Sensors & Actuators: A. Physical 347 (2022) 113887

Contents lists available at ScienceDirect

Sensors and Actuators: A. Physical

journal homepage: www.journals.elsevier.com/sensors-and-actuators-a-physical

Review

Recent development and futuristic applications of MEMS based piezoelectric microphones

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ARTICLE INFO

Keywords:
Piezoelectric microphone
MEMS
Thin film
Sensitivity
Dynamic range

ABSTRACT

This paper presents a comprehensive literature survey of MEMS based piezoelectric microphones along with the fabrication processes involved, application domains, and methodologies used for experimentations. Advantages and limitations of existing microphones are presented with the impact of process parameters during the thin film growth. This review identifies the issues faced by the microphone technologies spanning from the invention of microphones to the most recent state-of-the-art solutions implemented to overcome or address them. A detailed comparison of performance in terms of sensitivity and dynamic range is presented here that can be used to decide the piezoelectric material and process to be used to develop sensors based on the bandwidth requirement. Electrical and mechanical properties of different piezoelectric materials such as AlN, ZnO, quartz, PZT, PVDF, and other polymers that has great potential to be used as the sensing membrane in development and deployment of these microphones are presented along with the complications faced during the fabrication. Insights on the future of these sensors and emerging application domains are also discussed.

1. Introduction

Electret condenser microphone (ECM) was initially discovered by Gerhard Sessler and James West in the early 1960 at Bell Laboratory which is traditionally used for audio and aeroacoustic applications [1,2]. The traditional ECMs were composed of air gap capacitors with a movable diaphragm and back plate. These ECMs have very good stability, repeatability and enhanced performance over variable operating temperature and environmental conditions [2]. ECMs also show good sensitivity to the acceleration, pressure and force. The development of nano-sized, light weighted, low power, cheap, and compact sized ECM devices becomes possible with the help of Microelectromechanical systems (MEMS) technology [3]. MEMS sensors are widely used because of their enhanced performance as compared to macro-sensors [4]. Step by step development of MEMS devices enables engineers to think in new direction for the performance enhancement or optimization of the devices for dedicated work [5,6]. MEMS technology empowers the designer to meet the requirement of consumer electronic market. The gyroscopes, magnetometers and microphones/acoustic sensors are developed after successful implementation of the accelerometers.

The key features of MEMS microphones are enhanced performance density, reflow soldering, less temperature dependent sensitivity variations and very low vibration sensitivity as compared to traditional ECMs. Also, integration of MEMS microphones is easy with other MEMS devices. This makes it suitable for wide range of applications such as automobile, industrial, and medical applications [7,8]. Condenser microphone was initially discovered by E.C. Wente [9] in 1916. Improvement in condenser microphone was firstly reported by G. Sessler and J. West [10] in 1960 with electret material integration. Approximately, 20 years later the first working silicon micromachining based condenser microphone by G. Sessler and D. Hohm in 1983 [11] was reported. In 2002, USA based Knowles manufacturing company introduced the first commercial condenser microphone.

Little wonder, then, that prospects will be booming in the years to come for MEMS microphones—a class of miniscule devices using acoustic sensors in combination with a pressure sensitive diaphragm and an application specific integrated circuit (ASIC) circuit, fabricated on silicon wafers, to sense voice and sound. Global revenue for MEMS microphones reached $1.6 billion in 2020 and is forecast to be reach 2.3 billion by 2025 at a CAGR of 7.9% during this period. It is predicted

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https://doi.org/10.1016/j.sna.2022.113887
Received 8 May 2022; Received in revised form 10 July 2022; Accepted 16 September 2022
Available online 23 September 2022

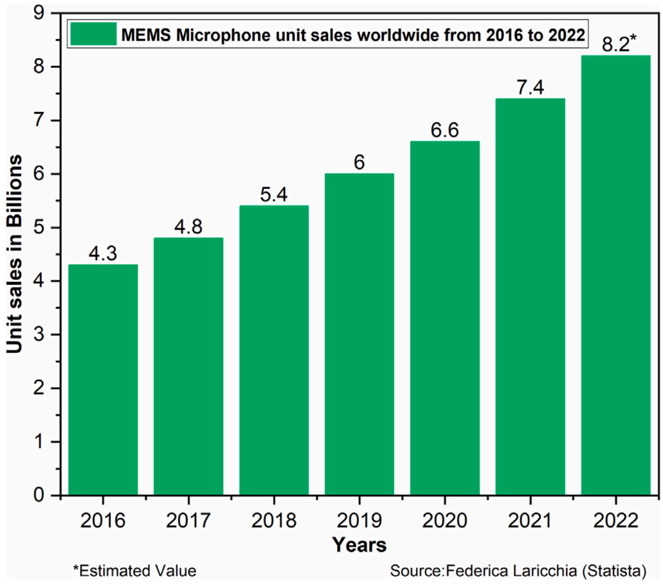


Fig. 1. Global market sales of MEMS microphone units during 2016 to 2022.

by research and markets team. Fig. 1 shows a global market demand for MEMS microphone units from 2016 to 2022 which is reported by Statista market research group. The MEMS microphones market is driven primarily by mobile handsets, with microphone consumption per smartphone on the rise since 2010. Aside from smartphones, MEMS microphones derive significant revenue from their use in earphones, laptops, hearing aids, and smart speakers.

With the inherent advantages of higher performance density, compatibility with micro-level circuitries, temperature stability, ability to be reflow soldering, and lower vibration sensitivities compared to conventional ECM sensors, MEMS microphones becomes promising competitors in various application domains not limited to tablets and smartphones but extending to medical, industrial, as well as automotive applications [7,8]. The miniature MEMS microphones can also help reduce the cumbersomeness when used in form of arrays of multiple microphones leading to development of small products [12–14].

