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Article

Keywords: MEMS, PMUT, Piezoelectric transducers, Ferroelectric materials, Resonators

Posted Date: October 15th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11070333/v1>

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Overcoming Material Trade-Offs in MEMS Transducers via Lateral Ferroelectric–Piezoelectric Thin-film Integration

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Abstract

Piezoelectric microelectromechanical systems (MEMS) transducers are constrained by a fundamental materials trade-off. Materials that enable strong electromechanical actuation typically exhibit high dielectric permittivity and loss and in contrast, materials optimized for electrical sensing generally provide weaker piezoelectric coupling. Here, we overcome this limitation through the first extensive experimental demonstration of a laterally integrated ferroelectric–piezoelectric resonator architecture designed to enhance transceiver efficiency and figure of merit (FoM). Lead Zirconate Titanate (PZT) and Aluminum Nitride (AlN) are integrated with equal area coverage within the same resonator plane. In this configuration, the high piezoelectric coefficient of PZT enables efficient electromechanical actuation, while the low permittivity and dielectric loss of AlN enable high-voltage sensing. The second resonant mode is used to directly compare actuation and sensing performance under identical strain conditions. This allows material-dependent transduction effects to be isolated. Experimental results demonstrate an approximately 10× increase in electrical output voltage when PZT is used for actuation and AlN for sensing, compared with the reverse configuration. This enhancement is observed across devices spanning frequencies from the kHz to MHz range and results in a substantial improvement in FoM. The architecture also enables DC-bias tunability and enhanced performance through ferroelectric poling of PZT while preserving low-loss AlN sensing. These results establish lateral material integration as an effective strategy for combining complementary ferroelectric and piezoelectric functionalities within a single MEMS resonator for sensing, signal processing, and ultrasonic applications.

Keywords: MEMS, PMUT, Piezoelectric transducers, Ferroelectric materials, Resonators

1 Introduction

Microelectromechanical systems have gained significant attention in recent years due to their ability to enable compact, energy efficient, and high performance sensing and actuation solutions by the advancement in microfabrication, material engineering, and device design. Over time, piezoelectric MEMS have stood out among various MEMS transduction schemes due to their excellent frequency scaling, plethora of materials, dynamic performance, and low power consumption [1–3]. Piezoelectric devices can be fabricated to operate across a wide frequency range, from a few hertz using suspended or bulk mechanical structures to several GHz by exploiting fundamental and higher order resonant modes. This wide operating bandwidth enables diverse applications such as physical sensing [4, 5], imaging [6, 7], biomedical systems [8, 9], range finding [10, 11], and quantum acoustics [12]. This broad operational range underscores the versatility of piezoelectric MEMS and motivates continued research into strategies for enhancing their performance, including optimizing mechanical structures, improving the intrinsic quality of piezoelectric materials, and advancing the integration of multilayer heterogeneous piezoelectric thin films.

In piezoelectric MEMS transducers, the key functional component is the piezoelectric material, as it plays a central role in both the actuation and sensing mechanisms. Each piezoelectric material possesses fundamental elastic, dielectric, and piezoelectric properties that collectively determine its performance and establish inherent trade offs among output parameters [13–15]. Achieving optimum device performance therefore requires selecting a material whose intrinsic properties are aligned with the specific application requirements. Furthermore, the performance of piezoelectric MEMS devices is often quantified using Figures of Merit (FoMs) [16–18], enabling fair comparison of different piezoelectric materials. For instance, the FoM for thin film piezoelectric actuators is proportional to the piezoelectric charge coefficient e (C/m²), and materials with a large e are therefore preferred for achieving strong electromechanical actuation [19, 20]. In contrast, the FoM for piezoelectric sensors is given by e/ε (GV/m), where ε is the permittivity. Accordingly, materials with lower permittivity exhibit a lower static capacitance and dielectric loss, leading to improved voltage sensitivity and signal to noise ratio [21, 22]. As a result, actuators commonly employ ferroelectric materials such as lead zirconate titanate (PZT) [23, 24], which exhibit high piezoelectric coefficients (5–26 C/m²), whereas sensors benefit from materials like aluminium nitride (AlN) [25, 26], whose intrinsically low permittivity (8 – 10) is advantageous for signal detection. However, a resonator that must simultaneously perform both actuation and sensing requires a material that achieves a balance between these properties. In such cases, the appropriate FoM can be obtained by combining the actuator and sensor FoMs.

As an illustrative case, when a Piezoelectric Micromachined Ultrasonic Transducer (PMUT) functions as a transceiver, its efficiency is commonly quantified using a FoM, defined as [27]

$$\text{FOM} = \frac{e_{31,f}^2}{Y \varepsilon_{33,f}}, \quad (1)$$

where Y is an effective rigidity of the elastic multilayer structure in resonance, subscript f represents thin film property and $\varepsilon_{33,f}$ is the permittivity. The PMUT is a key class of piezoelectric MEMS devices and offers several advantages over bulk ultrasonic counterparts, including improved bandwidth, better acoustic impedance matching, and lower operating voltages [28–31]. In addition, unlike Capacitive Micromachined Ultrasonic Transducers (CMUTs), PMUTs do not require a DC bias for transduction and are free from electrode gap and pull in limitations that constrain diaphragm displacement in electrostatic transducers [32, 33]. These advantages have led to their widespread use in applications such as medical ultrasonic imaging [34, 35], nondestructive testing [36], and short range navigation [37].

To meet the desired output parameters, considerable research effort has focused on enhancing PMUT performance or overall FoM through structural modifications [38], tailoring of boundary conditions [39], and advances in fabrication techniques [40]. Parallel to these developments, material engineering approaches have also been pursued [41], including increasing the piezoelectric coefficient through elemental doping [42] while maintaining or reducing permittivity. Additionally, advances in deposition technologies and improvements in piezoelectric thin films such as PZT [43] and AlN [44, 45] have further contributed to PMUT development. Nevertheless, improvements in the intrinsic properties of both PZT and AlN have largely reached saturation, thereby limiting the achievable performance. Achieving a high FoM requires a material that simultaneously provides a large piezoelectric coefficient and a low permittivity; yet it is challenging for a single material to satisfy both requirements [46]. Consequently, resonators fabricated from a single piezoelectric material inevitably face a trade off between actuation range and sensing limit.

To overcome these challenges, researchers have attempted to stack multiple layers of the same piezoelectric material on top of the first layer using an intermediate electrode. For example, Akhbari et al. [40] demonstrated a bimorph PMUT with two active piezoelectric layers, achieving a $4\times$ improvement in drive sensitivity compared to a single electrode unimorph PMUT. Following this work, bimorph PMUTs based on ScAlN and Lithium Niobate (LN) piezoelectric materials were also explored to enhance electromechanical coupling [47, 48]. While these bimorph PMUTs significantly improve drive sensitivity through strain coupling, the associated increase in capacitance and residual stress poses challenges for electrical sensing and device integration, and these bimorph studies predominantly focus on actuation enhancement with limited discussion of simultaneous electrical transmit receive operation. More recently, a different approach has been reported involving the vertical stacking of two dissimilar materials, such as a ferroelectric and a piezoelectric, within a single resonator, enabling independent optimization of actuation and sensing to improve both transmission and reception [49]. However, the reported demonstrations primarily emphasize transmission enhancement and lack experimental validation of electrical sensing performance or simultaneous transmit receive operation. Combining ferroelectric and piezoelectric materials within a single resonator nevertheless offers the simultaneous advantages of a high piezoelectric coefficient, low permittivity for improved voltage sensitivity, and electrically tunable response enabled by the ferroelectric layer [50]. Therefore, to realize these features at the singular device level, we introduce a novel architecture based on the lateral stacking of ferroelectric PZT and piezoelectric AlN in the same plane, spatially integrating these complementary material properties within a single resonator to enable efficient actuation, electrical sensing, and tunable operation. Unlike previously reported bimorph and vertically stacked PMUTs based on suspended piezoelectric membranes, this architecture employs a silicon diaphragm, enabling well defined flexural operation and robust device level characterization.

In this work, we successfully demonstrate the fabrication of a prototype laterally stacked PMUT incorporating ferroelectric PZT and piezoelectric AlN thin films in the same plane. We systematically investigate the performance of the fabricated PMUTs and demonstrate a $10\times$ higher electrical output voltage for the PZT drive/AlN sense configuration compared to the reverse configuration across a range of diaphragm thicknesses and radii. Additionally, we investigate the tunable response of the PMUT by applying a DC bias to the PZT layer and further explore the role of poling. To establish device robustness, multiple fabrication batches were fabricated using different SOI thicknesses and diaphragm radii, covering a wide frequency range from kHz to MHz, and the proposed concept was validated across multiple vibrational modes. Finally, we benchmark the performance of the laterally stacked PMUT against state of the art standalone PZT and AlN PMUTs with identical device dimensions.

2 Resonator design and fabrication

2.1 Resonator design

To demonstrate the fabrication and operating principle of laterally stacking distinct active layers ferroelectric, piezoelectric, or their combination within a single piezoelectric MEMS resonator, we employ a PMUT as the model platform. In this work, we establish a fabrication scheme in which a ferroelectric material and a piezoelectric material are deposited side by side in the same plane of the PMUT, enabling their complementary electromechanical properties to be harnessed within a single device. As a proof of concept, we utilize PZT and AlN, which serve as well established representatives of ferroelectric and piezoelectric thin films, respectively, and whose individual characteristics have been extensively studied. This approach enables an enhanced effective material figure of merit by combining the complementary electromechanical characteristics of distinct thin films specifically, the high piezoelectric coupling of PZT and the low permittivity of AlN without altering their intrinsic properties. Throughout this work, we refer to this integrated architecture as a Laterally Stacked Resonator (LSR).

