transducer is susceptible to parasitic capacitance of the connection circuity. This problem is solved by the monolithic formation of P(VDF-TrFE) transducers on CMOS LSI. In this study, such an ultrasonic array (16 elements × 4 channels) with a single-element area (190 × 190 μm²) was fabricated, and the receiving acoustic characteristics were evaluated.**

***Keywords*— *P(VDF-TrFE), CMOS, Ultrasonic transducer, Piezoelectric thin film, MEMS, PMUT***

## I. Introduction

The transducer material currently used in ultrasonic imaging systems is piezoceramics, comprising mainly $Pb(Zr,Ti)O_3$ (PZT) [1]. A piezoceramic is characterized by a piezoelectric strain constant $d$ and dielectric constant $\varepsilon$. The $d$ implies the strain response to voltage input on opposing electrodes. Larger $d$ is important for devices requiring significant displacement like actuators and ultrasonic transmitters. In most of the commercially available ultrasonic imaging systems, a piezoceramic is employed both as a transmitting element and as a receiving element. The high $\varepsilon$ of the piezoceramic is advantageous for a transmitting element but disadvantageous for a receiving element. This is because the figure of merit for the receiving sensitivity is the piezoelectric voltage constant $g = d/\varepsilon$. A material with a large strain constant and a small dielectric constant is therefore, more appropriate for a receiving element. Noteworthy is that, the transmitting element and the receiving element require conflicting dielectric properties. In view of the dilemma, the authors proposed an innovative piezoelectric micro-electro-mechanical systems (MEMS) transducer comprising independent transmitting and receiving elements. A conceptual illustration of the cross-sectional structure of the transducer element is shown in Fig. 1. By separating the transmission and the receiving elements, employing an appropriate piezoelectric material for each and optimal controlling the vibration structure becomes possible. This also enables provision of a suitable piezoelectric material

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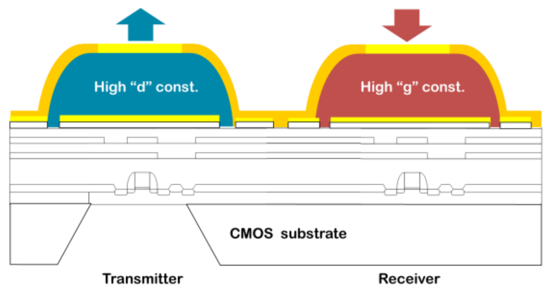


Fig. 1. Proposed piezoelectric MEMS transducer

and vibration mode for each element. This way, giving an independent design DOF to the material and structure, the sensitivity and bandwidth of the transducer is greatly improved. For the transmitting element (left side in Fig. 1), adequate ultrasonic pressure for medical imaging is radiated by utilizing deflection vibration resonances as a diaphragm structure with a PZT thin film [2].

As a material for the receiving element (right side in Fig. 1), an organic piezoelectric material like PVDF or its copolymer P(VDF-TrFE) is attractive. The material exhibits a piezoelectric strain constant $d$ about 1/10 as low as that of PZT, but the dielectric constant $\varepsilon$ is 1/100 as small as that of PZT. The piezoelectric voltage $g$ constant yields 10 times as large as that of PZT, thereby suggesting a more suitable material as a receiving element. Furthermore, the organic piezoelectric material displays broadband characteristics because of its low acoustic impedance that matches excellently with human tissue. However, a problem arises when applying an organic piezoelectric material to a small receiving element. It is susceptible to the parasitic capacitance on the wiring path, easily degrading the image quality to an unacceptable level. The wiring connection is more difficult compared to the transducers utilizing piezoceramics because of higher electrical impedance. Therefore, ultrasonic transducers containing organic piezoelectric materials have been studied for limited applications. The transducer element has been relatively wide like a single disc-shaped transducer or in a low electrical impedance region like 40 MHz or higher frequency [3]. Another challenging trial, a prototype 20 MHz 1D array transducer using a PVDF thin film was also proposed [4]. This involved an amplifier chip of high input impedance placed in the vicinity of each transducer element. It successfully provided high spatial resolution due to the broadband characteristics of the PVDF. However, its sensitivity remains low as compared to a conventional transducer using piezoceramics.

