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CAPACITIVE MEMS MICROPHONES FOR MEDICAL APPLICATIONS

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Microphones manufactured based on MEMS technology have been significantly applied in medicine. However, medical application requires more sensitive and low-frequency MEMS microphones. To achieve this goal capacitive microphones are the most appropriate as they have a low level of noise and high sensitivity compared to piezoelectric and piezoresistive microphones. The structure and materials enable to change electric parameters of microphones for better. To increase sensitivity it is possible to find a membrane structure when internal mechanical resistivity is minimal. When MEMS structures are ideally found, a frequencies range can be expanded. Membrane flexibility can be expanded by means of applying meshes at the edges, corrugations and springs.

Keywords: MEMS, capacitive microphone, low frequency microphone, sensitivity, membrans.

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ЁМКОСТНЫЕ МЭМС-МИКРОФОНЫ ДЛЯ МЕДИЦИНСКОГО ПРИМЕНЕНИЯ

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Микрофоны, произведенные по технологии МЭМС, находят новое применение и в медицине. Однако для медицины нужны более чувствительные и низкочастотные МЭМС-микрофоны. Для этой цели больше всего подходят ёмкостные микрофоны, так как они имеют низкий уровень шумов и высокую чувствительность по сравнению с пьезоэлектрическими и пъезорезистивными микрофонами. Конструкция и материалы позволяют изменять электрические параметры микрофона в лучшую сторону. Повысить чувствительность можно путем подбора такого состава в структуре мембраны, при котором будут минимальны внутренние механические напряжения. Подобрав конструкцию МЭМС, можно расширить и частотный диапазон. Увеличить податливость мембраны можно за счет применения прорезей по краям, гофр и пружин.

Ключевые слова: МЭМС, ёмкостный микрофон, низкочастотный микрофон, чувствительность, мембраны.

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Introduction

Microphones manufactured based on MEMS technology have found novel applications (microelectromechanical systems) due to their miniature sizes, low energy consumption with the temperature change. After the Internet of things technologies have been spread, the demand of miniature high efficiency MEMS microphones for healthcare devices increased [1]. Constant monitoring of human body characteristics allows detecting health problems at early stages and finding timely medical treatment. For example, article [2] presents the research results of the correlation between blood pressure and second heart sound S2. It is possible to check blood pressure by measuring tone heart sounds. However, the majority of MEMS microphones can process the sound frequency range thoroughly (20–20000 Hz). In addition, the blood pressure pulse frequency makes up 1.5–2.1 Hz [3]. Thus, developing low frequency MEMS microphones that can have appropriate electrical characteristics ranging from 1 to 20 Hz has become a critical task.

This article deals with the methodology that enables expanding a low frequencies range and improving microphones MEMS characteristics.

Microphones types: advantages and disadvantages

Currently, the market base for MEMS microphones is provided with the following microphones types: capacitive, piezoelectric and piezeoresistive.

The operational principle of piezoelectric microphone is associated with the piezoelectric effect. This microphone functions due to piezoelectric material that is placed on the surface of a sensing element (SE) of a microphone, emerging voltages change in time with changing sound pressure. Such microphones are ideal due to structure simplicity but inefficient due to high sensitivity to water and humidity penetration. And, the piezoresistive microphone is based on a different principle, i.e. electric resistance is changed when exposed to sound pressure.

Capacitive microphones consist of two parallel plates dividing by an air gap and function as a mass system – a spring, where a moving membrane functions as a string; the scheme is represented in Fig. 1. Sound pressure affecting on a membrane with certain mass forces it to oscillate; thus, resulting in changing a distance between two plates that, in its turn, changes the capacitor and, consequently, an electric signal.

Article [4] analyzes the advantages and disadvantages of piezoelectric microphones compared to capacitive microphones: low energy consumption and wide dynamic range; as well as identifying disadvantages, e.g. high noise level and low sensitivity. Piezoresistive microphones, in their turn, have a low energy consumption and high noise level compared to piezoelectric microphones. However, the authors of the article state that piezoresistive microphones demonstrated both improved and deteriorated characteristics unlike capacitive microphones. The majority of MEMS capacitive microphones have high sensitivity level, flat frequency response and low noise level; so, this determined the selection of the microphones.

