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Review Article

Design Approaches of MEMS Microphones for Enhanced Performance

Muhammad Ali Shah,[1,2] Ibrar Ali Shah,[3] Duck-Gyu Lee,[1] and Shin Hur[1,2]

[1]Korea Institute of Machinery and Materials, 156 Gajeongbuk-Ro, Yuseong-Gu, Daejeon 34103, Republic of Korea
[2]University of Science and Technology, Nano-Mechatronics, Daejeon 34113, Republic of Korea
[3]Department of Computer Software Engineering, University of Engineering and Technology, Mardan, Pakistan

Correspondence should be addressed to Shin Hur; shur@kimm.re.kr

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This paper reports a review about microelectromechanical system (MEMS) microphones. The focus of this review is to identify the issues in MEMS microphone designs and thoroughly discuss the state-of-the-art solutions that have been presented by the researchers to improve performance. Considerable research work has been carried out in capacitive MEMS microphones, and this field has attracted the research community because these designs have high sensitivity, flat frequency response, and low noise level. A detailed overview of the omnidirectional microphones used in the applications of an audio frequency range has been presented. Since the microphone membrane is made of a thin film, it has residual stress that degrades the microphone performance. An in-depth detailed review of research articles containing solutions to relieve these stresses has been presented. The comparative analysis of fabrication processes of single- and dual-chip omnidirectional microphones, in which the membranes are made up of single-crystal silicon, polysilicon, and silicon nitride, has been done, and articles containing the improved performance in these two fabrication processes have been explained. This review will serve as a starting guide for new researchers in the field of capacitive MEMS microphones.

1. Introduction

A vibration which propagates as a pressure wave in the air or any other elastic medium is called sound [1]. Humans can hear sound in the frequency range of 20 Hz~20 kHz, whereas that above 20 kHz is ultrasound and that below 20 Hz is called infrasound. To deal with the science of sound, the term "acoustics," which comes from the Greek word *akouein*, meaning "to hear" [2], is used. The instrument used to convert these sound pressure waves into electrical signals is known as a microphone. The conversion of sound pressure waves into electrical signals is performed by different transduction mechanisms, i.e., piezoelectric [3], piezoresistive [4, 5], optical [6, 7], and capacitive. Microphones based on these transduction mechanisms are briefly explained as follows.

1.1. Piezoelectric Microphone. This type of microphone works on the principle of piezoelectric effect. The piezoelectric effect can be direct or inverse. In the direct piezoelectric effect, charges are generated on the top and bottom plates of the sandwiched piezoelectric material due to the stress applied. In contrast, applying an electric field results in the generation of stress in the inverse piezoelectric effect. In the case of a microphone, direct piezoelectric effect happens, in which stress is applied in terms of sound waves, which then results in creating charges on the plates. This is further converted to voltage as an output signal.

1.2. Piezoresistive Microphone. A microphone in which change in the electrical resistance occurs due to sound waves of the semiconductor material is considered to be a piezoresistive microphone.

1.3. Optical Microphone. In the case of an optical microphone, transduction mechanism of converting the sound waves into electrical signals is produced by sensing changes in light intensity. Optical microphones are used in applications where the canceling of noise is required, e.g., in directional microphones [8, 9].

1.4. Capacitive Microphone. In capacitive microphones, a change in capacitance occurs between the static back plate and moving diaphragm which then converts into electrical signals through electronic circuitry.

Because of their high sensitivity, flat frequency response, and low noise levels, capacitive microphones are the focus of researchers. Capacitive microphones are further divided into two types.

1.4.1. Simple Condenser Microphone. A condenser is another term for a capacitor. A capacitive microphone that is polarized externally is simply known as a condenser microphone.

1.4.2. Electret Condenser Microphone. The microphone that is polarized internally using an electret is called an electret microphone. The term *electret* is a dielectric material that has to be polarized permanently to create charges on the capacitive plates [10].

The first traditional electret condenser microphone (ECM) was invented by Gerhard Sessler and James West at Bell Labs in the early 1960s [11, 12]. The traditional ECMs consisted of air gap capacitors with a moving diaphragm and a back plate. Their stability, repeatability, and performance were not good over various temperatures and other environmental conditions [12]. Electret microphones can also be sensitive to acceleration. MEMS technology has revolutionized this industry by developing ultra-small-size, lightweight, low-power, low-cost, and compact-size devices [13]. The performance of MEMS sensors is superior as compared to those of macrosensors [14] due to which a variety of commercial MEMS sensors are widely used. MEMS microphones have higher performance density, can be reflow soldered, have less variation in sensitivity over temperatures, and have lower vibration sensitivity than traditional ECMs. MEMS microphones can be easily integrated with other microlevel circuitry, which makes it perfect for various applications, including but not limited to smartphones and tablets, as well as automotive, industrial, and medical applications [15, 16]. Also, the reduced size of MEMS microphones makes it perfect for use in the form of arrays of multiple microphones for different applications [17–19] in small products.

Like conventional ECMs, a MEMS microphone contains a back plate and a flexible membrane fabricated on a silicon wafer. The perforated back plate allows the sound pressure wave to enter, which causes the flexible membrane to move. The movement of the flexible membrane causes a capacitance variation between the membrane and a fixed plate, which is converted into an electrical signal through various types of interface circuitry [20].

Directionality defines the microphone sensitivity to certain sounds, i.e., whether it picks up the sound from a specific direction or it does from all directions around it. The graphical representations of these directional patterns are known as polar patterns. In terms of directionality, MEMS microphones can be divided into two types:

(1) *Omnidirectional microphone*. A microphone which receives sound waves from all directions equally, i.e., it shows the same sensitivity to the sound source at every different position. This type of microphone is a good candidate for an application where the sound source changes its position around the microphone

(2) *Directional microphone*. Instead of generating an electrical response from sound waves arriving from all directions around the device, the directional microphone has its strongest output when sound waves arrive along a single axis vertical through or parallel with the surface of a moving membrane

Both omnidirectional and directional microphones have their advantages and disadvantages. For example, in hearing aid applications, if there is background noise, a directional microphone is the best candidate, while an omnidirectional microphone performs better in a quiet environment. Therefore, in modern hearing aid devices, manufacturers are using both types in their products so that the users can switch it to an omnidirectional or directional microphone according to the environment either manually or automatically.

This review paper provides the literature about MEMS omnidirectional and directional microphones with different design approaches to provide an insight to help improve the performance of these devices. The first section of this paper includes the omnidirectional microphones with varying approaches of design and solutions to improve performance, fabrication processes, and product developments for commercialization and minimize the effects of the harsh environment on these commercial products in the field. The second section includes a brief overview of the Ormia fly-inspired directional microphones with different design approaches and their applications. The final part concludes the paper and presents the future directions.

2. Technical Analysis and Discussions

2.1. Omnidirectional Microphones. Microphones which record sounds from all directions are referred to as omnidirectional microphones. An omnidirectional microphone picks up good gain from all directions where the user speaks from any side of the microphone. This microphone is a good candidate for applications where sound needs to be recorded from multiple directions. The omnidirectional microphones with different transduction mechanisms and with different design approaches are explained below.

2.1.1. Piezoelectric Microphones. Piezoelectric is one of the transduction mechanisms used to sense the motion of the flexible membrane of a microphone. A piezoelectric material attached to the microphone membrane gets stressed due to the membrane's movement from sound waves, which generates an electrical voltage as an output called a piezoelectric effect [21]. The commonly used piezoelectric materials are zinc oxide (ZnO), aluminum nitride (AlN), and lead zirconium titanate (PZT). Both ZnO and AlN are nonferroelectric materials while PZT is a ferroelectric material, i.e., its direction of polarization can be reversed by applying an electric field. All these three materials have advantages and disadvantages over each other. For example, the better availability and less demanding vacuum conditions of ZnO films, the compatibility of AlN with CMOS processing and A1N having a higher resistivity than ZnO, and the high piezoelectric coefficients of PZT [22] are the advantages of these materials over each other.

A piezoelectric microphone diaphragm can be formed by sandwiching the piezoelectric material between two metals. Diaphragms of piezoelectric microphones can be circular [23] or square [24] and cantilever [25] or double cantilever [26]. Cantilever-based diaphragms are free from residual stresses as compared to clamped-clamped diaphragms [25]. Circular diaphragms show higher sensitivities as the maximum stress distribution in circular diaphragm is uniform along the circumference as compared to that in the square diaphragm in which the maximum stress distribution is along a part of the edges [27]. The electrode distribution on the piezoelectric material can be at the edges or in the central portion of the diaphragm. The authors in [28] have analyzed these two distributed electrodes, in which the central-circle electrode can induce more charges as compared to the edge-surrounded electrode.

The first micromachined silicon piezoelectric microphone was presented by Royer et al. [29], in which a 30 μm thick diaphragm having a diameter of 3 mm was fabricated on a silicon wafer. A 3 μm thick ZnO piezoelectric film was deposited on the silicon diaphragm. After completing the deposition process, the diaphragm was etched from the back side of the silicon wafer. The measured sensitivity was found to be 25 μV/μbar with a 10 Hz~10 kHz frequency response. It was an integrated microphone with the metal oxide semiconductor (MOS) amplifier on the same silicon substrate in which the ZnO film was connected to the gate of the MOS amplifier. The cross-sectional view of this microphone is shown in Figure 1. Although this design shows a lower performance in terms of sensitivity and SNR as compared to traditional electret microphones, it paves ways for cost reduction, miniaturization, and performance improvement. For example, in terms of device thickness and with an improved sensitivity of 50 μV/μbar, the authors in [30] have presented a ZnO-based microphone with a 2 μm thick silicon nitride diaphragm. By decreasing the diaphragm thickness (thin film diaphragms), it can have residual stresses which can degrade the microphone performance, so an optimum residual stress compensation scheme will be needed to maximize the microphone sensitivity [31]. For the controlling of stress, another ZnO-based silicon nitride diaphragm was proposed in [32].

In the literature, most of the piezoelectric microphones are either ZnO [31, 33, 34], AlN [35–37], or PZT [38, 39] based having targeted consumer applications. Microphones with a wide bandwidth for aeroacoustic applications have been proposed in [23, 40–43], and their detailed analyses have been performed, and the parameters have been tabulated in Section 2.1.4 of this paper.

Piezoelectric MEMS microphones have some advantages and disadvantages over capacitive MEMS microphones. Low power consumption and a wide dynamic range [39] are the advantages, and high noise level [44] and low sensitivities [29] are the disadvantages of the piezoelectric microphones.

