Enhancement of piezoelectric micromachined ultrasonic transducer using polymer membrane for underwater applications

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An effort to enhance receiving response of piezoelectric micromachined ultrasonic transducers (pMUT) at low frequency was reported. PMUTs were fabricated with the vibrating membrane formed by a layer of polydimethylsiloxane (PDMS) polymer. Lead zirconate titanate, Pd (Zr,Ti)O$_3$ (PZT) was utilized as the piezo-active layer, sputtered with nickel electrodes. Spin coating and low temperature wafer bonding were proposed as part of the key fabrication methods. Fabricated transducers were characterized in the compact acoustic tank setup using 500 kHz and 1.25 MHz reference projectors. Analyses revealed the maximum receiving response was -36.6 dB re 1V of 200 kHz burst at 10 $\lambda$ hydrophone-projector separations and 20 V peak to peak of drive voltage on reference projector. Finally, response spectrum of the transducer was plotted against two commercialized bulk hydrophones at equivalent frequency band for validation and comparison.

[Keywords: Piezoelectric, Receiving response, Resonance frequency, Hydrophone]

Introductions

Last decade has seen various advancements and enhancements on piezoelectric micromachined ultrasonic transducers (pMUT) design and performance for multiple terrestrial as well as underwater applications. The main challenge for the engineers is circulating around “getting the right response at the right frequency” issues. Although it has been proven for quite some time that pMUT is not bounded by classical half-wavelength theory, there are still limited applications tailing at those megahertz range especially when it comes to underwater. High attenuation at higher frequency and hydrostatic pressure has become constant threat to immersed miniaturize structure and yet still offers great potential near the future. Extensive studies can be found focusing on different ways to improve pMUT performances such as manipulating device layers, optimizing structural integrity, improvements in fabrication process as well as performance predictions through modeling and simulation.

Recently, underwater imaging using pMUT array has been achieved at 3.5 MHz of frequency at 40 to 60 mm detection range inside acoustic tank using epitaxial PZT structure on silicon, as proposed earlier by other researcher whom achieved -243 dB re 1V between 1 to 15 MHz operating frequency. Furthermore, the usage of polymer as part of the vibrating membrane is not new. Polyvinylidene fluoride (PVDF) for example has been used as an active layer of pMUT by manipulating its piezoelectric capability. On other occasion, Cytop polymer has been utilized for dual-functionality; part of the vibrating membrane on epitaxial silicon and adhesive or intermediate layer for wafer bonding.

This paper reports the development of PZT-based pMUT using PDMS polymer as vibrating membrane. Performance wise, the objective of this work is to achieve flat receiving response for the frequency below 1 MHz to cater many demanding underwater applications. Simplified fabrication method was demonstrated using low temperature wafer bonding and the membrane was formed without using any lithography and etching processes. The device was characterized in a receiving mode using two reference projectors at 10 $\lambda$ and 100 $\lambda$ separation methods in a compact acoustic water tank for frequency range between 50 kHz and 1500 kHz. As the results, fabricated pMUT peak receiving response was determined at -36.6 dB re 1V at 10 $\lambda$ of 200 kHz burst. Developed device was aimed to be used in a
mobile underwater robot for passive sonar in obstacle avoidance and depth sounding.

Materials and Methods

Device Simulation and Material Selection

Material selection was carried out within computer simulation environment using CoventorWare™ 2008 finite element analysis package. Frequency analysis was done to determine resonance frequency of pMUT using three most commonly used polymers for adhesive wafer bonding namely Cytop®, polyimide and PDMS. Device that resonates at the lowest frequency will be selected for fabrication. Functional layer was formed by zinc oxide (ZnO) at 40 µm sandwiched between 500 nm of aluminium top and bottom electrodes. Structural layer consist of silica (SiO₂) at 200 nm of thickness on silicon <100> substrate. 5 µm of adhesive polymer material is placed between functional layer and structural layer forming a pMUT. Selected diameter for the device vibrating membrane is 1.5 mm.

The simulation was carried out by changing type of polymer adhesive used from Cytop to PDMS and polyimide at the same thickness of 5 µm. Structural dimensions were kept constant throughout the simulation procedures. Figure 1 shows different resonance frequencies of pMUT using three different adhesives at the same thickness from the simulation. The result clearly shows that 5 µm thickness of three different polymer adhesive capable to influence pMUT resonance frequency significantly. The outcomes were related to difference in density value of PDMS, Cytop and polyimide whom carry 970×10⁻¹⁵, 2.03×10⁻¹⁵ and 1.43×10⁻¹⁵ kgµm⁻³ respectively. As the most dense material with the lowest elasticity (0.87 MPa), pMUT with PDMS adhesive resonate at the lowest frequency which is 101 kHz. Device with polimide layer with the highest value of modulus of elasticity (7500 MPa) resonate at 127 kHz.