Microphones have wide range of applications such as surveillance, military application, ultrasonic and acoustic distinction under water, noise and vibration control [15]. According to the structural design most of the microphones having same structures either a diaphragm or cantilever beam. Applied input pressure level causes the occurrence of resonance in the diaphragm/cantilever beam but this resonance occurrence also depends on frequency band of applied input signal. Deflection of diaphragm is observed due to application of input sound pressure to it. This deflection is sensed by a sensor and converted into electrical form as the output of sensor. The important characteristics of microphones are the sensitivity, bandwidth, stability, dynamic range and cost of the manufactured device [1]. The basic element of microphone is diaphragm or cantilever and it is responsible for enhanced sensitivity. The three basic transduction mechanisms used in MEMS technology are electrostatic (capacitive), piezoelectric and piezoresistive. The selection of transduction mechanism is dependent on the sensitivity, stability, reliability, coupling coefficient, power consumption and complexity of development device [16]. Table 1 illustrates the comparison of three major transduction schemes.

Some materials such as Quartz, Zinc oxide (ZnO), Aluminum nitride (AlN), Lead zirconate titanate (PZT), Lithium niobate ($LiNbO_3$) Barium titanate ($BaTiO_3$) and some polymers like Polyvinylidene fluoride (PVDF), Polydimethylsiloxane (PDMS) have a unique property of electric charge generation when stressed by an applied pressure. This phenomena of charge generation from mechanical deformation is known as the piezoelectric effect and the materials that show this effect are called piezoelectric materials [17]. Similarly, some materials also show inverse piezoelectric effect where an electric field applied leads to generation of a mechanical strain [17]. The relation between mechanical quantities such as strain, stress and the electric quantities like electric field, displacement are generally explained linearly by a set of piezoelectric coefficients. The value of piezoelectric coefficients is used to determine strength of the piezoelectricity and its output response. An acoustic wave devices consist of a thin diaphragm (square or circular and cantilever) and a sandwiched form of piezoelectric material between top electrode and bottom electrode [1].

Table 1
Comparative analysis of three different transduction schemes.

Parameters	Piezoelectric	Piezoresistive	Capacitive
Input power	None	Required	Required
Sensitivity (μV/Pa)	Medium 10 to 500	Low 0.1 to 100	Good 400 to 1000
Dynamic range	Wide	Relatively wide	Narrow

Among these transduction mechanism, piezoelectric mechanism is having ideal coupling coefficient between electrical and mechanical domain. Piezoelectric materials are self-power generating materials therefore it does not require additional power. Piezoelectric actuators have a very good property of fast response and capability of achieving high displacement. The major drawback of piezoelectric transduction mechanism is that it can't sustain high temperature during the operation. This mechanism is having poor DC response because of the charge leakage inside the material [16]. Since Silicon does not have properties of piezoelectric materials, many efforts have been made to couple silicon with piezoelectric materials [18,19], so that best properties of both materials (better material properties and better electromechanical transduction) can be clubbed into the design. Despite advantages of using both materials at a time, there are some complexities such as interfacing issues and fabrication possibility limiting the performance of these devices till date.

Integration of silicon to piezoelectric material, for MEMS technology makes its suitable for wide range of applications such as acoustic sensors [20–22], force sensors [23,24], accelerometers [25–27], ultrasonic transducers [28,29] and pressure sensors [30,31]. A large number of trials have been performed for developing the highly efficient micromachined acoustic devices like as microphone and microspeaker [32,33], hearing aids [34,35], chemical and biomedical applications [36,37]. The performance of the device depends on various parameters such as coupling coefficient, orientation, thickness, piezoelectric layer material and its active area. Highly efficient acoustic devices for various applications with different piezoelectric materials such as ZnO, AlN, $LiNbO_3$ and PZT have been reported. Table 2 shows the comparisons of different piezoelectric properties. In spite of the high electromechanical coupling coefficients attained, the manufacturing process struggles in controlling the film texture and associated physical properties. Some authors have reported PZT based acoustic sensors [38–40], accelerometers [41,42] and ultrasonic transducers [43]. An acoustic sensor based on PZT has low sensitivity in comparison to ZnO based acoustic sensor [44]. It is also reported that PZT based acoustic sensor having low sensitivity as compared to ZnO based acoustic sensor. ZnO is widely used as piezoelectric material for MEMS acoustic sensor because of its small volume, ease of integration with prefabricated devices, good piezoelectric coefficient and dielectric properties. Hexagonal wurtzite structured polycrystalline ZnO make it most preferable piezoelectric material for various applications like as acoustic sensor [45], accelerometers [46], film bulk acoustic resonator (FBAR), energy harvesting devices and nanogenerators [47,48]. To the best of the author's knowledge, milestones of the progressive development of piezoelectric based MEMS microphones have been summarized in Fig. 2.

Table 2
Properties of commonly used piezoelectric materials.

Properties	Quartz	PZT	AlN	ZnO	GaN	$BaTiO_3$	$LiNbO_3$	PVDF	Parylene-C
Modulus (GPa)	71.7	61	300–350	110–140	320	67	245	2.5	3.2
Density (10^3kg/m^3)	2.65	7.57	3.25–3.3	5.61–5.72	6.095–6.15	5.7	4.64	1.78	1.289
Poisson's Ratio	0.17–0.2	0.27–0.3	0.22–0.29	0.36	0.183	0.35	0.25	0.33–0.4	0.4
Effective coupling coefficient k^2 (%)	0.1–0.2	20–35	3.1–8	1.5–1.7	0.13	0.34	5.6	2.9	–
Dielectric constant	4.3	380	8.5–10	8.66	–	3.8	44	6–8	2.95–3.15
Piezoelectric coefficient d_{33}(pC/N)	2.3 (d_{11})	289–380	4.5, 6.4	12	4.5	78, 85.6	7.9	−35	−3.0
Acoustic velocity of longitudinal (transverse) wave (m/s)	5000–5960 (3159)	4500 (3900)	10150–11050 (5800)	6336 (2720)	8050 (4130)	–	3992	2600	2135±85

