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PIEZOELECTRIC MICROMACHINED ULTRASONIC TRANSDUCER (PMUT) BASED ON BILAYER X-CUT LITHIUM NIOBATE

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ABSTRACT

This work demonstrates, for the first time, PMUTs based on bilayer X-cut lithium niobate (LiNbO₃). Different figures of merit (FoMs) for PMUT materials were first analyzed, highlighting LiNbO₃ as a promising and well-balanced alternative. To leverage its superior material properties, PMUTs were designed based on bilayer X-cut LiNbO₃ to fully harnesses the in-plane stress associated with the bending of the structure, thereby enhancing transduction efficiency. The fabricated devices show high electromechanical coupling (k_t^2) of 4.6%, albeit significantly lower than the simulated value due to parasitic effects. A comparison with PMUTs based on other materials is provided. Our devices show comparable performance to PZT-based PMUTs, and significant improvements with respect to ScAlN-based PMUTs in terms of static displacement sensitivity, by a factor of 5, and radiated acoustic power, by a factor of 7. These results showcase the strong potential of LiNbO₃ for high-performance PMUTs.

KEYWORDS

Piezoelectric micromachined ultrasonic transducers (PMUT), mechanical resonator, bending mode, lithium niobate.

INTRODUCTION

Piezoelectric micromachined ultrasonic transducers (PMUTs) have emerged as a promising technology for diverse applications of ultrasound, spanning medical imaging [1], [2], fingerprint sensing [3], [4], range finding [5], [6] and wireless communications [7], [8]. Compared to capacitive micromachined ultrasonic transducers (CMUTs), PMUTs offer distinct advantages, including the elimination of DC bias requirements, inherently linear responses, and high deflection dynamic ranges, while retaining on-chip integration capability. A key challenge for state-of-the-art PMUTs is their limited transmission and reception sensitivities, mainly constrained by the mechanical and electrical properties of available piezoelectric materials.

The figures of merit (FoMs) defined in Table 1 are used to compare piezoelectric materials for PMUTs independently of device geometry [9]. The transmitting FoM is defined as the effective piezoelectric coefficient e_f , since the deflection of a plate structure is directly proportional to it. For PMUTs functioning as receivers, the signal-to-noise ratio (SNR) is a crucial performance metric. The FoM that accounts for maximum SNR in ultrasound reception includes the thermal noise arising from the material's dielectric loss. This results in a receiving FoM defined as $e_f / \sqrt{\epsilon_f \tan \delta}$, where ϵ_f is the effective dielectric constant in the direction of the electric field and $\tan \delta$ is the dielectric loss tangent. Note that e_f and ϵ_f

differ from bulk material coefficients due to the boundary conditions experienced by the thin film [10]. Finally, the transceiving FoM, representing the ultrasound round-trip performance, is given by the product of the transmitting and receiving FoMs.

Table 1 compares different materials under their best operation mode, considering that LiNbO₃ operates more efficiently under lateral-field-excitation (LFE), whereas the other materials listed operate more efficiently under thickness-field-excitation (TFE). Fig. 1(a) illustrates the transceiving FoM of X-cut and 36°Y-cut LiNbO₃ as a function of in-plane rotation angle, defined as the angle of the electric field with respect to the polarization (Z-axis) of the material [Fig. 1(b)]. As shown, the maximum FoM of X-cut LiNbO₃ occurs at the in-plane rotation angle of 120°.

Table 1: FoMs of common materials for PMUTs.

Material	Transmitting FoM	Receiving FoM	Transceiving FoM	Ref.
	e_f (C/m ²)	$e_f / \sqrt{\epsilon_f \tan \delta}$ (10 ⁶) ^{1/2} /m ^{3/2}	$e_f^2 / \sqrt{\epsilon_f \tan \delta}$ (10 ⁶ C) ^{1/2} /m ^{7/2}	
AlN	1.05	3.40	3.57	[9]
ScAlN 70/30	2.25	3.10	6.98	[9]
PZT 53/47	18.70	1.10	20.57	[9]
PMN-PT	26	0.84	21.84	[9]
KNN	8.50-14.40	2.45-4.15	20.83-59.76	[11]
36°Y LiNbO ₃	5.29	6.09	32.22	[12]
X LiNbO ₃	5.45	5.97	32.54	[12]