The highest resonance frequency was achieved at 143 kHz when Cytop with modulus of elasticity at 2000 MPa was used. During simulation, bandwidth or Q was ignored where structural damping coefficient was set as a constant throughout the procedures. The result can be easily validated by referring to the modulus of elasticity value where polyimide as the most elastic material (compare to PDMS and Cytop) has resulted in higher deflection of pMUT structure. Resonance frequencies obtained from this simulation will only be used as guidance in selecting which polymer capable to decrease device’s resonance, since our interest was at the lowest frequency possible. It means that the frequency value obtained is not comparable to the actual result later on.

Device Fabrication

Fabrication process started with deposition of PDMS to form pMUT side wall structure on silicon substrate. First, two silicon substrates at 2 inches diameter and single-side polished were prepared. Both were cleaned using RCA method. One of them was deposited with 200 nm of SiO₂ on the polished side. RF sputtering of 200 nm of SiO₂ was done below 100 W of power for 30 minutes, including 10 minutes of gradual power increase during warm-up, followed by manual override of power control for the next 20 minutes to prevent non metallic SiO₂ target from breaking. Next, PDMS solution is mixed with epoxy at the ratio of 10:1 respectively. 10 µm of PDMS layer can be formed by two steps spin started at 1000 rpm for 5 seconds, followed by 3000 rpm for 60 seconds. After that, coated wafer is dried in the oven at 90 degree Celsius for 60 minutes. The steps were repeated five times on both wafers including the one without SiO₂, to achieve 50 µm of thickness. Side wall structure is formed by cutting and peeling-off the PDMS layer, leaving a hole on the wafer.

We found that peeling-off the PDMS on the silicon with SiO₂ coating was effortless and clean. Without silica coating, it is almost impossible to peeled-off the PDMS layer. Functional piezo-active layer was then prepared by deposition of 200 nm of the SiO₂ on top of the nickel electrode. Nickel sputtered PZT was undergone RF sputtering for 30 minutes on the same chamber as previous silicon wafer, thus producing the same thickness of silica. Piezo-active wafer was then
being spin-coated with PDMS at 1000 rpm for 10 seconds, followed by 3500 rpm for 90 seconds. PVC tape was used as a mask to form a soldering point at the bottom electrode, and removed right before baking process. Previous silicon substrate with 50 µm of PDMS side wall was flipped over, and placed on top of the PDMS-coated piezo active wafer. These two wafers were adhered without any induced force (only gravitational) and then baked in the oven for 60 minutes at 90 degrees Celsius. Preparation of these two wafers is illustrated in Figure 2 while Figure 3 shows adhered wafers after baking. Next, silicon wafer was removed carefully by peeling-off the PDMS side wall layer, forming a complete pMUT structure including membrane. Diced pMUT finally was adhered on the glass substrate also using a thin layer of PDMS. It was also prepared using spin-coating technique at 3000 rpm for 90 seconds. Finally, top and exposed bottom electrodes were cleaned using alcohol, followed by liquid DSA solder flux (Cleveland, OH). 30 gauge wires were soldered to the electrodes at 290 degree Celsius for 1 second and remaining flux was cleaned using alcohol. PDMS was used again to encapsulate the device, and it was baked for 60 minutes at 90 degrees Celsius. Figure 4 shows a developed pMUT with soldered wire lead to top and bottom electrodes ready for acoustic tank test, encapsulated in epoxy glue.

Characterization Setup
Fabricated pMUT was characterized inside 760 mm×360 mm×380 mm glass tank, filled with F

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**Figure 2** – Fabrication steps (a) Preparation of PDMS side wall (i-ii) PDMS was spin-coated on SiO2/Si wafer (iii) and peeled-off to form a side wall (b) Preparation of piezo-active layer (i) PVC tape mask for bottom electrode wire bond (ii) deposition of SiO2 and PDMS membrane (iii) removed mask. (c) Adhesion process (i) both wafers were adhered by PDMS membrane layer (ii) unpackaged pMUT on glass substrate with lead wires soldered to electrodes.

**Figure 3** – Bonded wafers (a) Ni sputtered PZT on Si <100> with SiO2 intermediate layer (b) Ni sputtered PZT on Si <100> without SiO2 intermediate layer (Silicon substrate is not visible)
300 mm deep of fresh water. The tank was not equipped with anti-reflection surface, considering face-to-face measurement method utilized throughout the characterization process. Two directional reference projectors (Technotronics, UNDT) were employed, one with 500 kHz resonance frequency with 25 mm diameter and another one rated at 1.25 MHz of resonance with 20 mm diameter. The diameters were measured by taking into account the thickness of the stainless steel body of both projectors.

Each projector was driven using square waveform with 50% duty cycle at 20 V peak to peak without offset voltage supplied by function generator (Hameg HM8150). The frequency was swept from 50 kHz to 1500 kHz with 50 kHz increment. Reference hydrophones A and B were placed facing the projector at a distance determined by 10 \( \lambda \) for 500 kHz and below. Above 500 kHz of frequency, separation distance was at 100 \( \lambda \) as demonstrated by other researcher elsewhere. Considering the speed of sound at 1483 m/s, separation distance involved lies between 30 to 300 mm for 10 \( \lambda \) and 90 to 30 mm for 100 \( \lambda \). pMUT were directly connected to the PC oscilloscope (PicoScope 2204, 10 MHz) through USB port, without any amplification and filtering so that noise level for each measurement can be recorded.