Although piezoelectric MEMS microphones have high noise levels and lower sensitivities, researchers are constantly making efforts to improve these parameters and make them competitive with capacitive microphones. For this purpose, the authors of [45] have presented improved SNR of piezoelectric microphones with their theory-based modeling. Also, developers are trying to commercialize piezoelectric microphones to compete with capacitive microphones. Vesper, which is specializing in piezoMEMS microphone technology, has developed its first commercially available piezoelectric MEMS microphones with the products named VM1000 and VM2000 [46], which target consumer applications, i.e., smartphones, wearable technologies, and the Internet of things (IoT). The product VM100 with a package size of 3.76 mm × 2.95 mm × 1.1 mm has a sensitivity of -38 dBV, SNR of 62 dBA (for 20 Hz to 20 kHz bandwidth) and 64 dBA (for 20 Hz to 8 kHz bandwidth), and a maximum pressure of 125 dBSPL [47]. This microphone was further improved in terms of an acoustic overload point of 135 dBSPL [48]. As shown in Figure 2, the microphone has a square diaphragm, having cuts in the central part to make four triangular cantilevers for vibration. This piezoelectric microphone can compete with capacitive microphones if we compare its parameters with the parameters of capacitive microphones shown in Table 1. Furthermore, this microphone is particle resistant, dustproof, and waterproof as compared to capacitive microphones [49], which can lead to the development of waterproof smartphones.

2.1.2. Piezoresistive Microphones. A piezoresistive microphone is composed of a diaphragm with two pairs of piezoresistors in a Wheatstone bridge configuration. Due to the mechanical stress or strain, a change in resistivity of a piezoresistive material occurs. For silicon membranes, a change in the number of charge carriers occurs due to which its resistivity changes [50]. A piezoresistive silicon microphone with a 1 μm thick highly boron-doped silicon membrane was presented by Schellin and Hess [51]. Another MEMS piezoresistive microphone with a low-stress silicon nitride membrane diameter of 210 μm having a sensitivity of 2.2 μV/V/Pa was presented in [52]. Although this microphone increases in sensitivity and decreases in power consumption over commercially available piezoelectric MEMS microphones, it has a higher noise floor of 92 dBSPL than expected. A MEMS microphone presented in [53] a with membrane diameter of 1 mm exhibited a reduced noise floor of 52 dBSPL, but having a lower sensitivity of 0.6 μV/V/Pa as compared to the microphone presented in [52]. These two MEMS

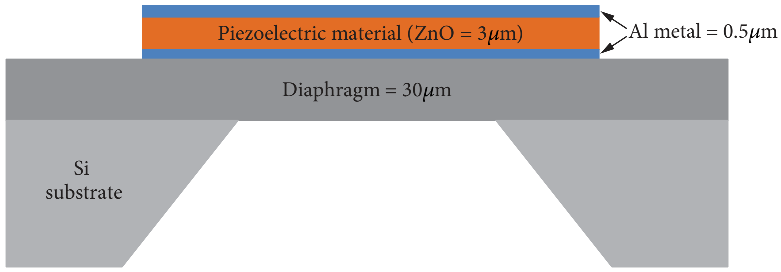


FIGURE 1: The cross-sectional view of the first silicon piezoelectric microphone [29].

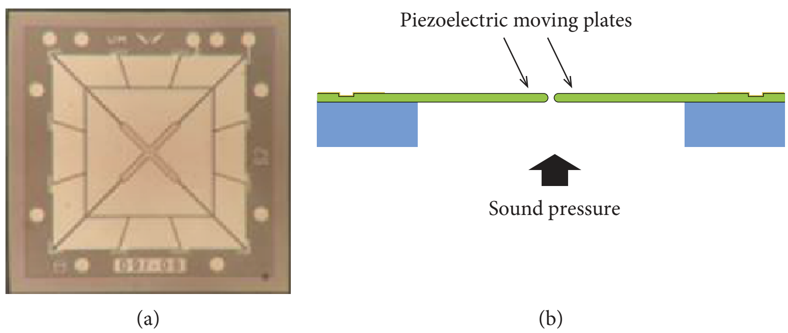


FIGURE 2: Vesper's piezoelectric MEMS microphone [49] with the (a) plan view and (b) cross-sectional view (source: Vesper Technologies Inc).

TABLE 1: Properties of microphones designed by different manufacturers.

Company's name (year)	Diaphragm size	Diaphragm thickness (μm)	Sensing gap (μm)	Sensitivity	SNR
Analog Devices [147] (2006)	NA	NA	3	-47 dBV/Pa	NA
Knowles [151] (2006)	0.56 mm$^{\$}$	1	4	-22 dBV/Pa	59 dB
Bosch [150] (2010)	0.6 mm$^{\$}$	NA	NA	NA	58 dB
Infineon [65, 153] (2013, 2017)	1.1 mm$^{\$}$, 4 × 3 × 1 mm$^{3¥}$	330 nm, NA	2.2, NA	-78 dBV/Pa, -46 dBFS*	66 dB, 67 dB
STM [154, 155] (2011, 2017)	0.73 mm$^{\$}$	NA	NA	-26 dBFS*, -38 dBV/Pa	61~65 dB

*dB full scale for digital microphones. $^{\$}$Diameter of the diaphragm. $^{¥}$Package size.

piezoresistive microphone designs show tradeoffs between sensitivity and noise floor. Since both the sensitivity and noise performance metrics depend on the geometry of the piezoresistor and on the electronic properties, the optimization of the design and electronic parameters has to be done to obtain higher sensitivities and lower noise floors [4]. To improve the performance of the microphones, researchers and designers are trying to come up with different design approaches. For this purpose, a piezoresistive MEMS microphone design with a new architecture has been proposed in [54, 55]. This microphone has silicon piezoresistive nanogauges attached to the microbeams which are placed between the inlet and outlet holes, as shown in Figure 3. Sound wave pressure from the inlet deflects the microbeams in the plane of the base wafer which induces stress in the nanoguages. Another design with the same sensing mechanism as that of [54] has been proposed in [56] with a measured resonant frequency of 16 kHz. Piezoresistive microphones can be found in applications of fluidic mechanics [57, 58] and aeroacoustics [52, 59].

2.1.3. Capacitive Microphones. Most of the silicon microphones presented in the literature are based on the capacitive principle because of the high sensitivity, flat frequency response, and low noise level. Capacitive microphones can be divided into electret microphones, condenser microphones, and condenser microphones with integrated field-effect transistors (FETs). In electret microphones, the electret is built-in charged while in condenser microphones, an external voltage is applied.

(1) Basic Theory and Operation Principle. Capacitive MEMS microphones are motion sensors composed of two parallel plates separated by an air gap and work on the principle of a mass-spring system where the moving membrane is acting as a spring, as shown in Figure 4, in

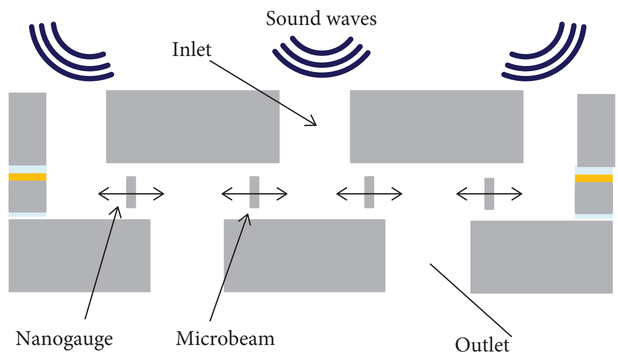


Figure 3: The cross-sectional view of a piezoresistive microphone having piezoresistive nanoguages and microbeams [54].

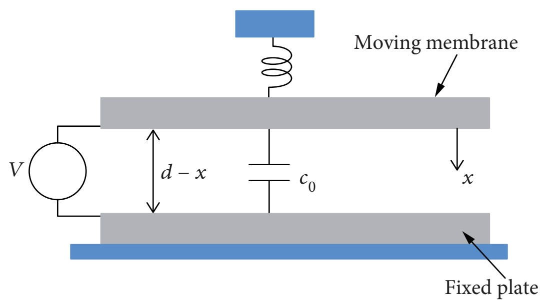


Figure 4: Schematic representation of a microphone defining its working principle with a membrane and back plate (fixed plate).

which "V" represents the supplying voltage, "x" represents the displacement of the membrane, and C_0 represents the nominal capacitance between the back plate (fixed plate) and the membrane. The mechanical force F_m of this mass-spring system is given by the following equation:

$$F_m = kx, \tag{1}$$

where "k" is the mechanical stiffness of the spring and "x" is the displacement of the moving membrane.

When a sound pressure is applied to the membrane, it moves with a displacement "x." The equation of the motion of the moving membrane can be represented as follows:

$$F_m = \frac{d^2x}{dt^2} + kx. \tag{2}$$

In equation (2), "m" represents the mass of the moving membrane.

The energy stored between these two plates is given by the following equation:

$$W = \frac{1}{2}CV^2. \tag{3}$$

Differentiating the stored energy of the capacitor with respect to the position of the movable plate defines electrostatic force (F_e) and is given by

$$F_e = -\frac{\partial W}{\partial x} = -\frac{1}{2}\frac{\varepsilon A}{(d-x)^2}V^2. \tag{4}$$

The capacitance (C) is given by

$$C = \varepsilon\frac{A}{d-x}, \tag{5}$$

where "ε" is the permittivity of the free space and "A," "d," and "x" are the area of the membrane, distance between the plates, and displacement of the membrane, respectively.

The bias voltage is applied to the membrane to operate the capacitive MEMS microphone. The electrostatic force increases with an increase in the applied bias voltage. A "pull-in" phenomenon occurs when the electrostatic force becomes greater than the mechanical force, where the membrane collapses with the fixed ground plate. The biased voltage magnitude can be chosen on the basis of the "pull-in" voltage. The pull-in voltage varies with the sensing gap variations [60]. The "pull-in" voltage (V_{PI}) can be represented by the following equation as presented in [61]:

$$V_{PI} = \sqrt{\frac{8kd^3}{27\varepsilon A}}. \tag{6}$$

The distance where the "pull-in" occurs and the "pull-in" gap are given by equations 7 and 8, respectively, [62].

$$X_{PI} = \frac{d}{3}, \tag{7}$$

$$d_{PI} = \frac{2d}{3}. \tag{8}$$

The electroacoustical sensitivity (S) of the capacitive MEMS microphone is given by

$$S = \frac{V_{bias}}{d} \times \text{displacement}. \tag{9}$$

By increasing the bias voltage (V_{bias}) and displacement and lowering the gap between the two plates, the microphone sensitivity can be increased. The mechanical sensitivity, S_m, of a circular membrane with a residual tensile stress, σ_0, is given by [63]

$$S_m = \frac{a^2}{8\sigma_0 h}, \tag{10}$$

where "a" is the radius and "h" is the thickness of the microphone membrane.

