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Academic Progress Report

Piezoelectric Speaker Technologies

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Abstract: The growing demand for thinner, lighter, and more energy-efficient electronic systems has driven the development of acoustic technologies toward compact and flexible sound generation platforms. Despite significant progress, conventional electromagnetic speakers remain limited by bulky structures, energy losses, and poor compatibility with modern ultrathin devices. In this review, recent advancements in piezoelectric acoustic systems are presented, demonstrating a new generation of speakers capable of producing high-fidelity sound from ultra-slim, lightweight, and mechanically compliant designs. Through refined structural configurations and efficient electromechanical coupling, these piezoelectric exciters achieve strong acoustic output, fast response, and wide frequency operation while drastically reducing component thickness. These exciters also show their suitability for seamless integration into flexible displays, wearable devices, and automotive panels, offering enhanced spatial audio practicality and multifunctional operation, including demonstrative output and sensing. This advancement marks a step toward the convergence of acoustic, haptic, and interactive technologies, for the realization of sustainable and immersive human-machine interfaces in future electronic and automotive systems.

Keywords: Piezoelectric, Speakers, Multilayers, Ceramics, Flexible, Display, Automobiles

1. INTRODUCTION

The growing demand for compact, lightweight, and energy-efficient acoustic components has catalyzed rapid progress in piezoelectric speaker (thin-exciter) technologies [1,2]. These solid-state devices, which convert electrical energy directly into mechanical vibrations, represent a paradigm shift in how sound can be generated and integrated into modern electronic systems [3]. In contrast to conventional voice-coil speakers, which rely on magnetic induction and require bulky coils, magnets, and diaphragms, piezoelectric exciters leverage the converse piezoelectric effect, a direct mechanical response to an applied electric field, to produce sound [4]. The piezoelectrics with planar geometry, low power consumption, and miniaturization potential make them especially attractive for ultra-thin displays, portable electronics, and next-generation automotive interiors [5,6].

In recent years, the field has moved beyond traditional single-layer piezoelectric buzzers toward thin and multilayer piezoelectric ceramic speakers, which integrate high-performance piezoelectric materials with advanced structural designs [6-8]. Thin piezoelectric ceramic exciters typically employ a ceramic layer directly bonded to a vibrating diaphragm [6-8]. When an alternating voltage is applied, the in-

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plane strain of the piezoelectric layer translates into out-of-plane diaphragm motion, creating acoustic pressure waves [6-8].

In parallel, multilayer piezoelectric ceramic speakers, constructed by stacking multiple thin piezoelectric layers separated by internal electrodes, have emerged as a superior architecture for low-voltage and high-output applications [9-12]. The multilayer configuration enhances the effective electric field and mechanical displacement at significantly reduced driving voltages, often below 20 V, while maintaining high-frequency response and structural integrity [11]. By integrating such multilayer actuators (MLAs) with flexible polymer diaphragms, designers can achieve hybrid devices that combine the electromechanical strength of ceramics with the acoustic compliance of polymers. This configuration enables precise control of vibration modes, improved acoustic efficiency, and wideband sound reproduction suitable for ultrathin TVs, transparent OLED displays, and automotive panels.

In the broader context of automotive and display system integration, the significance of piezoelectric exciters extends beyond their acoustic performance [11,13,14]. The low thickness, volume, and solid-state actuation allow direct embedding into structural components, such as vehicle dashboards, touch panels, or display glass, enabling sound to emanate from surfaces themselves. This functional convergence between materials and system-level design will enable us to display-integrated audio, interior acoustic personalization, and haptic-acoustic hybrid devices.

The purpose of this review is to provide a comprehensive overview of the scientific principles underlying piezoelectric speaker (thin exciter) technology and its system-level applications. We first discuss working mechanisms of both single and multilayer piezoelectric speaker architectures, then discuss the pros and cons of the piezoelectric speaker technology. Comparative analyses with traditional voice-coil speakers are presented to highlight unique advantages and engineering challenges. Finally, we will briefly discuss the benefits of applying piezoelectric speakers to future displays and automotive systems.

2. WORKING PRINCIPLES OF VOICE-COIL AND PIEZOELECTRIC SPEAKERS

The operation of acoustic transducers fundamentally relies on the conversion of electrical energy into mechanical vibration and, ultimately, into audible sound waves. While both voice-coil speakers and piezoelectric exciters perform this energy transformation, their mechanisms of actuation, structural design, and energy efficiency differ substantially. Understanding these distinctions provides critical insight into why piezoelectric exciters are increasingly considered for ultrathin and integrated acoustic systems.

2.1 Conventional Voice-Coil Speaker

As illustrated in Fig. 1(a), the voice-coil speaker is the most prevalent type in commercial audio systems that operate based on electromagnetic induction. The device consists of a lightweight diaphragm (or cone) attached to a voice coil, which is positioned within the magnetic field generated by a fixed permanent magnet. When an alternating voltage signal from an audio source is applied to the coil, an alternating current flows through it [4,15,16].

According to Lorentz's law, this current interacts with the magnetic field, producing a time-varying electromagnetic force on the coil. This electromagnetic force interacts with the magnetic field of the fixed permanent magnet, causing the mechanically connected coil and diaphragm to vibrate back and forth in response to this alternating force. The coil and diaphragm, being mechanically connected, oscillate back and forth in response to this alternating force. The diaphragm's vibration compresses and rarefies the surrounding air, generating longitudinal sound waves corresponding to the input electrical signal [15,16].

Voice-coil speakers are capable of producing wide frequency ranges and high sound pressure levels (SPL), making them the dominant choice in consumer and professional audio systems. However, their design inherently requires a magnet assembly, a suspended coil, and significant moving mass. These features limit their miniaturization, increase power consumption, and hinder integration into ultra-thin or flexible platforms such as displays or automotive interior panels.