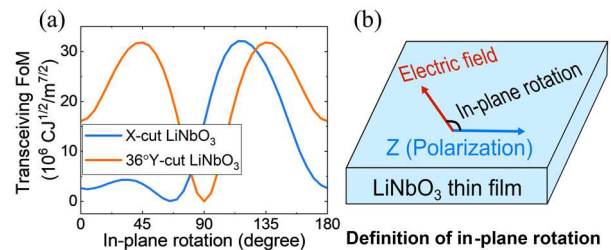


Figure 1: (a) Transceiving FoM of LiNbO₃ as a function of the in-plane angle of the electric field, as defined in (b).

The calculations in Table 1 show that, although lead-containing ceramics (PZT and PMN-PT) exhibit better transmission characteristics, LiNbO₃ provides over 5 times higher receiving FoM due to its lower permittivity and dielectric loss tangent. When benchmarked to the most widespread lead-free materials for PMUTs, AlN and ScAlN, LiNbO₃ offers nearly a factor of 5 of improvement in terms of transceiving FoM. Lastly, potassium sodium niobate (KNN) has emerged in last years as a competitive lead-free alternative [13]. While its processing is still complex, KNN shows a transceiving performance comparable to LiNbO₃ [11].

All in all, LiNbO₃ exhibits great characteristics for PMUTs, with well-balanced transmitting and receiving FoMs. Based on this analysis, this work aims to

demonstrate the potential of LiNbO₃ for PMUT implementation. For that, we rely on a bilayer structure of X-cut LiNbO₃ to fully leverage the excellent FoMs of LiNbO₃.

DESIGN AND MODELLING

PMUT devices were designed based on an X-cut LiNbO₃ bilayer structure [Fig. 2(a)]. This consists of two X-cut LiNbO₃ layers with a relative in-plane rotation of 180°, resulting in reversed orientations of the polarization axis (Z). The device features four 0.12 μm-thick gold (Au) electrodes connected in pairs on the top of the 2 μm-thick LiNbO₃ film stack on a silicon (Si) substrate [Fig. 2 (b)].

By applying a signal (V_{in}) to the interdigitated electrodes, lateral electric fields induce an alternating lateral in-plane stress within each LiNbO₃ layer, which excites flexural deformation of the structure. The reversed Z-axis orientation causes the two LiNbO₃ layers to produce in-plane stress with opposite signs when subjected to the same electric field [Fig. 2(b)]. This configuration fully harnesses the in-plane stress associated with the bending of the structure [Fig. 2(d)], thereby enhancing transduction efficiency. The thickness of the two LiNbO₃ layers was designed to be identical, ensuring the neutral axis of the plate was positioned at the interface.

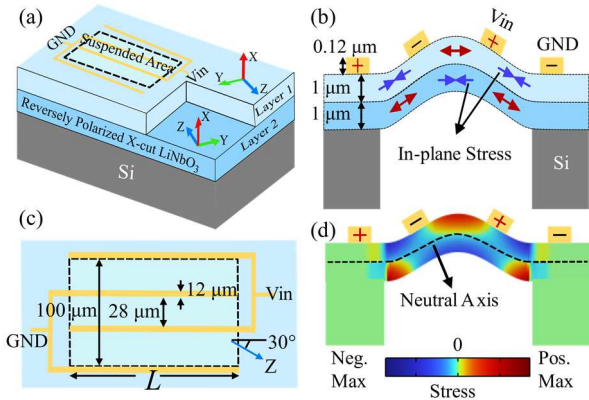


Figure 2: Schematic (a) 3D, (b) cross-sectional and (c) top view of our bilayer LiNbO₃ PMUT. The polarization axis (Z) of each LiNbO₃ layer is in the plane, with opposite directions. (d) FEM simulated cross-sectional stress distribution of the LiNbO₃ plate under bending deformation.

