

COMPARATIVE CHARACTERIZATION OF BIMORPH AND UNIMORPH ALN PIEZOELECTRIC MICRO-MACHINED ULTRASONIC TRANSDUCERS

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ABSTRACT

A comparative study of bimorph and unimorph AlN piezoelectric micro-machined ultrasonic transducer (pMUT) is reported for the first time. The bimorph is a suspended square diaphragm, comprised of two active AlN layers sandwiched by three Mo layers. This bimorphic structure (Mo/AlN/Mo/AlN/Mo stack) enables higher dynamic amplitude as the stack serves both actuation and structural functions. A unimorph counterpart is obtained by subjecting a bimorph device through FIB post process, which deactivates the actuation function of top Mo/AlN layers while preserving the device mechanical integrity. It allows same-device, high-fidelity comparative study between AlN bimorph and unimorph. Besides, the Mo layers are appropriately patterned for optimized signal configuration to maximize the pMUT performance. The reported bimorph pMUT has dynamic deflection as high as 1155.7 nm/V (diaphragm central displacement), a 77% increase compared to the unimorph. It allows low voltage actuation and high acoustic power generation for various ultrasonic applications.

INTRODUCTION

Aluminum nitride (AlN) based piezoelectric micro-machined ultrasonic transducer (pMUT) is a promising alternative for current prevailing PZT-based ultrasound transducers, thanks to its CMOS compatibility, volume manufacturability, great scalability and good acoustic matching [1]. It has demonstrated great potential in portable, wearable and biomedical applications [2, 3]. Ultrasound based applications, e.g., in the mobile electronics, usually require devices working at specified frequency, occupying a given limited area and driven by as low voltage as possible. Hence it is critical to design pMUTs of high coupling coefficient to enhance output power. Most of conventional pMUT utilizes unimorph structure including two planar layers, i.e., one active piezoelectric layer and one inactive elastic layer. This renders the unimorph structure lower electro-acoustic coupling efficiency. To improve the device coupling, approaches have been reported and can be classified by the existence of elastic layer. More specifically, one approach is structure modification while still maintaining the elastic layer. For example, A. Guedes et al reported a flexurally-suspended membrane with piston-like movement and hence improved acoustic pressure generation [7]. S. Akhbari et al presented a curved diaphragm pMUT that shows DC displacements one order of magnitude higher than the planar pMUTs of similar geometry [8]. Another approach is replacing the elastic

layer with piezoelectric actuation layer, i.e., using bimorph structure. Firas et al provided detailed theoretical analysis of a bimorph pMUT structure that suggests possible improvements over conventional unimorph structures [9]. Both approaches have pros and cons. It is of great importance to understand the performance improvement under a fair comparison. In this letter, we present the experimental data of a microfabricated bimorph pMUT and a comparative study with its unimorph counterpart. By utilizing FIB to modify one bimorph pMUT minimally into unimorph, we enable a fair comparison with two pMUTs of identical frequency and area. The dynamic deflection of the reported bimorph is 77% higher than that of the unimorph. To the best of our knowledge, this is the first comparison reported in the literature. It provides insight and guidance for related research on bimorph and pMUT, and potentially helps expedite its pace towards market.

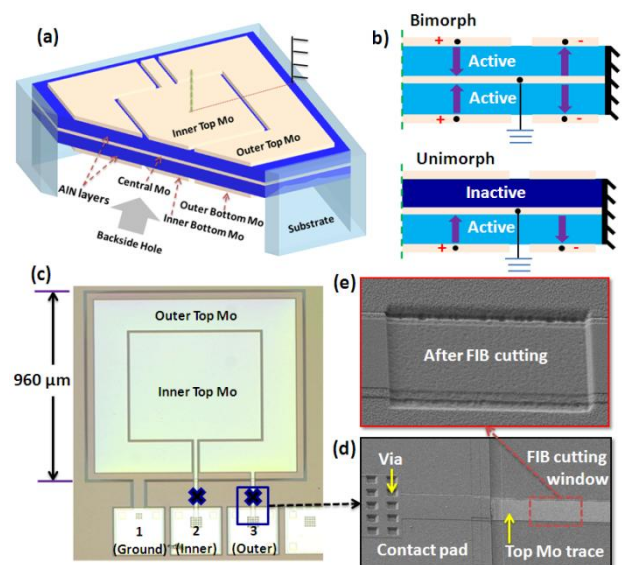


Fig.1. (a) Schematic drawing of the bimorph AlN pMUT; (b) Cross section view of the working modes of AlN bimorph and unimorph; (c) Top view of the fabricated bimorph AlN pMUT; (d) SEM image showing the contact pads and the top Mo line before FIB cutting ; (e) SEM image of the top Mo line after FIB cutting .