Generally, a silicon membrane moves when an incident sound wave reaches a membrane through a port from the back side of the package and through a perforated stiff back plate electrode (Figure 5) [64]. This leads to a change in capacitance between the membrane and back plate. A packaged microphone consists of a dual die, a MEMS sensor,

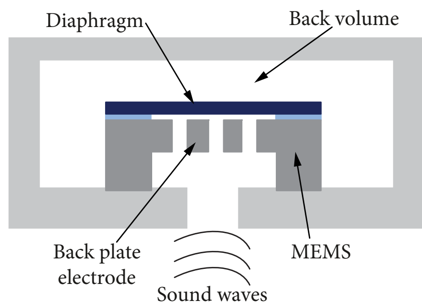


Figure 5: Cross-sectional representation of a microphone chip mounted on a package.

and an integrated circuit. Depending on the position of the sound outlet, the packaged microphone can be a bottom port or a top port, as shown in Figure 6. The sensor element can be connected to ASIC through wire bonding [65] or a flip chip-type package [66].

The space (back chamber) between the back side of the membrane and the rest of the package plays a vital role in MEMS microphones. Reducing the back chamber volume from $3\,mm^2$ to $2\,mm^2$ is equivalent to a sensitivity loss of about 1 dB [67]. A better acoustic performance can be achieved by making the chamber bigger. In this case, using the combination of isotropic and anisotropic etching, Kasai et al. from OMRON Corporation [68] have proposed a microphone with concave lateral sides, which increase the volume of the back chamber.

(2) Electret Microphones. In 1983, the first silicon-based electret microphone with an open-circuit sensitivity of 8.8 mV/pa and a frequency response of 8.5 kHz was presented by Hohm and Gerhard-Multhaupt [69]. In their design, a 13 μm thick aluminum-doped Mylar foil was used as a membrane with a 2 μm thick SiO_2 electret layer used to generate an electric field in the air gap. The electret was charged to about -350 V. The air gap between the metalized Mylar foil diaphragm and the electret is 30 μm. Another electret microphone, which has also a metalized diaphragm with a 2.5 μm thickness, was proposed by Sprenkels et al. [70]. The space between the diaphragm and electret was 20 μm.

The stability, repeatability, and performance of electret microphones are not good over temperature and other environmental conditions [12]. Moreover, electret microphones can also be sensitive to acceleration.

(3) Integrated Capacitive MEMS Microphones. The first integrated silicon condenser FET microphone was proposed by Kühnel [71]. The membrane of the microphone acts as a gate for the FET and is electrically connected with the source through the gate-to-source voltage. Another silicon condenser microphone with an integrated FET was presented by Graf et al. [72], in which they have focused on the increase of microphone sensitivity by taking attention to the membrane construction and air gap. This design was further improved in terms of size, stability, and ease of fabrication process [73]. Many other research studies have addressed the need to improve integrated microphones [74–77]. Integrated FET microphones have the advantage of having low output impedance [63]; however, they suffer from high noise levels [78, 79]. Properties of some of the FET-integrated microphones are tabulated in Table 2.

(4) Capacitive MEMS Microphones with Miscellaneous Designs and Different Approaches for Better Performance. To describe the microphone's behavior, a simplified network modeling has to be done due to the complexity of coupled mechanical, electrical, and acoustical components. For this purpose, a number of research articles have been published using the network modeling extensively [79–81]. Also, a high degree of miniaturization of these devices is needed to boost their applications in MEMS industries. To reduce the size, new design approaches and improved fabrication processes are needed. For this purpose, a condenser microphone with lateral dimensions of $0.8 \times 0.8\,mm^2$ and 150 nm thick silicon nitride diaphragm was developed by Kühnel and Hess [82]. This device was biased from an external voltage of 28 V. Although they have reduced the size of the device with an air gap of 2 μm, it still has lower sensitivity and poor frequency response as compared to the electret microphone proposed in [69]. The poor performance in terms of frequency and sensitivity is mainly due to the resistance caused by the air trapping between the diaphragm and back plate electrode. A perforation in the back plate or in the diaphragm is the widest scheme to reduce this air resistance (squeeze film damping) [83]. Analytical solutions of squeeze film damping in perforated back plate devices have been presented in [84, 85]. Surface roughness can affect this squeeze film damping [86]. The location of holes in the back plate has more effect as compared to the number of holes [87, 88].

To weaken the air resistance, Yoo et al. [89] suggested a microphone with an increased number of ventilation holes in the back plate electrode. This microphone showed a flat frequency response between 2 and 20 kHz. This device still has a lower sensitivity and needs to be decreased in size. Another design proposed in [90] has 5 holes with a diameter of 12 μm, each in the center of the membrane to reduce air trapping and improve the sensitivity and frequency response. They also showed that with the increase in membrane diameter, the effect of the center hole increases. To improve the sensitivity, a diaphragm having slits at the edges was proposed by Yoo et al. [89]. The authors in this research study have investigated a circular diaphragm with and without slits at the edges, in which the diaphragm with slits shows a higher displacement. The SNR of this microphone was found to be 70 dB. When the membrane of a microphone is deflected, the effective area for the change in capacitance is decreased, causing the sensitivity to be decreased. To overcome this problem, the authors in [90] suggested two connected membranes as shown in Figure 7, in which the first part was exposed for acoustic wave while the second one, which is attached to the center of the first part, acts as a moving electrode.

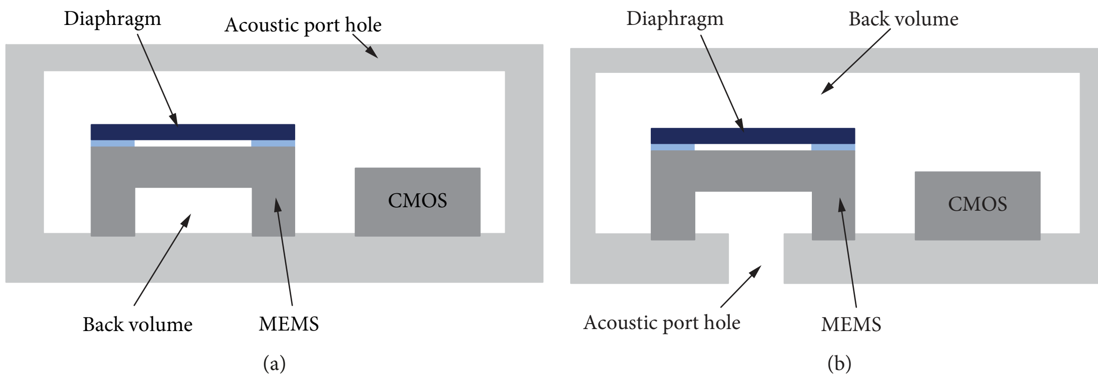


FIGURE 6: (a) Top port MEMS microphone and (b) bottom port MEMS microphone.

TABLE 2: Properties of FET-integrated microphones.

Author (year)	Diaphragm size (mm^2)	Diaphragm thickness (μm)	Sensing gap (μm)	Drain current (μA)	Drain-to-source voltage (V)	Bias voltage (V)	Sensitivity (mV/Pa)	Noise level (dBA SPL)
Kühnel [19, 26] (1991-92)	1	NA	2	2~2.5 mA	0~9	30	3	62
Malcovati et al. [20] (1993)	NA	5	3.5	150	15	15	38	58
Arnau and Soares [21] (1996)	0.25	4.5	1.5	17	NA	9	20 μV/Pa	69

NA: not available.

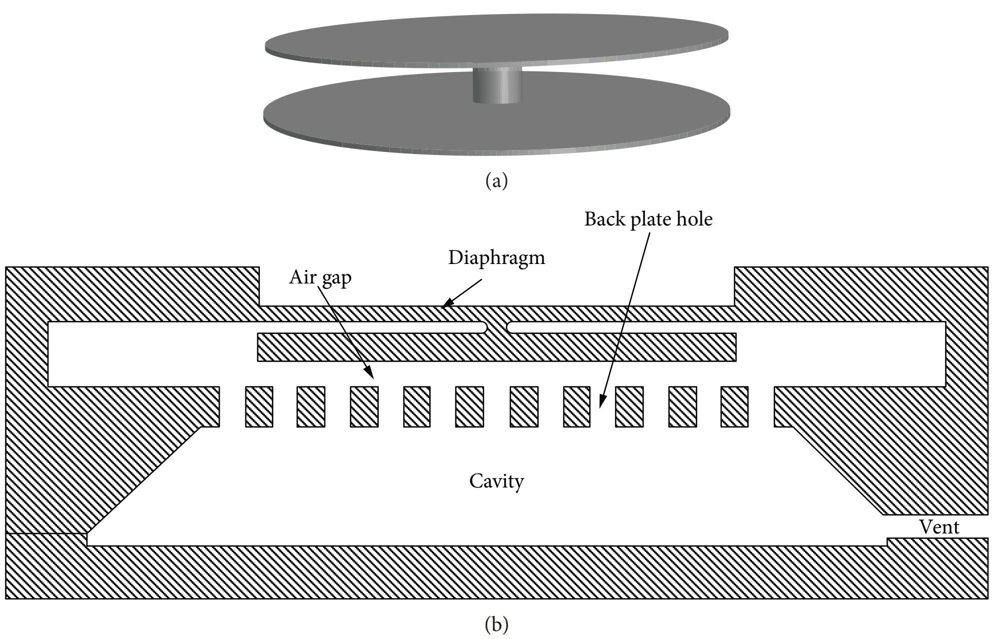


FIGURE 7: (a) 3D structure and (b) cross-sectional view of a microphone design with two coupled membrane structures at the center for higher sensitivities [90].

(5) Microphones with Back Plate Support. Lee et al. have proposed a surface-micromachined microphone with a back plate anchored by 11.5 μm [91] and 25 μm [92, 93] deep pillars to prevent the back plate from deformation during the operation. The back chamber volume affects the sensitivity and frequency response, i.e., the lower the back chamber volume is, the poorer will be the sensitivity and frequency response [94]. The small back chamber volume in [91–93] acts as a resistance when the sensing membrane vibrates, which reduces the sensitivity and frequency response. The proposed design was further improved by making the back chamber and back plate anchors 100 μm deep, which results

in an improved frequency response [95–97]. The cross-sectional view representing the concept of back plate-supporting pillars is shown in Figure 8.

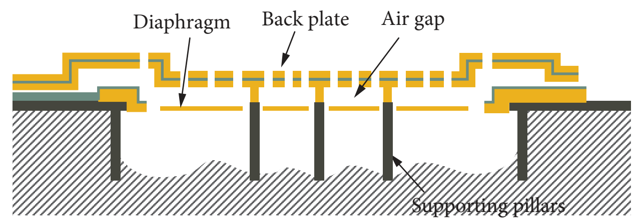


Figure 8: A cross-sectional view of a microphone with the back plate-supporting pillars [96].