2.2 Single-Layer Piezoelectric Ceramic Speaker

The single-layer piezoelectric speaker operates through the converse piezoelectric effect, shown schematically in

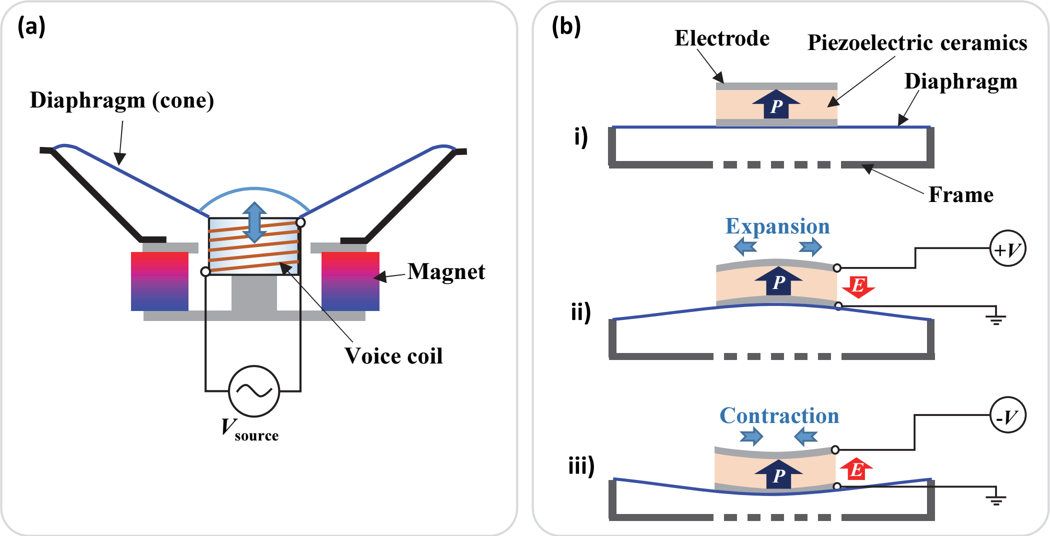

Fig. 1. Comparison of the working principles of (a) a conventional voice-coil speaker and (b) a piezoelectric ceramic speaker.

Fig. 1(b, i-iii) [1,2,17]. The actuator consists of a thin piezoelectric ceramic plate bonded to a flexible diaphragm substrate, typically made of polymeric materials such as PET or PI. When a voltage is applied across the electrodes deposited on both sides of the piezoelectric ceramics, an electric field is generated, inducing mechanical strain in the material [2,18]. If the applied electric field is opposite to the polarization direction of the piezoelectric ceramic, the piezoceramic layer contracts in thickness and expands laterally, causing the diaphragm to bend upward (Fig. 1(b-ii)). Conversely, if the applied electric field is in the same direction as the polarization direction of the piezoelectric ceramic, the piezoceramic layer expands in thickness and contracts laterally, bending the diaphragm downward (Fig. 1(b-iii)) [19,20]. The alternating expansion and contraction, driven by the audio-frequency voltage, generate mechanical vibrations that propagate as acoustic waves.

This bending-mode operation allows the single-layer piezoelectric speaker to function without coils or magnets, offering significant reductions in thickness, weight, and energy consumption. Moreover, since there are no magnetic components, electromagnetic interference (EMI) is minimized, an advantage for high-density electronic environments such as mobile devices or integrated automotive dashboards. However, due to limited strain amplitude and relatively small displacement of the piezoceramic layer, the acoustic output at low frequencies is typically lower compared to voice-coil speakers.

2.3 Double-layer and Multilayer Piezoelectric Ceramic Speakers

The structural evolution of piezoelectric exciters from single- to multilayer configurations aims to enhance acoustic output, reduce driving voltage, and improve mechanical coupling between the actuator and the diaphragm. Figure 2 schematically illustrates three representative architectures: (a) a single-layer piezoelectric speaker, (b) a double-layer sandwich structure, and (c) a multilayer piezoceramic exciter with a diaphragm.

In the single-layer configuration, a thin piezoelectric ceramic plate is bonded to a metallic or polymeric diaphragm. When an alternating voltage is applied across the electrodes, the piezoelectric layer expands and contracts in-plane due to the converse piezoelectric effect (Fig. 2(a)). This cyclic strain induces flexural deformation in the diaphragm, producing sound waves. The acoustic output in this configuration primarily depends on the bending stiffness of the diaphragm, the thickness ratio between the piezoelectric layer and the substrate, and the effective electromechanical coupling coefficient of the ceramic material [11]. Although simple in design and easy to fabricate, the single-layer system typically requires a relatively high driving voltage to generate sufficient displacement and sound pressure.

In contrast, the double-layer (sandwich-type) exciter incorporates a diaphragm between two piezoelectric ceramic layers

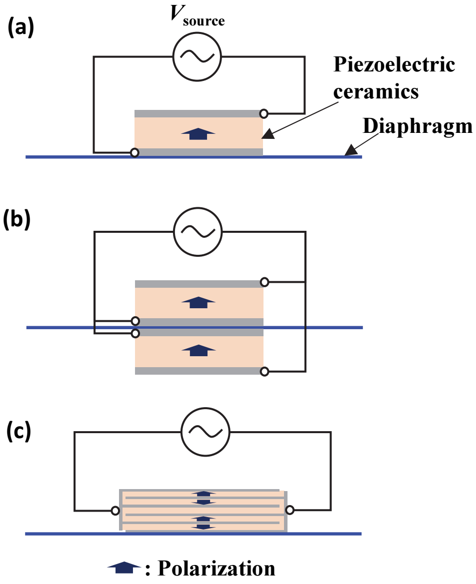

Fig. 2. The schematic illustration of the piezoelectric ceramics speakers based on the (a) single-layer piezoceramic exciter with a diaphragm, (b) double-layer piezoceramic exciters sandwiching a diaphragm, and (c) multilayer piezoceramic exciter with a diaphragm.

whose polarization directions are intentionally arranged to be opposite to each other (Fig. 2(b)). Under an applied electric field, one layer experiences the field in the same direction as its polarization, while the other experiences it in the opposite direction. When an alternating voltage is applied, this configuration causes one layer to expand and the other to contract, producing a bending mode that greatly amplifies diaphragm deflection. This balanced architecture not only increases actuation strain at a given voltage but also enhances mechanical stability and suppresses unwanted vibration modes.