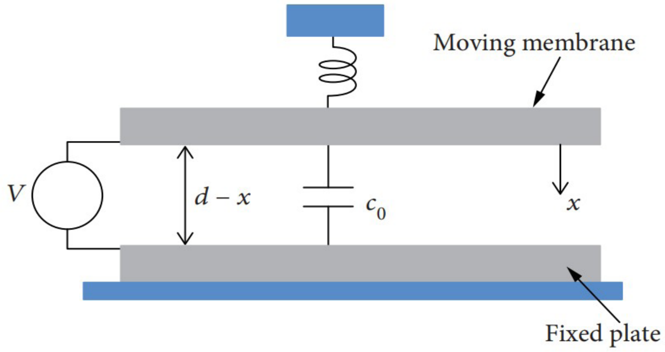

Fig. 1. Schematic of capacitive microphone structure with a fixed back plate:
V – voltage, x – membrane dislocation, c_0 – nominal capacity between a fixed plate and a membrane [4]

Materials and construction characteristics of a capacitive MEMS microphone

The characteristics of capacitive MEMS microphones can be significantly improved by changing the structure and materials selection. The sensing element of a capacitive MEMS microphone is a membrane that registers oscillations of the acoustic range. The membrane can be fabricated from different materials: semiconductors, metals and polymers. The majority of designers prefer semiconductor materials or metals as they are the most efficient in microelectronic applications. Carbon or semi carbons are mostly preferred from semiconductor materials as a sensing element (SE) [5, 6].

Due to long connection between atoms Si-Si carbon is mostly used for developing a sensing element (SE) to measure insignificant mechanical deformations. Local deformation of a crystalline lattice occurs during a technological process of sensing element fabrication, thus resulting in irreversible areas of mechanical stress. Mechanical stresses, in their turn, affect mechanical sensitivity and MEMS microphone sensitivity, in general. To decrease a number of dislocations it is necessary to control mechanical stresses during a technological process of fabricating a sensing element at every stage that increases the cost of the device.

To increase mechanical sensitivity it is possible to find such content of the membrane structure where internal mechanical stresses are minimal. For example, the combinations of dielectric films made of carbon dioxide and carbon nitride are used [7]. This sandwich structure type where layers with the combined contraction stress and elongation are generally applied. Carbon dioxide layers gained as a result of thermal oxidation have contraction stress, and carbon nitride films have elongation stresses [8]. The designers generally prefer tensile stress to contraction stress [9]. That is why silicon nitride [10, 11], metals (aluminum) [12], as well as silicon carbide [13] are applied as a membrane material.

Ooi et al. [13] compared the sensitivity of different membranes. Fig. 2 provides an amplitude frequency response (AFR) of membranes manufactured from different materials. As it can be seen in the graph the membrane fabricated from aluminum, carbon and silicon nitride show proper sensitivity within the low frequency range.

Also, silicon nitride is appropriate as an additional layer for carbon to decrease residual stresses. Grigoriev D.M. et al. [14] decreased residual stresses in the center of the back electrode owing to a thin layer of silicon nitride.

Besides the membrane there is also a back plate in a microphone. Semiconductor materials are widely applied in MEMS fabrication processes. A positively charged membrane (semiconductor of p-type) and a negatively charged back plate (semiconductor of n-type) function as positive and negative results, respectively. The majority of researchers used Si and poly-Si as a back plate material for the same reason – compatibility with microelectronic technologies and appropriate mechanical and electric material properties.

Mechanical sensitivity depends on multiple factors, including the membrane material as the least as it is mostly affected by sensing element form and sizes. For example, article [10] sates that membrane sensitivity fabricated from carbon nitride increased up to –48 dBV/Pa by changing a membrane form.

The majority of articles devoted to MEMS microphones state that a SE form has a square and circular form. The form of the MEMS microphone influences the characteristics and their repetitive cycle. As it has been described above, the membrane material has always certain structural defects due to which a SE has internal and residual stresses. A membrane functions under changing pressures conditions, and the residual stresses in the elastic stress area can contribute to forming new structural defects and distort device characteristics [15]. The researchers carried out simulation of elastic stress in square and circular membranes. It turned out that a square membrane has significant and unevenly distributed elastic stress on the fixing borders and at the corners and the center. A circular membrane has smaller values of elastic stress evenly distributed along the contour in the membrane material. Consequently, a circular form suits best for this purpose. This fact his been supported by the application of sensing elements in commercial MEMS microphones that have a circular form.