As shown in Fig. 2(c), the electrodes were oriented at 30° with respect to the Z-axis of the top LiNbO₃ layer to maximize the FoMs. The cavity width was designed as 100 μm, setting the resonance frequency (f_r) in vacuum around 1.2 MHz. The cavity length (L) was varied from 400 μm to 800 μm, which was optimized to be more than 4 times the width to minimize mode distortion and maintain maximal electromechanical coupling. To optimize the transduction, the inner electrodes, each 12 μm wide and separated by 28 μm, were centered at the nodal lines of the in-plane stress. The outer electrodes, also 12 μm wide, were placed just outside the suspended area along the edges to maximize the electric field at the edges.

Finite element analysis (FEA) was performed to simulate the electrical admittance (Y_{11}) and the dynamic displacement sensitivity (d_d). For devices of varying lengths, pronounced flexural modes were obtained at around 1.2 MHz, indicating the resonance frequency is dominated by the cavity width. The simulated Y_{11} admittance parameter is shown in Fig. 3(a), along with a Butterworth-Van Dyke (BVD) model fitting. The extracted electromechanical coupling k_t^2 (defined as $\pi^2/8 \cdot C_m/C_0$) is 19.25% for $L = 400$ μm. Remarkably, this k_t^2 is over 4 times higher than the previous demonstration of a single layer 36°Y-cut LiNbO₃-based PMUT [14] and 10 times higher than best ScAlN-based PMUTs [15].

Devices with varying lengths exhibit similar dynamic displacement sensitivity d_d . For a device length of 400 μm, a dynamic displacement sensitivity $d_d = 85$ nm/V was extracted, assuming a quality factor $Q = 61$ [Fig. 3(b)]. Normalized by Q , the static displacement sensitivity is $d_s = d_d/Q = 1.27$ nm/V, approximately 8 times higher than those reported for ScAlN devices [15].

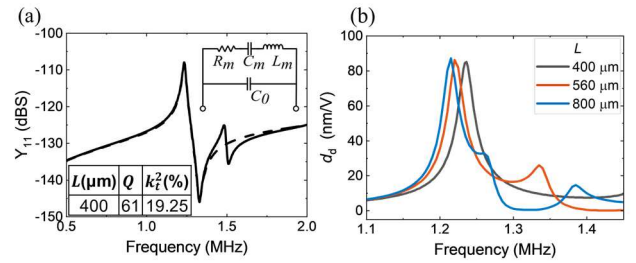


Figure 3: (a) Simulated admittance (Y_{11}). Parameters extracted from BVD fitting (dashed line) are listed in the table. Inset in (a): BVD model. (b) Simulated dynamic displacement sensitivity (d_d), evaluated at the center of the device, for various lengths.

Alongside k_t^2 and d_s , the transmitting acoustic power P is an essential metric for PMUTs. This can be modelled by modifying the device BVD model to incorporate an acoustic radiation port based on a piston model [Fig. 4]. The model includes the following parameters: static capacitance (C_0), mechanical damping (b), membrane stiffness (k), effective mass (m), acoustic impedance (Z_{ac}), electromechanical coupling coefficient (η), and effective area for acoustic radiation (A_{eff}).

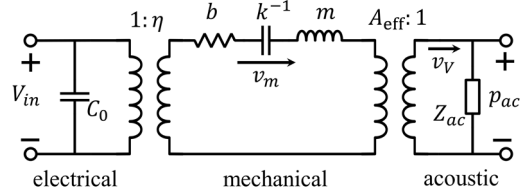


Figure 4: Equivalent circuit model of a PMUT including the electrical, mechanical, and acoustic domains.

Applying a driving signal V_{in} induces membrane vibrations with peak velocity v_m , resulting in an effective volume velocity $v_v = v_m \times A_{eff}$. The transmitting acoustic pressure is then given by $p_{ac} = v_v \times Z_{ac}$, where $Z_{ac} = z/A_{eff}$ and z is the medium's characteristic impedance [16]. Consequently, the acoustic power P is expressed as

