Piezoelectric Micromachined Ultrasonic Transducers Based on P(VDF-TrFE) Copolymer Thin Films

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ABSTRACT: Representing a new approach to ultrasound generation and detection, study on piezoelectric micromachined ultrasonic transducers (pMUTs) has been a growing research area in recent years. Intensive research work has been directed on the deposition of lead zirconate titanate (PZT) films on silicon substrates for their excellent piezoelectric coefficients and electromechanical coupling coefficients. However, the high processing temperature required for PZT crystallization results in a low device yield and also makes it difficult to integrate with control circuits. In this paper, a fabrication technology of pMUTs based on piezoelectric P(VDF-TrFE) 70/30 copolymer films has been adopted, with the maximum processing temperature not exceeding 140°C allowing for post-IC compatibility. The entire processing procedures are simple and low cost, as compared with those of capacitive micromachined ultrasonic transducers (cMUTs) and ceramic-based pMUTs. The applications of the fabricated pMUTs as airborne ultrasonic transducers and transducer arrays have been demonstrated. Reasonably good device performances and high device yield have been achieved.

Key words: Piezoelectric thin film, Ultrasonic transducer array, Micromachining

1. INTRODUCTION

Micromachined ultrasonic transducers (MUTs) represent a promising approach to ultrasound detection and generation. Unlike conventional transducers, diaphragm type MUTs are nearly perfect unidirectional radiators that require no backing materials and have no observable acoustic coupling with the transducers' supporting structure. They are typically much thinner than conventional piezoelectric transducers for a given aperture size. Therefore, MUTs offer advantages of improved bandwidth, easy fabrication of large arrays with compact designs, and integration with support electronics [1–5]. These advantages, inherent in MUTs enable revolutionary advances in ultrasonic imaging and many other promising applications, such as acoustic devices [6], low cost phase arrays in distance measurement and simple object recognition [7].

A number of approaches based on integrated circuits (ICs) manufacturing technology have been developed to manufacture capacitive MUTs (cMUTs) [4, 5]. A cMUT is basically a parallel plate capacitor with a back plate fixed while the other one is a flexing membrane. Due to its virtually zero membrane mass, a cMUT possesses high coupling coefficient. However, high bias voltages are required that may complicate the driving circuit design. In addition, parasitic capacitance may be another problem due to the relatively low capacitance of each cMUT element.

Combining the deposition technique of piezoelectric film with MEMS technology further enables the construction of piezoelectric MUTs (pMUTs) [7-11]. A pMUT uses a piezoelectric layer adhered to an inert membrane and operating in flexural mode, exploiting the piezoelectric d_{31} coefficient to drive it. Compared with cMUT, the electromechanical coupling in a flexural mode pMUT is compromised by the presence of the inert membrane. However, unlike cMUTs which inevitably possess a very thin gap in the structure, pMUTs have a much simpler and more robust structure. This is a favorable feature from the viewpoints of processing and reliability. pMUTs have been investigated for ultrasonic reception as well as for transmitter applications in a number of publications [6-11]. Most work has been directed to the deposition of lead zirconate titanate (PZT) films on silicon substrates for their excellent piezoelectric coefficients and electromechanical coupling coefficients [12]. However, the high processing temperature required for PZT crystallization results in high thermal stress in the membrane structure and also makes it difficult to integrate with electronic circuits on the same silicon chip. Poly-vinylidenefluoride-trifluoroethylene (P(VDF-TrFE)) copolymer is another important electroactive material with moderate piezoelectricity (d_{33}~20 pm/V) and considerable electrostrictivity once being subjected to electron irradiations [13]. Its low processing temperature (<150 °C) make it an ideal material candidate for IC-compatible MEMS devices. Earlier work has been focused on sensing applications, such as micromachined diaphragm-type microphone with P(VDF-TrFE) coatings [14]. Recently, new developments on electrostrictive P(VDF-TrFE) based micro actuators have been reported [15]. High load capacity and high displacement voltage ratio have been demonstrated. However, the application of P(VDF-TrFE) micro actuators as air-borne ultrasonic transmitters has not been investigated sufficiently. In this paper, a fabrication technology of pMUTs based on P(VDF-TrFE) copolymer films has been developed. Air-borne pMUTs and pMUT arrays based on the copolymer films have been successfully fabricated with high device yield. Both the transmitting and the sensing performances of the transducers have been characterized in terms of output sound pressure, directivity, sensitivity, etc. Reasonably good properties have been demonstrated.