In this study, an ultrasonic transducer array involving a P(VDF-TrFE) film monolithically integrated on a CMOS LSI is fabricated. Its higher receiving sensitivity and wider bandwidth in the 20MHz range relative to the conventional PZT transducer is demonstrated. The parasitic capacitance of the wiring is minimized by directly depositing the P(VDF-TrFE) thin film on the CMOS die.

## II. TRANSDUCER AND CMOS DESIGN

The schematic of the fabricated transducer array is shown in Fig. 2. The single element is 190 × 190 μm² (Fig. 2(a)) and the cross-sectional view (Fig. 2(b)) shows the stacking structure of the CMOS circuit and the P(VDF-TrFE) thin film, the three important capacitive components, and the positional relationships. Figure 2(c) represents a small signal equivalent circuit for the reception signal.

The signal-to-noise ratio (SNR) of the transducer is examined below. The generated voltage $v_{\mathrm{sig}}$ on the piezoelectric material in response to pressure input $P_{\mathrm{in}}$ is expressed as:

$$v_{\mathrm{sig}} = g \cdot P_{\mathrm{in}} \cdot t, \tag{1}$$

where $g$ and $t$ are the piezoelectric voltage and the thickness of the P(VDF-TrFE) film. When the Miller capacitance between the field effect transistor (FET) drain and the gate terminal is negligible, the gate voltage $v_{\mathrm{g}}$ is expressed as:

$$v_{\mathrm{g}} = \frac{1}{1+\frac{C_{\mathrm{g}}+C_{\mathrm{para}}}{C_{\mathrm{PVDF}}}} v_{\mathrm{sig}}, \tag{2}$$

where $C_{\mathrm{g}}$, $C_{\mathrm{para}}$, $C_{PVDF} = \varepsilon_0 \varepsilon_r S/t$, $t$, and $S$ are gate capacitance, parasitic capacitance, capacitance of the P(VDF-TrFE), P(VDF-TrFE) thickness, and area of the bottom electrode, respectively. The signal voltage $v_{\mathrm{g}}$ increases with decreasing $C_{\mathrm{g}} + C_{\mathrm{para}}$ based on Eq. (2). Thermal noise is assumed as the noise source, and if the noise impedance of the FET is enough high, the input conversion noise $v_{\mathrm{ni}}$ per unit frequency is written [5-7] as:

$$\overline{v_{\mathrm{ni}}{}^2} = \frac{8kTL}{3\sqrt{3\mu_{\mathrm{n}} C_{\mathrm{g}} i_{\mathrm{d}}}}, \tag{3}$$

where $L$, $\mu_{\mathrm{n}}$ $k$, $T$ , and $i_{\mathrm{d}}$are the FET channel length, the carrier mobility, the Boltzmann constant, the absolute temperature, and the $i_{\mathrm{d}}$ drain current, respectively. The noise $v_{\mathrm{ni}}$ increases as the gate capacitance $C_{\mathrm{g}}$ decreases.

Using Eqs. (2) and (3), the transducer element capacitance dependence on the $\mathrm{SNR} = 20\log(v_{\mathrm{g}}/v_{\mathrm{ni}})$ is calculated as shown in Fig. 3. The following parameters and stated values are used in the calculation: g = 0.2 Vm/N as the typical value of the P(VDF-TrFE) and $P_{\mathrm{in}}$ = 25 Pa as the minimum sound pressure defined empirically, $\mu_{\mathrm{n}}$ = 1500 cm²/Vsec, $L$ = 0.6 μm, $i_{\mathrm{d}}$ = 100 mA, $T$ = 300 K, 10 MHz as the bandwidth. Figure 3 reveals the following: (i) the SNR increases by increasing the P(VDF-TrFE) film thickness, (ii) the influence of the parasitic capacitance increases with the P(VDF-TrFE) film thickness, and (iii) the SNR maximum peak depends on the film thickness and the parasitic capacitance. Alternatively, a high SNR requires increasing the P(VDF-TrFE) thickness and lowering the parasitic capacitance to the minimum, as well as matching the gate capacity so as to obtain the maximum SNR. Because the operation of the noise impedance of the FET is assumed in a high area in this study, the noise in Eq. (3) remains unchanged when $C_{\mathrm{g}}$ is constant. Therefore, the profile of the SNR is equivalent to that of the receiving voltage $v_{\mathrm{g}}$.