To enable a direct and optimal comparison of the electromechanical performance of PZT and AlN within a single resonator, the diaphragm was divided into two equal regions, onto which the AlN and PZT layers were deposited along with their respective bottom and top electrodes. Figure 1(a) shows a 3D schematic of the lateral stacking configuration, where the ferroelectric layer (PZT) and the piezoelectric layer (AlN) are placed side by side in the same plane. Figure 1(b) presents a 3D profilometry top view of the LSR, illustrating the routing of the ground and individual top electrodes. To evaluate the ideal output performance arising from the complementary properties of PZT and AlN, the LSR is actuated through the ferroelectric PZT layer and sensed using the piezoelectric AlN layer. Actuating the PMUT via the PZT region leverages its high piezoelectric coefficient ($e_{31,f}$), while sensing through the AlN region benefits from its lower permittivity ($\epsilon_{33,f}$). This arrangement reduces capacitive feedthrough and increases the measured output voltage. Figure 1(c) shows a representative electrical response of the second flexural mode of the PMUT under this configuration. When the device is driven through the high coupling PZT and sensed through the low permittivity AlN, the output voltage is substantially higher compared to the reverse actuation sensing configuration. In addition, a key advantage of ferroelectric materials is that their piezoelectric properties can be tuned by applying a DC bias voltage. This tunability can be exploited for amplitude modulation and frequency tuning, both of which are desirable functionalities for resonator applications. Figure 1(d) presents an example of the resonator response under varying DC bias. It is evident that the output voltage is amplified and the resonance frequency shifts with the applied bias, demonstrating the characteristic tunable nature of the ferroelectric driven and piezoelectric sensed LSR.

2.2 Fabrication

The fabrication was carried out using standard bulk micromachining techniques on a double side polished, $\langle 100 \rangle$ -oriented, n-type silicon on insulator (SOI) wafer comprising 10 μm device layers, a 2 μm buried oxide, and a 450 μm handle layer. The complete process flow for the laterally stacked PMUT is illustrated in Figure 2(a). For high-quality ferroelectric and piezoelectric thin film deposition, the choice of bottom electrode plays a critical role in achieving lattice matching, controlling residual stress, thereby ensuring optimal material growth. Because this work integrates two piezoelectric materials with distinct intrinsic properties and thermal constraints, separate bottom electrodes were employed: titanium/platinum (Ti/Pt) for the PZT region and molybdenum (Mo) for the AlN region.

The process begins with an SOI wafer on which a multi layer stack comprising a 30 nm AlN seed layer, a 150 nm Mo electrode, and a 900 nm AlN piezoelectric layer was deposited, as shown in step (i) of Figure 2(a). The multilayer stack deposition was carried out by Advanced Molecular Systems (Goleta,

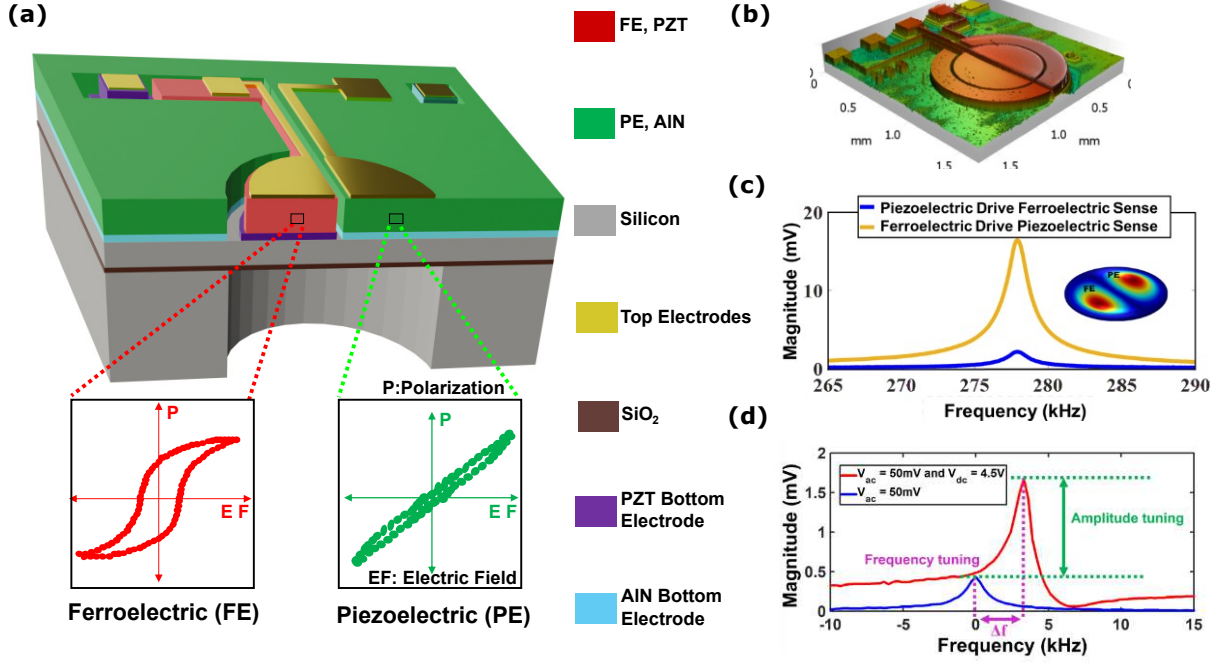


Fig. 1 (a) Three dimensional schematic of the LSR cross section. (b) Optical profilometer image of the fabricated LSR. (c) Electrical frequency response comparing the performance of the ferroelectric drive/piezoelectric sense configuration and the reverse case. (d) Electrical frequency response showing that applying a DC bias to the ferroelectric material enables both amplitude and frequency tuning.

California, USA). To realize the hybrid PMUT by laterally stacking PZT and AlN within the same planar plane with individually patterned top and bottom electrodes, AlN and Mo were selectively removed from regions where Ti/Pt and PZT were subsequently deposited. Within these precisely defined etched pockets, a 20 nm Ti/130 nm Pt bottom electrode was sputter deposited at room temperature. Photoresist coating, Ti/Pt deposition, and the lift off process are explained through steps (iv) to (vii). The PZT thin film was deposited via a sol gel process using a commercially sourced precursor solution (Quintess Co., Ltd., Republic of Korea) and annealed at 650 °C (step (viii)). After annealing, the PZT layer is patterned using reactive ion etching (RIE), as shown in step (ix). Top electrodes for both the AlN and PZT regions are formed by sputter deposition of chromium/gold (Cr/Au), followed by a lift off process (step (x)). In selected fabrication batches, the AlN region was also provided with a Ti/Pt top electrode, ensuring that the AlN surface remained pristine during subsequent PZT processing. To access the Mo bottom electrode, AlN is selectively removed by wet etching after photolithographic patterning. After both piezoelectric layers are successfully formed side by side and individually sandwiched between their top and bottom electrodes, backside alignment is performed and silicon trenches are created by deep reactive ion etching (DRIE), forming the circular membranes, as shown in step (x). The 2 μ m buried oxide layer acts as the etch stop during backside silicon etching and is subsequently removed by RIE.

During the fabrication of the laterally stacked PZT AlN PMUT, extensive process development and optimization were performed through multiple trial runs, and only the key steps enabling the hybrid integration are highlighted here. Specifically, AlN, seed AlN, and Mo were patterned using wet etching, where precise control of the Mo etch recipe was critical to achieve a controlled lateral undercut of

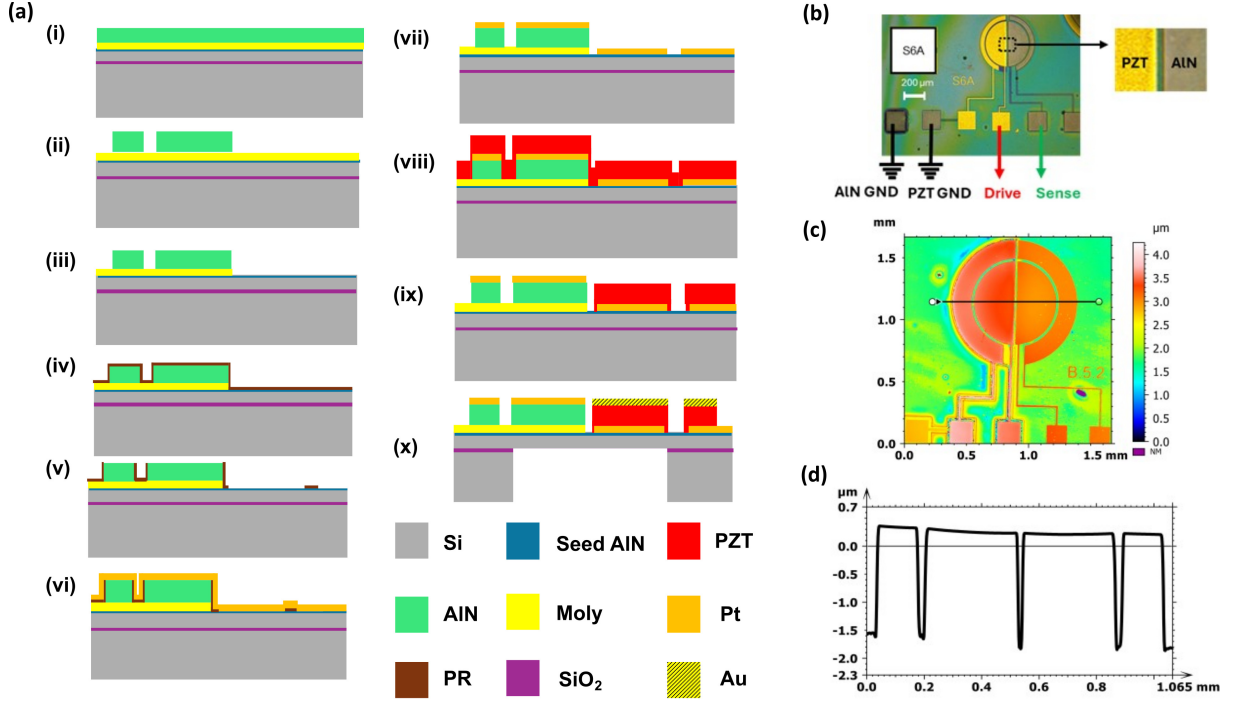


Fig. 2 (a) Fabrication process flow of the laterally stacked PMUT. (b) Optical micrograph of the fabricated LSR. (c) Optical profilometry (OP) image of the fabricated LSR. (d) Cross sectional OP profile along the diaphragm diameter of the LSR.