2. FABRICATION OF pMUT ARRAY

Figure 1 schematically shows the structure of an individual element in the p-MUT arrays with P(VDF-TrFE) thin film. The fabrication process of the transducers is briefly described with reference to Figure 1. (1) A 1.8 µm thick thermal silicon dioxide, which is used as a structural layer of the diaphragm, was first grown on a double side polished silicon wafer; (2) A silicon nitride layer with thickness of 200 nm was then deposited by LPCVD on both sides of the wafer. The Si_3N_4 layer is serving as the etching mask during the backside silicon KOH etching, and also can compensate the compressive stress in SiO_2 layer.; (3) Backside dry etching of Si_3N_4 and SiO_2 by RIE using SF_6+Ar gas to open the etching window; (4) Backside silicon diaphragm anisotropic wet etching by KOH until the remained thickness of silicon is about 50 µm; (5) Cr/Au layers, 50nm/150nm thick, were sputtered and patterned as bottom electrode by using lift-off technique. (6) Thin P(VDF-TrFE) layers with required thickness, usually within the range of 2 to 5 µm, were deposited by spin-coating a single layer of P(VDF-TrFE) copolymer solution (formed by dissolving 10~15 wt% of copolymer pellets in methyl-ethyl-ketone (MEK)). The as-coated samples were then subjected to an annealing process at 140 °C for 2 hours to enhance the crystallinity. (7) P(VDF-TrFE) patterning was achieved by dry etching using O_2 plasma to open the contacting hole for the bottom electrode. (8) Corona poling was then carried out at a dc voltage of -10 kV for 5 minutes. The sample was placed on a grounded metal holder and the corona tip was suspended 3 cm above the sample surface. (9) Cr (50nm)/ Au (150nm) layers were sputtered and patterned on the front side as top electrode by using wet etching. In this step, a modified photolithography process was employed. The pre-baking of photoresist was set at a lower temperature (80 °C) in order to avoid depolarization of P(VDF-TrFE) copolymer film. After Au/Cr etching, the residual photoresist was removed by diluted KOH. (10) The back side silicon was etched off by KOH or low temperature reactive ion etching to obtain the required thickness, usually within the range of 0 to 10 µm depending on the required resonance frequency of the transducer.

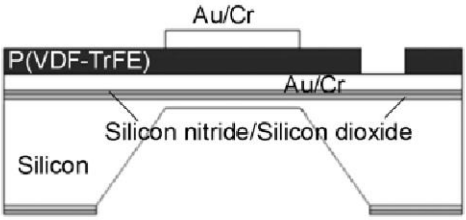
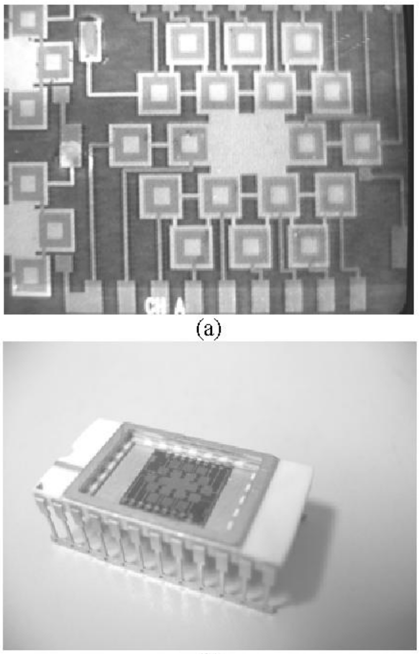


Figure 1 Basic structure of one pMUT element.

Based on the above described micromachining process, we have successfully fabricated diaphragm type pMUTs and pMUT arrays on 4-inch silicon wafers. By using Corona poling technique, the entire P(VDF-TrFE) film on one silicon substrate can be uniformly poled at the same time, eliminating the need of dc poling of every single device element and avoiding breakdown failure which frequently occurs during dc poling process. Therefore, very high throughput and high device yield have been achieved. Figure 2(a) shows the front view of various types of pMUT arrays with 6 elements and 18 elements on one silicon wafer. Each square is actually an individual transducer. After wafer dicing, the individual silicon dies were then glued and wire-bonded to standard dual-inline packages (DIP), as shown in Figure 2(b).