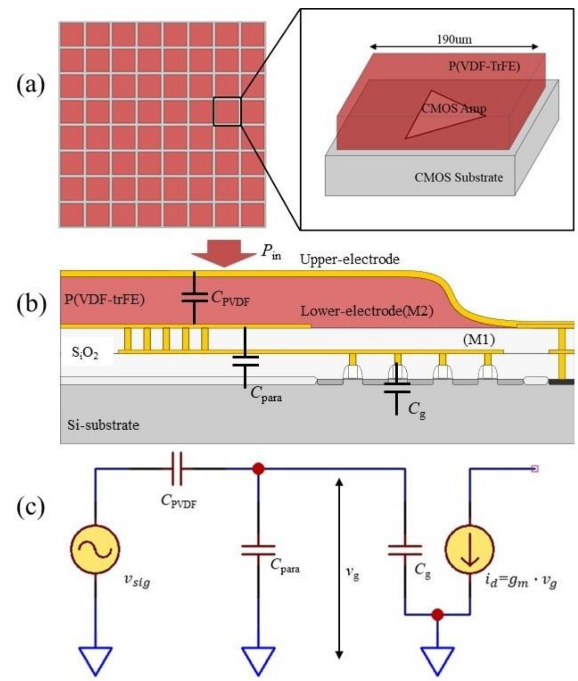


Fig. 2. The schematic illustration of fabricated P(VDF-TrFE) transducer and equivalent circuit model.

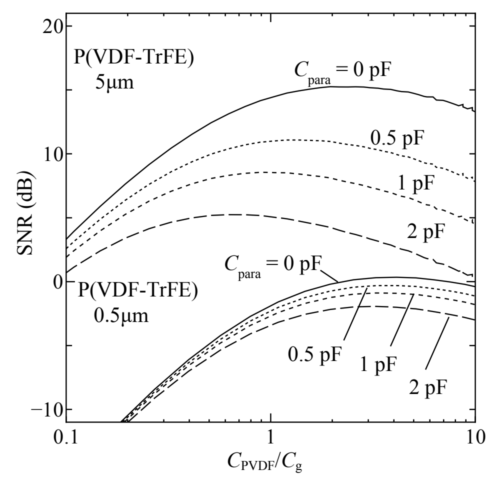


Fig. 3. Transducer element capacitance and SNR

At the CMOS design stage, the P(VDF-TrFE) film thickness is assumed to be 5 µm. The FET gate size is determined in order that the gate capacity $C_g$ is 0.2 pF. The calculated parasitic capacitance $C_{para}$ of 0.56 pF is the interlayer capacitance between M1 and the substrate. According to the design, the transducer is detected by SNR of +11 dB at 25 Pa input pressure.

## III. Transducer Fabrication

A photomicrograph of the fabricated CMOS LSI is shown in Fig. 4. The fabrication and device setup processes for the transducer is illustrated in Fig. 5.

### A. Preparing CMOS die

We fabricated a CMOS amp array of 190 ×190 µm$^2$ as a unit receiving aperture, and 16 × 4 channels and 200 µm pitch, using the standard 0.6 µm, 5 V CMOS process. No passivation layer was formed for the subsequent piezoelectric film deposition.