approximately 4 μm. This ensured that the Mo layer remained recessed and protected during the high temperature annealing required for subsequent PZT deposition, thereby preventing any potential shorting with the PZT top or bottom electrodes. In contrast, wet etching of PZT produced substantial lateral undercut, which was mitigated by employing reactive ion etching (RIE) with a C₄F₈-based chemistry.

Overall, the developed process flow enables reliable and repeatable lateral stacking of ferroelectric and piezoelectric materials within the same diaphragm plane without degrading the individual material properties. To demonstrate the proof of concept, the PMUT diaphragm was designed with a radius of 500 μm and a stack thickness of ≈ 11 μm. An optical micrograph of the fabricated PMUT is shown in Figure 2(b), where the PZT and AlN regions and their corresponding ground, drive, and sense electrode configurations are highlighted. To examine the surface topography of the fabricated device, optical profilometry was performed, and the top view is shown in Figure 2(c). The profilometry results indicate an essentially flat surface, suggesting the absence of residual stresses induced buckling. Figure 2(d) presents a cross-sectional profile along the diaphragm diameter. To support the observed trends, multiple fabrication batches were subsequently carried out using different SOI substrate thicknesses and various diaphragm dimensions, covering a range of operating frequencies.

2.3 Structural and Material Characterization

The ferroelectric and piezoelectric materials used in this work differ in their inherent properties, deposition methods, annealing requirements, and allowable thermal budgets. Therefore, it is essential to verify that integrating one material does not compromise the thin film properties of the other. In particular, since

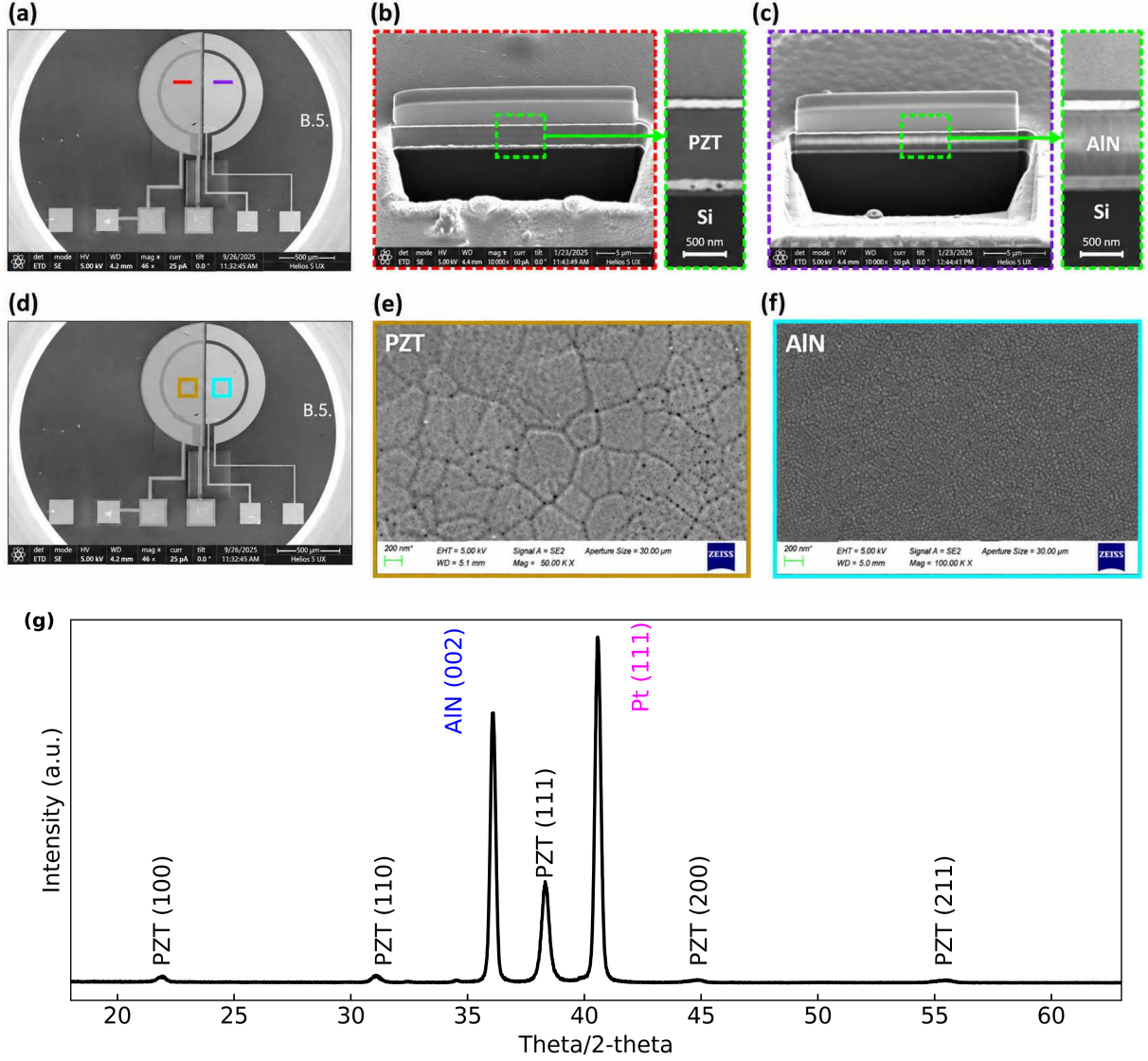


Fig. 3 FIB images of the fabricated LSR. (a) Top view of the LSR, where small grooves are milled across the PZT and AlN regions (indicated by the red and purple lines, respectively) to obtain cross-sectional images. (b) Magnified cross-sectional view of the milled PZT region, including a zoomed in image showing the 900 nm-thick PZT film sandwiched between the top and bottom electrodes. (c) Magnified cross-sectional view of the milled AlN region, including a zoomed in image showing the 900 nm-thick AlN film sandwiched between the top and bottom electrodes. (d) SEM image of the top surface of the fabricated LSR, with regions of interest highlighted in brown and cyan boxes. (e) Grain structure of the PZT region. (f) Grain structure of the AlN region. (g) XRD θ - 2θ scan of the LSR, showing characteristic diffraction peaks corresponding to AlN and PZT.

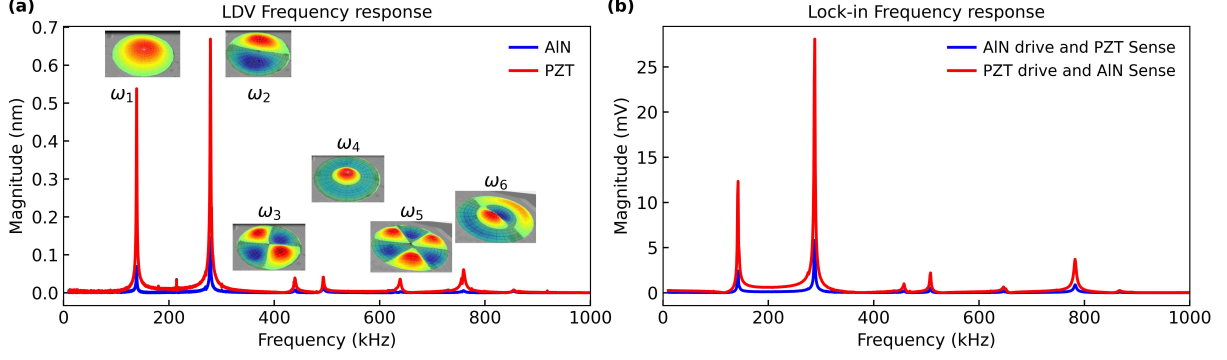


Fig. 4 (a) Mechanical frequency response of the first six modes of the LSR measured using LDV, along with their corresponding mode shapes, obtained by exciting the PZT and AlN regions individually. (b) Electrical frequency response of the first six modes of the LSR for both the PZT drive/AlN sense and the reverse configurations.

AlN is deposited prior to PZT in the LSR stack, it must be ensured that the subsequent PZT deposition, along with its associated thermal treatments and etching steps, does not degrade the underlying AlN layer.

The thicknesses of the AlN and PZT thin films are expected to be approximately 900 nm based on the deposition parameters. To verify the thin film thicknesses on the fabricated LSR, focused ion beam (FIB) milling and imaging were performed, as shown in Figure 3(a). Two small grooves were introduced on the PZT and AlN sides of the diaphragm to expose the layer stack for cross-sectional inspection, as indicated by the red and purple lines, respectively, in Figure 3(a). Figures 3(b) and 3(c) show enlarged cross-sectional views of the milled regions, including zoomed in images used to extract the film thicknesses. The cross-sectional images confirm that the AlN and PZT layers are approximately 900 nm and 920 nm thick, respectively, and are properly sandwiched between their respective top and bottom electrodes.