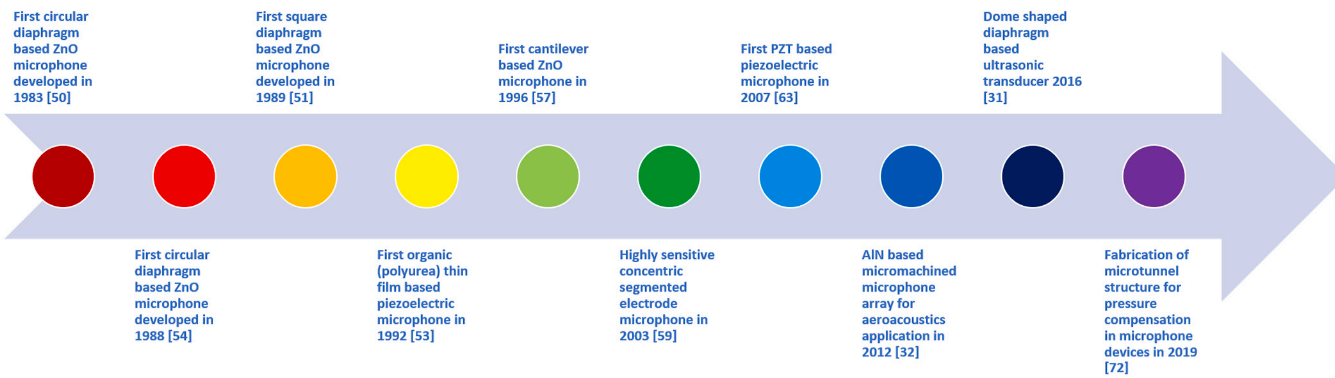


Fig. 2. Milestones in the development of the MEMS microphone.

2. MEMS based piezoelectric microphone

The literature on MEMS based microphones is extensive, with most efforts focused on microphones for consumer audio applications. The requirements associated with audio microphones differ significantly from those of an aeroacoustic measurement microphone. In the former application area, the minimum detectable pressure requirements are particularly stringent (usually <30 dB) in air medium, while requirements for bandwidth (10–15 kHz) and maximum pressure (typically <120 dB) are less important. Maximum pressure and bandwidth requirements for microphones targeted at aeroacoustic measurements vary with the specific measurement, sometimes reaching or exceeding 160 dB and 100 kHz, respectively. The noise floor, meanwhile, is less critical than for audio microphones. This discussion is restricted to MEMS acoustic sensor utilizing piezoelectric transduction and MEMS microphones targeted at acoustic applications.

The first MEMS based piezoelectric microphone was fabricated and reported in [50]. It consists of circular diaphragm of silicon and sputtered ZnO thin film as piezoelectric layer. The sensitivity (250 μV/Pa) of fabricated device was obtained and reported for wide frequency range. Kim et al. (1987) [49] of the Berkeley Integrated Sensor Center reported a piezoelectric MEMS microphone using ZnO thin film as shown in Fig. 3. A square shaped diaphragm of silicon nitride was reported as easily stress and thickness controllable than silicon. A segmented concentric aluminum top electrode and a polysilicon bottom electrode were used as shown in Fig. 3.(b). The fabricated device was tested and reported a sensitivity of 50 μV/Pa. In 1989, Kim et al. [51] reported the same microphone design with CMOS amplifier circuitry on single chip through a partnership with Orbit semiconductor. A patent was issued on the same design in 1989. A number of improvement in microphone design were made to enhance sensitivity and flat frequency range as shown in Fig. 4 by Kim et al. (1991) [52]. The modified microphone design resulted as (i) reduction in residual strain of silicon due to optimized process of low power chemical vapor deposition (LPCVD) layer, and (ii) improvement in sensitivity due to placement of electrodes according stress distribution pattern. The sensitivity and flat frequency range was improved than reported earlier [51].

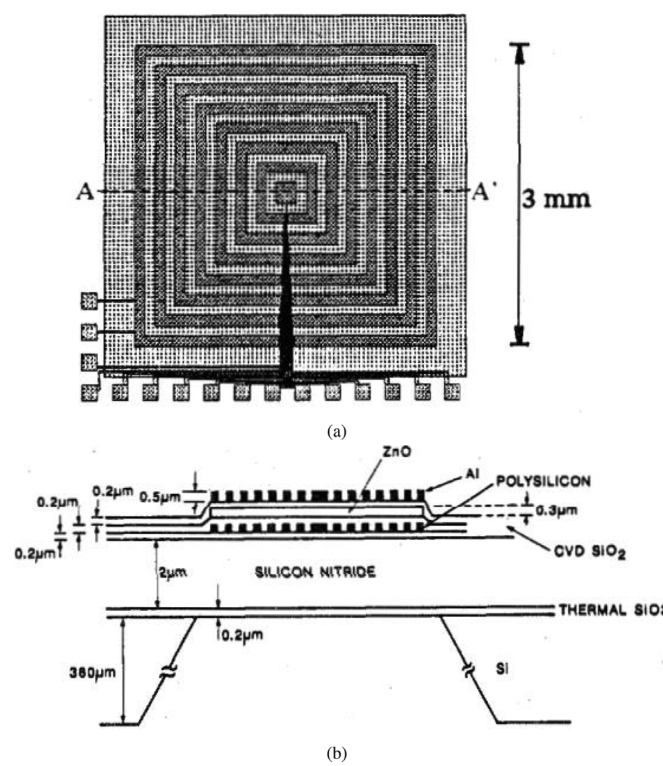


Fig. 3. ZnO based MEMS microphone: (a) top view image of concentric electrodes and (b) cross section of fabricated sensor as line AA' [49].

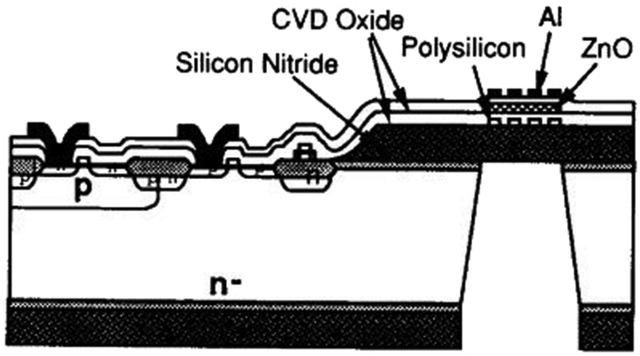


Fig. 4. Cross sectional view of microphone with CMOS circuit [52].

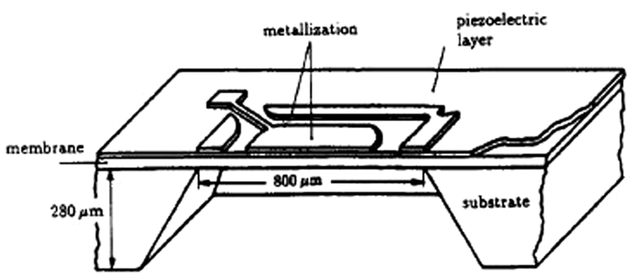


Fig. 5. A schematic of aromatic polyurea based piezoelectric microphone [53].

