A Piezoelectric Micromachined Ultrasonic Transducer Using Piston-Like Membrane Motion

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***Abstract*— Piezoelectric micromachined ultrasonic transducer (pMUT) is a promising candidate for the next-generation 3-D diagnostic ultrasonic imaging. However, the transmitting sensitivity of reported pMUT is not satisfied so far. Enhancement of the transmitting sensitivity hence is always desirable. In this letter, we report a piston-like pMUT. With the help of etching holes in the membrane, the mode shape becomes from Gaussian-like to piston-like, which enables higher transmitted acoustic pressure. In addition, frequency of such pMUT does not decrease after etching holes are fabricated, but slightly increases. Higher frequency for ultrasonic imaging thus is practical, and the frequency can be predicted by well-established methods. Sensitivity of 73 nm/V at 2.31 MHz is achieved for the piston-like pMUT with three rows of etching holes. Benefited from the piston-like membrane motion, the space pressure level is 5.3 dB higher than the classical pMUT.**

***Index Terms*— Piezoelectric micromachined ultrasonic transducer (pMUT), MEMS, Piezoelectric, Ultrasound.**

I. Introduction

PIEZOELECTRIC micromachined ultrasonic transducer (pMUT), which is able to both transmit and receive ultrasonic waves, has gained increasing interests from researchers recently. As a MEMS device, pMUT is superior to conventional bulk piezoelectric ceramic based ultrasonic transducer (UT). The pMUT has miniaturized size, lower cost, better acoustic impedance matching, and most importantly the high density 2-D array can be realized. The 2-D array is necessary for implementing the next-generation 3-D diagnostic ultrasonic imaging [1]. Lead zirconate titanate (PZT) is the most widely used piezoelectric material, and PZT based pMUT usually has good performance [2]. In recent years, aluminum nitride (AlN) gains interests of researchers because of its CMOS process compatibility [3]. Low cost pMUT thus may be achieved, or even be integrated with ASICs. Despite the piezoelectric coefficient of AlN is not as high as PZT, its lower dielectric constant enables a comparable receiving sensitivity with PZT based pMUTs [4]. Although the pMUT functions well as a receiver for most of applications, unfortunately its transmitting sensitivity is significantly lower than the predictions from analytical models or finite elements analysis (FEA) models. Such performance degradation is mainly attributed to the residual stress during fabrication processes [5]. Despite that several trials are made to address this issue, the improvement of device performance is very limited [6]. Some researchers even have to suggest that pMUT may only be used as receiver and another bulk UT as transmitter [7]. Therefore, enhancement of pMUT transmitting sensitivity, *i.e.* increasing the transmitted acoustic pressure is always desirable.

One possible method of increasing the transmitted acoustic pressure is to enable a piston-like membrane motion. Usually the classical pMUT has a Gaussian-like mode shape. For such mode shape, only the center of membrane is able to achieve the maximum displacement amplitude. If a piston-like mode shape can be realized, the membrane remains flat during vibration, and larger portion of membrane can vibrate with the maximum amplitude. Hence more acoustic medium (*e.g.* air, water, or soft tissue) can be pushed back and forth, generating higher ultrasonic pressure. The piston-like vibration has been realized with a capacitive micromachined ultrasonic transducer (cMUT), which is proven to offer several advantages [8]. However, the approach of realizing piston-like membrane motion may be difficult to be compatible with pMUT. Guedes *et al.* report a pMUT with flexurally suspended membrane, of which the mode shape is piston-like [9]. As the membrane is supported by three beams, its resonant frequency is significantly lowered than classical pMUT. Higher frequency for diagnostic ultrasonic imaging (2 to 10 MHz) may be difficult to realize with such design. In this letter, we report a piston-like pMUT using etching holes. The resonant frequency nearly changes after etching holes are fabricated. The membrane remains flat during vibration, resulting in a higher acoustic pressure. Sensitivity of 73 nm/V at 2.31 MHz is achieved for pMUT with three rows of etching holes. It shows promise in diagnostic ultrasonic imaging.

II. Concept and Design

The structure of piston-like pMUT is illustrated in Fig. 1. The frame-shaped top electrode partially covers the surface, with coverage of 35%. This top electrode design ensures

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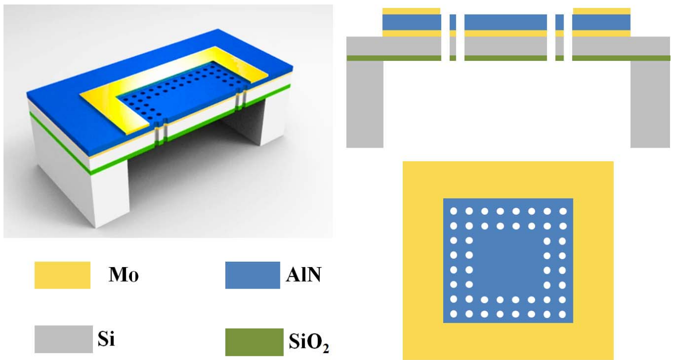

Fig. 1. Illustrations of the piston-like pMUT. The etching holes located inner top electrode, are through all layers.