To investigate any changes in the morphology of PZT and AlN during fabrication, scanning electron microscope (SEM) analysis was performed. Figure 3(d) shows the top surface of the fabricated LSR, with the regions of interest highlighted in brown and cyan. Figures 3(e) and (f) show the corresponding grain structures of PZT and AlN, respectively. The grain morphology in both regions remains uniform and consistent with their standalone thin film characteristics, indicating that the subsequent deposition and annealing steps in the LSR process did not degrade either material. Additionally, X-ray diffraction (XRD) analysis was performed to further confirm the crystallographic quality of the stacked thin films. Figure 3(g) shows the θ - 2θ scan of the LSR, where the peaks at 36° and 38.8° correspond to the AlN $\langle 002 \rangle$ and PZT $\langle 111 \rangle$ orientations, respectively. These peaks indicate that both materials retain their expected preferred orientations after the lateral stacking and subsequent processing steps.

3 Results and Discussion

3.1 Basic characterization

After completing the device level fabrication of the LSR with a radius of 500 μm and a thickness of $\approx 11 \mu\text{m}$, we performed mechanical and electrical characterization using a LDV and a lock-in amplifier. To observe the influence of the piezoelectric coefficient on actuation, the LSR was driven by individually applying an AC signal to the AlN and PZT electrode regions, and the resulting displacement was recorded separately for each case using LDV. Figure 4(a) shows the LDV measured frequency response of the first

six flexural modes of the circular LSR for both AlN driven and PZT driven actuation, along with their corresponding mode shapes (experimental setup is shown in section S1 of supplementary material). As expected, the PZT driven displacement magnitude is significantly higher than that obtained under AlN drive for all modes, owing to the substantially larger piezoelectric coefficient of PZT. Among these modes, the second mode exhibits the highest measured displacement because the LDV laser spot is positioned near the antinode of one of the semicircular regions. Additionally, the LDV frequency response of the second mode was independently characterized under separate PZT and AlN actuation, confirming that PZT yields a higher displacement amplitude due to its larger piezoelectric transduction coefficient (see Section S2 of supplementary material). Furthermore, this mode provides an effective comparison between PZT and AlN actuation, as both materials occupy equal areas of the diaphragm.

For electrical measurements, to obtain the optimal electromechanical response enabled by the LSR design, we first drive the device using the higher piezoelectric coefficient material unpoled PZT and sense using the lower permittivity AlN, and then reverse these roles for comparison. Figure 4(b) presents the electrical frequency response measured using a lock-in amplifier for both configurations (for the experimental setup, see section S3 of the supplementary material). Similar to the LDV measurements, we record the electrical response of the first six resonant modes. The dominance of the second mode arises from the electrode configuration, which couples more effectively to the strain distribution of this mode. Across all observed modes, the configuration employing PZT for actuation and AlN for sensing consistently yields a higher output signal than the reverse configuration. This behavior is expected, as PZT offers stronger actuation owing to its higher piezoelectric coefficient, whereas AlN improves electrical sensitivity due to its lower permittivity, resulting in reduced static capacitance and a higher output voltage. Thus, these measurements experimentally validate the underlying concept of the LSR, namely, that combining a high-coupling material for actuation with a low-permittivity material for sensing yields a superior electrical output, which is critical for fully electronic interfaced applications. As the second mode provides the most effective basis for assessing the performance of the present LSR design, we next focus on this mode in detail, outlining the proof of concept and examining the effects of DC bias and poling on the LSR response.

3.2 Proof of Concept

To demonstrate the proof of concept, we evaluate the electrical response of the second resonant mode, whose strain profile distributes equally across the PZT and AlN regions, making it suitable for comparing PZT drive/AlN sense and AlN drive/PZT sense configurations. Figure 5(a) shows the frequency response of the second mode for both cases: driving the device through the unpoled PZT electrode and sensing through the AlN electrode, and the reverse configuration. The responses were recorded using the sweep module of a lock in amplifier on a probe station, with an input AC signal of 100 mV and zero DC bias. Additionally, we use independent ground terminations for the PZT and AlN electrodes to reduce the cross talk. This configuration suppresses capacitive feedthrough, prevents unintended motional current pathways, and improves the signal to noise ratio, as the two ground electrodes are electrically isolated. It is found that, the output voltage obtained with unpoled PZT drive and AlN sensing is approximately $7.7\times$ higher than that of the reverse configuration. This validates, at the device level, the underlying concept that driving with a material of higher piezoelectric coefficient and sensing with a material of lower permittivity enhances the output response.

Further, to examine the influence of the input AC voltage on the output magnitude ratio between the two configurations, we repeated the frequency response measurements while increasing the AC actuation amplitude, with zero DC bias. Figures 5(b) and (c) show the second mode response for the AlN

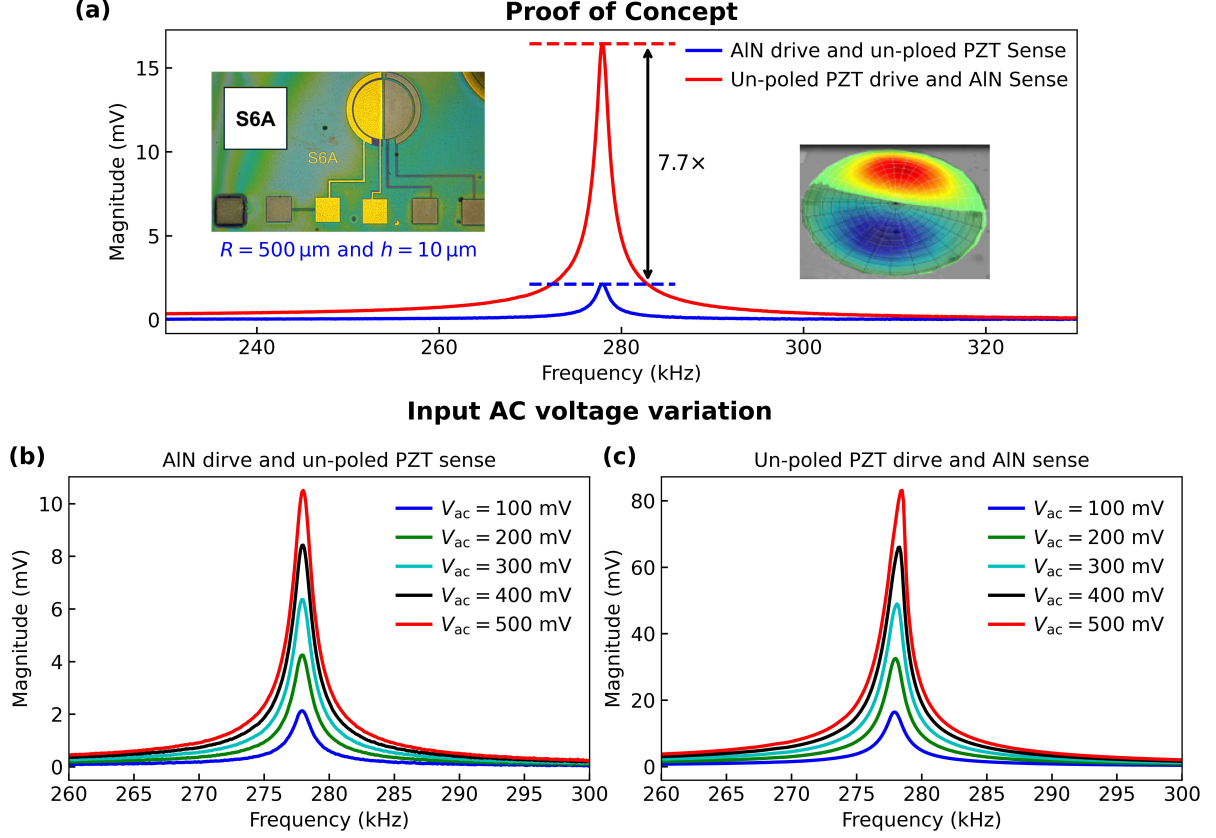


Fig. 5 The electrical frequency response of the second mode of the LSR. (a) Unpoled PZT drive/AIN sense and reverse configurations under a 200 mV AC excitation. (b) AIN drive/PZT sense configuration for varying AC voltages from 100 mV to 500 mV without DC bias. (c) PZT drive/AIN sense configuration for varying AC voltages from 100 mV to 500 mV without DC bias.

drive/PZT sense configuration and the PZT drive/AIN sense configuration, respectively, as the AC voltage is increased from 100 mV to 500 mV. In both cases, the output voltage increases proportionally with the input AC amplitude. However, the ratio of the output magnitudes PZT drive with AIN sensing relative to AIN drive with PZT sensing remains nearly constant at approximately $7.7 - 7.9\times$. Additionally, the PZT drive/AIN sense configuration begins to exhibit a slight hardening type nonlinear response at higher AC amplitudes, whereas the AIN drive/PZT sense response remains predominantly linear up to 500 mV. Now that the basic concept has been established, we next examine another important aspect of ferroelectric materials: the ability to tune their piezoelectric properties through DC bias and to enhance them through poling, and we investigate how these effects influence the resonator performance.