The multilayer piezoelectric exciter represents a further refinement of the double-layer configuration, in which multiple thin piezoelectric sheets, typically several tens of micrometers thick, are sequentially stacked with internal electrodes (Fig. 2(c)). Each layer contributes to the overall displacement; however, because the layers are electrically connected in parallel and mechanically in series, the total driving voltage is markedly reduced. This multilayer architecture enables high acoustic output even at low operating voltages (below 20 V), making it particularly attractive for portable electronic devices and integrated display systems. The multilayer piezoelectric exciter also adopts a structure in which the upper and lower piezoelectric layers are polarized in opposite directions with respect to the central dummy layer. This antiparallel configuration enhances the effective piezoelectric strain, allowing the device to generate substantial vibration amplitudes even under relatively low electric fields. However, precise control during lamination and sintering is essential to ensure uniform layer thickness, prevent delamination, and maintain reliable electrode connectivity throughout the multilayer stack.

Collectively, the evolution from single- to multilayer architectures illustrates the tradeoff between structural complexity and performance enhancement. While the single-layer design favors simplicity and low cost, multilayer stacks deliver superior actuation efficiency, broader frequency response, and higher SPL output within compact form factors. These advantages render multilayer piezoelectric exciters ideal candidates for flat-panel acoustic systems, automotive speakers, and next-generation display-integrated speakers, where high-fidelity sound emission must coexist with ultra-thin, flexible, and power-efficient designs.

2.4 Comparative Analysis: Piezoelectric Exciters vs. Voice-Coil Speakers

The operational distinction between voice-coil speakers and piezoelectric exciters arises from their fundamentally different actuation mechanisms. Voice-coil systems employ electromagnetic induction based on the Lorentz force, where an alternating current through a coil interacts with a static magnetic field, driving the diaphragm to oscillate and generate sound waves. In contrast, piezoelectric exciters rely on the converse piezoelectric effect, wherein an applied electric field induces mechanical strain within a piezoceramic layer. This strain produces diaphragm vibrations without requiring any magnetic components, resulting in a simpler, more compact, and energy-efficient design [11].

From a point of view of performance, piezoelectric exciters offer a rapid mechanical response and exceptional high-frequency capability due to their minimal inertia and direct electro-mechanical conversion. These exciters typically exhibit superior efficiency and faster transient response compared to electromagnetic speakers, which are constrained by coil inductance and magnetic hysteresis. However, traditional voice-coil speakers maintain a clear advantage in low-frequency reproduction, as their larger mechanical stroke enables significant diaphragm displacement, essential for

Table 1. Quantitative comparison between voice-coil and piezoelectric speakers [8,11,25-30].

Parameter	Voice-coil speaker	Piezoelectric speaker
Operating principle	Lorentz-force electromagnetic actuation	Converse piezoelectric actuation
Typical frequency range	20 Hz – 20 kHz	400 Hz – 40 kHz
Sound pressure level (SPL)	90 – 110 dB (low-mid freq.)	75 – 105 dB (mid-high freq.)
Response time	1 – 10 ms	< 0.1 ms
Device thickness	> 10 mm	< 1 mm (only piezoelectric ceramic exciter)
Power consumption	High (tens to hundreds of mW)	Low (< 10 mW typical)
Integration capability	Limited (bulky and magnetic)	Excellent (planar, transparent, flexible)
Distortion level (THD)	1 – 3%	< 0.5%
Low-frequency performance	Excellent	Moderate to limited

achieving strong bass and subsonic output. In contrast, the limited strain of piezoceramics restricts low-frequency sound pressure unless compensated through multilayer stacking or acoustic cavity engineering [11].

In terms of form factors, piezoelectric exciters exhibit significant advantages. Their solid-state architecture eliminates bulky coils and magnets, enabling thicknesses below 0.5 mm and compatibility with rigid, flexible, or transparent substrates. This ultra-thin and lightweight structure allows integration into display panels, vehicle interiors, and wearable devices, where electromagnetic designs would be impractical. Voice-coil speakers, by comparison, are limited by the volumetric space required for the coil, magnet, and suspension, making them unsuitable for surface-mounted or planar applications [11].

Acoustically, piezoelectric exciters exhibit wide bandwidth, strong directivity, and minimal harmonic distortion at high frequencies, making them ideal for mid-to-high frequency sound reproduction and haptic feedback systems. However, their response can be nonlinear near mechanical resonance, which may cause localized amplification or frequency-dependent sound pressure variations. Voice-coil speakers generally provide smoother low-frequency linearity but at the cost of higher distortion and slower transient recovery [11].

The advantages of piezoelectric exciters are therefore multifold: these exciters are compact, lightweight, and energy-efficient, with extremely fast response times and no reliance on magnetic materials. Their potential use of lead-free ceramics (such as KNN, BNT-BKT systems) further enhances environmental compatibility, supporting sustainable device engineering [21-24]. Nonetheless, limitations remain, chiefly, reduced displacement at low frequencies, potential mechanical resonance effects in thin diaphragms, and the complexity of fabricating defect-free multilayer ceramics with consistent polarization alignment. Ongoing advances in material engineering, bonding interfaces, and acoustic cavity design continue to mitigate these challenges [11]. A quantitative comparison between both technologies highlights these tradeoffs, as summarized in Table 1.