### B. Spincoating P(VDF-TrFE) thin film

The P(VDF-TrFE) film was deposited on the CMOS die by the spin coating method. It was adjusted the desired film thickness 0.5 to 4.5 µm by controlling the rotational speed and the solution concentration. After coating, the sample was dried at 80 °C for 1 hour, followed by crystalized annealing at 140 °C for 1 hour.

### C. Etching of P(VDF-TrFE)

The P(VDF-TrFE) on the CMOS aluminum pad was removed for subsequent wire-bonding. Dry etching was performed with oxygen gas plasma after a photoresist mask was laminated on the sample. Residual resist after the etching was peeled off by using an ethanol-amine type solvent, to prevent damage of the P(VDF-TrFE) film.

### D. Depositing of top electrode

For the top electrode, the Au was uniformly deposited (150 µm) on the P(VDF-TrFE) by an RF magnetron sputter. The Au was patterned using an ICE-RIE apparatus with Ar as the etching gas.

### E. Wiring and passivation

The power supply and signal output pad on the CMOS were connected by wire bonding using Al wire. The top electrode was connected to GND and COMMON using conductive silver paste and Al wire while a water tank of acrylic resin was bonded to the sample with silicone rubber. A 3 µm parylene film was deposited by vapor deposition for underwater operation.

Polarization processing of the P(VDF-TrFE) was necessary to generate high piezoelectricity. The entire CMOS substrate was grounded and a DC voltage applied between the top and bottom electrodes on the P(VDF-TrFE). The DC voltage required to saturate the polarization was determined by generating a Polarization-Electric field hysteresis loop. The voltage input duration was fixed for 30 minutes at room temperature.

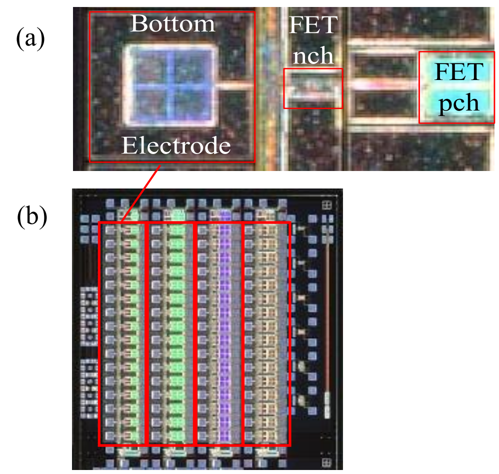


Fig. 4. Photomicrographic images of CMOS amplifier. (a) Unit channel with 190 × 190 µm$^2$ receiving aperture and (b) the die containing 16 × 4 receiver channels,

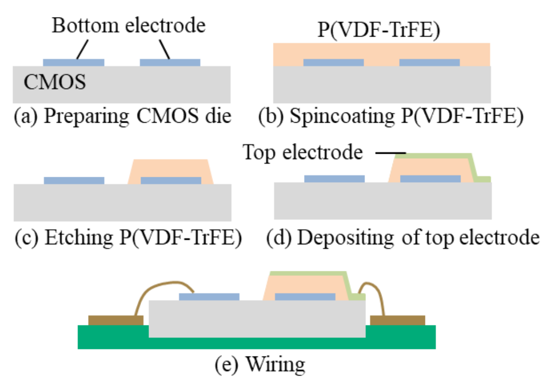


Fig. 5. Fabrication process of transducer.

## IV. Measurements

The measurement environment is depicted in Fig. 6, with ultrasonic wave transmitted using a hydro-speaker (Japan Probe, B10C5) fixed at 10 mm from the transducer surface. The driving conditions applied to the hydro-speaker are: waveform is sinusoidal, cycle number is 5, and amplitude is 10 $V_{pp}$. The acoustic output characteristics in response to the driving waveform $P_{in}$ in the frequency range 2 to 20 MHz was measured by a hydrophone (ONDA HGL-0400) placed at the same distance.