(6) Microphones with Stress-Free Diaphragms. Thin diaphragms can have residual stresses (tensile or compressive) due to which the sensitivities can be decreased [98]. These stresses in the diaphragm are often caused by its fixed boundaries [99]. Due to these stresses, buckling in the radial or circumferential directions (Figure 9) can occur in the membrane. Buckling in the radial direction may be reduced by making some cuts in the circumferential direction [100]. Moreover, buckling in the circumferential direction can be reduced by making cuts in the tangential direction as shown in Figure 10. In some situations, the residual stress can become quite high which leads to membrane stiffness and, hence, degradation of the microphone performance. Reduction of tensile stress is needed to improve the sensitivity of the microphone. A number of research studies have been conducted to reduce the residual stresses in the diaphragm with different approaches. Corrugations in the diaphragms, spring-supported diaphragms, and controlling of deposition parameters in the fabrication process are some of the techniques used to reduce the initial stresses in the thin film diaphragms.

(6.1) Corrugated Diaphragms. A decrease in stress, thereby increasing sensitivities, can possibly be achieved by corrugated diaphragms [101–105]. With the increase in the number of corrugations in the diaphragm, the mechanical sensitivity can be increased [106]. The optimized number of corrugations and corrugation depth can be achieved by finite element analysis (FEM) [107]. Corrugations can be made on the sides of the membrane to keep the central area of the diaphragm flat to yield a high capacitance. Corrugation depth is the most effective parameter to influence the behavior of corrugated diaphragms [102]. With the increase in corrugation depth, a large number of membranes can be damaged during the cutting process which will decrease the yield; therefore, an optimum corrugation depth should be selected [108]. Also, very deep corrugations stiffen the diaphragm, which leads to a decrease in mechanical sensitivity [102]. In contrast to the etching process used in [102], the authors in [108] suggested local oxidation of silicon (LOCOS) for making the grooves, which can lead the diaphragm to be having higher mechanical stability. Also, the shallow corrugated diaphragms increase the mechanical stiffness while releasing the stress [109]. In [109, 110], the authors have proposed a microphone with a single deeply corrugated diaphragm with improved sensitivity. The cross-section views of the multi-corrugated diaphragm and a single deeply corrugated diaphragm are shown in Figures 11(a) and 11(b), respectively

(6.2) Spring-Supported Diaphragms. The membranes with different types of springs (Figure 12(a)) have been analyzed analytically, and FEM simulations have been performed in [106] to check and compare their sensitivities (Figure 12(b)), in which the membranes with large and thin springs have shown higher sensitivities as compared to the membranes with short and thick springs and flat circular membranes with no springs. Other spring-supported diaphragms have been presented in [111, 112]. In [111], the authors have proposed a microphone design with a frog arm-supported diaphragm, which shows higher sensitivities as compared to that with a simple clamped diaphragm. A simple fully clamped diaphragm design was also compared with a folded spring-supported diaphragm, in which the authors have achieved improved sensitivity with reduction in diaphragm radius as compared to the simple clamped diaphragm design [112]. The same is the case for square membranes in which sensitivities were improved [113–115]. Furthermore, the residual stresses can also be reduced due to the spring-supported base diaphragms for a round [112] or square [113] diaphragm. Instead of using a flexible diaphragm, the authors in [116] have proposed a microphone consisted of a rigid diaphragm supported by flexible springs. Thus, the deformation of the diaphragm by thin film residual stress can be significantly reduced. This design was further improved in terms of sensitivity, SNR, and bandwidth by using a flexible V-shaped spring, silicon nitride electrical isolation, and the ring-type oxide/polySi mesa, respectively [117]

(6.3) Deposition Parameters. The residual stress of doped polysilicon highly depends on the deposition temperature and process pressure. Generally, on silicon wafers, the deposited LPCVD thin film polysilicon shows large residual stress [118, 119] and depends on the deposition temperature and process pressure [120]. This initial stress can be controlled by the parameters of the deposition process. In this case, a low-stress boron-doped polysilicon membrane has been presented in [121], in which the authors have adjusted the annealing temperature to achieve the desired stress Another stress-releasing technique is to use a sandwich-type structure in which layers with compressive and tensile stress are combined [122].

(7) Dual-Diaphragm or Dual-Back Plate Microphones. To increase the sensitivity, authors in [123] have presented a dual-diaphragm microphone for differential read-out. The microphone contains a central static electrode encapsulated by two movable diaphragms. The symmetric structure increases the possibility of force balancing. Interconnecting pillars have been used in the center instead of being in the overall area of the diaphragm. This reduces the rigidity against the sound pressure.

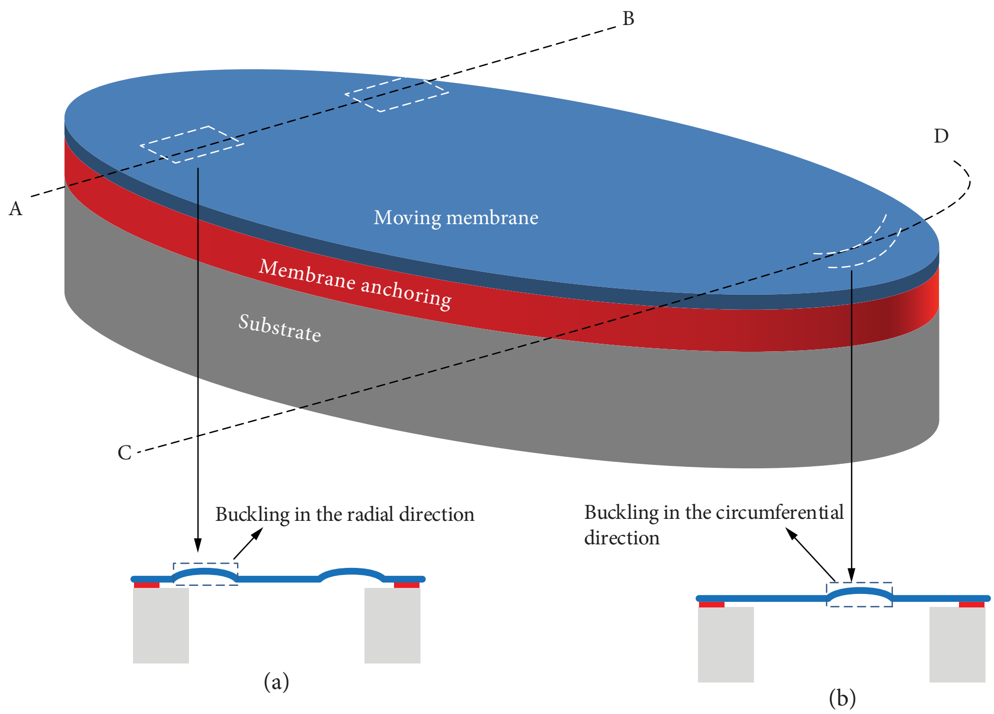


Figure 9: A circular microphone membrane having buckling (a) in the radial direction (AB) and (b) in the circumferential direction (CD).

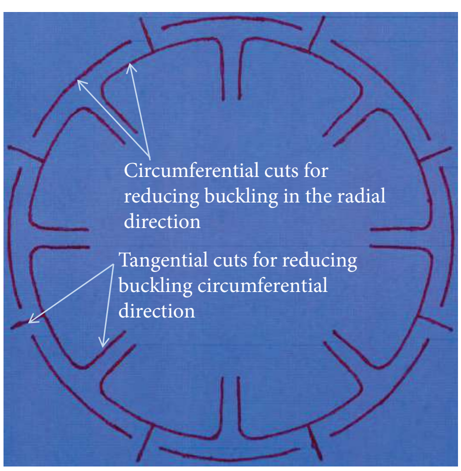


Figure 10: A plan view of a microphone membrane representing cuts in the membrane for reducing buckling of the membrane [100].

This type of design can increase the sensitivity and the force balancing. However, the complicated fabrication process, stability problems, and the need of force balancing make it disadvantageous. To overcome these disadvantages, the same authors have proposed a dual-back plate microphone with a flexible membrane in the center [124]. Another improved design with dual back plates and a central diaphragm which is insensitive to common-mode pressure changes was proposed in [125]. Owing to the higher sensitivities and SNR of the dual-back plate microphone over the single-back plate microphone [126], a series of other research studies targeting dual back plates have also been published with improved parameters, different applications, and a combination of surface and bulk micromachining processes [127–130]. Other dual-back plate microphone designs have been presented in [131], in which a nonlinear dynamic model of the microphone has been developed using lumped element modeling and a solution of large displacement through the energy method has been utilized to provide linear and cubic lumped stiffness of the diaphragm.

(8) Microphones with SNR Improvement. Signal-to-noise ratio (SNR), an indicator of performance, is the most important parameter of MEMS microphones. SNR is defined to be the difference between a microphone's sensitivity and its noise floor and is expressed in dB. Improved quality of the captured signal and an extended distance between the microphone and source of the sound can be achieved by a higher SNR. A microphone with a lower SNR and high self-noise results in poor signal, especially in far field applications where the microphone is not located near the sound source. Current MEMS microphones can be found in the range of about 55 dB to 70 dB SNR. Currently, Infineon Technologies has a high-performance microphone with the highest SNR of 69 dB with an acoustic overload point (AOP) of 130 dBSPL [132]. A noise floor is defined to be the amount of noise on a microphone's output when there are no environmental effects. The noise can be from a microphone sensor, which is called a Brownian noise, or it can be from interface ASICs. The noises generated from the sensor and interface ASIC are due to the acoustical holes and thermal noise, respectively, of the load resistor [133]. A very small movement of mechanical components can cause a mechanical-thermal noise [134].

Some studies have been done to check the microphone response to different noises and how to get an optimized

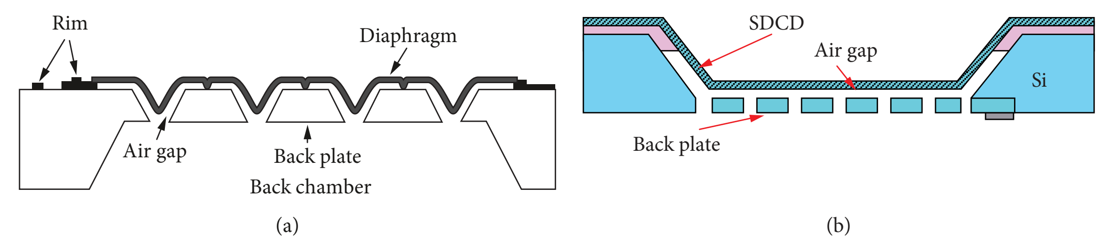


Figure 11: The cross-sectional view of a corrugated diaphragm with (a) multicorrugations in the diaphragm [107] and (b) a single deep corrugation in the diaphragm [110].