A recent study demonstrated a ceramic PZT-based MEMS loudspeaker with a 6.7 mm × 6.7 mm footprint and only a 5 μm-thick piezo layer, achieving a maximum sound pressure level (SPL) of ~108 dB at 8.2 kHz under only 5 V driving voltage [29]. While the SPL is impressive for such a form factor, the authors note that it is achieved at a resonant frequency and small radiating area and cannot claim a high broadband electrical-to-acoustic power efficiency [8]. One of the advantages of such devices is that piezoelectric materials exhibit intrinsically higher electroacoustic conversion efficiency than conventional voice-coil counterparts, making them attractive for low-power applications. However, it should be noted that the value for overall acoustic conversion efficiency in air-coupled operation is not yet reported.

3. CONVERGENCE OF DISPLAY AND ACOUSTIC TECHNOLOGIES

3.1 Evolution of Display Technologies: Toward Thinner, Larger, and Multifunctional Platforms [8,14,31,32]

The trajectory of display technologies over the past six decades represents one of the most transformative evolutions in modern electronics, driven by an enduring pursuit of thinner profiles, larger panel sizes, higher resolution, and integrated multifunctionality. Beginning with the cathode-ray tube (CRT) displays of the mid-20th century, display systems were characterized by significant bulk and power consumption, with thickness exceeding 300 mm and limited scalability. The transition to liquid-crystal displays (LCDs) and plasma display panels (PDPs) in the late 1990s marked the first major reduction in thickness to below 100 mm, enabling flat-panel designs that redefined aesthetic and ergonomic standards in consumer electronics (Figs. 3 and 4). The introduction of light-emitting diode (LED) backlighting further revolutionized this trajectory, allowing even slimmer and more energy-efficient panels, while dramatically enhancing brightness and contrast. By the early 2010s, organic light-emitting diode (OLED) technology emerged as the pivotal milestone, offering self-emissive pixels that eliminated the need for external backlights. OLED panels achieved ultra-thin profiles below ~4 mm, accompanied by unprecedented image fidelity, faster response times, and wide viewing angles (Figs. 3 and 4). This breakthrough not only transformed display performance but also enabled mechanical flexibility and curvature, paving the way for foldable, rollable, and transparent displays (Fig. 3). Beyond conventional visualization, display surfaces have evolved into multifunctional interactive interfaces, capable of sensing, emitting sound, and responding to external stimuli. Recent advancements emphasize mechanical stretchability, transparent electrode integration, and functional hybridization, combining optical, electrical, and acoustic functionalities into unified platforms. Companies such as LG Display, Samsung Display, and BOE are now developing stretchable and frameless OLED panels that blur the boundary between structure and function. The industry's focus has shifted from merely displaying information to creating immersive, intelligent, and responsive surfaces (Fig. 3). This continuous miniaturization and functional integration of displays further requires thinner and lighter speaker elements for integrated sound functionality.

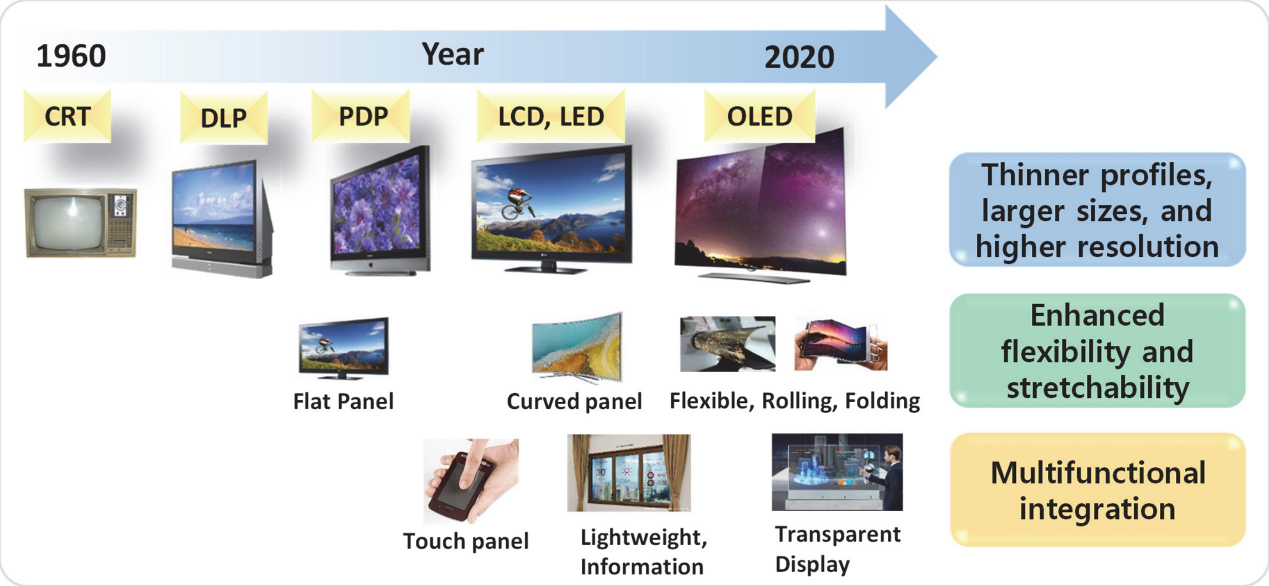

Fig. 3. Evolution of display technologies from CRT to OLED, highlighting key advancements in image quality, device thinness, flexibility, and multifunctional integration [14,31-33]. Abbreviations: CRT (cathode ray tube), DLP (digital light processing), PDP (plasma display panel), LCD (liquid crystal display), LED (light emitting diode), and OLED (organic light emitting diode).