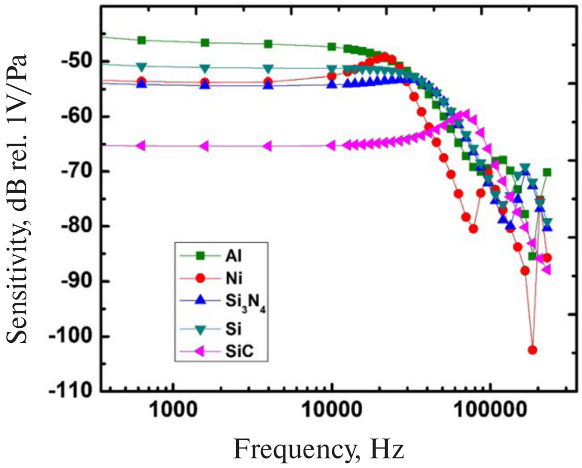

Fig. 2. AFR MEMS microphones with membranes fabricated from different materials [13]

The geometric approach to changing or optimizing a membrane design – a simpler way allowing improving mechanical sensitivity. Mechanical sensitivity can be controlled by membrane topology and sizes. It is important to refer to the formula of the mechanical sensitivity for a flat circular membrane [16]:

$$S_m = \frac{R^2}{8\sigma_d t_d}, \tag{1}$$

where R – membrane radius, σ_d – membrane stress, t_d – membrane thickness.

It should be stated that mechanical sensitivity increases when the membrane size increases too. But the current trend focuses on a high level of miniaturization of microphone sizes; so, it does not seem feasible to increase sensitivity by increasing sensing element (SE) sizes. Mechanical sensitivity increases when the thickness increases. A rather thin membrane with a large radius has a bigger flexibility but at the same time it can be rather fragile and have strong mechanical stresses, a thick membrane with a small radius has a small flexibility; as a result, a poor flexibility. Therefore, it is necessary to find an optimal size correlation. Article [17] discusses the researches on capacitive microphones and provides the data on main microphone characteristics in the table. Having analyzed the table data, the measurements have been made: the average membrane diameter makes up 600 micron but the thickness makes up 1 micron.

It is important to take into consideration the material, form and sizes of a membrane. It is necessary to consider engineering solutions aimed at decreasing effect of mechanical stress such as slots at the edges, corrugations and spring membranes.

To minimize the residual stresses that emerge after fabricating a sensing element Ming-Chih Yew et al. suggested making slots at the edges of a membrane (Fig. 3) [18]. The maximal residual stresses focus on the stationary part of a membrane and lead to bending in the radial direction. Radial direction bending can be reduced by making certain number of slots along the circumference.

One more approach applied to decreasing the residual stresses is to design corrugated membrane. Earlier multiple researches on corrugated membrane have been carried out to eliminate the mechanical sensitivity. It has been stated that the depth of corrugation and the membrane thickness are rather important factors to design the equivalent level of noise a corrugated membrane that influence flexibility [16].

Article [19] analyzed the influence of corrugation parameters on microphone characteristics by applying the finite element method in COMSOL Multiphysics program. The simulation of mechanical sensitivity in correlation to depth of corrugation has proved that rather deep corrugation decrease the membrane tension. The authors of the article have chosen the depth of 3.3 micron, and the research