In 1988, a dissertation was submitted by Franz [54] at Darmstadt university of technology. An AlN based microphone was fabricated, tested and reported a sensitivity of 25 μV/Pa. In 1992, an organic film polyurea was introduced as piezoelectric layer in acoustic sensor as shown in Fig. 5 by Schellin et al. [53]. However, the results showed a non-flat frequency response in the audio range due to a damped mechanical resonance of the film. A second incarnation of the organic piezoelectric film P(VDF/TrFE) based microphone was reported by Schellin et al. (1994) [55]. An improved sensitivity of 150 μ/Pa was achieved. However the frequency response was still not flat in audio range.

In 1993, an extensive part of the reported work of Kim et al. [52] was reported by Ried et al. [57] of the Berkeley Sensor and Actuator Center. The extended work included a stress control mechanism in silicon nitride layer based square diaphragm of 2.5 mm × 2.5 mm × 3.5 μm. This layer was designed to be thick relative to other diaphragm layers, which were fabricated at corporate partner Orbit Semiconductor and not controlled for stresses. A ZnO based piezoelectric microphone with integrated CMOS circuit was reported and it had a sensitivity of 920 μV/Pa with a flat frequency response range from 100 Hz–18 kHz. In 1996, Lee et al. [58] reported a new type of cantilever based piezoelectric (ZnO) microphone with controlled stress. The cantilever structure was a stack of thermal oxide and low stressed silicon nitride which enhanced compliance of the stack resulted as high sensitivity of 3 mV/Pa. However this compliance resulted as lower resonant frequency. Some more iteration had been done to improve sensitivity and wide frequency range by the same group [56]. A schematic of modified structure had been shown in Fig. 6. This microstructure showed improved sensitivity of 30 mV/Pa with wide frequency range from 50 Hz to 1.8 kHz.

In 2003, Ko et al. [59] developed a next piezoelectric acoustic device, pictured in Fig. 7. A square diaphragm of LPCVD silicon nitride was formed and piezoelectric ZnO layer was sandwiched between two concentric segmented aluminum electrodes. The acoustic device had a sensitivity of approximately 0.51 mV/Pa at first fundamental resonant frequency 7.3 kHz. However this silicon nitride had stability and residual stress issues. A new piezoelectric material (PZT) based acoustic sensor was reported by Polcawich et al. (2004) [60]. The circular diaphragm with different diameters from 500 μm to 2000 μm was developed with 80% coverage in the center of the diaphragm and 20% coverage of PZT layer on the outside edge of the diaphragm. The fabricated devices had sensitivity range of 97.9 nV/Pa to 920 nV/Pa with the highest resonant frequency of 100 kHz but a dynamic range and a flat frequency range were not reported.

In 2004, a charged cellular polypropylene (also known as VHD40) as the piezoelectric material was used in acoustic sensor as piezoelectric layer by Hillenbrand et al. [62]. They reported a five layer glued stacks of metallized VHD40 design which had total harmonic distortion within limit of 1% at 164 dB and sensitivity of 10.5 mV/Pa. This design had a capability of work with large maximum pressure and wide frequency range from 20 Hz to 140 kHz. This operation range makes it suitable for use in aeroacoustic application. However, the development process was not batch fabricated and concerns about the temperature stability of the charged film were noted.

In 2007, Horowitz et al. [61] introduced a first piezoelectric MEMS microphone designed specifically for aeroacoustic applications. They reported a circular diaphragm based microphone using sandwiched PZT material between Ti/Pt electrodes. This piezoelectric stack supported by silicon layer as pictured in Fig. 8. The device performance was predicted using lumped element model (LEM). The resonant frequency of the fabricated device was measured and found to be 59 kHz using LDV measurement system. The sound pressure range from 37.5 dB to 169 dB was reported for the device. This suggested a usable bandwidth nearly sufficient for 1/4 scale model aeroacoustic measurement applications. Fazzio et al. (2007) [63] of Avago technologies reported a variant of FBAR process based microphones. The reported circular diaphragm based microphone was a combination of piezoelectric AlN and molybdenum (Mo) electrodes in three configurations such as inner disk, annular disk or combination of these two. The measured results showed a flat frequency band (1 kHz–6 kHz) and wide sound pressure range (60 dB–155 dB) but sensitivity was not reported.

Cho et al. (2008) [65] reported a piezoelectric AlN based microspeaker. The AlN layer was deposited on Mo/Ti electrodes and its dependent residual stress was analyzed. This was achieved by a comprehensively stressed silicon nitride in support of diaphragm and high quality AlN thin film. This composite diaphragm generated more than 60 dB SPL in frequency range from 100 Hz to 15 kHz and the highest SPL generated was 100 dB at 9.3 kHz with 20 V peak to peak sinusoidal input. The compressively stressed microspeaker with enhanced SPL showed performance enhancement over the tensile counter part.

In 2008, Lee and Lee [64] reported the circular and square diaphragms based microphones using a stack of ZnO and Mo electrodes as pictured in Fig. 9. The diaphragm made of low stress silicon nitride was fabricated using boron etching stop method. The thickness of the supported boron layer for diaphragm was 7.4 μm which optimized using simulation results of stress and displacement distribution. The average sensitivity of the circular diaphragm microphone and square diaphragm microphone was 39.6 V/Pa and 20.1 V/Pa in the frequency range from 400 Hz to 10 kHz respectively. An amplifier circuit with 200 gain was used to reproduce human voice. It was observed that circular diaphragm microphone had higher displacement and sensitivity at the same applied inputs. However, fabrication of the circular diaphragm is very difficult due to traditional bulk micromachining techniques and anisotropic etching control. Yi et al. (2008) [66] also presented a microfabricated microspeaker that can produce a signal of SPL range from 40 dB to 97.2 dB in the frequency range of 400 Hz to 12 kHz at 5 V peak to peak input signal. To obtain compressive residual stress ZnO film, the required conditions were optimized and residual stress of −1.3 GPa was achieved.