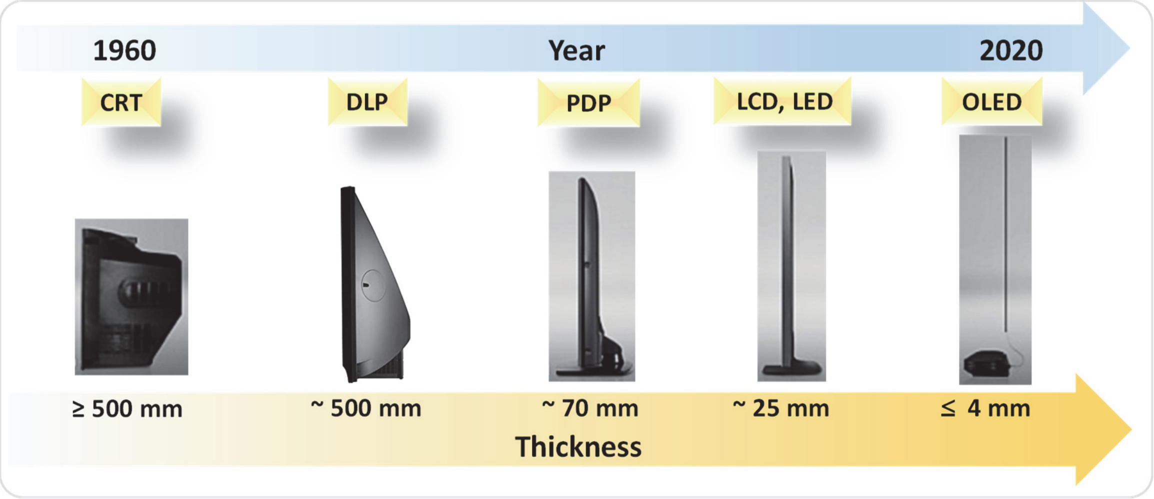

Fig. 4. Progressive reduction in display thickness from CRT to OLED technology, illustrating major generational shifts in form factor [14,31-34].

3.2 From Conventional to Screen-Integrated Sound Systems [13,16,34-36]

Recent advances in display and mobile device technologies have accelerated the demand for thinner, lighter, and more integrated audio solutions. Conventional electromagnetic speakers, comprising diaphragms, coils, and magnetic structures, impose inherent constraints on the miniaturization and integration of modern electronic systems. Their reliance on mechanical resonance chambers and spatially separated acoustic outlets often limits the form-factor flexibility of devices such as smartphones, tablets, and automotive displays. As reported by IEEE Spectrum (2024), these mechanical dependencies not only hinder compact design but also cause perceptual mismatches between visual and auditory cues, as sound typically originates from regions peripheral to the display (Figs. 5(a) and 5(b)). This spatial separation leads to a diminished immersive experience.

To address these limitations, researchers and manufacturers have shifted toward display-integrated piezoelectric audio systems, where a thin piezoelectric exciter is directly bonded to the rear surface of the display panel or substrate. In this configuration, the display itself serves as the sound-emitting surface, converting electrical signals into localized mechanical vibrations that radiate acoustic waves toward the viewer (Fig. 5(c)). This approach eliminates bulky acoustic cavities and speaker grilles, resulting in ultra-thin, water-resistant, and

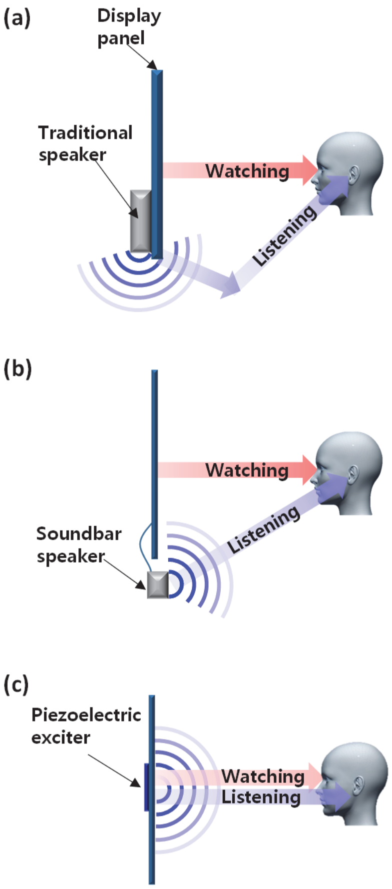

Fig. 5. Spatial relationship between sound and image by sound propagated by (a) a traditional speaker mounted on the back of the display panel, (b) a soundbar speaker separated from the display, and (c) a piezoelectric exciter mounted on the display [14,16,35,36].

dustproof designs. More importantly, because the sound originates from the visual surface itself, the audiovisual alignment is greatly improved, enhancing realism and immersion in user interaction.

However, several technical challenges persist in achieving uniform performance across large display areas. As emphasized by IEEE Spectrum (2024), the limited driving voltage available in mobile systems requires high-efficiency driver amplifiers capable of producing sufficient displacement without waveform distortion. In addition, maintaining wideband frequency response, minimizing harmonic distortion, and ensuring consistent output intensity across flexible display substrates remain active research areas. Nonetheless, the convergence of piezoelectric, MEMS, and thin-film technologies is paving the way for fully integrated sound and haptic displays, marking a fundamental shift in audio interface design for next-generation smartphones, tablets, laptops, and automotive systems.

3.3 Smartphone Screens are about to Become Speakers [14,32,36]

Recent progress in display and mobile device engineering is driving a strong push toward thinner, lighter, and fully integrated audio systems. Traditional electromagnetic speakers, constrained by their coils, magnets, and resonance chambers, limit further device miniaturization and design flexibility. Their side-mounted sound emission also creates a disconnect between the visual and auditory sources, diminishing user immersion. To address these issues, researchers and manufacturers are developing display-integrated speaker technologies, where a thin piezoelectric or electroactive layer is bonded directly to the display surface (Fig. 6). In this configuration, the screen itself vibrates to produce sound, eliminating the need for acoustic cavities or openings. This not only reduces device thickness and weight but also improves water resistance and delivers sound directly from the image plane, enhancing spatial audio realism.