3.3 Effect of DC Bias and Poling on LSR Performance

Ferroelectric materials exhibit electric field dependent piezoelectric properties that can be tuned through an applied DC bias. This bias-dependent behavior enables several functional advantages, including

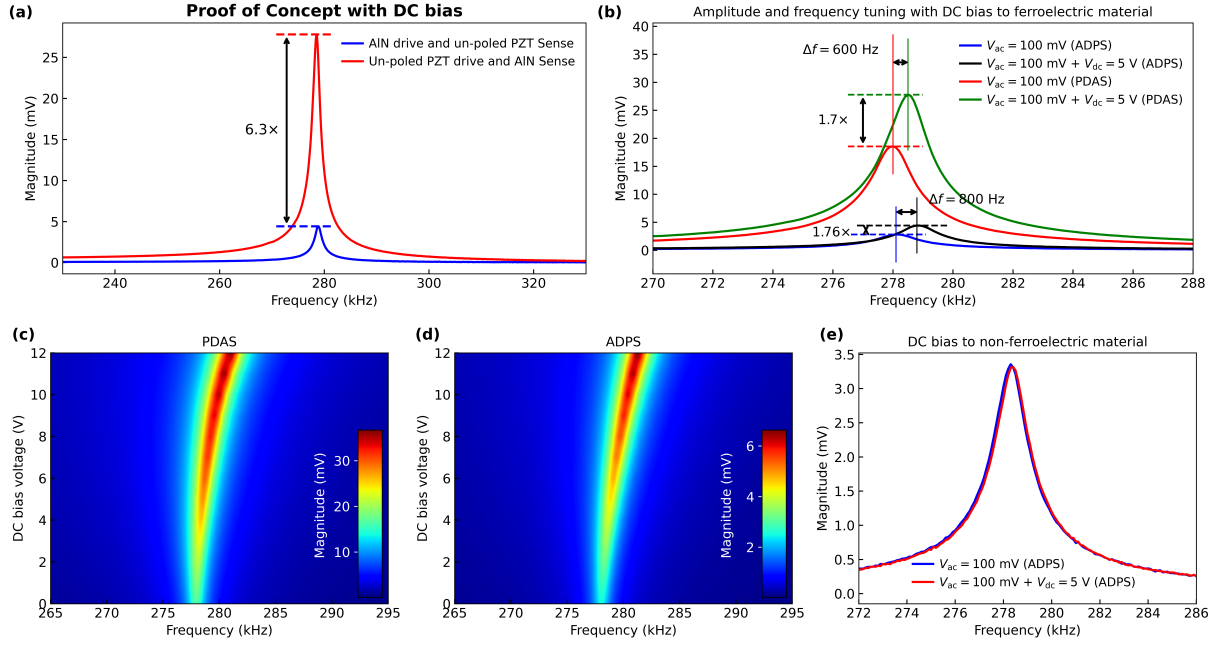


Fig. 6 Electrical response measured using a lock in amplifier with an applied DC bias to the ferroelectric material of the stack. (a) Verification of the proof of concept after applying a 5 V DC bias to the ferroelectric layer for both the PZT drive/AlN sense and the AlN drive/PZT sense configurations. (b) Amplitude and frequency tuning observed upon applying a 5 V DC bias in both PZT drive/AlN sense and AlN drive/PZT sense configurations. (c,d) Increase in output amplitude with increasing DC bias applied to the ferroelectric material in both PZT drive/AlN sense and AlN drive/PZT sense configurations. (e) Electrical response showing that applying a DC bias to AlN, a non ferroelectric material, produces no observable change in either frequency or amplitude.

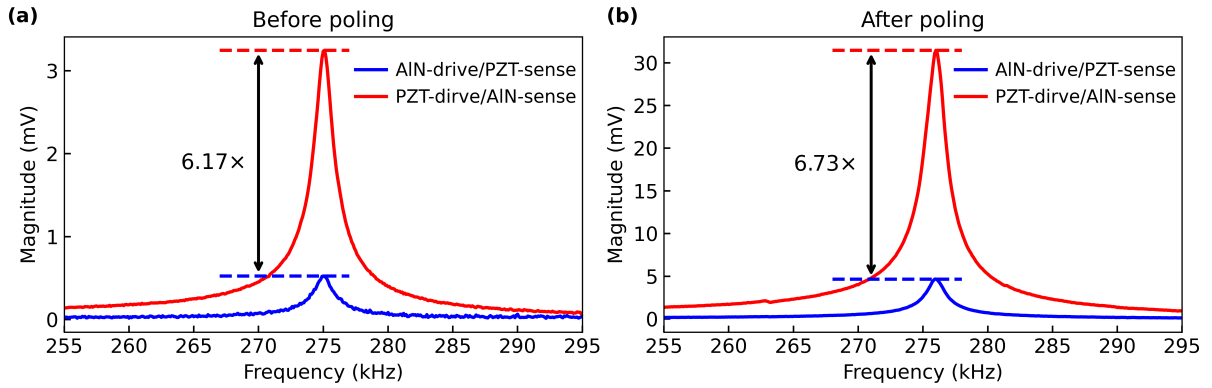


Fig. 7 Electrical response measured using a lock in amplifier (a) before and (b) after poling the ferroelectric material of the stack.

frequency tunability and amplitude control in MEMS resonators, frequency-adjustable ultrasonic transducers, and reconfigurable sensors. In addition, it facilitates effective stiffness modulation, frequency comb

generation, and compensation for performance drift caused by aging and temperature variations [51–53]. Since the LSR incorporates a PZT ferroelectric layer alongside a piezoelectric AlN film, it provides a suitable platform for examining how DC bias modifies the resonance characteristics and overall electromechanical response. Next, we remeasure the frequency response under a 500 mV AC excitation while applying a 5 V DC bias to the unpoled PZT, for actuation in the PZT drive/AlN sense configuration and, conversely, for sensing in the AlN drive/PZT sense configuration. Figure 6(a) shows the frequency responses for both configurations with a DC bias applied to the PZT. The output magnitude increases in each case due to bias induced enhancement of the effective piezoelectric coefficients of the PZT compared to the unbiased state (see Figure 5(a)). However, the ratio of the output magnitudes of PZT drive with AlN sensing relative to AlN drive with PZT sensing decreases from $7.7\times$ to $6.3\times$, as the AlN drive/PZT sense configuration experiences a comparatively larger increase in output magnitude. These results confirm that the LSR follows the same trend observed in the proof-of-concept, wherein ferroelectric actuation combined with piezoelectric sensing yields a superior response. Although applying a DC bias enhances the piezoelectric properties of the ferroelectric layer, the overall device response improves in both actuation and sensing configurations.

Another important aspect of DC biasing the ferroelectric layer is that it enables tunability in both the resonant frequency and the output amplitude. Hence, we also examine the extent of tunability in the LSR response when a DC bias is applied relative to the unbiased case. Figure 6(b) shows the frequency response without and with a 5 V DC bias for both the PZT drive/AlN sense and the reverse configurations. The application of bias introduces clear tunability in both magnitude and frequency. Specifically, the magnitude increases by $1.76\times$ and the resonance shifts by $\Delta f = 800$ Hz in the AlN drive/PZT sense case, while they are $1.7\times$ and $\Delta f = 600$ Hz in the opposite configuration. This demonstrates that tunability can be effectively leveraged along with improved LSR performance by incorporating a ferroelectric thin film together with a piezoelectric material. To further quantify this effect, we carried out electrical frequency response measurements over a range of DC bias values from 1 V to 12 V. Figures 6(c) and (d) illustrate the corresponding 2D contour maps for the PZT drive/AlN sense and the reverse configurations, respectively (see line plots in section S4 of supplementary material). For the AlN drive/PZT sense configuration, the response exhibits a maximum magnitude enhancement of $2.66\times$ and a frequency shift of $\Delta f = 3.2$ kHz at a 12 V bias relative to the unbiased case, whereas the reverse configuration shows a $2.27\times$ magnitude increase with a frequency shift of $\Delta f = 2.9$ kHz. Here, we limit the tunability demonstration to 12 V. However, this is not a fundamental limit, and both tunability and overall LSR performance can be further increased by selecting ferroelectric materials with superior intrinsic coefficients and higher film quality. To confirm that the observed tunability originates from the ferroelectric layer, we also applied a 5 V DC bias to the AlN film in the AlN drive/PZT sense configuration. As expected, the frequency responses with and without bias (Figure 6(e)) show negligible change in magnitude and frequency because AlN is a non ferroelectric piezoelectric material whose coefficients remain essentially unchanged under static electric fields. While DC bias provides reversible control over the LSR response, enabling tunability advantageous for applications such as medical ultrasound, precision sensors, and microrobotics, certain applications further require predictable and linear output, enhanced sensitivity, and a well-defined actuation direction, for which fixed and stable electromechanical performance achieved through electrical poling becomes essential.

We therefore investigate how poling permanently alters the LSR characteristics compared to the unpoled state. By applying a high electric field, often in combination with elevated temperature, the randomly oriented ferroelectric domains become uniformly aligned, resulting in significantly improved piezoelectric and dielectric properties. To perform poling, we select a separate device from the same chip on which no prior DC bias was applied. Figure 7(a) depicts the frequency response of the second mode for the PZT drive/AlN sense and the reverse configuration, along with their output magnitude ratio of $6.17\times$.