DESIGN AND FABRICATION

The schematic drawing of the bimorph AlN pMUT is illustrated in Fig.1(a). The diaphragm is a 960 μm square. Vertically, two 1 μm AlN layers are sandwiched in three 0.15 μm Mo layers to form the Mo/AlN/Mo/AlN/Mo stack; Horizontally, both top and bottom Mo are patterned into inner and outer Mo, respectively. The inner top Mo and inner bottom Mo are connected together to form inner electrode. Similarly, the outer top Mo and outer bottom

Mo form the outer electrode.

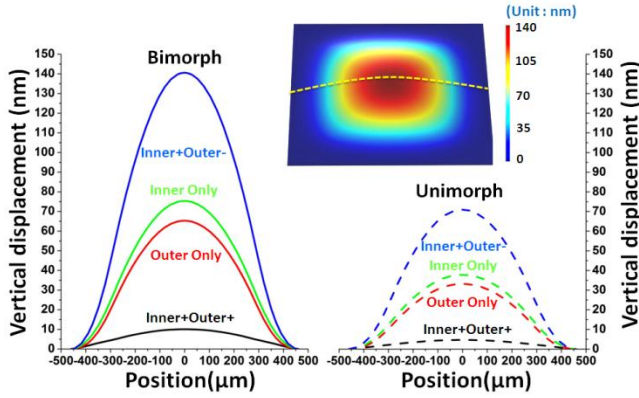


Fig.2. Simulation of the diaphragm deflection under static voltage for the bimorph and unimorph. Four voltage configurations are applied. The bimorph shows double deflection of the unimorph.

The central Mo is used as ground electrode. The ground, inner, and outer electrodes are connected out to Pad #1, #2, and #3, respectively, for external electrical connection. A backside hole is defined to release the free-standing AlN bimorph stack. Fig.1 (b) shows the center-to-edge cross section view of the bimorph and unimorph diaphragms. A unimorph is obtained by deactivating the top Mo/AlN layers. The deactivation process is discussed in detail in the following sections.

Fabrication starts with a <100> DSP Si wafer. Thermal oxidation is conducted to form the backside DRIE stopping layer. Followed by a sequence of deposition and patterning of Mo/AlN/Mo/AlN/Mo stack. By etching contact vias (seen in Fig1.(d)) in the AlN layers before 2nd and 3rd Mo deposition, the top, central and bottom Mo can be connected together as needed. Finally, backside silicon DRIE and oxide RIE are conducted to release the free-standing AlN bimorph structure. Fig.1 (c) shows the fabricated pMUT.

To deactivate the top AlN/Mo stack, a 300 nm-deep cut is performed on the conduction lines between the top Mo electrodes to the contact pads, using Focused Ion Beam (FIB) at the “x” marked points shown in Fig.1 (c). SEM images of one top Mo line before and after FIB cutting are shown in Fig.1 (d) and (e). Compare to the top AlN thickness of 1 μm , this 300 nm shallow cutting ensures that the whole diaphragm remains intact and the middle/bottom Mo lines are totally unharmed for electrical signal conduction. Such post process maintains the bimorph and uniform identical except the deactivation of the top Mo/AlN from actuation.

MODELING AND CHARACTERIZATION

Finite Element Analysis software COMSOL is used for the transducer modeling. Static deflection of diaphragms at 1 V DC voltage under four voltage application configurations (“Inner only”, “Outer only”, “Inner+outer+”, “Inner+outer-”) is presented in Fig. 2. For example, “Inner+outer-”, as shown in Fig.1 (b), refers to the configuration in which inner and outer electrodes are applied voltages of same amplitude but opposite polarity; “Inner only” means that inner electrode is applied voltage, outer electrode floating. The other two configurations are similarly defined. The measurement

shows that the diaphragm deflection amplitude of bimorph doubles that of unimorph for any of the four configurations. This is because both AlN layers are activated and generate structure deformation under d31 mode in case of the bimorph. For unimorph, only one AlN layer is activated and the other AlN layer is inactive, thus serves as a resistance to deformation. For “Inner+Outer-” configuration, both inner and outer electrodes cause diaphragm deflection towards the same direction, hence maximizes the diaphragm deformation for both bimorph and uniform. In the following sections, “Inner+outer-” is used for AC testing to compare the dynamic response of bimorph and uniform.