The convergence of display and acoustic technologies is rapidly approaching commercial viability. Future smartphones, tablets, and automotive displays are expected to use their screens as both visual and acoustic interfaces, marking a pivotal shift toward seamlessly integrated, ultrathin, and immersive electronic systems.

Fig. 6. Conceptual illustrations of display-integrated piezoelectric actuators enabling sound generation and haptic feedback. Thin piezoelectric speakers embedded in laptops, smartphones, and automotive display panels emit acoustic waves while simultaneously providing localized tactile vibration in response to user touch [14,32,36].

4. DIFFERENT CLASSES OF PIEZOELECTRIC EXCITERS

Recent advancements in acoustic actuation technologies have given rise to multiple categories of piezoelectric exciters, each optimized for distinct performance requirements, fabrication constraints, and application domains. These include (1) MEMS-based piezoelectric speakers, (2) multilayer piezoceramic actuators, and (3) polymer-based piezoelectric speakers. While all three rely on the fundamental electromechanical coupling of piezoelectric materials, their structural configurations, fabrication routes, and functional properties differ considerably, reflecting the diverse approaches adopted to achieve high-efficiency, miniaturized sound generation.

4.1 Structural Design and Operation of Multilayer Piezoelectric Actuators Speakers

The multilayer piezoceramic exciter architecture represents a macroscopic yet highly efficient form of piezoelectric actuation, optimized for strong sound pressure generation. Representative structural and acoustic characteristics of multilayer piezoelectric actuators (MLAs) used for acoustic excitation (Figs. 7(a-g)) [10,37]. The SEM micrograph reveals a dense, laminated microstructure with well-defined interfaces between the piezoceramic and electrode layers, demonstrating uniform stacking, as shown in Fig. 7(a). The alternating electrode-ceramic configuration, where each layer is poled in the same direction to achieve a cumulative strain under an applied electric field (Fig. 7(b)). A typical integration configuration of the MLA attached to a flexible polymeric substrate (PET, thickness ~250 μm), supported by a frame containing air holes to allow acoustic radiation, as depicted in Fig. 7(c). The inclusion of air vents prevents acoustic reflection and enhances low-frequency response, while the compliant PET substrate improves device flexibility and durability under repeated actuation.

The acoustic performance of these actuators demonstrates that lead-free BNKT-based MLAs ($Bi_{1/2}Na_{1/2}TiO_3$-$Bi_{1/2}K_{1/2}TiO_3$ systems doped with CuO) can achieve comparable SPLs to conventional lead-based counterparts, presented in Fig. 7(d). The SPL-frequency curves show that the CuO-doped BNKT22 MLA exhibits enhanced response in the mid-to-high frequency range (2-10 kHz), attributed to improved domain mobility and reduced internal damping. Additionally, integration with a PET substrate further increases SPL efficiency by enhancing acoustic impedance matching. The practical device configuration reveals the compact assembly of a multilayer actuator within a stainless-steel frame encapsulated by polyolefin insulation, illustrated in Fig. 7(e) [37]. The cross-sectional SEM image confirms a total actuator thickness of approximately 330 μm in Fig. 7(f), with uniform sublayer thickness around 20 μm per piezoelectric element, signifying precision in tape-casting and co-firing processes.

The frequency-dependent SPL response under varying measurement distances (10, 15, and 20 cm), plotted in Fig. 7(g), indicates consistent sound output and stable resonance characteristics across the 1-10 kHz range. The minor attenuation with distance suggests efficient acoustic propagation and low signal distortion, validating the potential of multilayer piezoelectric actuators as compact and energy-efficient acoustic emitters for next-generation devices. Overall, the integration