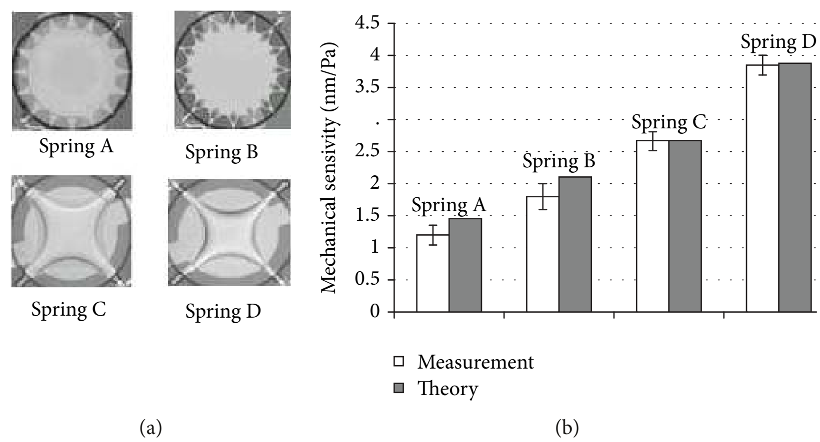


Figure 12: (a) Membranes with different types of springs [106] and (b) a graph representing different types of springs vs mechanical sensitivity, in which springs C and D, which make an X-shaped structure with the membrane, show higher sensitivities as compared to the other membranes with springs A and B [106].

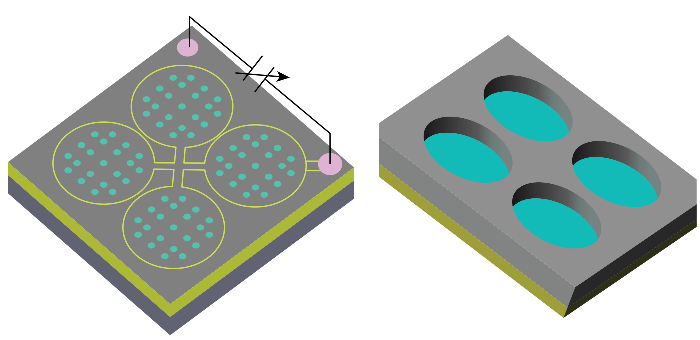


Figure 13: Multiple microphones in a parallel connection [138].

and improved SNR. For example, noise from the sound inlet of electret microphones was demonstrated by Thompson et al. [135] who provided a way to reduce these internal noises. A multimicrophone noise reduction technique for speech recognition has been devised in [136]. In [133], the authors have achieved an improved and optimized SNR of 64 dB by tuning a load resistor value. By designing the optimized size of the ventilation holes in the back plate, the authors of [126] have minimized the air flow resistance between the membrane and back plate. Johnson-Nyquist's relation was used for the flow resistance to estimate the acoustical-thermal noise sources, and then an estimated SNR was achieved. The effect of thermal noise on stability and frequency response of capacitive microphones was studied in [137]. Multiple microphones can be put together in a parallel configuration (Figure 13) to improve the SNR with a reduction of overall acoustic noise by 6 dB [138]. Another design using two microphones in a differential configuration yielding a 3 dB SNR improvement has been proposed in [139]. Improving an SNR can also be achieved by designing a double-diaphragm [123] or double-back plate [128] microphone which has a differential output [138]. A microphone with comb fingers is also an approach to enhancing SNR [140, 141]. In [141], the authors have achieved an SNR of up to 73 dB (A-weighted) by developing a system-level modeling and performing simulations of their proposed comb finger microphones.

(9) Microphone Designs with No Back Plate. Microphones with no back plate have some advantages; first, there is no need for an extra fabrication step to make the back plate. Second, the bias voltage is not required to pull the diaphragm to the back plate, and third, the stiction issues between the membrane and back plate can be prevented. Due to these advantages, researchers have proposed some designs with no back plate [140, 142–146]. In [142], the authors have proposed a design with in-plane gap-closing sensing electrodes to detect acoustic pressure. For better temperature stability and lower residual stresses, the authors in [143] have fabricated the silicon on insulator (SOI) diaphragm as compared to CMOS multilayer stacking used in [142]. The microphone was further improved in [144] by using a polysilicon trench-refilled process with a high aspect ratio (HAR) sensing electrodes. In [146], the authors also proposed a capacitive finger microphone. To avoid pull-in instability between the membrane and the substrate, this membrane was biased by repulsive force instead of attractive force to achieve higher sensitivity by increasing the bias voltage.

A no-back plate star-comb microphone concept for enhancing the SNR has been presented in [140]. In this design, the interdigitated combs are placed in the center of the membrane in which one set of comb fingers is attached to the membrane while the other is fixed to the substrate as shown in Figure 14. For the slide film damping reduction, the comb fingers are arranged with small gaps (for sensing) and with wide gap (to open the path for fluid flow). A 73 dB (A-weighted) SNR has been achieved from their system-level model, which they have claimed to be expected in the actual scenario also.

(10) Microphone Designs from Different Manufacturers. Different companies have published research articles about microphone designs for audio applications. Some of them are already commercialized, which are used mostly in iPhone mobiles. These designs are briefly explained below.

(10.1) Design from Analog Devices. Weigold et al. [147] from Analog Devices have fabricated a round polysilicon moving membrane with a single-crystal silicon-perforated back plate on silicon on insulator (SOI) wafers. The gap between the diaphragm and the back plate was 3 μm. Previously proposed designs were either fixed from some points at the corner or fixed from the whole corner edges [148, 149]. In Analog Devices design, a spring-supported diaphragm was proposed to increase the sensitivity. The cross-sectional view and plain section of Analog Devices microphones are shown in Figure 15(a).

(10.2) Design from Robert Bosch GmbH. Another microphone with a spring-attached circular diaphragm for stress relief was proposed by Leinenbach et al. [150]. The membrane is made up of a polysilicon with 0.6 mm in diameter. The total chip size of the microphone is 1 mm^2. The frequency response of this microphone was found to be 12 KHz, and the SNR was calculated as 58 dB. The membrane structure in plain view and the membrane with the bottom electrode in cross-sectional view are shown in Figure 15(b).

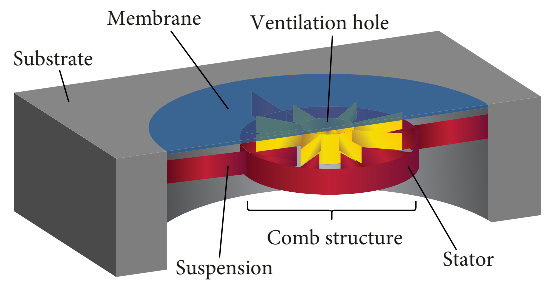


Figure 14: A "star-comb" MEMS microphone design with no back plate [140].

(10.3) Design from Knowles Electronics. Loeppert and Drive have proposed the first commercialized MEMS microphone [151], with a product name, SP0103BE3 [152]. They have proposed a 1-micron-thick polysilicon free-floating diaphragm with a diameter of 560 μm separated by an air gap of 4 μm from the back plate. The MEMS die size is 1.65 × 1.65 millimeters. As the stresses in the diaphragm are often caused by its fixed boundaries, a free-floating diaphragm was used to make it stress free and to increase the sensitivity. The maximum sensitivity was found to be -18 dBV/Pa from the datasheet [152]. They have successfully fabricated and tested their design with a peak frequency of around 14 KHz. The device operates at a bias voltage of 11 V. The plan and cross-sectional views are shown in Figure 15(c).

(10.4) Design from Infineon Technologies. Designs with different membrane diameters were analyzed by Dehé et al. [65] from Infineon Technologies. A high signal-to-noise ratio (SNR) of 66 dB (A-weighted) and sensitivity of -38 dBV/Pa at 1 KHz were achieved for a 1.1 mm membrane diameter. The microphone membrane is shown in Figure 15(d).

In the year 2017, Infineon Technologies presented a paper in the literature about a digital CMOS MEMS microphone with an improved SNR of 67 dB [153]. This is a dual-back plate microphone with a supply voltage of 1.8 V achieving a sensitivity of -46 dBFS and a sound pressure level (SPL) of 140 dB.

(10.5) Design from STMicroelectronics. The STMicroelectronics microphone design, found in iPhones, having a square membrane of 0.73 mm fabricated by OMRON with anchoring positions at the four corners of the membrane, has been analyzed by Chipworks [154]. More details about ST's microphone products can be found in their tutorials for MEMS microphones with an application note AN4426 [155], with the SNR values ranging from 61 dB to 65 dB.

The abovementioned membrane design, integrated with another small membrane to make a dual-channel microphone for an ultrawide dynamic range, was suggested with a product name "the MP34DTW01" [156]. The sensing element was proposed by OMRON Corporation, having a dual channel (normal and high) with a single diaphragm and single back plate on the same die [157]. This microphone diaphragm has flat frequency responses for both the channels from 20 Hz to 20 KHz and an SNR of 63 dB and 43 dB and

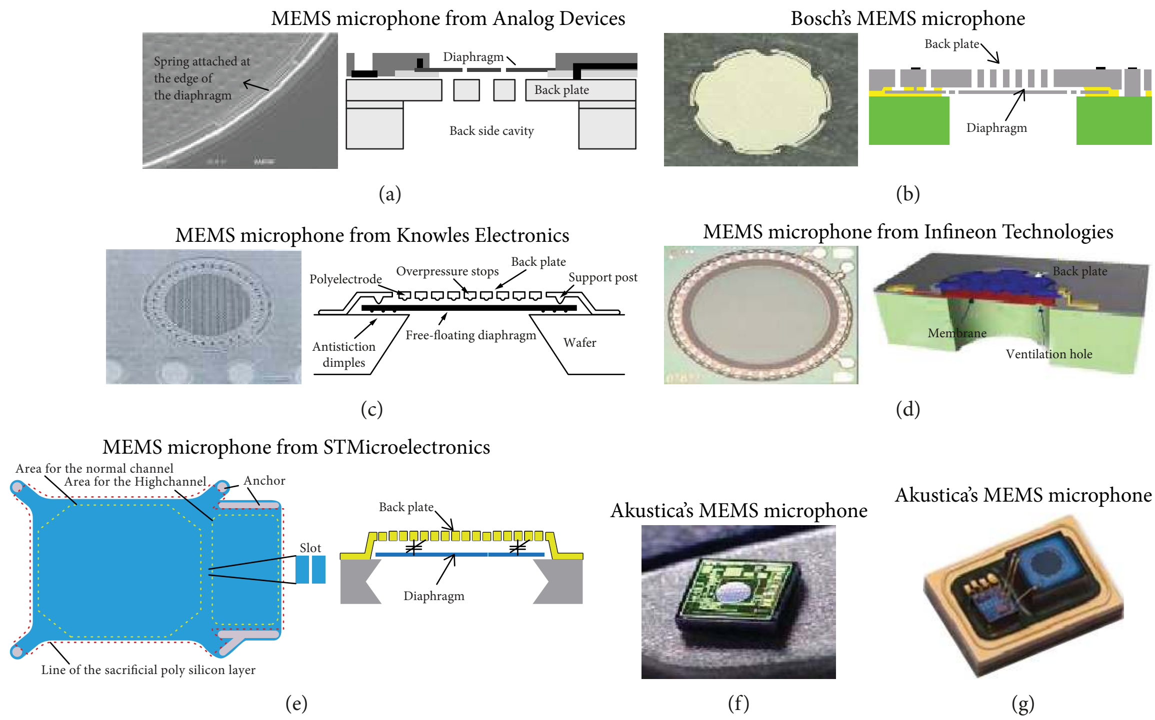


Figure 15: Microphone designs from different companies: in (a, b), the spring-supported diaphragm microphones for stress relief have been presented by Analog Devices [147] and Bosch [150]. (c) is a MEMS microphone design presented by Knowles [151], which has a free-floating diaphragm for reducing the stress, thereby increasing the sensitivity. (d) shows a microphone design from Infineon [65], which has the highest SNR compared to the other designs presented in Table 1. (e) shows ST's dual-channel MEMS microphone design for higher dynamic range [157].

sensitivities -25.1 dBFS and -44.5 dBFS for normal and high channels, respectively. The cross-sectional view and plain section of a dual-channel MEMS microphone is shown in Figure 15(e).