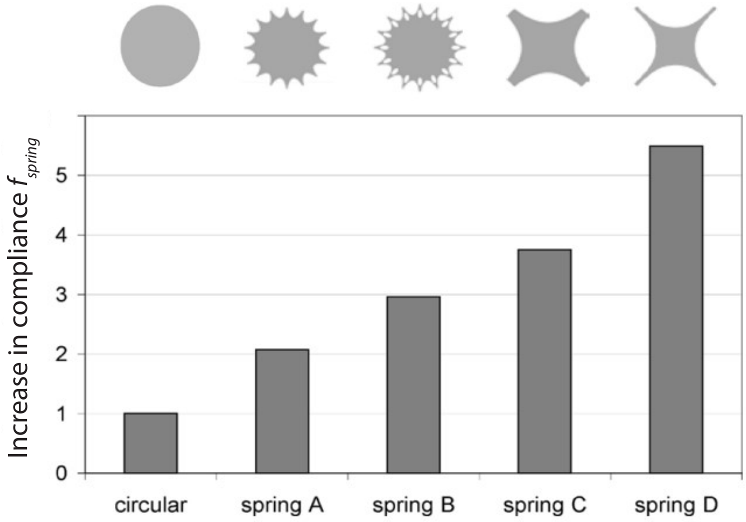

Fig. 3. The chart illustrating the correlation of mechanical flexibility of the spring membrane to the fixed circular membrane [21]

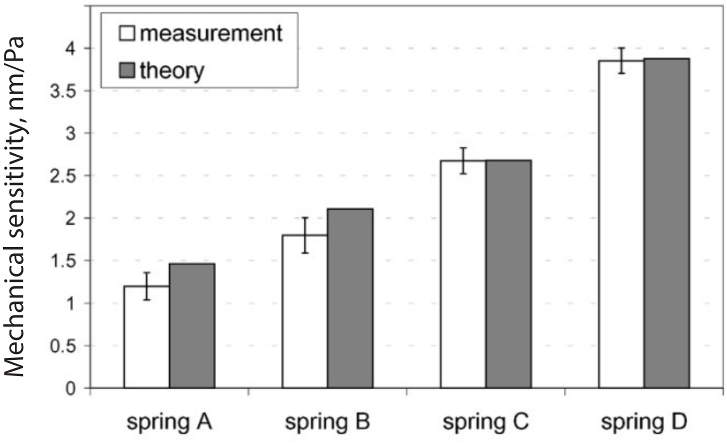

Fig. 4. Mechanical sensitivity of different membrane types [21]

on influence of such depth of corrugation on sensitivity and the equivalent level of noise. Application of more flexible corrugated diaphragm result in increasing the sensitivity from 0.5 to 2.9 mV/Pa and decreasing the equivalent level of noise from 54 to 39 dB (A).

Though more advanced research state a number and thickness of corrugated influence the mechanical sensitivity [20, 21]. S. Shubham in [21] studied the influence on number and thickness of corrugated on the acoustic flexibility. A circular membrane has been obtained from carbon nitride, its diameter makes up 1.4 mm, and the thickness makes up 1.1 micron and depth of corrugation makes up 3.5 micron. The membranes with one, two and three corrugations have been studied. The analysis of the dependence of the acoustic flexibility from number and thickness of corrugations showed that the high flexibility (13.8 nmicron/Pa for a membrane with the membrane stress of 120 MPa) can be for 3 corrugations with the width of 65 micron (the width correlation to the depth makes up approx. 60:1). Similar results have been achieved by the authors [20]. The results analysis has showed that the maximal mechanical sensitivity of 22 nmicron/Pa has a membrane with 8 corrugations.

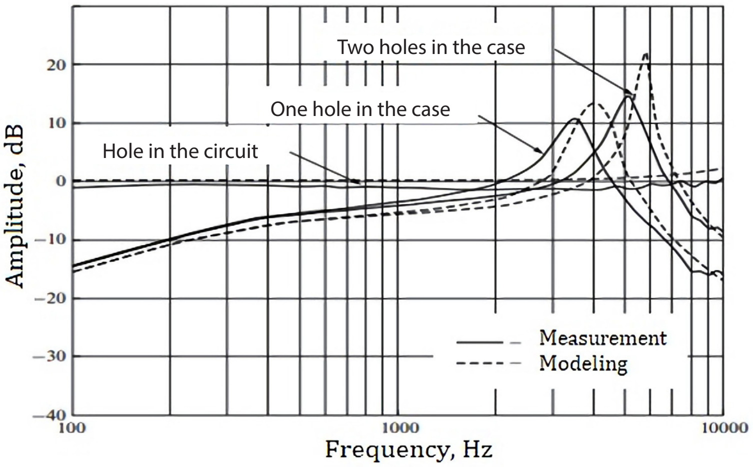

Fig. 5. The results of the finite-element simulation
and measurement of AFR-design of a MEMS microphone [22]