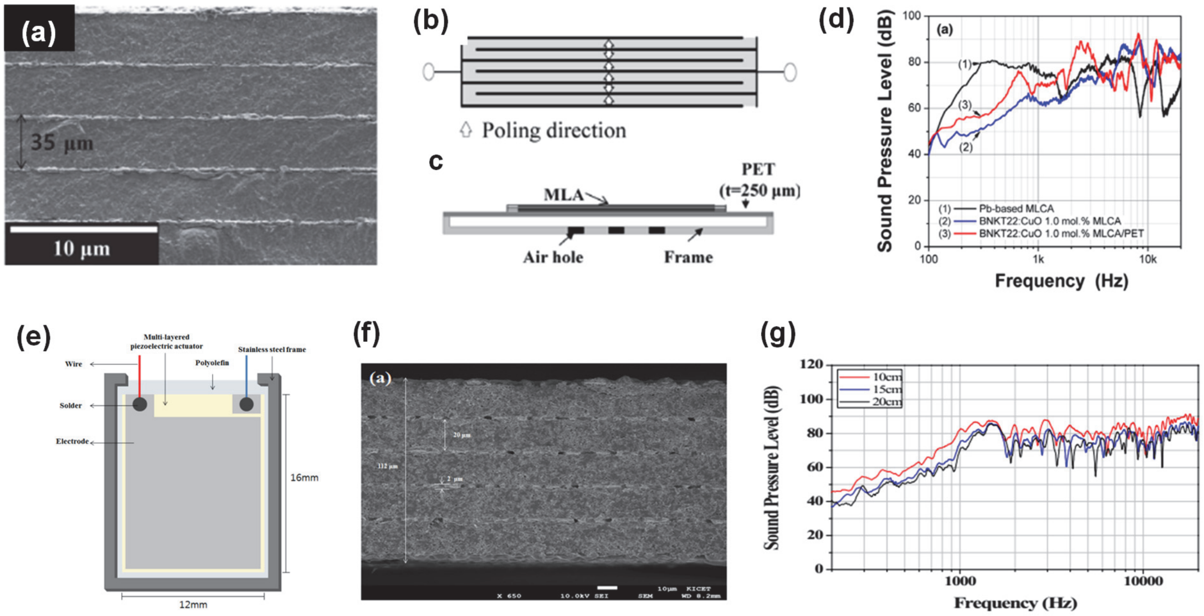

Fig. 7. Representative structures and performance of multilayer piezoelectric acoustic actuators (MLPAs). (a) Cross-sectional SEM image showing the laminated ceramic layers (~35 μm total thickness). (b) Schematic of the internal stacked electrode-ceramic configuration with aligned poling direction. (c) Structural model of MLA on PET substrate with air holes for sound propagation. (d) SPL-frequency characteristics of Pb-based and BNKT22:CuO-based MLAs with and without PET backing (Adapted with permission from [10]. Copyright 2015 The American Ceramic Society). (e) Device assembly schematic showing the multilayer actuator mounted in a stainless-steel frame. (f) Cross-sectional SEM micrograph of fabricated MLA (total thickness ~330 μm). (g) SPL-frequency response measured at different distances, showing consistent acoustic output and resonance stability (Adapted with permission from [37]. Copyright 2016 The Korean Institute of Electrical and Electronic Material Engineers).

of MLAs with polymeric and oxide-based structures marks a critical technological evolution toward ultra-thin, cavity-free, and display-integrated acoustic systems.

4.2 Microelectromechanical Systems (MEMS)–Based Piezoelectric Speakers

The development of ceramic PZT-based piezoelectric MEMS speakers represents a significant advancement in miniaturized acoustic technologies for compact electronic systems. These devices exploit the superior electromechanical coupling and mechanical resilience of ceramic PZT films to achieve high SPL under low driving voltages, effectively addressing the long-standing trade-off between acoustic intensity and device thinness [38].

System-level characterization was performed by mounting the device on a printed circuit board (PCB) with a central through-hole, as shown in Fig. 8(a) [6]. This configuration effectively eliminates back-chamber resonance by allowing the rear acoustic volume to approximate infinity, ensuring accurate frequency response evaluation. Comparative SPL spectra reveal enhanced low-frequency output (1 - 4 kHz) by more than 3 dB in the proposed design relative to a reference microspeaker (Fig. 8(b)). Furthermore, the phase-compensated configuration eliminated spectral dips (SPL zeros) near 10 and 16.8 kHz, resulting in a smooth, continuous acoustic response with up to 15 dB improvement across key auditory frequencies.

The total harmonic distortion (THD) profiles further demonstrate superior harmonic suppression in the proposed configurations, as shown in Fig. 8(c). Both filtered and unfiltered designs exhibit reduced THD between 8 - 10 kHz, attributed to stabilized resonant transitions and the removal of destructive interference modes. The phase-compensated design also improves THD behavior in the 15 - 18 kHz range, mitigating harmonic peaks induced by overlapping resonances. A minor distortion peak around 14 kHz, likely originating from subharmonic coupling of the seventh vibration mode (~28 kHz), can be further minimized through structural tuning or geometric optimization. Collectively, these findings underscore the remarkable scalability and acoustic potential of ceramic PZT-based MEMS speakers.

4.3 Polymer–Based Piezoelectric Speakers

In addition to multilayer piezoceramics and MEMS-based speakers, recent advances in polymer-based piezoelectric loudspeakers highlight the potential of eco-friendly, low-cost, and flexible acoustic devices for next-generation electronics. The concept, fabrication workflow, and functional mechanism of the transparent piezoelectric loudspeaker based on blended P(VDF-TrFE) and P(VDF-TrFE-CTFE) polymers were demonstrated in Fig. 9 [5]. By carefully tuning the copolymer-terpolymer ratio, the originally nonpolar α-phase was progressively converted into the highly polar β-phase, which was further strengthened through electric and thermal poling. Using a custom-built film-casting applicator, uniform transparent films with an average thickness of ~12 μm were prepared and subsequently laminated between two ITO sheets without any

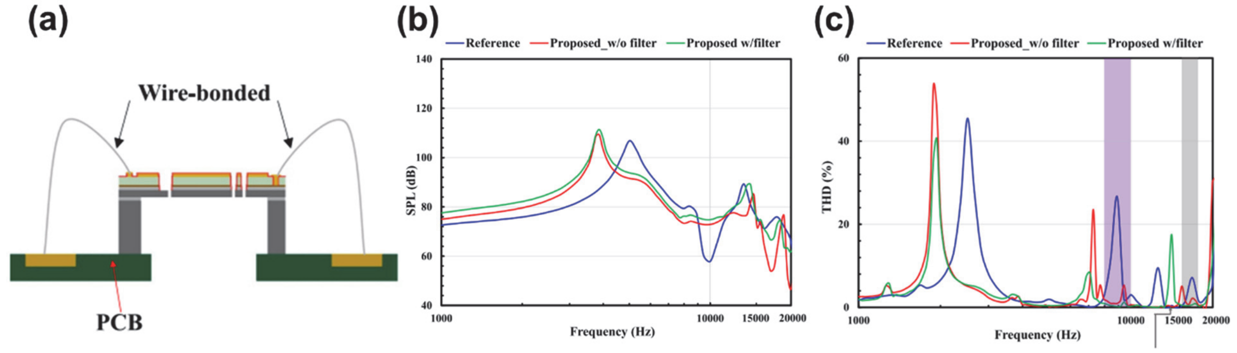

Fig. 8. (a) Cross-sectional view of the DUT mounted on PCB with open back volume for accurate SPL measurement. (b) Sound Pressure Level (SPL) comparison of reference, proposed without filter, and proposed with all-pass filter designs, showing clear SPL enhancement and suppression of spectral zeros. (c) Total Harmonic Distortion (THD) characteristics under identical conditions, illustrating improved distortion control with the filtered design (Adapted with permission from [6]. Copyright 2024 IOP Publishing).