The waveform was displayed and captured using PicoScope\textsuperscript{TM} 6 and PicoLog\textsuperscript{TM} software, in spectrum mode using blackman windows function displaying magnitude in logarithmic scale, with arbitrary decibel unit selected referring to 1 V. Generated voltage by the hydrophones and pMUT was recorded at each of the selected frequency. Characterization system setup is shown in Figure 5. Reference spectrum curve were plotted as a comparison to the generated spectrum by pMUT to determine resonance frequency of pMUT as well as maximum receiving response. It was carried out by replacing hydrophone A (Technotronics UNDT, 500 kHz 25 mm) with hydrophone B (Technotronics UNDT, 1.25 MHz 20 mm), followed by pMUT and generated voltage is recorded and compared.

**Results and Discussion**

Average background noise throughout experiment was recorded at -108.9 dB re 1V, along all tested frequency band (50 kHz to 1.5 MHz). This is due to the size of the acoustic tank used in this experiment plus the inner surface of the tank that has not been treated with any wave absorber material. However, the magnitude of noise can be considered small compare to the generated signal by pMUT and tested reference hydrophones. PMUT was characterized at 15 mm of depth, facing reference projector at 10 (50 to 500 kHz) and 100 \( \lambda \) (550 to 1500 kHz). The step was repeated twice, using projectors rated at 500 kHz and 1.25 MHz of resonance.

Figure 6 shows how pMUT has responded to the projected signal at different frequencies. Using 500 kHz projector, maximum response of -42.3 dB re 1V occurred at 300 kHz of frequencies at 10 \( \lambda \). When 1.25 MHz projector was utilized over the same distance, maximum output is recorded at 200 kHz, producing -36.6 dB re 1V. PMUT has responded well to the projected signal between 150 to 300 kHz of frequency, noticeable from the almost flat response within that spectrum band. Projected signal frequencies have been increased to 1.5 MHz and pMUT was found to resonate at 1.25 MHz of frequency, generating -42.5 and -46.6 dB re 1V of response using 500 kHz and 1.25 MHz projectors respectively. However maximum response did not cover wider frequency band as previous findings at the near post. As a standard practice, receiving response is measured using 1 \( \mu \)Pa of sound pressure level (SPL). It means that the ratio is referred to 1V for 1 \( \mu \)Pa SPL or simply –dB re 1V/\( \mu \)Pa. Negative sign denote that the generated voltage by the transducer is less than 1V. In our case however, we were unable to project precise 1 \( \mu \)Pa of SPL at all selected frequency band (50 to 1500 kHz) by just using two reference projectors.

Previously, -243 dB re 1V of response is achieved over 1 to 15 MHz of frequency using 3 \( \mu \)m thick PZT (Pb(Zr, Ti)O\textsubscript{3}) at 1 mm of device diameter.
Figure 5 – (Top) Schematic diagram for acoustic calibration setup (Bottom) Equipments setup for acoustic calibration

Figure 6 – pMUT receiving response obtained using two reference projectors
Comparatively, we have utilized way thicker PZT ceramic at 124 µm and wider diameter at 3 mm, thus -36.6 dB re 1V at 200 kHz is what we expect without any signal amplification. It was already proven that PVDF-based pMUT is able to resonate at 41 kHz with 2.5 mm vibrating membrane, but the characterization was done airborne with 84 µV/Pa of receiving response. For validation and comparison, response spectrum by pMUT is compared with commercialized hydrophone A (Technotronics UNDT, 25 mm ϕ) and hydrophone B (Technotronics UNDT, 20 mm ϕ) as shows in Figure 7.

Figure 7 – Response comparison between pMUT and hydrophone A and B using (a) 500 kHz reference projector (b) 1.25 MHz reference projector
Hydrophone A has a maximum response at 550 and 600 kHz using 500 kHz and 1.25 MHz reference projectors respectively while hydrophone B resonate at 1.05 MHz using 1.25 MHz projector. The difference in response magnitude at different frequency for all three hydrophones (pMUT, Hydrophone A and Hydrophone B) has validated our findings using 10 and 100 \( \lambda \) separation method inside compact water tank. As for the future work, we would like to improve our characterization method by adding more reference projectors, calibrated for standardize SPL projection. Furthermore, 5 kHz frequency increment will be implemented so that spectrum with better resolution can be produced. Characterization of pMUT in transmitting mode will also be included in our future work.

Conclusion

In conclusion, pMUT with low resonance frequency has been successfully fabricated and characterized for underwater use. PZT on PDMS polymer membrane structure has contributed to -36.6 dB re 1V of pMUT receiving response at 200 kHz frequency. Device structure was mainly formed by PDMS polymer including membrane and wave-front layer. PDMS was selected using finite element analysis in computer simulation. Device fabrication is simplified by utilizing spin-on-polymer, adhesive wafer bond at only 90 degrees Celsius. Receiving response of fabricated pMUT was determined using 10 \( \lambda \) and 100 \( \lambda \) separation methods inside compact water tank.

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