(10.6) Summary of the Microphones Presented by Different Manufacturers. Table 1 shows the summary of the \microphones suggested in the literature by the abovementioned manufacturers for mobile applications, in which the best design in terms of size and sensitivity was found to be from Knowles and, in terms of SNR, it was from Infineon Technologies. The microphone designs from Knowles, Infineon, Akustica, and STMicroelectronics are already commercialized and used mostly in Apple iPhone mobiles [158, 159], with Infineon being a big winner currently [159].

Although the data of microphones presented in the data sheets from some of the companies are well analyzed, these microphones may still have some hidden issues [160]. These issues are power supply rejection and degradation at low frequencies. Further, pollution from radio frequency interference has been found in analog and digital microphones. Similarly, a type of noise called swirling noise is present only in digital microphones when working in a stereo configuration. The reasons and possible solutions to these hidden issues are presented in [160].

(11) Fabrication Process of Capacitive Microphones. Microphones require a moving membrane and a rigid back plate separated by an air gap to sense the sound pressure. Micromachining technologies fabricate these thin membranes at a micro level and merge them with the electrical components. This makes it possible to fabricate hundreds of thousands of devices for these complex electromechanical systems on a single wafer. Micromachining techniques involve lithography, deposition, etching, and bonding processes.

The moving membrane can be made out of various materials, e.g., polyimide, silicon dioxide, silicon nitride, single-crystal silicon, and polysilicon. Polyimide is an organic material which cannot stay strong in high temperature while the others are inorganic materials which are strong enough in high temperature. Silicon nitride needs a metal electrode to deposit on it, as it is an insulating material. The same is the case for polyimide. Single-crystal silicon, which has an extremely high tensile strength [161], and polysilicon can be conductive; thus, there is no need for extra electrodes to be deposited. Different bonding techniques are used to bond these stacks of materials. In this section of the paper, the fabrication processes of polysilicon [121], silicon nitride [162], and single-crystal silicon [163] membranes with different approaches will be explained.

(11.1) Double-Chip Microphones. Capacitive silicon microphones are generally made up of two wafer chips, a membrane, and a back plate. These two wafer chips can be fabricated on separate wafers which are bonded together by anodic bonding, direct silicon bonding (SDB), and eutectic or polymer adhesive bonding processes. Some of the double-chip microphone designs are presented in [164–167]. The silicon oxide bonding method (SODIC) was used in [164] to bond the two wafers. In [165–167], gold-tin (Au/Sn) eutectic bonding was used.

Another double-chip microphone was presented by Hur et al. [168], and a eutectic bonding was conducted to bond the two chips. The fabrication process of one of the double-chip microphones has been explained below.

In [163], the authors have used surface and bulk micromachining technologies with thermal oxide as a sacrificial layer to fabricate the device. Due to the undesirable resonance of the back plate in their proposed design, a wide frequency range was not obtained, which was further improved by Iguchi et al. [169–171], in which a double-chip microphone was proposed. Both the back plate and moving membrane were formed from single-crystal silicon. Boron etch-stopper was used to keep the silicon thickness safe from TMAH etching. Boro-silica glass (BSG) was used as a sacrificial layer. The fabrication process starts from doping of the boron stop-etch layer on handle wafer. After that, the BSG layer was deposited on base wafer and then both the handle wafer and base wafer were bonded together by using the soot-deposited integrated circuit (SODIC) process. Details of the SODIC process are presented in [172]. After growing thermal oxide layers on both sides of the bonded wafer as etching mask to form the back plate and move the membrane (Figure 16(c)), both sides (top and bottom) of the bonded wafers were etched with TMAH solution to form the moving membrane and back plate, as shown in Figure 16(d). Finally, the BSG sacrificial layer was removed with HF solution and aluminum electrodes were deposited. The process flow is shown in Figure 16.

(11.2) Single-Chip Microphones. The double-chip fabrication process was replaced by a single-chip fabrication process, which was proposed by Hijab [173] and implemented by Scheeper et al. [174]. This was a reduced-size, simple process with no need of a bonding technique, one suitable to integrate with electronic circuitry. Scheeper et al. replaced the silicon wafer back plate electrode used in [124] by a 1 μm thick metalized highly perforated silicon nitride layer. The performance of the microphone mentioned in [174] was further improved by increasing both the stress and acoustic hole density of the back plate [80]. Another single-chip microphone was proposed in [175], in which both the back plate and membrane were made from polysilicon separated by an air gap of 1.5 μm. In [121], the authors have fabricated the polysilicon membrane, which starts from the front and back side oxidation of the p − type < 100 > silicon wafer. The oxide was used as an insulator for the electrodes and a stopper layer in etching. A moving membrane is then deposited and patterned (Figure 17(b)), followed by the deposition of the oxide layer and the etching of antisticking bumps as shown in Figure 17(c). Another polysilicon-perforated back plate was then deposited and patterned (Figure 17(d)). In Figure 17(e), the deposition of silicon nitride and then the etching of contact holes for aluminum electrodes and substrate were performed. The silicon nitride was used as an insulator between the top two electrodes, polysilicon and aluminum electrodes (Figure 17(f)). To protect the wafers from the strong tetramethylammonium hydroxide (TMAH) etching, the front side of the wafer was covered by depositing a protective low-temperature oxide (LTO) layer and patterning the thermal oxide at the back side (Figure 17(g)). The TMAH etch was performed to etch silicon substrate as shown in Figure 17(h). After TMAH etching, all the sacrificial oxide layers were etched in a phosphosilicate glass (PSG) etch and a final microphone membrane with a perforated back plate has been achieved as shown in Figure 17(i).

Another single-chip silicon nitride diaphragm using porous silicon as a sacrificial layer for the air gap has been published by Kronast et al. [162]. In their design, for an air gap, a supplementary sacrificial layer of porous silicon with the combination of SiO_2 was used to keep the materials of the diaphragm and back plate electrode safe from the attack of etching solutions. Also, as the sacrificial porous silicon layer surface is in the same plane with the surface of the single-crystal silicon, the diaphragm layer will have no steps. This results in reduction of internal stresses, which makes the diaphragm stable. Another improved sacrificial technology of porous silicon has been presented in [176].

2.1.4. Broadband Microphones. Mostly, omnidirectional microphones in the literature are for audio applications, i.e., mobile and hearing aids, which need a bandwidth less than 20 kHz and a maximum pressure that is less than 120 dB. Microphones beyond the audio range of hundreds of kHz, in which a high dynamic range and high bandwidth are the major requirements in a microphone's parameters, also show the need for several applications. For this purpose, a number of microphones have been proposed in the literature. For example, a microphone with a bandwidth from 0.1 to 100 kHz was proposed by Hansen et al. [177, 178]. This microphone [178] has a higher noise floor of 63.6 dBA. A microphone with a lower noise level of 23 dBA and having a bandwidth of 20 kHz was presented in [179]. Another microphone with a bandwidth of 10 Hz to 50 kHz and noise floor of 39 dBA has been proposed by Kressmann et al. [108]. However, these devices have either a high noise floor or a lower bandwidth, which needs to be improved for specific applications. Aeroacoustics is one of the applications in which a microphone with a high dynamic range and a high bandwidth is needed to study the sources of noise of various aircraft components. For this purpose, the authors in [128] have presented a dual-back plate microphone for aeroacoustic measurements with a resonant frequency of 178 kHz and a noise floor of 41 dB/$\sqrt{\text{Hz}}$. Another microphone with a wide bandwidth from 10 kHz to 230 kHz has been presented in [180]. This microphone has the same noise issues, i.e., feedback resistor thermal noise at low frequency and amplifier voltage noise at high frequency, as in [128]. The design presented in [111] can be a good candidate for broadband applications due to its promising results from analytical and simulation analyses. Table 3 shows a summary of wideband and high-dynamic range microphones in which the microphones with the highest maximum pressure are the piezoelectric microphones, presented by Williams et al. [40] and Horowitz et al. [42]. The microphone presented in [42] shows lower sensitivity as compared to the other piezoelectric microphone presented in [40], but the sensitivity will not be stressed here because it is not the immanent parameter of the device as the sensitivity of the device can be increased by

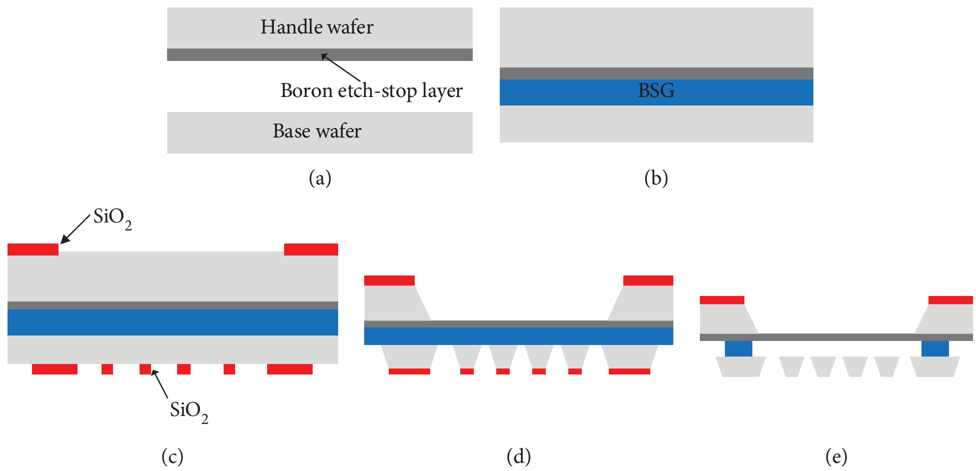


Figure 16: Fabrication process of a double-chip microphone design with a single-crystal silicon membrane [169]: (a) a boron etch-stop layer was doped, (b) a BSG layer was deposited and bonding was performed, (c) etching masks were formed, (d) etching of a diaphragm and back plate was performed, and (e) a BSG layer was removed.