$P = v_v \times p_{ac} = (v_m)^2 A_{eff} z$. Given that $v_m/V_{in} = \omega_r d_s Q$, where $\omega_r = \sqrt{k/m}$ is the resonance angular frequency, the transmitted acoustic power normalized by characteristic impedance and applied voltage squared can be used to compare device performance regardless of the propagation medium:

$$\frac{P}{zV_{in}^2} = (\omega_r d_s Q)^2 A_{eff}. \quad (1)$$

FABRICATION

The PMUTs were fabricated on a bilayer X-cut LiNbO₃-on-Si stack, as outlined in Fig. 5. First, 120 nm-thick Au electrodes with a 10 nm-thick Cr adhesion layer were deposited and patterned with lift-off. Subsequently, a 3 μ m-thick SiO₂ layer was deposited to protect the electrodes during backside processing, via inductively coupled plasma chemical vapor deposition (ICPCVD). A 9 μ m-thick SiO₂ hard mask was then deposited on the Si substrate using the same ICPCVD recipe. Following backside alignment, the SiO₂ hard mask was patterned using deep reactive ion etching (DRIE). The Bosch process was employed to achieve a vertical profile during through-wafer Si etching. After complete Si etching, the residual SiO₂ on both sides was removed using buffered HF (BHF). Finally, the suspended LiNbO₃ films were critical point dried (CPD) to prevent breakage.

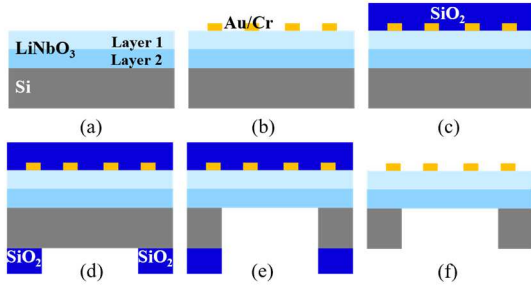


Figure 5: Fabrication process of the PMUTs.

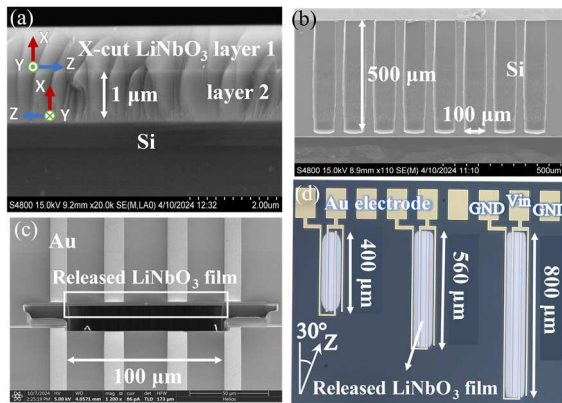


Figure 6: (a) SEM image of cross section of bilayer X-cut LiNbO₃ with Si substrate. (b) DRIE etching on a Si sample. (c) FIB-SEM image of suspended film (with 52° tilt angle). (d) Top-view optical image of the fabricated PMUTs.

The cross-sectional morphology of the wafer stack, shown in Fig. 6(a) by scanning electron microscopy (SEM), clearly reveals the interface between the two LiNbO₃ layers. The DRIE process was optimized using a

standard Si sample, achieving a satisfactory vertical profile [Fig. 6(b)]. Fabricated PMUT devices are presented in Fig. 6(d), demonstrating precise alignment between the top electrodes and the backside etched regions. To examine the cross-section of the suspended LiNbO₃ film, focused ion beam (FIB) milling was performed. The resulting SEM image [Fig. 6(c)] confirms uniform thickness of the released films and the absence of Si leftovers underneath.

CHARACTERIZATION

The fabricated devices were first characterized in air using a Keysight E4990A impedance analyzer. As shown in Fig. 7(a), the measured Y_{11} exhibits a distinct resonance peak at approximately 1.2 MHz, closely matching the simulations. However, an anti-resonance peak as expected from Fig. 3(a) was not observed. We attribute this behavior to parasitic effects arising from contaminants on the Si substrate. A modified BVD (MBVD) model was used to fit the measured Y_{11} [Fig. 7(a)], which incorporates these effects by additional circuit elements R_p and C_p in parallel to the device. The good agreement between fitting and the measured Y_{11} confirms the presence of parasitic effects. Although the extracted k_t^2 (4.6% for $L = 400 \mu$ m) is significantly lower than simulated value, attributed to the parasitic effects, it still surpasses ScAlN-based PMUTs [15] by more than a factor of 2.