(a)

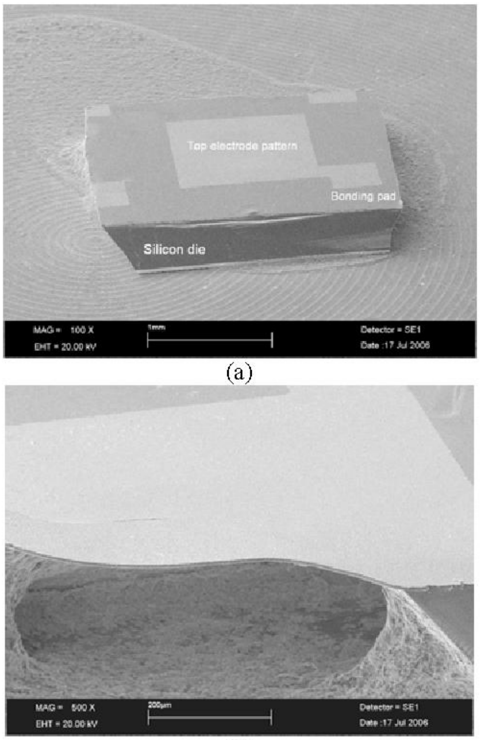
(b)

Figure 2 Piezoelectric ultrasonic transmitter arrays on a 4-inch silicon wafer. (a) array layout; (b) 18-element array bonded in a 24-lead DIP.

3. CHRACTERIZATION AND DISCUSSION

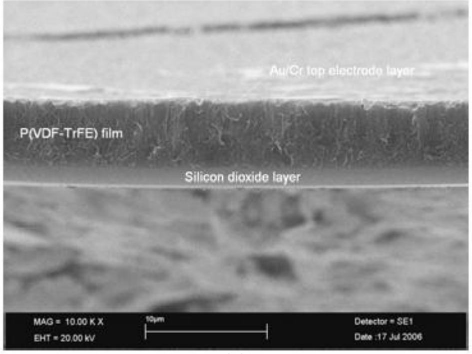
3.1 SEM observation

Figures 3(a), (b), (c) show typical SEM micrographs of a fabricated pMUT element and the detailed multilayer structure of the membrane. As shown in Figure3(c), the thicknesses of P(VDF-TrFE) layer and the inert membrane (Si_3N_4/SiO_2) are measured as 5 µm and 2 µm, respectively. The Au/Cr layer is about 200 nm. The silicon was almost completely etched off, and the Si_3N_4 layer is too thin to be observed in this magnification.



(a)

(b)



(c)

Figure 3 SEM micrographs of a single pMUT element. (a) a pMUT silicon die; (b) a fractured membrane structure; and (c) detailed cross-sectional image of the membrane.

The multilayer structure observed through SEM clearly shows that the actual thickness of each layer is in well accordance with the design parameters, suggesting that the entire fabrication process is quite reliable.

3.2 Vibration measurement

An ac voltage is applied across the piezoelectric film to set the membrane into vibration. The vibration profile of the transducer element was measured by using a modified scanning Mach-Zehnder interferometer [16] specially designed for high resolution characterization of MEMS devices. Figure 4 shows a typical 3-dimensional electromechanical response of a square membrane (1.27×1.27 mm^2) at its resonance frequency (101.4 kHz). The ac driving voltage was 0.1 V_p. The deflection per volt at the center of the membrane was measured as about 70 nm/V.

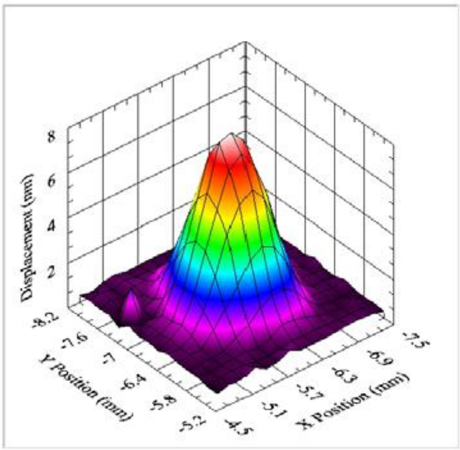
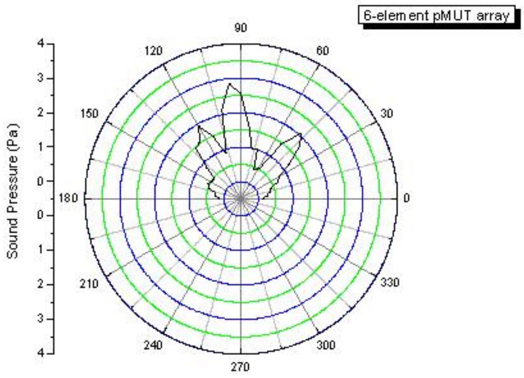


Figure 4 Deflection of a p-MUT element in response to an ac driving voltage measured by a scanning homodyne Mach-Zehnder interferometer.