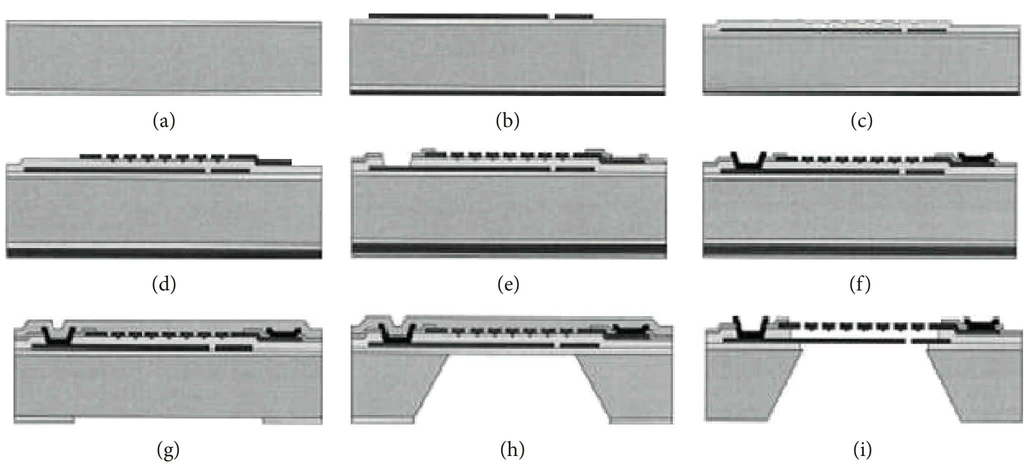


Figure 17: The fabrication process of a single-chip microphone with a polysilicon membrane [121]: (a) thermal oxidation, (b) membrane deposition and patterning, (c) sacrificial oxide deposition and patterning holes for antisticking spikes, (d) perforated membrane polysilicon deposition and patterning, (e) silicon nitride deposition and contact hole patterning through nitride and oxide, (f) aluminum sputtering and contact pad patterning, (g) back side stripping and oxide patterning, (h) TMAH etching, and (i) sacrificial oxide etching.

adding a suitable amplifier to the microphone without changing its noise level and bandwidth.

2.1.5. Microphones under Harsh Environment. During the field use, MEMS microphones are exposed to challenging environments, i.e., temperature changes, corrosive gasses, and humidity [181, 182], which can degrade the device performance. For example, mechanical shock can cause fracture cracks in the structures [183, 184], stiction problems [185], short circuiting [186], wire bond failure [187], and package failure [124]. The corrosive gasses and humidity can cause wire bond corrosion and failures [188, 189]. Investigations are needed to provide solutions to these issues to make MEMS microphones mature for commercialization. Li et al. [184] have analyzed the shock impact reliability of a MEMS microphone by finite element simulations and experiments by applying various shock levels ranging from 1.5 kg to 80 kg. The cracks were found in the diaphragm and back plate under the acceleration level of 65 kg in the Z+ and Z-orientations. Saeedi Vahdat et al. investigated the stability of circular capacitive microphones under mechanical shock loads and proved that the mechanical shocks can induce noises in the response of the circular microphone. To overcome these noises, a unique structure having two capacitors and an electrical circuit to separate sound pressure signals from the shock ones in the microphone output was proposed [190]. The effect of structural noise due to the nonlinear behavior of capacitive microphones was investigated in [191]. The reliability of MEMS microphones was studied under a mixed flowing gas (MFG) environment; failure mechanism is identified and solutions for improved reliability were presented [192]. MFG is a type of testing in which the product's resistance to corrosion caused by the different gasses in the atmosphere is evaluated. The effect of the 90-day MGS test on the microphone is shown in Figure 18, in which both the membrane and back plate got cracks

Table 3: Properties of wideband microphones.

Author (year)	Microphone type	Diaphragm size	Diaphragm thickness (μm)	Maximum pressure (dB)	Sensitivity	Noise floor	Bandwidth
Kressmann et al. [108] (2002)	Capacitive	1mm[¥]	NA	123	2.9 mV/Pa	39 dBA	10 Hz-50 kHz
Scheeper et al. [179] (2003)	Capacitive	1.95 mm[*]	0.5	141	22 mV/Pa	23 dBA	251 Hz-20 kHz
Hansen et al. [178] (2004)	Capacitive	70 × 190 μm	NA	NA	43 dBV/Pa	64 dBA	0.1 Hz-100 kHz
Horowitz et al. [42] (2007)	Piezoelectric	1.8 mm[¶]	3	169	1.66 μV/Pa	48 dB	100 Hz-50.8 kHz
Martin et al. [128] (2007)	Capacitive	0.46 mm[¶]	2.25	164	390 μV/Pa	41 dB	300 Hz-20 kHz
Williams et al. [40] (2012)	Piezoelectric	0.82 mm[¶]	2.14	172	39 μV/Pa	40 dB	69 Hz-20 kHz
Kuntzman and Hall [180] (2014)	Capacitive	0.63 mm[¶]	2.25	NA	159 μV/Pa	32 dB	10 kHz-230 kHz
Sedaghat and Ganji [111] (2018)	Capacitive	0.25mm^2	3	NA	27.45 fF/Pa[§]	NA	~22 kHz[#]

[¥]Side length of a square diaphragm. [*]Radius of a diaphragm. [¶]Diameter of a diaphragm. [§]Capacitive sensitivity. [#]Simulated resonant frequency.

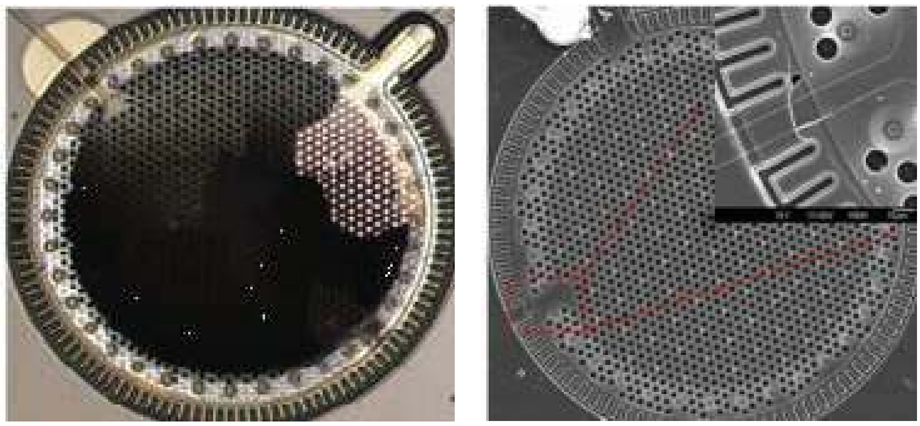
[192]. The shock analysis was also performed up to 80000g in all the three directions, in which the fractures were only detected in the out-of-plane direction under the level of 65000g acceleration. Figure 19 shows the missing and cracked membranes due to shock analysis. In [193], the authors have investigated the reliability of commercially available MEMS microphones using the three harsh environmental conditions, i.e., high temperature operating life (HTOL), temperature humidity bias (THB), and low-temperature storage (LTS). The HTOL analysis creates distortions at lower and higher frequencies, degradation in the power supply rejection ratio, lower pressure detection at higher frequencies, and amplitude reduction of output voltage signals. Similarly, the THB test also creates distortions at lower and higher frequencies and degradation in power supply rejection. The LTS test has no significant drifts in these output parameters as compared to HTOL and THB.

2.1.6. Optical Microphones. In the case of an optical microphone, the transduction mechanism of converting the sound waves into electrical signals happens by sensing changes in light intensity. The modulated light has three properties, i.e., intensity, polarization, and phase [194]. The simplest way in these is intensity modulation. The simplest intensity-modulated microphone can be constructed with an LED, multimode or single-mode fibers, a membrane or other vibrating reflective surfaces, and a photodetector [195]. The intensity modulation-based microphone can be divided into two configurations: one is where a fiber optic lever is configured in which an incident light source on the membrane is arranged in such a way that, when the membrane moves due to the sound waves, the light reflects back to the photodetector, where it is converted into an electrical signal and processed through an electronic circuitry [195]. This type of microphone is presented in [196], in which the incident and reflected lights are in the same fiber bundle placed near the cavity of the microphone, as shown in Figure 20(a). Another way is to place an integrated waveguide near the cavity to separate the paths of incident light and reflected lights, as shown in Figure 20(b) [197].

There are some advantages and disadvantages to the use of optical microphones. Electronics are not needed at the measurement locations; thus, optical microphones are not affected by electromagnetic interference and do not emit electromagnetic radiation. Moreover, an optical microphone is a promising candidate for use in the harsh environments that are not suitable for electronics. On the other hand, difficulty in packaging, the need for an external reference light source, and the influence of reference light source fluctuations on the output voltage are the disadvantages of optical microphones [129].

2.2. Directional Microphones. In applications where the background noise cancellation is the greatest consideration, directional microphones are the first choice for researchers and developers. Instead of generating an electrical response from sound waves arriving from all directions around the device, as the omnidirectional microphone does, the directional microphone has its strongest output when sound waves arrive along a single axis vertical through or parallel with the surface of a moving membrane, which can be sensed either by capacitive [198–200], piezoelectric [201–204], or optical [8, 9, 205] sensing mechanisms.