In 2010, A double-layered AlN/Mo cantilever based piezoelectric microphone was proposed to fulfill a doctoral dissertation in University of Michigan by Robert Littrell [67]. The objective of this work was

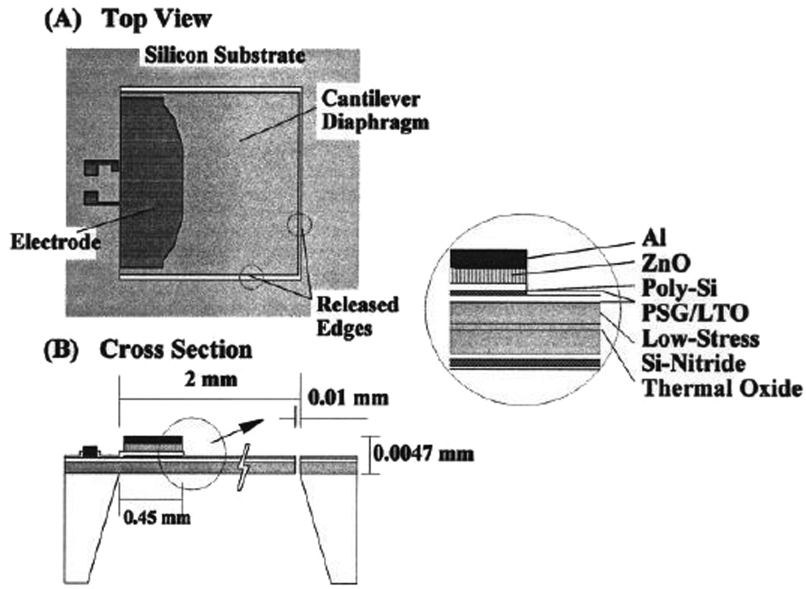


Fig. 6. A schematic of cantilever based piezoelectric transducer [56].

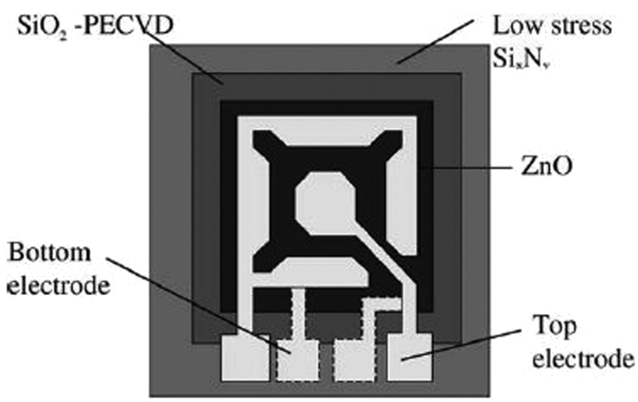
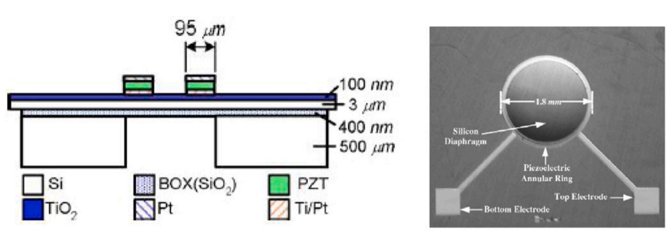


Fig. 7. A schematic view of acoustic device using segmented electrode [59].



(a) (b)

Fig. 8. PZT microphone for aeroacoustic application: (a) cross section schematic and (b) an optical image of fabricated device [61].

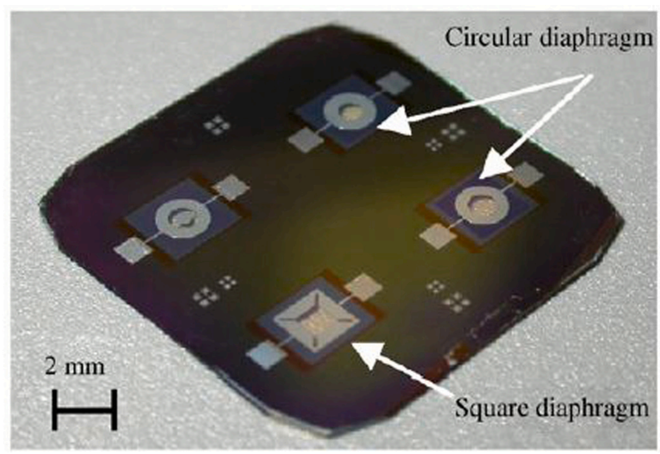


Fig. 9. An image of the fabricated piezoelectric microphone [64] .

to demonstrate a low noise piezoelectric microphone. In this thesis work, two types of devices were fabricated. The first proposed device have an array of 20 cantilevers as sensing elements with 0.5 μm thick AlN layers which was selected by prediction model. However, testing results showed higher noise floor (58 dB(A)) than expected due to high dielectric loss and poor film quality. In addition, the vent resistance was reduced due to stress in the cantilever structure. To get better quality of the AlN film, modification in the first device has been done with thicker AlN film of 1 μm thickness. The modifications to the fabrication process that enabled individual patterning of AlN and Mo, and reduction of the number of cantilevers to 2, in order to reduce the gap around them which leads to increment in the vent resistance. The Fabricated device had a sensitivity of 1.82 mV/Pa with low noise floor level and resonated at 18 kHz.

In 2012, an AlN based micromachined microphone for aircraft fuselage arrays was designed and fabricated that are utilized by aeroacousticians to help identify aircraft noise sources and assess the effectiveness of noise-reduction technologies. A design optimization has been done using LEM model and noise model was presented by Williams et al. [32]. The optimal design was fabricated at Avago Technologies and characterized. The fabricated device had sensitivity of 39 μV/Pa and maximum detectable pressure was 172 dB at 3% distortion limit. The device had a flat response in the frequency range of 69 Hz–20 kHz.

In 2013, Kim et al. [69] demonstrated a polymer Parylene-C (PA-C) based circular diaphragm microphone. The device had response in wide pressure level (30 dB–110 dB) and its open circuit sensitivity had variation from 1 to 110 μV/Pa over an audio range of 1–10 kHz. The proposed device was suitable only for audio application not for aeroacoustic application. The standard of polymer deposition was not used which had repeatability issues. A square shaped diaphragm having 3 mm side length and 25 μm thick structure has been designed and

Table 3
Summary of previously done work on piezoelectric based devices.