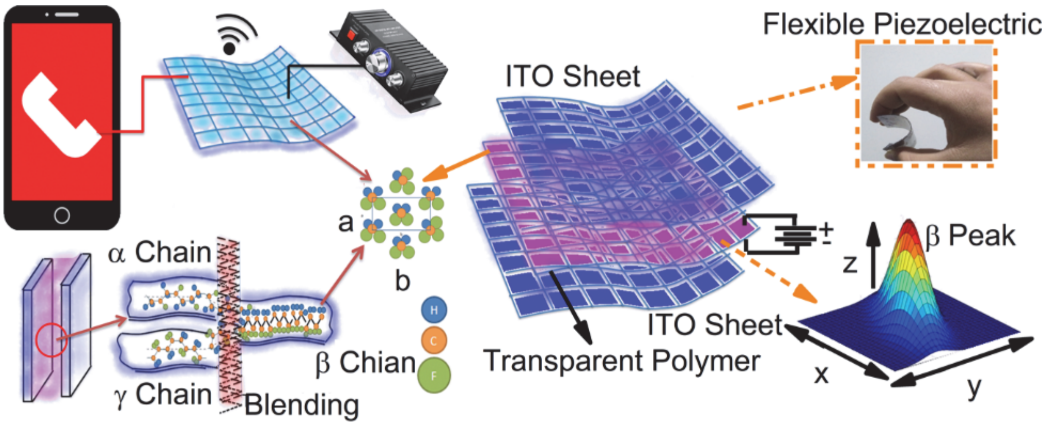

Fig. 9. A schematic illustration of the flexible and transparent piezoelectric loudspeaker formed by laminating blended polymer films between two ITO electrodes. This figure also shows the emergence of the polar β-phase backbone in P(VDF-TrFE), generated through the blending-induced interaction of the α- and γ-phase chains from the constituent polymers (Adapted with permission from [5]. Copyright 2021 Springer Nature).

paper interlayers, preserving device transparency while maintaining electrical reliability. The resulting 6.5 cm × 5 cm flexible loudspeakers exhibited enhanced remnant polarization and strong β-phase signatures, directly contributing to improved acoustic output. Sound pressure level (SPL) measurements, recorded under varying microphone positions and continuous poling, demonstrated that these devices outperform previously reported transparent loudspeakers, achieving SPL values above 91 dB while retaining high optical clarity.

5. FUTURE PROSPECTS AND CHALLENGES

The evolution of thin, flexible, and eco-friendly acoustic devices defines a new frontier in next-generation sound technologies. Despite major progress in multilayer piezoceramic actuators and polymer-based transducers, key challenges persist in achieving large-scale, reliable integration. From a device-engineering standpoint, incorporating piezoelectric emitters into display panels, wearables, and haptic systems demands precise vibration control, high energy efficiency, and stable multimodal operation. Large-area arrays require accurate phase synchronization and suppression of unwanted harmonics to ensure consistent audio fidelity. As devices continue to shrink in size, developing compact, low-voltage driving circuits becomes critical to maintain strong acoustic output with minimal power use. A further frontier lies in multifunctional transduction, where acoustic, haptic, and sensing functions coexist within a single platform. Such adaptive systems could enable interactive, immersive interfaces that unify sound and touch, requiring fine control of frequency-dependent mechanical responses and real-time tuning between acoustic and tactile modes.

Moreover, recent progress of highly crystalline freestanding oxide (such as $BaTiO_3$ and $Pb(Zr,Ti)O_3$) membranes would offer a promising route for the realization of next-generation piezoelectric exciters [39]. These oxide membranes on host substrates exhibit superior electromechanical coupling, exceptional mechanical flexibility, and superelasticity. Owing to these advantages, the piezoelectric oxide membranes have great potential for high-fidelity acoustic generation within ultrathin, transparent, and flexible form factors, positioning oxide membranes for the realization of display-integrated and wearable acoustic systems.

The automotive sector is undergoing a profound transformation toward electrification and mobility integration, creating new opportunities for lightweight and energy-efficient acoustic systems. Conventional car audio systems, comprising multiple heavy voice-coil speakers, can weigh up to 40 kg, significantly affecting fuel efficiency and cabin design flexibility. The piezoelectric speaker system reduces both weight and space by up to 90%, enhances fuel efficiency, and improve cabin acoustics [14]. Ultrathin piezoelectric speakers, due to their minimal mass and high integration capability, can be employed in: (i) Active Noise Cancellation (ANC) systems to suppress cabin noise using anti-phase sound waves, (ii) In-

Vehicle Communication (IVC) for clearer speech transmission between passengers, (iii) Emergency (eCall) systems, enabling real-time voice communication with responders during accidents [40]. For electric vehicles (EVs), where power efficiency directly translates into extended driving range, the high acoustic conversion efficiency of piezoelectric exciters offers a distinct competitive edge.

6. CONCLUSION

The advancement of piezoelectric speakers results in a transformative step in acoustic engineering, moving beyond the physical and design limitations of conventional electromagnetic systems. Through innovations in material composition, structural design, and fabrication, both ceramic and polymer transducers have achieved high acoustic output within ultrathin, flexible, and sustainable formats suited for next-generation electronics. Multilayer piezoceramic actuators, particularly those based on lead-free systems such as BNKT-CuO, exhibit excellent densification, electrode uniformity, and operational stability, positioning them as viable alternatives to lead-based materials for compact, high-fidelity sound modules. Similarly, polymer-based devices, such as PVDF-based polymer speakers, offer lightweight, low-cost, and eco-friendly solutions with promising acoustic and mechanical performance. Their adaptability to printing and large-area fabrication further supports integration into wearable audio systems.

Beyond portable electronics, these piezoelectric technologies hold significant potential for automotive applications, where space, weight, and durability are critical. Display-integrated or surface-vibration-based audio panels can replace conventional loudspeakers, reducing bulk while enhancing spatial sound perception within vehicle cabins. Moreover, their inherent compatibility with haptic feedback and sensing functions enables interactive dashboards and multifunctional infotainment systems. Overall, the convergence of ceramic precision and polymer versatility is paving the way for ultrathin, high-efficiency, and environmentally sustainable acoustic interfaces.

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