Directionality can be achieved either by combining the electrical outputs of two omnidirectional microphones or by combining the acoustic inputs of two ports within a single microphone; however, the existence of an internal noise floor limits the success of these two techniques [206]. The ears of a parasitoid fly, *Ormia ochracea*, inspired the directional microphone as a promising candidate to overcome

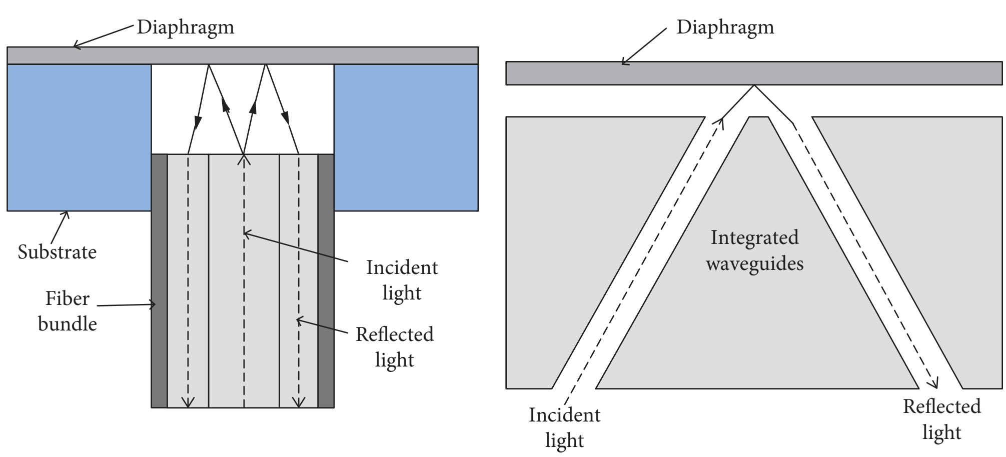


(a) (b)

Figure 18: Top view of a capacitive microphone in which cracks occurred due to MGF testing [192] (a) in both the diaphragm and back plate and (b) in the back plate only [192].

(a) (b)

Figure 19: Shock analysis of a capacitive microphone of up to 80000g acceleration, in which (a) the whole membrane is missing and (b) most of the membrane is cracked [192].



(a) (b)

Figure 20: Optical fiber intensity modulated microphones with (a) incident and reflected lights in a single-bundle fiber [196] and (b) incident and reflected lights separated by integrated waveguides [197].

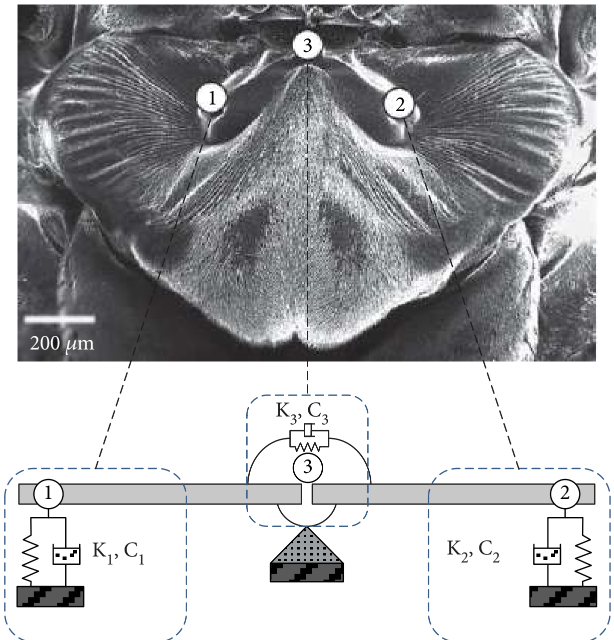


Figure 21: Ears and mechanical model of a fly, *Ormia ochracea* [208], in which the two membranes, 1 & 2 are coupled by the central point, 3, which makes the system able to detect directional sound waves. All these three points make a mass-spring system with their corresponding dampers and spring stiffness.

the noise issue in the two combined omnidirectional microphones [207]. The mechanical response of this fly shows the ability to detect acoustic waves [208]. Figure 21 [208] shows the ears and mechanical model of *Ormia ochracea*, in which the central point, 3, connects the two membranes (1 and 2), which makes the overall system sensitive to the directional sound waves. K_1, K_2, and $K3$ represent the corresponding stiffness of the springs while C_1, C_2, and C_3 represent the viscous dash pots. Measurements were performed in [209] using a laser Doppler vibrometer to check the fly ear's mechanical responses. In the pioneering work of Miles et al. [208, 210] and Robert et al. [209, 211], which contain the mechanical and measurement analyses, two natural modes of vibration, one with a rocking motion (two wings are moving out of phase) and the other with an in-phase motion (bending mode), have been achieved, which has opened the ways for the researchers to design directional microphones with different design transduction approaches for directional sound sensing. For example, a design with membrane dimensions of $1\,\text{mm} \times 2\,\text{mm} \times 20\,\mu\text{m}$ was proposed in [212]. The design was further fabricated using an integrated surface and bulk micromachining process on silicon on insulator (SOI) wafer, and the natural-frequency sound-induced modes were measured using laser vibrometry [213].

More details about the applications and transduction methods of a directional microphone can be found in a review paper [214]. The recent and missing directional microphone designs in [214] will be our focus in this part of our review paper.

The abovementioned directional microphone designs are first-order directional microphones (FODMs). The improved performance, especially a stronger ability to reject the off-axis sound as compared to that of a FODM, can be achieved by second-order directional microphones (SODMs). Furthermore, the SODM designs are more sensitive to incident sound waves. Miles et al. and Liu proposed an SODM design [215, 216] in which two FODM designs have been coupled by a coupling spring (Figure 22(a)) in the center to achieve second- and higher-order differential pressure sensing. Due to the mismatch of the two coupled FODM designs (Figure 22(b)), the SODM design proposed in [215, 216] shows an omnidirectional response (Figure 22(c)) at the first resonant frequency [217]. Investigations carried out in [217] show that the coupling spring between the two FODM designs could be the source of performance limitations. To cancel the omnidirectional response, the two coupled FODM designs need to be balanced and have the same sensitivity. For this purpose, the design proposed in [216] was modified by [217] by changing the coupling spring (Figure 22(d)) and making both the FODM designs balanced (Figure 22(e)), which shows a figure eight-type directional response as shown in Figure 22(f). Although the SODM has higher rejection of unwanted sounds, it shows lower sensitivity at lower frequencies and has a poor frequency response as compared to the omnidirectional and FODM designs [215].

A directional microphone with circular membranes having different types of gimbals was also an interest of the researchers [218–220]. All these microphones had one circular membrane which may have an omnidirectionality in their response. Another circular-type design, which is divided into 4 heart-shaped membranes for 2D sound localization having AIN piezoelectric materials for sensing, was proposed by Zhang et al. [221]. The authors have introduced two directional microphones in the same structure having independent acoustic directionality responses, leading to a 3D sound localization potential. This single microphone can thus be regarded as two individual bidirectional microphones. The four heart-shaped membranes are coupled by two bridges which are anchored in the center. Cantilevers, coated with piezoelectric materials, were attached at both sides of each membrane.

A directional microphone can be used in hearing aids where the user of the hearing aid has difficulty in understanding the speech in noisy environments [222]. Furthermore, Ormia's ear-inspired directional microphones are also used in the form of array for sound source localization in different civil and military applications [223, 224]. Directional MEMS microphone arrays can also be used in noise source localization and characterization. For this purpose, an array of MEMS piezoresistive microphones has been presented in [225] for aeroacoustic measurements.

For commercialization, a MEMS directional microphone needs to be packaged. Two packaging concepts, one with a back-mounted damping material on a cap and the other with small perforation holes in the cap, have been presented in [226]. In these two concepts, in terms of the thermal instability of the damping materials and the sequential process of

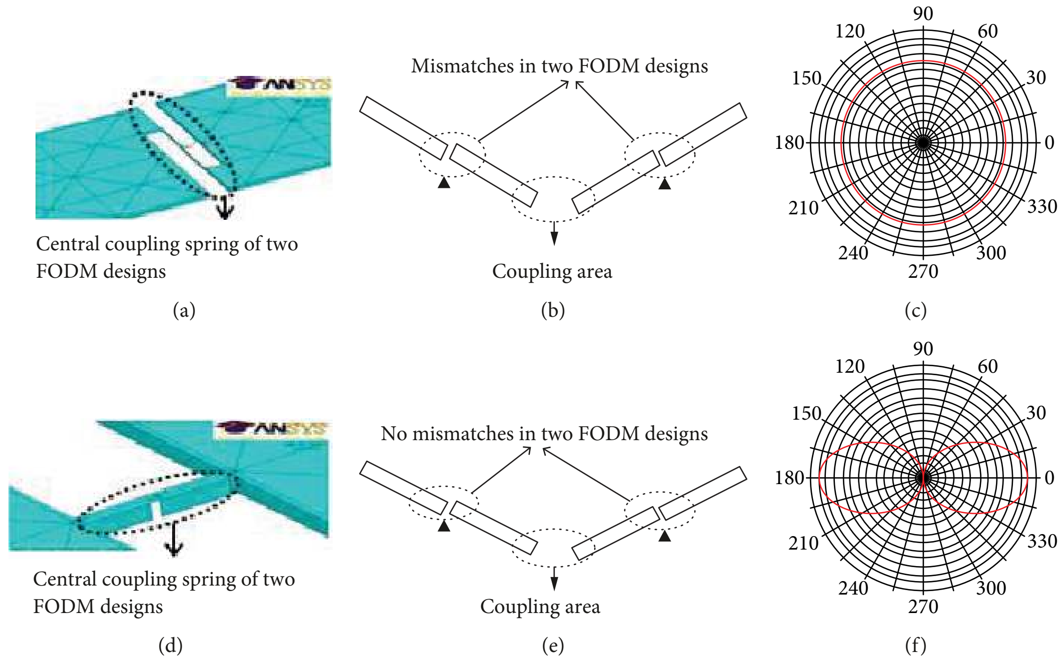


Figure 22: Second-order directional microphone designs [217] with (a) a coupling spring, (b) mismatch in two FODM designs, (c) omnidirectional response due to the mismatches in two FODM designs, (d) other suggested coupling springs in [217], (e) no mismatches in the two FODM designs (balanced designs), and (f) figure eight-type directional response.

laser cutting, a metallic cap with chemically etched perforation holes is most advantageous.

3. Conclusions

In this review paper, the literature of different MEMS microphones has been thoroughly analyzed. The paper presented different design issues, and possible solutions were identified and discussed. Stresses in the thin film membranes of microphones are the concerned parameter to be handled well, as it degrades the microphone performance. Furthermore, the matured commercialized omnidirectional capacitive MEMS microphone designs from different developers have been presented and comparative analysis has been performed. Although the capacitive transduction has adapted a dominant technique due to its lower noise level and higher sensitivity as compared to the piezoelectric microphones, piezoelectric MEMS microphones are also gaining popularity because they do not require a biasing voltage, have a wider dynamic range, and are dustproof and waterproof as compared to capacitive microphones [50].

For a clearer voice call experience and easy integration into other portable devices, high-quality audio and small footprints for MEMS microphones are the requirements in the future perspective and needed to be addressed in research studies. The integration of an omnidirectional microphone with the pressure gradient microphone on a common silicon die can possibly be achieved in future studies. In these designs, the omnidirectional microphone can help to acquire the sound pressure information while the pressure gradient microphone can perform the task of sound source localization. This type of hybrid design can be a good candidate in smart hearing aids where the user can change directivity response from omnidirectional to directional if the user is in an environment where the background noise is affecting speech recognition.

Conflicts of Interest

The authors declare no conflict of interest regarding the publication of this paper.

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