The membrane vibration was measured in air using a Polytec vibrometer MSA400. Devices with varying lengths exhibited similar maximum dynamic displacement [Fig. 7(b)]. For the device with a length of 800 μ m, the measured dynamic displacement sensitivity was $d_d = 53.8 \text{ nm/V}$ with $Q = 61$ in air, yielding a static displacement sensitivity of $d_s = d_d/Q = 0.88 \text{ nm/V}$. This value is 30% lower than the simulated d_s , likely due to a slight mismatch in the thickness of the two LiNbO₃ layers.

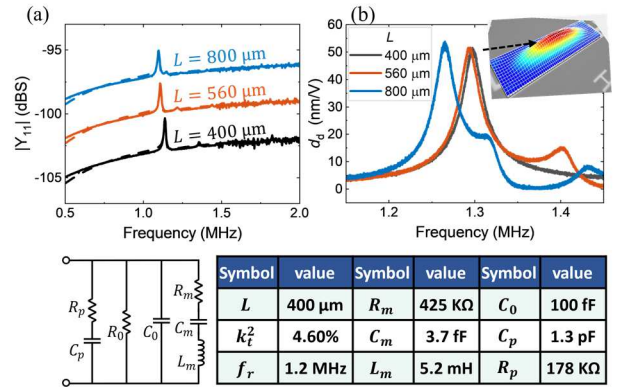


Figure 7: (a) Measured admittance and MBVD fitting (dashed lines). MBVD model and extracted parameters for the device with $L = 400 \mu$ m are shown below. (b) Measured dynamic displacement sensitivity (d_d). Inset in (b): Measured modal shape at resonance.

Fig. 8(a) compares the measured static displacement sensitivity d_s with previously reported values for other materials. As shown, the measured d_s is 5 times higher than that of reported ScAlN-based PMUTs (0.16 nm/V) [15] and close to monocrystalline PZT-based PMUTs (1 nm/V) [2]. In practice, the bandwidth of PMUTs should

be adjusted to suit the requirements of various applications. Recognizing the inherent trade-off between radiated acoustic power and fractional bandwidth ($FBW = 1/Q$), Fig. 8(b) presents a comparison of PMUTs based on the normalized acoustic power (P/zV_{in}^2), as defined in equation (1). These curves were calculated based on the reported resonance frequency, quality factor, displacement sensitivity and area. For this comparison, we assume the effective area A_{eff} equal to 1/3 of the suspended area for all devices. Specifically, at $FBW = 100\%$, the normalized acoustic power of our device is $1.32 \times 10^{-12} \text{ W/V}^2\text{Rayl}$ ($L = 800 \mu\text{m}$), which is nearly 7 times higher than ScAlN PMUTs [15] and comparable to monocrystalline PZT PMUTs [2].

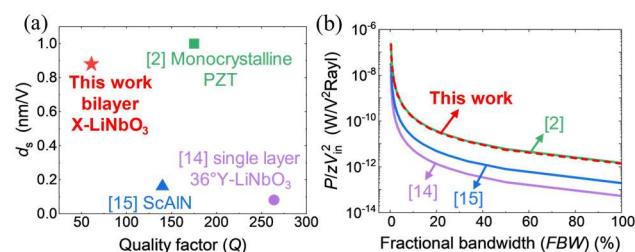


Figure 8: Comparison of (a) static displacement sensitivity (d_s) with the reported quality factor; (b) normalized acoustic power (P/zV_{in}^2) versus fractional bandwidth.

CONCLUSION

This work has demonstrated, for the first time, PMUTs based on a bilayer X-cut LiNbO_3 structure. A comprehensive material comparison highlighted the outstanding properties of LiNbO_3 for PMUTs. Based on this, PMUTs were implemented to fully harness the in-plane stress to excite the flexural vibration of the membrane, resulting in enhanced transduction efficiency. The fabricated devices exhibit a transmission performance significantly better than ScAlN devices, and comparable to monocrystalline PZT devices. The balanced FoMs of LiNbO_3 for transmission and reception of ultrasound suggest outstanding capabilities of the material to implement ultrasound transceivers. All in all, the demonstrated performance, established manufacturing process and lead-free composition of bi-layer LiNbO_3 offer great promise for a wide range of ultrasound applications.

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