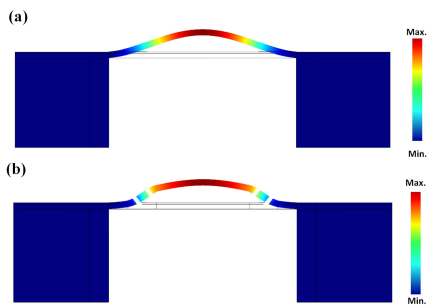

Fig. 2. Simulated mode shapes by finite elements analysis (FEA) modeling: (a) classical pMUT and; (b) piston-like pMUT. With the help of etching holes, the mode shape has a relatively flat surface.

the maximum electromechanical coupling for pMUT [6]. Compared to the classical pMUT, 5 μm etching holes locate inner the electrode, which are through the released membrane. To realize piston-like mode shape, stiffness difference should be introduced in the membrane. One reported approach is to attach an additional silicon mass on the center of membrane to stiffen the central portion of membrane [8]. Wafer bonding and handle wafer removal processes are employed to realize the silicon mass, which is not standard or necessary processes for pMUT. In addition, the composite membrane of pMUT is relatively thick, and hence the additional mass has to be very thick to enable the piston-like mode shape, which may bring in undesirable effects on the frequency and performance. Therefore another approach is proposed to introduce the stiffness difference. Etching holes are fabricated in the membrane as shown in Fig. 1. The perforated portion becomes more flexible and most of the deflection is confined within this softened region. Benefited from such softened region, the central ridged region hence suffers small deflection and remains flat. The central region moves up and down like a piston during vibration. Fig. 2 shows the simulated mode shapes using FEA model by COMSOL. The mode shape of classical pMUT is shown in Fig. 2 (a), which is Gaussian-like. Meanwhile, with the help of etching holes, the membrane surface becomes relatively flat, shown in Fig. 2 (b).

To avoid the ventilation of two sides of the membrane, the etching holes need to be sealed. The 5 μm etching holes ensure that they can be sealed by a thin polymer layer. According to previous studies, neither Parylene [10] nor PDMS [11] thin

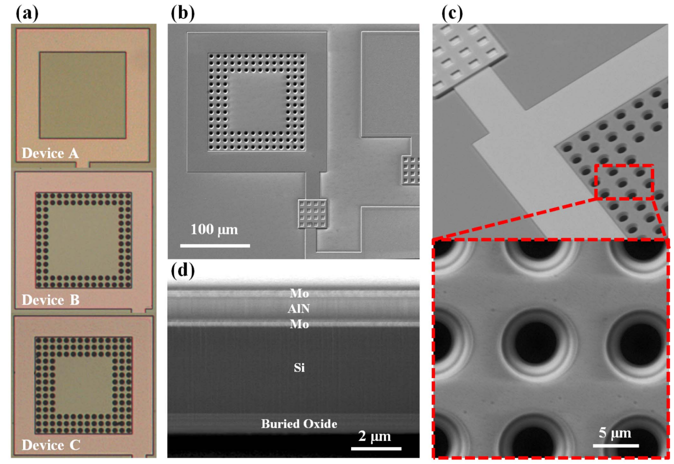

Fig. 3. (a) The optical microscope (OM) images of fabricated pMUTs. The classical pMUT is denoted as Device A, and the piston-like pMUTs with two and three rows of etching holes are denoted as Device B and Device C, respectively; (b) the secondary electron microscope (SEM) image of Device C; (c) SEM images showing the etching holes and; (d) cross-sectional view of pMUT membrane.

film on the surface affects the pMUT performance largely. For the piston-like pMUT reported in [9], the SiO_2 layer is intentionally not fully etched and 0.02 μm SiO_2 is left. However, without pre-designed stop layer, such thin SiO_2 layer can nearly be ensured using time control. Once the SiO_2 is etched through, the large trenches may not be able to re-seal. Hence, employment of etching holes to enable piston-like membrane motion is a more reliable approach.

III. Characterization and Discussion

The fabricated pMUTs are shown in Fig. 3 (a) and (b). The pMUTs with two and three rows of etching holes are denoted as *Device B* and *Device C*, respectively. A classical pMUT without etching holes is also fabricated for reference, denoted as *Device A*. Fig. 3 (c) shows the etching holes through the membrane, with diameter of 5 μm. Such small diameter ensures the holes are able to be re-sealed. The cross-sectional view of the membrane is shown in Fig. 3 (d), which contains 0.2 μm Mo, 1 μm AlN, 5 μm Si and 1 μm SiO_2. All the pMUTs share the same dimension of 200 μm.

Digital holographic MEMS analyser (DHM-R2100 from Lyncée Tec) is employed for device characterization. Surface profiles of *Device A* to *C* at their resonance are extracted and plotted in Fig. 4 (a). As is expected, the mode shapes of *Device B* and *C* become much flatter. For *Device B*, its profile at maximum deflection is still slightly curved; meanwhile the profile of *Device C* remains flat at the maximum deflection. Comparison of the surface profiles (*Device C* and *A*) is shown as well. It is clearly shown that larger portion of membrane is able to achieve the maximum amplitude for *Device C*. Captured 3-D images of *Device C* are shown in Fig. 4 (b) as well, and the central region of membrane moves like a piston.