Author	Sensing element	Sensing element dimension	Sensitivity	Dynamic Range	Bandwidth (Predicted)
Royer et al. 1983 [50]	ZnO	1.5 mm[a] × 30 mm	250 μV/Pa	66 dB-NR	10 Hz–10 kHz
Kim et al. 1987 [49]	ZnO	3 mm[b] × 3.6 mm	50 μV/Pa	72 dB-NR	20 Hz–5 kHz
Franz 1988 [54]	AlN	0.72 mm^2 × 1.0 μm	25 μV/Pa	68 dB-NR	NR–45 kHz
Kim et al. 1989 [51]	ZnO	2 mm[b] × 1.4 μm	80 μV/Pa	NR	3 kHz–30 kHz
Kim et al. 1991 [52]	ZnO	3.04 mm[b] × 3 μm	1000 μV/Pa	50 dB-NR	200 Hz–16 kHz
Schellin et al. 1992 [53]	Polyurea	0.8 mm[b] × 1 μm	30 μV/Pa	NR	100 Hz–20kHz
Ried et al. 1993 [57]	ZnO	2.5 mm[b] × 3.5 μm	920 μV/Pa	57 dB-NR	100 Hz–18 kHz
Schellin et al. 1993 [55]	P(VDF/TrFE)	1 mm[b] × 3.0 μm	150 μV/Pa	60 dB-NR	50 Hz–16 kHz
Lee et al. 1996 [58]	ZnO	2 mm[c] × 4.5 μm	3 mV/Pa	NR	100 Hz–890 Hz
Lee et al. 1998 [56]	ZnO	2 mm[c] × 1.5–4.7 μm	30 mV/Pa	NR	50 Hz–1.8 kHz
Ko et al. 2003 [59]	ZnO	3 mm[b] × 3 mm	0.51 mV/Pa	N/R	1 kHz–7.3 kHz
Polcawich et al. 2004 [60]	PZT	1 mm[a] × 2.18 mm	97.9–920 nV/Pa	N/R	N/R
Hillenbrand et al. 2004 [62]	VHD40	0.3 cm^2 area × 55 mm	2 mV/Pa at 1 kHz	37 dB–164 dB	20 Hz–140 kHz
Horowitz et al. 2007 [61]	PZT	1.80 mm[a] × 267 nm	1.66 μV/Pa	35.7 dB–169 dB	100 Hz– 6.7 kHz
Fazzio et al. 2007 [63]	AlN	350 mm[a] × 1.44 mm	N/R	60 dB– 155 dB	1 kHz–6 kHz
Cho et al. 2008 [65]	AlN	0.5 mm thick AlN	N/R	60 dB–100 dB	100 Hz–15 kHz
Lee et al. 2008 [64]	ZnO	2 mm[a] × 1 μm	39.6 μV/Pa	N/R	N/R
Yi et al. 2008 [66]	ZnO	3 mm[b] × 0.5 mm	N/R	40 dB–97.2 dB	400 Hz–12 kHz
Littrell et al. 2010 [68]	AlN	0.62 $mm^{2\$}$ × 2.3 mm	1.82 mV/Pa	37 dB–128 dB	50 Hz–8 kHz
Williams et al. 2012 [32]	AlN	414 μm[a] × 2.14 μm	39 mV/Pa	40 dB–171.6 dB	69 Hz–20 kHz
Kim et al. 2013 [69]	Parylene-C	6 mm[a] × 30μm	1–110 μV/Pa	30 dB–110 dB	1 Hz–10 kHz
Prasad et al. 2013 [44]	ZnO	3 mm[b] × 25 μm	382 μV/Pa	120–160 dB	30 Hz–8 kHz
Ali et al. 2015 [70]	ZnO	3 mm[b] × 50 μm	116.4 μV/Pa	120–200 dB	N/R
Tang et al. 2016 [71]	ZnO	4.4 mm[b] × 2.2 μm	N/R	>92.12 dB	10 Hz–40 kHz
Kumar et al. 2019 [72]	AlN	1.75 mm[b] × 20 μm	N/R	120–180 dB	12 Hz–22 kHz
Ali et al. 2021 [73]	ZnO	1.75 mm[b] × 15 μm	136.53 μV/Pa	120–180 dB	35.2 Hz–15 kHz
Prasad et al. 2022 [74]	ZnO	3 mm[b] × 25 μm	320.1 μV/Pa	120–180 dB	30 Hz–8 kHz

[a]Radius of circular diaphragm.
[b]Side of square diaphragm.
[c]Area of cantilever.
[NR]Not Reported.

fabricated by Prasad et al. [44]. The fabricated device showed good response with 382 μV/Pa sensitivity in wide dynamic range (120–160 dB) and in the frequency range 30 Hz–8 kHz. This dynamic range can be enhanced by increasing the diaphragm thickness with 50 μm thick which showed linear response in the range of 120–200 dB but increment in thickness decreased its overall sensitivity to 116.04 μV/Pa as reported by Ali et al. [70].

A microfabricated ultrasonic transducer based on a piezoelectric actuated dome-shaped diaphragm supported at the center of a flat square diaphragm was demonstrated by Tang et al. (2016) [75]. To develop dome and square shaped diaphragms, silicon isotropic wet etching and KOH etching were used respectively. The patterning of deposited film on the dome shape structure was done using shadow masking. The sound pressure signal of 88.21 dB over frequency range (10–40 kHz) was generated by the fabricated transducer at 30 V peak to peak voltage. This measurement was done at 5 mm away in open space. The linearity of the sound output as a function of input voltage is measured to be very good. In addition, post-process laser cutting was utilized to form a cantilever-like diaphragm structure, which boosted the maximum SPL to 95.12 dB without degrading the linearity.