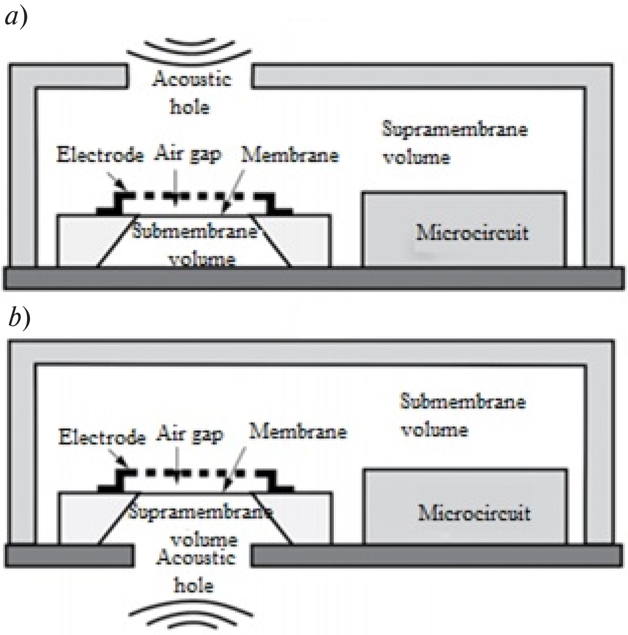

Fig. 6. The arrangement of microphone crystal and предусилителя in a case:
a – lid hole (big supramembrane volume); *b* – a hole in a circuit (small supramembrane volume) [22]

The method described below consists in applying a spring to fix a membrane to a microphone case. Article [21] analyzed different spring types and the finite element method simulation has been used to check their sensitivity. Fig. 3 illustrates the spring types, and the chart shows mechanical flexibility of the spring membrane and the circular membrane. As it can be seen from the chart, the membranes with thin and long springs have larger mechanical flexibility and higher sensitivity level (Fig. 4) compared to the membranes with short and thick springs.

The arrangement of the acoustic hole affects the frequency range and sensitivity. Grigoriev et al. [22] have identified the correlation between the holes arrangement on a case and AFR of a microphone. Fig. 5 shows the graph of dependencies.

So, the arrangement of a single acoustic hole on the circuit can be an optimal solution for linear AFR. First, it seems logical to determine submembrane and supramembrane volume. The detailed clarification is provided in Fig. 6.

The microphone with an acoustic hole on a lid has a decline in AFR at low frequencies. It can be explained by the fact that when decreasing a submembrane volume the resistance increases that moves a membrane, i.e. sensitivity decreases Consequently the frequency in the low range can be improved by increasing a submembrane volume.

Technique to decrease background noise

Low efficiency of a microphone is mostly correlated with the background noise regarding frequency and sensitivity. The background noise is an important characteristic that sets minimal identified acoustic stress and limits on the microphone sensitivity [23]. The background noise consists of both external sources: radio interferences and vibrations and internal ones: mechanical and thermal, fluctuation, electric and thermal noises as well as an amplifier noise and a flicker noise [23]. To eliminate external noises can be by means of microphone packaging with radio and vibration stability. Internal sources are difficult to be eliminated. The problem of an amplifier can be solved by changing a regular amplifier into a low noise amplifier as it has been applied in, for example, a commercial microphone IM69D120 [24]. A flicker noise has a low frequency noise (approx. 0.1–10 Hz) with the density that is inversely proportional inversely proportional to the frequency. Flicker noises are illuminated by increasing chopper amplifiers into the circuit [25]. The study of eliminating such noises has become a wide research scope requiring the analysis of circuit technique solutions that are not researched in the article.

Membrane moving negatively affects thermal movement of molecules that further influence mechanical and thermal noise. Air thin film moving between the back plate and the membrane results in dempering of the condensed film that can negatively influence the dynamic response of the system. The dempering problem is normally eliminated by etching holes on the back plate and the membrane and by finding an optimal thickness of the air layer. Also, plates perforation enables easing the etching of low layers during the micro processing. To decrease dempering of the condensed film, it is necessary “to drill” more and more holes nut every new hole adds its own resistance to the total dempering as besides this there is the resistance of the vertical air movement through the holes [26]. So, the holes number and size as well as their arrangement influence the dempering mechanism.