Frequency responses of displacement amplitude with 1 V excitation are shown in Fig. 4 (c). Considering the 2.24 MHz resonant frequency of *Device A*, frequency of the piston-like pMUT does not decrease but slightly increases. This is mainly

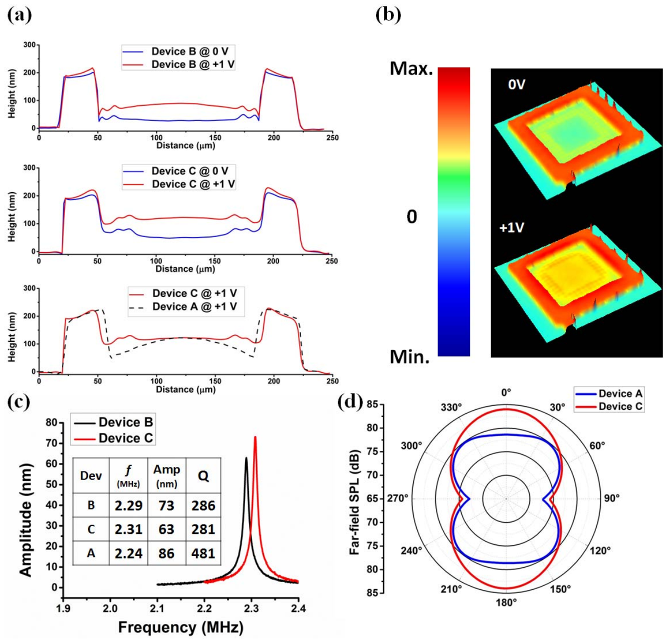

Fig. 4. (a) Surface profiles of the pMUTs at resonance; (b) 3-D images of *Device C*; (c) frequency responses of displacement amplitude for piston-like pMUT. Inset table shows the comparison of the three devices and; (d) simulated far field space pressure levels for *Device A & C*.

attributes to the etching holes and their location. When the membrane of a classical pMUT deflects, the portion covered by top electrode has the largest strain, while the portion inner the electrode has minimum strain [6]. Therefore, etching holes locating inner top electrode have minimum influence on the spring constant of the membrane. On the other hand, since part of the membrane is etched, its mass reduces accordingly. Resonant frequency hence slightly increases with the number of etching holes (2.29 MHz and 2.31 MHz for *Device B* and *C*, respectively). For such piston-like pMUT using etching holes, the resonant frequency can be predicted by well-established analytical and FEA models prior to fabrication, and higher frequency for diagnostic ultrasonic imaging (2–8 MHz) is able to be realized by changing the dimension. In contrast, for the piston-like pMUT reported in [9], the grooves locate where the membrane has largest strain, which significantly lowers the spring constant and results in much lower frequency. Fig. 4 (c) provides the comparison of the three devices. The relatively higher displacement amplitude of *Device A* could be caused by less air damping. The lower Q in *Device B* and *C* should be attributed to the larger effective vibration area, which results in larger damping. The two piston-like pMUTs do not show significant difference in Q factor, and therefore the higher displacement sensitivity of *Device C* is not caused by larger Q. In fact, Q factor of *Device C* is slightly lower than *Device B*, which may be resulted from more etching holes and more air damping. Considering the flatter mode shape of *Device C*, piston-like pMUT with three rows of etching holes is a superior design.

Acoustic-piezoelectric interaction model is also built to evaluate the performances of *Device C & A* in water, and the simulation results are shown in Fig. 4 (d). Benefited from the piston-like membrane motion, the directivity of *Device C* is better than *Device A*, and the far field space pressure level (SPL) of *Device C* is 5.3 dB higher than *Device A*. The receiving sensitivity is studied by applying 1 kPa acoustic pressure to the water medium, where the dimension of water is over 10 λ to eliminate unwilling interferences. The receiving sensitivity of Device C at resonance is obtained as 95 mV/kPa, while Device A shows receiving sensitivity of 48 mV/kPa based on the modeling data. Sealing the etching holes by Parylene and performance testing will be our future works.

IV. Conclusions

A piston-like pMUT is implemented using etching holes in this letter. Measurement results show that the mode shape of such pMUT has a flat surface. The resonant frequency does not decrease like prior reported piston-like pMUT, but slightly increases by 2%. This implies that higher frequency for diagnostic ultrasonic imaging can be realized, and the frequency can be predicted using well-established analytical and FEA models. Piston-like pMUT with two- and three-rows of etching holes are studied as well. The pMUT with three rows of etching holes has flatter mode shape, and its transmitting sensitivity is 10 nm/V higher, which is superior to the pMUT with two rows of etching holes. Compared to a classical pMUT, the piston-like pMUT with three rows of etching holes is of better directivity, which has almost doubled transmitting and receiving sensitivities. The piston-like pMUT using etching holes may be a promising alternative for next-generation diagnostic ultrasonic imaging.

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