The receiving sensitivity $v_g$ (0 dB = 1 V/MPa) measured at 2 to 20 MHz is shown in Fig. 7 for P(VDF-TrFE) film thicknesses of 0.5, 0.8, 2.2 and 4.5 µm. The amplifier gain was subtracted and not included in $v_g$. Evidently, the receiving sensitivity increases with increasing the film thickness, consistent with Eq. (2). It exhibits flat broadband characteristics in the region above 4 MHz. The highest measurement frequency was 20 MHz. This limit is related to the upper limit frequency of the hydro-speaker so does not indicate the limit of the transducer. In the same manner, the measured lower cut-off frequency at 4 MHz is related to the lower limit frequency of the hydro-speaker.

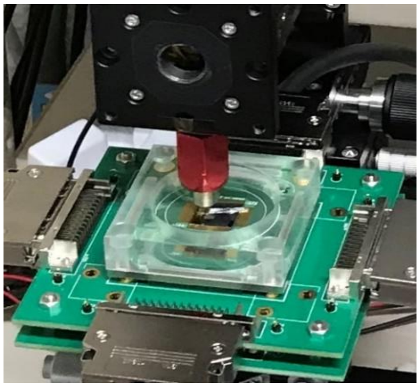

Fig. 6. Measurement environment for receive sensitivity in water

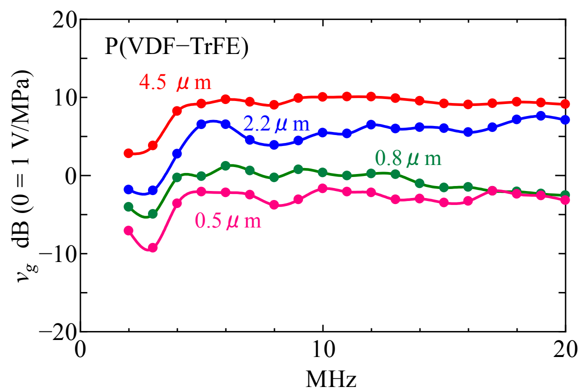


Fig. 7. Frequency response of receiving sensitivity
The P(VDF-TrFE) thickness is 0.5μm, 0.8μm and 2.2μm and 4.5μm.

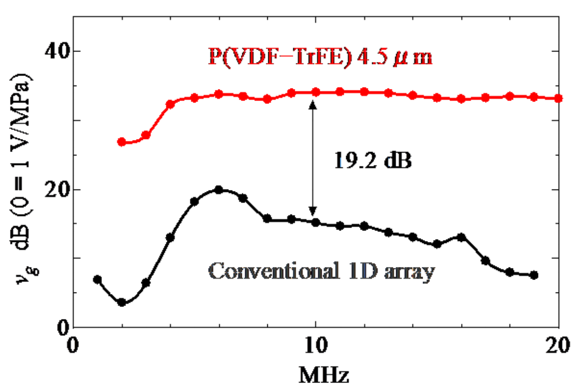


Fig. 8. Comparison of receiving sensitivity

The receiving sensitivity of the fabricated transducer compared with a commercially available 1D array transducer of 10 MHz center frequency is shown in Fig. 8. The conventional transducer is composed of a PZT-based piezoceramic, a few layers of an acoustic matching layer, and an acoustic lens layer of silicone rubber. Since the conventional transducer has the single element area of 200 μm × 3 mm, 16 channels results of P(VDF-TrFE) transducer were added so that the both element areas are identical. It is reasonable treatment and can easily be in realized with a CMOS circuit. Thus our proposed transducer exhibits a higher receiving sensitivity of +19.2 dB at 10 MHz and covers the bandwidth of 2 to 20 MHz or broader. Optimization of transducer design may attain even higher sensitivity.

## V. SUMMARY

We developed a novel ultrasonic transducer involving a P (VDF-TrFE) thin film monolithically integrated on a CMOS LSI. Its higher receiving sensitivity of +19.2 dB and wider bandwidth over the 2 to 20 MHz range compared to a conventional 1D array transducer is demonstrated.

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