Tan C. et al. has carried out a profound analysis of correlation between holes arrangement on the back plate and the sensitivity of the no load operation and the background noise level. The AFR analysis provided in [27] showed that the holes moving from the center to the plate edge can expand the operational frequency range but insignificantly changes the sensitivity. The microphone has the minimal noise when the holes number makes up 24, and the minimal noise is when the holes number is 8. So, it is obvious that sensitivity increase is achieved by increasing the holes number.

The scientists [26] have identified an analytical equation to calculate the minimal coefficient of dempering and calculated the dependence of the holes number from AIR. AIR is understood as correlation of the hole squared radius to the distance between the holes. When AIR is ≈ 0.32, the holes number can be increased to 1,300. Although it is important to keep in mind that an increase of holes leads to decreasing the surface area of the back plate and sensor capacity, respectively. The capacity decrease results in decreasing the electrical sensitivity.

Also, the research [23] analyzed the influence of the air layer thickness on the noise and sensitivity level. The authors of the article have concluded that a thin air gap leads to increasing dempering and cause a lower flow rate and higher mechanic and heat noise. The situation is reverse with an air gap: gap increase leads to decreasing capacity and increasing dislocation stress supplied to a microphone. The increase in voltage characteristics results in microphone increased consumed power. These conclusions are confirmed by the article results [28], where microphone CV-characteristics have been calculated for different thicknesses. A

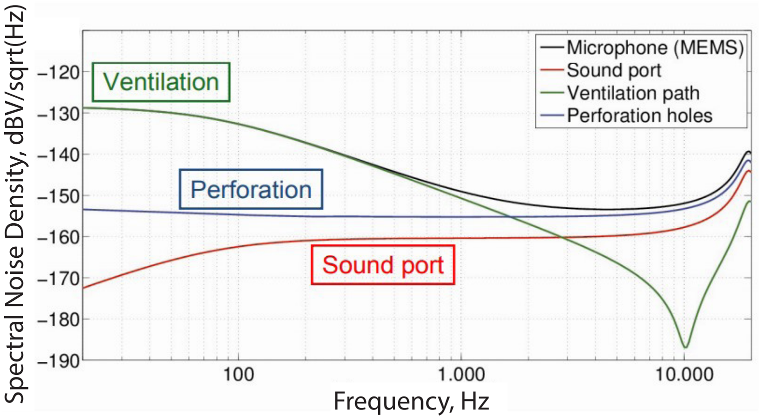

Fig. 7. Microphone spectral noise density (black) and different resulting contributions: from the back plate (blue), from the sound port (red) and ventilation holes inside the membrane (green) [30]

microphone has the pull in voltage level of 10V with the thickness of 2 micron and the maximal capacity of approx. 2 pF and the pull in voltage level of – 10V with the thickness of 1 pF, respectively.

Besides the back plate, a membrane has to be supplied with holes. Ventilation holes are thin channels in a sensing element (SE) which align or compensate for the membrane pressure from both sides. These certain holes contribute to noise in a lower part of the sound range [29] (Fig. 7). The research [30] provides the chart of Spectral noise density.

The holes arrangement in the membrane differs in various articles. The authors of articles [29–31] spaced the ventilation holes at the membrane edges. The article [32] considers the ventilation holes to be evenly distributed along the membrane. The significant positive results have been achieved in the research [33]. The authors of the article perforated the holes in the amount of from 4 to 36 at the membrane edges. It turned out that the low threshold frequency value of 2 Hz was obtained on the membrane with the smallest hole dimeter (5 micron) and smallest holes number (4 holes).

Modern microphones reviews

Based on the above stated, certain types of MEMS capacitive microphones have been studied [31, 33–36] which have sufficient electric characteristics. Structural and electric characteristics of such microphones have been presented in Table 1.

MEMS microphones [34] have high SNR compared to others. Such characteristics have been achieved by means of reducing squeeze film dampering by increasing an air gap up to 4 micron due to making 60.8 % of perforated holes areas and 34 % of ventilated slots areas in the membrane. However, such high percentage of occupied space in the membrane negatively affects the low frequency area that is confirmed by the designers. Spring membranes significantly stretch when inclined and pass the signal in the low frequency area. This research also focuses on the solution with two back plates leading to the dynamic range increase of 3 dB(A). Such a structure strengthens mechanic and heat noise because of two dampering areas because such increase in sensitivity does not justify deterioration of general operational dynamic frequency range.