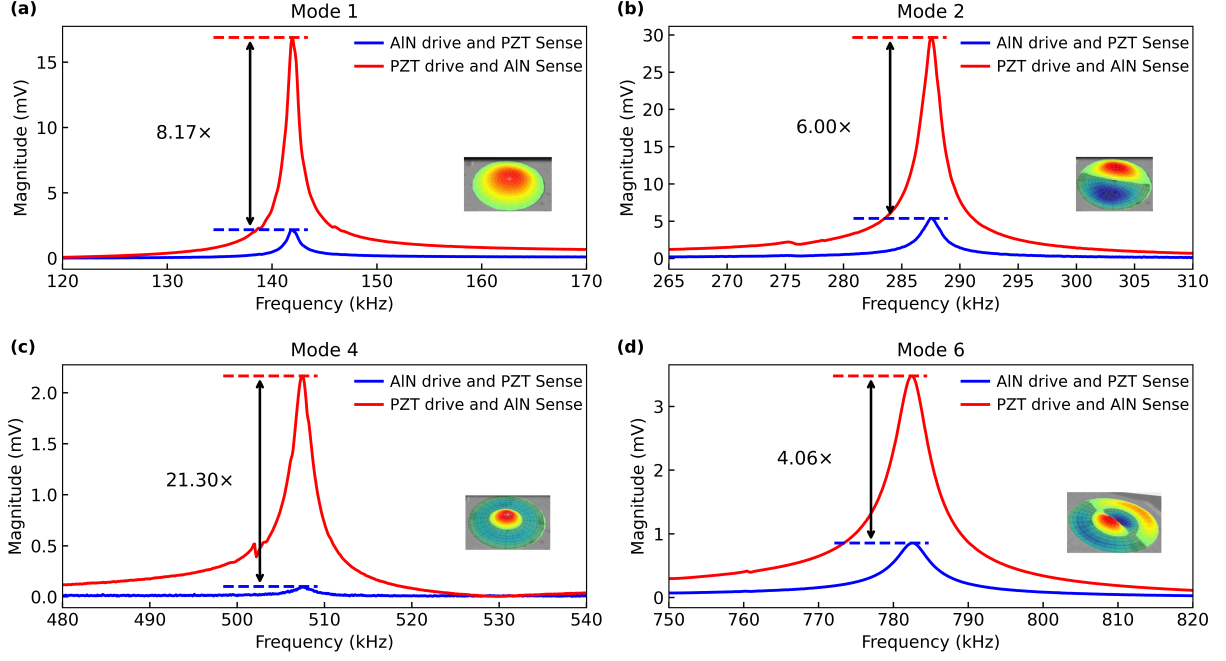


Fig. 8 Proof of concept verified across different mode shapes, with the corresponding output ratios shown for (a) Mode 1, (b) Mode 2, (c) Mode 4, and (d) Mode 6.

Although the absolute output magnitude of this device is lower than that of the previously discussed one, poling produces a substantial enhancement, with the output magnitude in both configurations increasing by nearly $10\times$ and the magnitude ratio rising from $6.17\times$ to $6.73\times$, as shown in Figure 7(b). These results clearly demonstrate that poling substantially improves both the actuation capability and the sensing functionality of the ferroelectric layer, thereby enhancing the overall performance of the LSR.

3.4 Extension of the Concept to Other Modes and Device Dimensions

Till now, the proof of concept for LSR performance enhancement using a PZT and an AlN layer has been demonstrated through the second mode of the device. The second mode provides a fair comparison between the roles of PZT and AlN in actuation and sensing, as its strain distribution and displacement profile allow both materials to contribute in a similar manner. However, we also measured the frequency response of other modes and evaluate the output-magnitude ratio between the PZT drive/AlN sense configuration and its reverse. Figures 8(a)–(d) present the frequency responses of the first, second, fourth, and sixth flexural modes of the LSR for both drive and sense configurations, along with the corresponding output magnitude ratios for each mode. A consistent trend is observed across all modes, with the PZT drive and AlN sense configuration producing a higher amplitude than the reverse AlN drive and PZT sense configuration. Nonetheless, the degree of improvement varies from mode to mode, as reflected in the amplitude ratios. For example, the fourth mode exhibits the highest ratio of $21.30\times$, followed by the first mode with approximately $8.17\times$, while the sixth mode shows a ratio around $4\times$. Although the fourth mode yields the largest ratio, the absolute output magnitude of the frequency response is highest for the second mode, followed by the first mode. The variation in output among modes is governed by

Table 1 Ratio of the electrical response of the second mode between the PZT drive/AlN sense and AlN drive/PZT sense configurations across multiple fabrication batches with varying diaphragm dimensions, SOI thicknesses, and operating frequencies.

SOI Thickness	Diaphragm Radius	Ratio of	Operating Frequency
		PZT drive/AlN sense and AlN drive/PZT sense	
10 μm	500 μm	Device 1: 6.02	270 kHz
		Device 2: 6.17	
		Device 3: 7.70	
10 μm	300 μm	Device 1: 4.08	700 kHz
		Device 2: 4.00	
		Device 3: 3.72	
10 μm	150 μm	Device 1: 2.70	2.5 MHz
		Device 2: 2.10	
5 μm	500 μm	Device 1: 9.65	200 kHz
		Device 2: 9.46	
		Device 3: 9.31	
5 μm	300 μm	Device 1: 7.97	470 kHz
		Device 2: 7.51	
		Device 3: 9.50	

how strain is distributed within each mode and by how effectively this strain couples to the piezoelectric transduction.

To confirm that the observed enhancement is not limited to a particular set of dimensions or operating frequencies, and to evaluate how variations in the deposition area affect the material properties and the resulting LSR response, we fabricated additional batches with two different layer thicknesses and three different diaphragm radii. As seen above, the device with a 10 μm diaphragm thickness and a 500 μm radius demonstrates the concept effectively. To verify repeatability, we performed the same measurements on two additional devices with identical dimensions, focusing on the second mode. Both devices exhibited a similar trend, with an output voltage ratio of approximately $6\times$ within the same operating frequency range. The results from these devices also appear in the poling and multimode analyses (see Figures 7 and 8). Along with these devices, we fabricated additional LSR with diaphragm radii of 300 μm and 150 μm , corresponding to operating frequencies of about 700 kHz and 2.5 MHz, respectively. Notably, the device with a 300 μm radius exhibits an output voltage magnitude ratio between the PZT drive/AlN sense configuration and its reverse in the range of $3.7\text{--}4\times$ for three devices, while the 150 μm device shows ratios in the range of $2.1\text{--}2.7\times$ for two devices, as illustrated in Table 1.

For further comparison and to validate the performance, we also fabricated devices with a lower device layer thickness of 5 μm while maintaining radii of 500 μm and 300 μm , corresponding to operating frequencies of 200 kHz and 470 kHz, respectively. Table 1 presents the output magnitude ratios between the PZT drive/AlN sense configuration and its reverse, which fall in the ranges of $9.3\text{--}9.65\times$ for the 500 μm radius devices and $7.5\text{--}9.5\times$ for the 300 μm radius devices, with three devices tested for each case. These trends likely arise because thinner diaphragms exhibit lower flexural rigidity, leading to enhanced stiffness modulation; similarly, larger diaphragm radii further reduce the effective flexural rigidity, thereby improving electromechanical transduction. As a result, this variation in flexural rigidity governs the overall effective FoM of the flexural resonator, leading to higher output magnitude ratios, which is also consistently observed in the simulation analysis (for more details, see Section S7 of the supplementary material). Overall, these results confirm and generalize the robustness of the enhancement mechanism across different

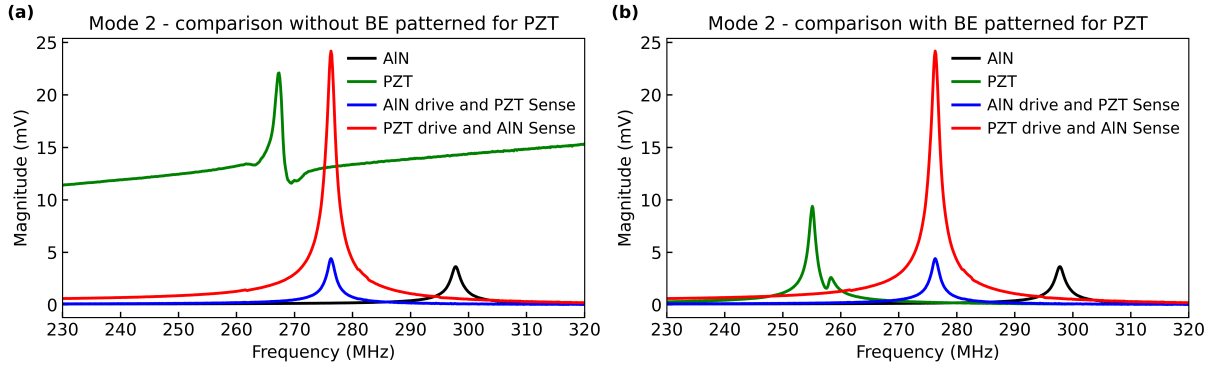


Fig. 9 Electrical frequency response of the LSR at the second mode compared with conventional single material resonators. (a) Comparison among the PZT drive/AIN sense, AIN drive/PZT sense, standalone PZT resonator, and standalone AIN resonator. (b) Same comparison as in (a), but using a standalone PZT resonator with a patterned bottom electrode.

device geometries and indicate that device scaling, through diaphragm radius and thickness, along with ferroelectric and piezoelectric material properties, serves as an effective parameter for tuning LSR performance. Having established the potential of lateral stacking, we next compare the LSR with standalone AIN and PZT resonators to quantitatively assess the performance benefits offered by this architecture.