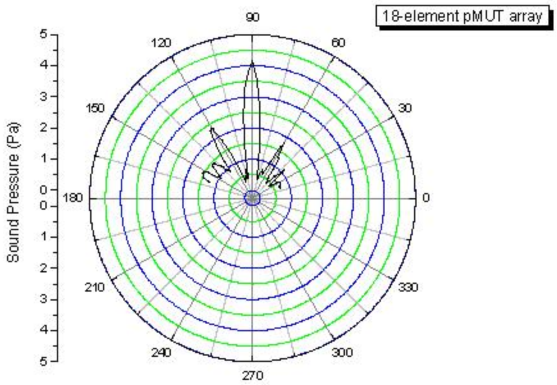
3.3 Transmitting and sensing performances

The output sound pressure of the fabricated transducer arrays in response to a continuous ac driving voltage has been measured in air with a Brüel & Kjær test system, including Type 2690 signal conditioning amplifier and a 4138-A-015 microphone, which has a wide bandwidth of over 100 kHz. When an ac driving voltage of 8.5 V_p was applied to the 18-element pMUT array, the output sound pressure reaches its maximum at its resonance frequency of 165.6 kHz. The highest sound pressure value at a distance of 30 mm is around 4 Pa. This value is comparable to that of a dc biased PZT thick film pMUT with similar aperture size reported by Wang et al. [17]. Considering the dielectric constant of P(VDF-TrFE) copolymer is 100 times lower than that of PZT, the copolymer based pMUTs have a much larger impedance, thus much lower power consumption when driving under a given ac voltage. This suggests that, although the electromechanical coupling coefficient of P(VDF-TrFE) is lower than that of PZT, the ultrasound irradiating performance of our copolymer based pMUTs can be even better than that of PZT based pMUTs in term of energy efficiency. This may be owing to the high-quality, sufficiently poled copolymer films and the very light membrane structure of copolymer pMUTs.

On the other hand, a 6-element array has been packaged into a microphone-like metal housing for directional ultrasound sensing applications. To characterize the sensitivity, the sensor array was subjected to an ultrasound (165.6 kHz) field of 3.6 Pa generated by a ceramic transducer and calibrated by a Brüel & Kjær test system. The unamplified output voltage amplitude measured directly by HP 54645A oscilloscope (1 MΩ, 13 pF) was 6.937 mV. As the impedance of the sensor array was measured as 8.3 kΩ at resonance (by using HP 4194 impedance analyzer) and the input impedance of the oscilloscope is 73.93 kΩ at 165.6 kHz, we can actually calculate the open-circuit output voltage as 7.716 mV. Therefore, the open-circuit sensitivity of the sensor array is 2.14 mV/Pa, or -53.4 dB re 1 V/Pa at 165.6 kHz.



(a)



(b)

Figure 5 Measured directivity patterns of pMUT arrays with different number of elements at resonance frequency of 165.6 kHz. (a) 6-element array; (b) 18-element array.

3.4 Directivity patterns

The directivity of the ultrasonic array is what we most concern about in beam forming and beam steering applications. A characterization system has been setup to measure the directivity of the pMUT array. The array was held in a holder for stable support and rotated by a rod attached to the holder. All the elements was electrically connected in parallel and excited simultaneously by an ac voltage source. The Brüel & Kjær 4138-A-015 microphone was placed in symmetrical axis perpendicular to the plane of the array to detect the output ultrasound. The distance between the sensor and the array was 30 mm (> 10 wavelength). Figure 5 (a) and (b) shows the measured directivity patterns of a 6-element array and an 18-element array respectively. It can be clearly seen from the figure that, with the number of elements increasing, both the output sound pressure and the directivity of the pMUT arrays have been improved. The measured sharp main lobe in Figure 5 (b) indicates that the 18-element p-MUT array can be used for ultrasound beam focusing and steering applications. However, the side lobes at 60 and 120 are larger than theoretically estimated. This is because the actual resonance frequency of the array runs higher than the design value (120 kHz) so that the inter-element spacing were designed a bit too large with respect to the wavelength of ultrasound at 165.6 kHz. The asymmetric nature of side lobes is due to the slight scattering of the resonance frequencies of different transducer elements. The cause of the problem may be the non-uniformity of the membrane thickness through the entire array. More advanced membrane thickness control schemes are required to further improve the performances of the transducer arrays.

4. CONCLUSION

PMUTs and pMUT arrays based on piezoelectric P(VDF-TrFE) 70/30 copolymer thin films have been fabricated and demonstrated in the frequency range of 100 kHz to 170 kHz for air-borne ultrasound applications. The fabrication process enables high throughput and high device yield. Both the transmitting and the sensing performances of the pMUTs have been characterized. Reasonably high output sound pressure and sensitivity have been achieved. The directivity patterns of the ultrasound transmission by the pMUT array suggest that high performance pMUT arrays fabricated using the present process are promising for various new applications, such as miniaturized devices and systems for in-air distance detection and 3-dimensional object recognition.

5. ACKNOWLEDGEMENT

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