In 2019, Kumar et al. [72] tried miniaturization in the square shaped diaphragm structure of 1.75 mm side length and 20 μm thickness. The proposed structure was fabricated with AlN piezoelectric which provides stable response at high temperature and humidity level. It has capability to handle the large SPL range of 100–180 dB with wide operational frequency 12 Hz–12 kHz. But the sensitivity parameter was not reported by the authors. The same structure with 15 μm thick diaphragm with ZnO piezoelectric has been fabricated by Ali et al.[73]. The fabricated device showed 136.53 μV/Pa. In 2022, Prasad et al. [74] reported experimental analysis of square shaped diaphragm with microtunnel structure especially for pressure measurement of satellite launching vehicles. The proposed dynamic SPL range and operational frequency range is verified with experimental measurement setup and it found in order to simulation results. Important sensor parameters key and chronological contribution of the researchers have been summarized in Table 3. This summary will help the researcher in providing required interpretation in order to judge the true performance of any particular device.

3. Challenges in device fabrication process

In last few decades, diaphragm structure based devices have become very popular in micromachining and manufacturing technology. These structures are widely being used in development of acoustic sensors, pressure sensors, accelerometers, magnetometer, ultrasonic transducers, tactile sensors and energy harvester etc. The two critical steps in the MEMS acoustic sensor development are the fabrication of the Si-diaphragm and microtunnel. A microtunnel or microchannel is used for pressure compensation. The microtunnel helps the device attain pressure compensation by relating deep cavity to the external atmosphere. The similar microtunnel is also used in other applications such as microfluidics, MEMS and microelectronic integrated circuits [76–78]. Also, the microtunnel can be used as substitute for the acoustic holes present in various acoustic sensors. The reliability of the device however gets enhanced due to the microtunnel formation making the structure less fragile. Acoustic sensor fabrication necessitates the development of smooth microtunnel in the cavity region in order to achieve pressure compensations. In addition to the smooth microtunnel formation its protection also becomes a critical issue during the fabrication of diaphragm or deep cavity. In integrated circuits, a new trend of developing package technology of heterogeneous integration of dissimilar devices on single chip has been raised temperature issues. Since the electrical properties of materials depends strongly on temperature, and a higher temperature usually results in reduced performance of electronics devices. The generated heat must be dissipated effectively. Traditional thermal dissipation system such as liquid cooling, air cooling and other natural cooling techniques are widely being used. These natural cooling techniques have advantages for portable devices such as smartphones. The micro-channels can be used as heat dissipation technique in silicon based integrated circuits [79]. In microfluidics, micro-channel could be used to transport a variety of fluids and performs a couple of tasks which include chemical analysis, biomolecular sensing and detection in the micro-scale to combinatorial chemical synthesis for bio-molecular detection, medical, genetics and diagnostics in micro scale [80,81].

Over the past decades, researchers have laid focus on fabricating the microtunnel variants using materials like PNB (polynorbornene), Si, zeolites, etc [45,82,83]. Unlike Si based device, the other materials when deployed in fabrication, complexity in process flow arises due to the non compatibility with standard CMOS process flow due to the high temperature processes involved. Bulk micromachining technique is used to selectively remove silicon substrate in the process of developing a variety of structures like microtunnels, trenches, cavities, holes, etc. Another important key parameter is selection of etchant and masking layer. The etchant properties such as Si etch rate, roughness of etched surface, CMOS compatibility, safety, masking layer etch rate etc. are crucial in deciding the etchant of interest. i.e. either wet is required or dry. The DRIE technique, uses dry etchant (C_4F_8 and SF_6) which has many advantage such as high etch rate, low surface roughness, isotropic nature, low oxide etch rate, low metal etch, high accuracy, safe and CMOS compatible process [84]. The selection of masking layer during cavity etching is an important aspect because it affects fragility of wafer, roughness, extra pin holes in wafer etc.

4. Proposed applications of piezoelectric microphone

An acoustic sensor has become an integral part of systems used for locating and understanding noise sources in launching vehicle and aircraft [85]. The high pressure sound generated in launching vehicle and aircraft is recognized as pollutant in areas surrounding airports and launching pads. This sound pollution can adversely affect the living organisms creating blood pressure, fatigue, and stress in humans and animals [86].

4.1. Applications in aircraft design

In commercial passenger and cargo aircraft applications, acoustic sensors are used as a part of measuring the noise levels. This should be done in order to reduce the impact of noise on passengers, airports, and surrounding environment [87]. This impact of noise reduction should be done by identifying the noise sources and squeeze its effect to local level of noise generation. Localization can be done by shielding those noise sources with insulating panels. But this conventional way of providing the insulating sheets limit the size and weight of these panels in reducing the noise levels [88]. Treating the noise at its source is a promising method for reduction of low-frequency noise with weight savings compared to insulating panels. The NASA and Gulfstream jointly conducted Airframe Noise Flight (AFN) test at the NASA Wallops Flight Facility during October, 2006 [85]. An advanced experimental techniques such as Airframe Noise Flight (AFN) test can be used while during the aircraft component design process for reducing the noise effects [85,89]. The AFN test involved rigorous noise measurements using the NASA microphone array system as well as Gulfstream free-field (certification) and aircraft mounted (surface) microphones. These deployed microphone provided source localization maps for frequencies between 200 Hz and 8 kHz and high SPL range up to 160 dB.

4.2. Applications in rocket launching vehicles

Acoustic sensors are also useful in the field of avionics where the measurement of noise levels is extremely critical. During the take off of rocket launcher, these generate enormous amount of acoustic energy with the main source noise coming from collision of supersonic exhaust with surrounding ambiance. Because of this, several components of launcher such as concentric slits, barriers, foils, thin-film windows, gratings, buildings and humans can be prone to damage. These noise levels need to be measured and attenuated before any damage occur to the launcher. Highly sensitive sensors are required to measure low pressure levels and lower sensitive sensors are required to measure high pressure levels. On the basis of these measurements, heat shields with good attenuation characteristics will be designed. In general, the highest internal sound pressure in heat shield is observed at lift-off at an overall level of 133 dB over a bandwidth of 20–2000 Hz whereas outside heat shield it is 149 dB [90]. On the basis of noise measurement, heat shields for launch vehicles are designed with good attenuation characteristics (15–25 dB) in frequency range of 40–1000 Hz [91].

4.3. Application in biomedical engineering

Biomedical engineering is a field where acoustic sensor has wide ranges of application, some of which are mentioned below.