3.5 Performance Comparison Between the LSR and Standalone AIN/PZT Resonators

To further verify the advantages of integrating ferroelectric and piezoelectric materials within a single resonator, and to provide direct evidence that lateral stacking offers performance benefits beyond those of individual materials, we fabricated standalone AIN and standalone PZT PMUTs on the same chip alongside the hybrid LSR. All three device types were produced using identical thin-film stacks and fabrication parameters, ensuring a fair and controlled comparison of their electromechanical response. To continue our analysis with the second mode, we compare the frequency response for all four configurations using devices with the same diaphragm radius and thickness. Figure 9(a) shows the second mode frequency responses for the PZT drive/AIN sense, AIN drive/PZT sense, standalone AIN, and standalone PZT configurations. Notably, the PZT drive/AIN sense configuration exhibits the highest output magnitude among all four cases, while the standalone AIN resonator shows the lowest amplitude. Although the standalone PZT resonator outperforms the AIN drive/PZT sense and standalone AIN configurations, its high dielectric ferroelectric layer introduces substantial feedthrough capacitance, which increases the noise floor. To obtain a fairer comparison with the standalone PZT resonator by minimizing feedthrough effects, we fabricated all four configurations while keeping every parameter identical except for the bottom electrode of the standalone PZT device, which was patterned. Patterning the bottom electrode disrupts the unintended bypass path for the current at the base of the PZT resonator, thereby reducing parasitic effects. Figure 9(b) depicts the second mode frequency responses of the LSR and the standalone AIN/PZT PMUTs with the patterned PZT bottom electrode. Notably, patterning significantly reduces the feedthrough in the standalone PZT device, enabling a much clearer comparison among the four configurations. The results explicitly confirm that the PZT drive/AIN sense configuration yields the highest output magnitude, owing to the combined advantage of the high piezoelectric coefficient of PZT and the low permittivity of AIN (a comparison over a broader frequency range up to 5 MHz is presented in Section S5 of the Supplementary Material).

Overall, the LSR demonstrates superior resonator performance by efficiently facilitating both actuation and sensing when compared with conventional standalone ferroelectric or piezoelectric MEMS resonators. The results across multiple device dimensions, modes, and material configurations consistently highlight the effectiveness of lateral stacking in enhancing electromechanical coupling, suppressing feedthrough, and improving signal amplitude. These combined advantages establish the LSR as a robust and versatile platform offering significant potential for next-generation MEMS technologies.

4 Conclusion

This paper presents a novel fabrication platform that enables the lateral integration of two distinct piezoelectric and ferroelectric materials within a single MEMS resonator. To demonstrate the fabrication process and working principle, a ferroelectric material PZT with a high transduction coefficient and a piezoelectric material AlN with low permittivity are laterally deposited in equal areas within the same plane to realize a hybrid circular PMUT. To validate the proof of concept, the electrical response of the second resonant mode of the PMUT is used to enable a direct comparison of the roles of the ferroelectric and piezoelectric materials in transduction under identical strain conditions. When unpoled PZT is used for actuation and AlN for sensing, the electrical response magnitude is significantly higher than that obtained for the reverse configuration. These results establish the efficacy of the proposed fabrication approach in harnessing the complementary advantages of multiple piezoelectric and ferroelectric thin films within a single device. Specifically, this architecture also enables DC tuning through the ferroelectric layer while benefiting from the low capacitive feedthrough of the piezoelectric material. In addition, the influence of ferroelectric poling on LSR performance is demonstrated through a comparison of device responses before and after poling. To further highlight the performance distinction between the LSR and conventional resonators, additional benchmarking against single material resonators is performed, clearly demonstrating the advantages of the proposed architecture. The LSR exhibits stable performance with frequency sweeps up to 5 MHz, indicating its potential for reliable operation in higher frequency regimes. Beyond second mode operation, devices with different resonant modes and a range of dimensions are also fabricated and evaluated to support the generality of the concept. Finally, the compatibility of the proposed approach with standard fabrication techniques makes it well-suited for the scalable development of advanced MEMS applications, such as imaging and adaptive sensing.

Supporting Information

The online version contains supplementary material available at journal website.

Acknowledgements

This work was financially supported by the Prime Minister’s Research Fellowship (PMRF), Anusandhan National Research Foundation (ANRF) under grant CRG/2023/007133 and the Department of Science & Technology (DST) under grant DST/TDT/AM/2022/084. The authors would like to thank the National Nanofabrication Centre (NNFC) for the fabrication facility, the Micro Nano Characterization Facility (MNCF), the MEMS Packaging Lab for the characterization facilities, and the Multidisciplinary Micro and Nano Systems (MMNS) Lab at the Centre for Nano Science and Engineering, Indian Institute of Science, for access to characterization tools.

References

- [1] P. Muralt, Recent progress in materials issues for piezoelectric mems. *Journal of the American Ceramic Society* **91**(5), 1385–1396 (2008)

- [2] H.C. Song, P. Kumar, D. Maurya, M.G. Kang, W.T. Reynolds, D.Y. Jeong, C.Y. Kang, S. Priya, Ultra-low resonant piezoelectric mems energy harvester with high power density. *Journal of Microelectromechanical Systems* **26**(6), 1226–1234 (2017)
- [3] G. Pillai, S.S. Li, Piezoelectric mems resonators: A review. *IEEE Sensors Journal* **21**(11), 12589–12605 (2020)
- [4] Y. Hui, J.S. Gomez-Diaz, Z. Qian, A. Alu, M. Rinaldi, Plasmonic piezoelectric nanomechanical resonator for spectrally selective infrared sensing. *Nature communications* **7**(1), 11249 (2016)
- [5] P. Kumar, D. Sahana, L. Chandrashekar, A. Jeyaseelan, M. Nayak, R. Pratap, G. Pillai, Ultrasensitive pressure sensor based on an integrated circular piezoelectric mems resonator and diaphragm structure. *IEEE Sensors Letters* **7**(12), 1–4 (2023)
- [6] Y. Qiu, J.V. Gigliotti, M. Wallace, F. Griggio, C.E. Demore, S. Cochran, S. Troler-McKinstry, Piezoelectric micromachined ultrasound transducer (pmut) arrays for integrated sensing, actuation and imaging. *Sensors* **15**(4), 8020–8041 (2015)
- [7] X. Jiang, Y. Lu, H.Y. Tang, J.M. Tsai, E.J. Ng, M.J. Daneman, B.E. Boser, D.A. Horsley, Monolithic ultrasound fingerprint sensor. *Microsystems & nanoengineering* **3**(1), 1–8 (2017)
- [8] S. Panda, S. Hajra, K. Mistewicz, P. In-na, M. Sahu, P.M. Rajaitha, H.J. Kim, Piezoelectric energy harvesting systems for biomedical applications. *Nano Energy* **100**, 107514 (2022)
- [9] Q. Zhou, S. Lau, D. Wu, K.K. Shung, Piezoelectric films for high frequency ultrasonic transducers in biomedical applications. *Progress in Materials Science* **56**(2), 139–174 (2011)
- [10] Y. Lu, H.Y. Tang, S. Fung, B.E. Boser, D.A. Horsley, *Short-range and high-resolution ultrasound imaging using an 8 MHz aluminum nitride PMUT array*, in *2015 28th IEEE International Conference on Micro Electro Mechanical Systems (MEMS)* (IEEE, 2015), pp. 140–143
- [11] Z. Zhou, S. Yoshida, S. Tanaka, Epitaxial pmnn-pzt/si mems ultrasonic rangefinder with 2 m range at 1 v drive. *Sensors and Actuators A: Physical* **266**, 352–360 (2017)
- [12] Y. Chu, P. Kharel, W.H. Renninger, L.D. Burkhart, L. Frunzio, P.T. Rakich, R.J. Schoelkopf, Quantum acoustics with superconducting qubits. *Science* **358**(6360), 199–202 (2017)
- [13] P. Muralt, R.G. Polcawich, S. Troler-McKinstry, Piezoelectric thin films for sensors, actuators, and energy harvesting. *MRS bulletin* **34**(9), 658–664 (2009)
- [14] J. Tichý, J. Erhart, E. Kittinger, J. Prívratská, (Springer Science & Business Media, 2010)
- [15] L. Jin, F. Li, S. Zhang, Decoding the fingerprint of ferroelectric loops: comprehension of the material properties and structures. *Journal of the American Ceramic Society* **97**(1), 1–27 (2014)
- [16] M.A. Dubois, P. Muralt, Measurement of the effective transverse piezoelectric coefficient e_{31} , f of aln and pb (zrx, ti1-x) o₃ thin films. *Sensors and Actuators A: Physical* **77**(2), 106–112 (1999)
- [17] P. Muralt, Ferroelectric thin films for micro-sensors and actuators: areview. *Journal of Micromechanics and Microengineering* **10**(2), 136 (2000)
- [18] S. Troler-McKinstry, F. Griggio, C. Yaeger, P. Jousse, D. Zhao, S.S. Bharadwaja, T.N. Jackson, S. Jesse, S.V. Kalinin, K. Wasa, Designing piezoelectric films for micro electromechanical systems. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control* **58**(9), 1782–1792 (2011)
- [19] K. Uchino, Piezoelectric actuator renaissance. *Phase Transitions* **88**(3), 342–355 (2015)
- [20] G.L. Luo, Y. Kusano, D.A. Horsley, Airborne piezoelectric micromachined ultrasonic transducers for long-range detection. *Journal of Microelectromechanical Systems* **30**(1), 81–89 (2020)
- [21] X. Jiang, H.Y. Tang, Y. Lu, E.J. Ng, J.M. Tsai, B.E. Boser, D.A. Horsley, Ultrasonic fingerprint sensor with transmit beamforming based on a pmut array bonded to cmos circuitry. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control* **64**(9), 1401–1408 (2017)