Similar structure and sizes have a microphone described and studied in [33]. On the other hand, it has an insufficient signal/noise ratio as the acoustic window is located above the ASIC circuit (Fig. 8), and the microphone has a tiny air layer.

Article [36] describes a commercial low frequency microphone with the operation frequency ranging between 6 to 20 000 Hz. Having analyzed the datasheet, it was supposed that ICS-40300 microphone designers have gained these characteristics by increasing submembrane space and peculiar ASIC circuit design. The microphone case height increased from the typical size of 1 to 3.5 mm. Table 1 data allows concluding that every microphone is designed in accordance with the standard requirements: the frequency

Table 1

Structure and electric characteristics of MEMS microphones

References	Membrane					Back plate			Acoustic hole	Specifications					
	Material	Shape	Diameter, μm	Thickness, μm	Air gap, μm	Electrode material	Material	Dampering mechanism		Bias voltage, V	Capacitance, pF	Signal to noise ratio, dB(A)	Sensitivity, dBV/Pa	Frequency range, Hz	Resonant frequency, kHz
[34]	Poly-Si	Circular	540	1.2	4	Au/Ti	Si	60.8 % of the back plate area and 34.7 % of the membrane area are perforated	Radius 300 μm, length 400 μm	10	N/A	73	–38.4	100–20000	29.7
[31]	Al (0.4 μm) Si_3N_4 (0,5 μm)	Circular	600	0.9	2.45	Al (0,5μm)	$Si0_2$/ Si_3N_4 (2 μm)	1668 holes in the back plate with 4 μm diameter	N/A	10.4	1.02	N/A	–48	100–15000	100
[33]	Poly-Si	Circular	700	0.3	2.2	N/A	Poly-silicon/ Si_3N_4	69 % of the back plate area and 4 holes in the membrane with a 5 μm radius	Radius 0.9 mm, length 0.4 mm	N/A	N/A	61	–38	80–15000	N/A
[35]	Poly-Si	Circular	500	0.5	2.0	Al	Poly-silicon/ Si_3N_4 2.3	N/A	N/A	6.24	0.76	N/A	–	N/A	29.1

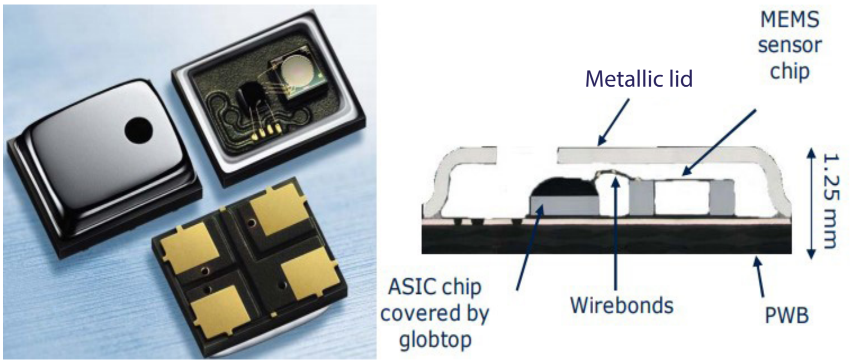

Fig. 8. Structure of the MEMS microphone [33]

range of 20(100)-20000 Hz, sensitivity of approx. –40 dBV/Pa, signal/noise ratio of approx. 60 dB(A); as such microphones are mainly applied in smartphones and hearing aids where low or high frequencies are not required. Nevertheless, there is a steady increasing demand for low frequency microphones because of developing technologies and implementations of MEMS microphones in the form of sound pressure sensors in medical devices.

Conclusion

The article analyzed microphones types, their advantages and disadvantages, material and structural characteristics of capacitive MEMS microphones and methods and techniques to decrease background noises as well as particular types of the developed microphones. The analysis has shown that the researchers have gained results and improved electric characteristics of capacitive MEMS microphones. Meanwhile, only a few articles deal with low frequency ranges. So, since there is a steady increasing demand for such devices, the research into these aspects seems promising and critical.

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