- Novel surface acoustic wave biosensors are useful for detecting liquid phase ligand. Human embryonic kidney cells act like specific ligand receptors and these are connected to electroacoustic transducer [92]. Apart from this, these biosensors are useful in detecting other substances such as toxins, drugs, etc.
- Surface acoustic wave biosensors find its application in identification of environmental health hazards, bacterial pathogens, etc. A durable bacteria sensor can be developed through the integration of highly sensitive dual-mode acoustic wave platform with phage based selective detection elements [93]. Wide band-gap piezoelectric layer aluminum nitride (AlN) materials are used for developing these kind of sensors. By shifting from different wave resonant modes, sensor platform can be adjusted to sense in vapor, liquid and gas. These kinds of biosensors usually fit hospitals, radiation control units, water quality maintenance units where identifying ineffective bacteria is absolute critical.
- Acoustic sensors also find its application monitoring different bio signals such as breathing sounds of apnea patients, chest sounds in neonatal care units etc. This is possible by developing surface acoustic wave inter-digital transducer (SAW-IDT) sensors. These measurements are typically made using air-coupled microphones, and/or light-weight accelerometers attached to skin [94].

4.4. New areas of application

- The detection of gunshots or screams for military and urban security systems has become an important area of research which can be used in audio and video surveillance systems [95]. It requires a high SPL detection capable and sensitive acoustic sensor which provides local source localization. At the same time further processing of source localization information has been done and video camera is steered according to that. These sensors based automated surveillance system once implemented can be used in harsh environments and remote locations where human intervention is not feasible.
- The trend of water resistant smartphones is increasing but the major hindrance in the development of smarter devices is the capacitive microphones used which are less susceptible to dust and water egress. The replacement of capacitive microphones with MEMS based piezoelectric microphones will not only provide the system water and dust resistance but also elevate its performance compared to the existing systems. Further, these water resistive acoustic sensors that are economic and power efficient can find incredible potentials for applications in underwater wireless networking and surveillance enabling a variety of IoT (internet-of-things) type applications [96].

- The requirement of healthy environment boosted the demand of automatic electronic vehicles. The automatic operation of these vehicles requires an array of microphones and signal processing unit to detect horn and siren sounds for decision making [97]. The range of these signals fall in wider ranges that conventional microphones struggle to capture, hence MEMS based microphones are an emerging alternative with its wide frequency range of operation and increased sensitivity. Another interesting domain of application of the hydrophobic microphones is in pipeline leakage detection where automated monitoring of pipeline pressures can be ensured even in remote locations thereby ensuring fast detection and rectification [98].

5. Future scope

The fabricated sensors with high sensitivities along with low cost and process overheads once commercialized can find applications in space vehicles, aircraft, submarines, leakage detection in pipelines, automated vehicles, and so on. The developed sensors exhibit enhanced performance over the conventional devices in terms of dynamic and frequency ranges, process costs and complexities. However the design can further be improved along with optimization of growth conditions to yield sensors with better performance. The various proposed diaphragm and microtunnel dimensions structures have contributed to improving wide dynamic range and frequency response to the acoustic sensor, but still these ranges needs to be improved to meet the demands of the aeroacousticians. Thus, there still exists room for improvement to achieve the ultimate aim of sensitivity, dynamic and frequency range of the device operation which can be achieved through the following future perspectives.

- The focus of future work will be on improving the acoustic sensor packaging and the electronics circuitries involved. The circuitry used in this work for device testing may be adequate for few applications but there are many other applications demanding higher sensitivity, lower output impedance, higher power supply rejection ratio, lower power consumption, etc. The use of an ASIC would not only improve all these metrics but also reduce the noise floor.
- The packaging utilized in this work was designed for laboratory characterization purpose. Moving to the commercial application requires development of a low-cost, robust, thin package with adequate electromagnetic interference (EMI) shielding for the high-impedance sensors.
- In biomedical engineering where acoustic sensors are used in analysis of body signals such as breathing sounds of sleep-apnea patients, chest sounds and neonatal care units. The body signals usually fall in the low frequency range where conventional sensors struggle. The sensor developed due to its wide frequency range (12 Hz to 22 kHz) ensures the detection of all vital body signals with minimal losses involved [99,100] .
- The flat frequency range of the device can be broadened towards lower frequency, so that the same device can also be used for other applications such as detection of earthquakes, volcanoes and avalanches (low frequency vibrational waves).
- Standardization of design and development process of an acoustic sensor should been done. Its applications can be extended for gunshot detection [101], under water application as hydrophone [102], siren sound or alarming situation detection using an array of microphones in automating driven electronic vehicles [103], pipeline leakage detection using wireless acoustic sensor network [104], etc.
- Further they find applicability in automated vehicles where wide range of operational frequencies become necessary for detection of alarms and signals.

Recently huge demand for MEMS microphone has been seen in leading research organizations for space, underwater, aircraft and military applications. However, the specifications necessary for these applications cannot be met by the existing systems that are currently in use. Piezoelectric-based sensors do not require any additional power supply to operate them which make them suitable candidate for satellite devices, implantable hearing devices, real-time security surveillance, and gunshots etc. The development of these devices can be done with the integration of micromachined diaphragm/ cantilever Si-structures and the standard RF-sputtered stack of Al/ZnO/Al at low-cost processes and easy availability. Recently, a few organic piezoelectric materials have also been reported but its deposition technique is still a part of the research.The proposed application areas are a sincere effort towards providing new insights on development of a cheap and self powered acoustic sensor that can be a boon to the society and can effectively meet the demands of the future generations.

6. Conclusion

Since the first MEMS piezoelectric microphone was demonstrated in 1983 and microphone for aeroacoustic application was presented in 1998. A significant progress has been seen to obtain high performance sensors for audio and aeroacoustic application. The piezoelectric materials have many advantages such as zero biasing voltage, linear response at large SPL, good coupling coefficient, etc. These advantages of the piezoelectric materials pushed to optimize deposition conditions and to develop piezoelectric devices. Different piezoelectric materials (ZnO, AlN, polyurea, PZT, etc.) have been used to develop MEMS microphones with a number of geometries such as circular, cantilever, square membranes, concentric electrode configurations, etc. Many trails have been made to obtain desired dynamic range, linear response, bandwidth, etc. Sufficient evidence exists to suggest that the piezoelectric based MEMS microphone have capability to fulfill the present requirement of aeroacoustic applications.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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