- [22] Y. Kusano, I. Ishii, T. Kamiya, A. Teshigahara, G.L. Luo, D.A. Horsley, High-spl air-coupled piezoelectric micromachined ultrasonic transducers based on 36% scaln thin-film. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control* **66**(9), 1488–1496 (2019)
- [23] Z. Liu, S. Yoshida, D.A. Horsley, S. Tanaka, Fabrication and characterization of row-column addressed pmut array with monocrystalline pzt thin film toward creating ultrasonic imager. *Sensors and Actuators A: Physical* **342**, 113666 (2022)
- [24] J.L. Lin, Y.H. Liu, C.L. Kao, S.W. Wu, H.J. Hsu, H.C. Lin, C.Y. Li, C.Y. Chen, Y.H. Wang, C.H. Huang, Air-coupled piezoelectric micromachined ultrasonic transducer array based on low-cost and large remnant polarization pzt thin film. *Scientific Reports* **15**(1), 38158 (2025)
- [25] Y. Lu, D.A. Horsley, Modeling, fabrication, and characterization of piezoelectric micromachined ultrasonic transducer arrays based on cavity soi wafers. *Journal of Microelectromechanical Systems* **24**(4), 1142–1149 (2015)
- [26] Q. Wang, Y. Lu, S. Mishin, Y. Oshmyansky, D.A. Horsley, Design, fabrication, and characterization of scandium aluminum nitride-based piezoelectric micromachined ultrasonic transducers. *Journal of Microelectromechanical Systems* **26**(5), 1132–1139 (2017)
- [27] P. Muralt, *Which is the best thin film piezoelectric material?*, in *2017 IEEE International Ultrasonics Symposium (IUS)* (IEEE, 2017), pp. 1–1
- [28] K. Roy, J.E.Y. Lee, C. Lee, Thin-film pmut: A review of over 40 years of research. *Microsystems & Nanoengineering* **9**(1), 95 (2023)
- [29] K. Roy, A. Kumar, V. Shastri, I. Munjal, K. Kalyan, A. Ashok, A. Jeyaseelan, J. Prakash, R. Pratap, Pmut-powered photoacoustic detection: Revolutionizing microfluidic concentration measurements. *IEEE Transactions on Instrumentation and Measurement* **73**, 1–8 (2024)
- [30] E. Moisello, L. Novaresi, E. Sarkar, P. Malcovati, T.L. Costa, E. Bonizzoni, Pmut and cmut devices for biomedical applications: A review. *IEEE Access* **12**, 18640–18657 (2024)
- [31] P. Kumar, D. Sahana, L. Chandrashekar, A. Jeyaseelan, G. Pillai, et al., *Evolution of Phononic Frequency Combs in Curved Piezoelectric Micromachined Ultrasonic Transducers (PMUTs) under Single-tone Actuation*, in *2024 IEEE Ultrasonics, Ferroelectrics, and Frequency Control Joint Symposium (UFFC-JS)* (IEEE, 2024), pp. 1–3
- [32] H. Nazemi, J. Antony Balasingam, S. Swaminathan, K. Ambrose, M.U. Nathani, T. Ahmadi, Y. Babu Lopez, A. Emadi, Mass sensors based on capacitive and piezoelectric micromachined ultrasonic transducers—cmut and pmut. *Sensors* **20**(7), 2010 (2020)
- [33] Y. Wang, N. Lv, L. He, J. Ren, Analysis, modeling and design of piezoelectric-capacitive hybrid micromachined ultrasonic transducer. *Smart Materials and Structures* **34**(1), 015020 (2024)
- [34] B.L. Turner, S. Senevirathne, K. Kilgour, D. McArt, M. Biggs, S. Menegatti, M.A. Daniele, Ultrasound-powered implants: a critical review of piezoelectric material selection and applications. *Advanced Healthcare Materials* **10**(17), 2100986 (2021)
- [35] T.G. La, L.H. Le, Flexible and wearable ultrasound device for medical applications: A review on materials, structural designs, and current challenges. *Advanced Materials Technologies* **7**(3), 2100798 (2022)
- [36] J. Yin, Z. Zhou, L. Lou, A novel nondestructive testing probe using aln-based piezoelectric micromachined ultrasonic transducers (pmuts). *Micromachines* **15**(3), 306 (2024)
- [37] M. Sarafianou, D.S.W. Choong, D.J. Goh, S. Merugu, Q.X. Zhang, P.H. Chang, D. Giusti, A. Leotti, R. Shankar, G. Koppiseti, et al., *Short-Range Small-Form-Factor 2D Source Localization Using pMUT-Based Delay-Multiply-and-Sum Imaging Towards Catheter Coordination*, in *2024 IEEE Ultrasonics, Ferroelectrics, and Frequency Control Joint Symposium (UFFC-JS)* (IEEE, 2024), pp. 1–4

- [38] S. Akhbari, F. Sammoura, S. Shelton, C. Yang, D. Horsley, L. Lin, *Highly responsive curved aluminum nitride pMUT*, in *2014 IEEE 27th International Conference on Micro Electro Mechanical Systems (MEMS)* (IEEE, 2014), pp. 124–127
- [39] S. Pala, L. Lin, *Piezoelectric micromachined ultrasonic transducers (pMUT) with free boundary*, in *2020 IEEE International Ultrasonics Symposium (IUS)* (IEEE, 2020), pp. 1–4
- [40] S. Akhbari, F. Sammoura, C. Yang, M. Mahmoud, N. Aqab, L. Lin, *Bimorph pMUT with dual electrodes*, in *2015 28th IEEE International Conference on Micro Electro Mechanical Systems (MEMS)* (IEEE, 2015), pp. 928–931
- [41] W. Kang, J. Jung, W. Lee, J. Ryu, H. Choi, A thickness-mode piezoelectric micromachined ultrasound transducer annular array using a pmn–pzt single crystal. *Journal of Micromechanics and Microengineering* **28**(7), 075015 (2018)
- [42] S. Yoshida, H. Hanzawa, K. Wasa, S. Tanaka, Fabrication and characterization of large figure-of-merit epitaxial pmnn-pzt/si transducer for piezoelectric mems sensors. *Sensors and Actuators A: Physical* **239**, 201–208 (2016)
- [43] V. Singh, H. Kumar, D. Kharat, S. Hait, M. Kulkarni, Effect of lanthanum substitution on ferroelectric properties of niobium doped pzt ceramics. *Materials Letters* **60**(24), 2964–2968 (2006)
- [44] M. Pirro, B. Herrera, M. Assylbekova, G. Giribaldi, L. Colombo, M. Rinaldi, *Characterization of dielectric and piezoelectric properties of ferroelectric alscn thin films*, in *2021 IEEE 34th International Conference on Micro Electro Mechanical Systems (MEMS)* (IEEE, 2021), pp. 646–649
- [45] H.H. Nguyen, Y. Takayama, H. Kuwano, *MgHf Co-Doped Aln Thin Films Toward Low Signal-to-Noise Ratio in Piezoelectric Micromachined Ultrasonic Transducers*, in *2025 IEEE 38th International Conference on Micro Electro Mechanical Systems (MEMS)* (IEEE, 2025), pp. 95–98
- [46] S. Trivedi, D.J. Goh, P.C. Ramegowda, J. Liu, Y.S. Teo, H. Yan, R. Shankar, N.G. Zakiyyan, A. Das, C. Lazzari, et al., Beam and cantilever supported pmut for enhanced transmit sensitivity and linearity. *IEEE Sensors Journal* (2025)
- [47] M. Ji, H. Yang, Y. Zhou, X. Xiu, H. Lv, S. Zhang, Bimorph dual-electrode scaln pmut with two terminal connections. *Micromachines* **13**(12), 2260 (2022)
- [48] Z. Yao, V. Chuluhadze, Z. Liu, X. Niu, T.H. Hsu, B. Kim, N. Hall, R. Lu, *Bimorph Lithium Niobate Piezoelectric Micromachined Ultrasonic Transducer*, in *2025 IEEE International Ultrasonics Symposium (IUS)* (IEEE, 2025), pp. 1–3
- [49] X. Qi, S. Yoshida, S. Risquez, A. Ghosh, M. Moridi, S. Tanaka, Fabrication of a piezoelectric micromachined ultrasonic transducer (pmut) with dual heterogeneous piezoelectric thin film stacking. *Journal of Micromechanics and Microengineering* **34**(3), 035005 (2024)
- [50] L. Thomas C, P. Kumar, S. Khan, G. Pillai, *Novel Fabrication Scheme Using Lateral Stacking of Hybrid Piezo/Ferroelectric Thin-Films for MEMS Resonators*, in *2025 23rd International Conference on Solid-State Sensors, Actuators and Microsystems (Transducers)* (2025), pp. 731–734
- [51] Y. Gao, L. Zhao, C. Yang, Y. Lu, *Ultra-wide range frequency tuning of piezoelectric micromachined ultrasonic transducers via DC bias voltage*, in *2024 IEEE 37th International Conference on Micro Electro Mechanical Systems (MEMS)* (IEEE, 2024), pp. 935–938
- [52] P. Kumar, L. Chandrashekar, A. Jeyaseelan, G. Pillai, Evolution of tunable phononic frequency combs via three-mode interaction in curved piezoelectric micromachined ultrasonic transducers. *Scientific Reports* **15**(1), 16105 (2025)
- [53] Q.M. Wang, T. Zhang, Q. Chen, X.H. Du, Effect of dc bias field on the complex materials coefficients of piezoelectric resonators. *Sensors and Actuators A: Physical* **109**(1-2), 149–155 (2003)

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