Diaphragm movement under given AC voltages is used to characterize the dynamic response of the pMUT. Laser Doppler Vibrometer (Polytech Micro System Analyzer) is used to measure the diaphragm movement at different actuation frequencies. As shown in the Fig.3 inset, the pMUT’s 1st resonant mode is 71.2 kHz. In this mode, the entire diaphragm moves up and down in sync for maximum acoustic power output. Both bimorph and unimorph pMUT performance under different applied AC voltages, i.e. 0.25, 0.5, 0.75, 1.0, 2.0, and 3.0V, are evaluated. It is clearly observed that the amplitude of unimorph is significantly less than that of the bimorph, further proving the top Mo/AlN layers have been deactivated successfully. The frequency response curves of bimorph and unimorph have similar pattern. The diaphragm movement amplitude increases as the voltage increases, so that the device progressively enters from linear to non-linear region, attributed to the spring-hardening effect. This is supported by the observations of gradual up-shift of the peak frequency as well as the non-symmetric response curves as voltage increases. As shown in Fig. 3, both effects are more prominent with 3V of applied AC voltage, regardless of bimorph or unimorph.

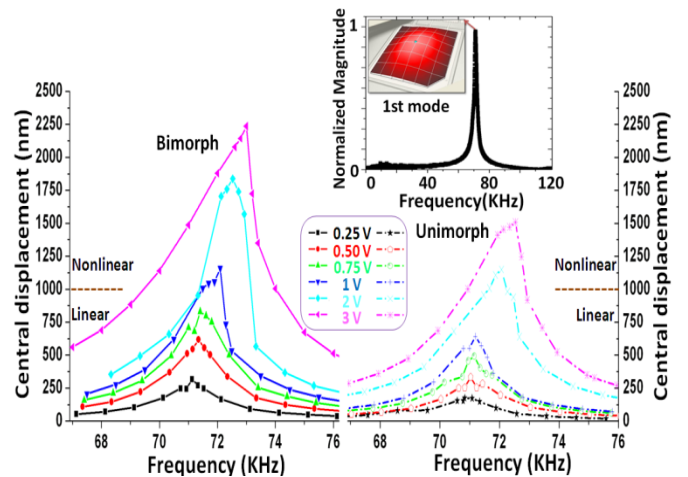


Fig.3. Characterization of pMUT under different AC voltages. Inset shows the first working mode of the bimorph pMUT. The response curves become non-symmetric as voltage increases.

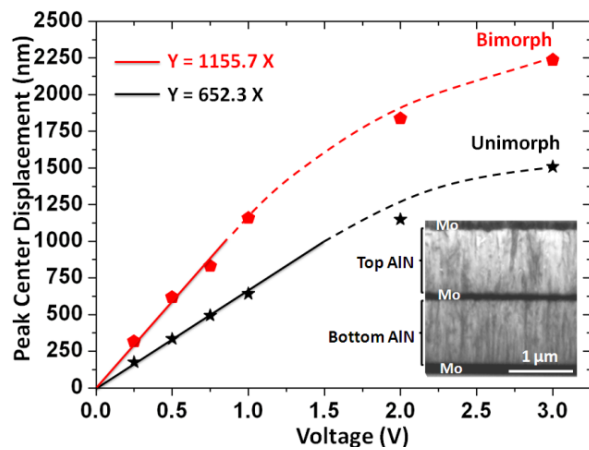


Fig.4. Peak displacement of pMUT diaphragm center against different AC voltages. Inset shows the TEM picture of the diaphragm cross section.

The peak values of the diaphragm center displacement at different applied voltages are extracted for both bimorph and unimorph, and plotted in Fig.4 to clearly compare the device vibration amplitude. Diaphragm center displacement values less than half diaphragm thickness (i.e., 1 μm) are considered to be within linear vibration region. Linear fitting to these points is performed to both bimorph and unimorph, and the corresponding coefficients are 1155.7 nm/V and 652.3 nm/V, respectively. This means the bimorph has 1.77X dynamic amplitude of the unimorph. Although this marks a significant improvement over the unimorph, it is still slightly lower than the expected 2X improvement based on simulation (Fig.2). We attribute this performance gap to the poorer AlN crystalline quality/directionality, seen in the TEM image (inset of Fig.4). The poorer AlN crystalline quality/directionality is likely the result of roughness accumulation during the stack deposition process. In fact, we observed higher roughness of the top AlN (~ 6 nm r.m.s.), compared to bottom AlN (~ 2 nm r.m.s.). It may compromise the performance of the top AlN, resulting in a lower piezoelectric coupling coefficient. More testing structures in the next round of fabrication are planned to further evaluate the AlN thin film performance, understand the origin of the performance gap, and guide the process development of better quality AlN top layer. Further improved performance of AlN bimorph is expected.

CONCLUSION

In this paper, we reported the experimental data of a bimorph AlN pMUT with two active AlN layers; and the same-device comparison with its own unimorph counterpart by deactivating the top AlN layer. For the first time, we observed the nearly doubled dynamic deflection of bimorph structure than unimorph. This indicates a drastically improved electro-mechanical coupling and acoustic power generation capability. TEM picture of the two AlN layers shows room for further device performance improvement. This work lays the foundation of a brand new AlN process platform for practical deployment of low actuation voltage, high acoustic power pMUT for applications including mobile, wearable, and medical imaging.

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