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New Potential for Portable Audio with MEMS based Speakers

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Abstract

There is a high demand for portable audio on the market. Hence, manufactures of headphones and hearing aids have to deal with miniaturization of electroacoustic transducers (micro speakers) but maintain sound quality and energy efficiency (battery life time) at the same time. Different techniques are known for downsizing transducers. A very successful method is provided by the semiconductor industry. The use of the so-called MEMS technology (Micro-Electro-Mechanical-System) has already led to great success in microelectronics and MEMS applications such as microphones and accelerometers. This success has triggered a high interest in implementing MEMS technology also for speaker manufacturing. Based on patents, the initial approaches of MEMS loudspeakers will be presented. An outlook of the arising new potentials for portable spatial audio with MEMS based speakers will be given.

1. Motivation

3D audio is not only of high interest for loudspeaker reproduction, but also for headphones. Especially in the popular field of virtual reality (VR) and augmented reality (AR), headphones are the first choice. The connection to the ear is mostly fixed and every ear can directly be provided with audio content without any cross-talk. By the use of HRTFs (Head-Related Transfer Function) the virtual environment can be presented in a physical correct way [3, p. 9]. Knowing the exact sound pressure level of the headphones plays an important role in this application and could be much better achieved through the use of MEMS loudspeakers than classical approaches. In combination with a MEMS microphone this could be a perfect tool.

Other applications like active-noise-canceling (ANC) are also very popular. Nowadays hybrid feed-forward and feed-back filtering is used in mid to high prizing headphones. This means there is the need of at least two microphones per ear. When using in-ear headphones with small space requirements, the MEMS technology with all elements integrated in one chip can bring a big benefit.

In the manufacture of dynamic headphones derivations of several dB are common. Figure 1 shows the variation between left and right earphones in a dynamic in-ear headphone, which is not uncommon in the lower to mid price range.

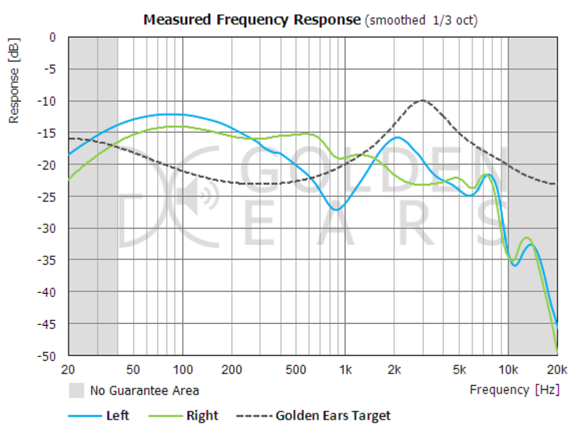

Fig. 1: Frequency response of an earphone with deviations between left and right loudspeakers [8].

Big differences can cause a confusion because of inconsistent amplitude and phase of the audio signal [2, pp. 206–212]. In Fig. 2 the principle influence of phase and amplitude are shown in dependency of the frequency. Especially in the use for VR and AR, differences to the visual cues can be a problem. If the derivation is not too large, the brain can compensate this, but best way is to deliver an audio signal most accurate like a real sound event.

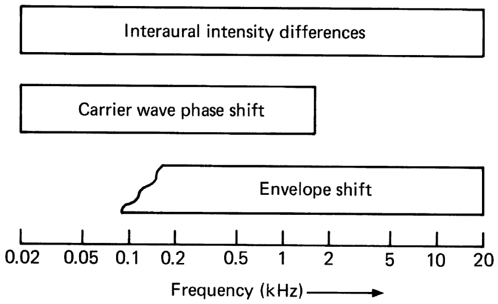

Fig. 2: Influence of various interaural advices on left and right hearing as a function of frequency [16, p. 639].

For higher pricing headphones the so called pairing (the two most similar drivers in one headphone) gives a better stereo representation. But the derivation from headphone to headphone is still there. Adaptive correction by microphone or signal processing can solve this problem. MEMS technology is ideal for this solution, as it allows a combination of high-precision MEMS loudspeakers with the smallest dimensions, MEMS microphones and digital signal processors (DSP) to be fabricated directly on a printed circuit boards (PCB).

2. MEMS Speakers

The following section explains MEMS technology in its basic principle and manufacturing process, including loudspeaker implementation. The historical and present approaches are presented.

2.1. MEMS Technology

The abbreviation MEMS stands for **M**icro-**E**lectro-**M**echanical **S**ystem. Hence, MEMS represent a rational combination of miniaturized components that operate typically in the mechanical and electrical domain. Based on the fact that semiconductor microelectronics and MEMS fabrication utilize in principle the same set of microtechnologies, enables (sub-)micrometer feature precision, high integration density, parallel high yield device manufacturing, high reproducibility and so-called monolithic device fabrication. Monolithic device fabrication means that all elements, comprising the micromechanical components and the required microelectronics are assembled in a miniaturized manner on the same substrate or at least within a single device package. This allows driving MEMS devices in principle with high energy efficiency and high performance signal processing. The packaged MEMS are relatively robust and furthermore allow a direct combination with conventional PCB surface-mount technology. The monolithic integration combined with the aforementioned possibilities for high yield, high volume and parallel microdevice fabrication enables overall new design strategies for loudspeakers and potentially a device fabrication at relatively low costs. Nevertheless, the implementation of MEMS technologies also requires rethinking the overall speaker design. In contrast to a conventional speaker assembly, MEMS fabrication relies on the stacking of patterned functional layers (2.5D technology). These layers are created by additive and subtractive technologies comprising, for instance, vapor phase thin film deposition, optical lithography for micropattern transfer, and material dry as well as wet etching for area-selective material removal.

MEMS emerged from the developing microelectronics in the 60s. The so-called resonant gate transistor, demonstrated by Nathanson and Wickstrom [14], is typically considered as the first appearance of a MEMS device. In the 70s, pressure sensors and ink jet printer nozzles were developed based on MEMS principles [12, pp. 2] followed by the first MEMS based microphone in 1982 [17]. Since then, MEMS inertial sensors, microphones, magnetometers, micro-optical components and various other components were developed and represent today the foundation of modern sensor systems and communication devices.

2.2. Early MEMS Speaker Approaches

The following overview is focused on MEMS based speakers for the reproduction of the audible frequency range. To the knowledge of the authors, the first approach of MEMS speakers was published in 1994 by Lee et al. [10] and was based on a piezoelectric cantilever. The concept itself was based on a sound generation by the stimulated bending of the microcantilever. Notably, the device was originally designed for microphone applications. A cross section of their speaker is shown in Fig. 3.

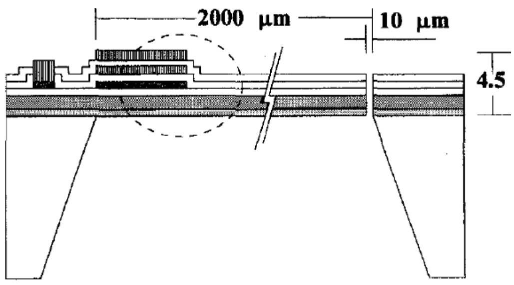

Fig. 3: Cross section of the piezoelectric MEMS-speaker from Lee et. al [10].

Only three years later Harradine et al. introduced the first electrodynamic MEMS speaker [6]. Attached to a membrane device, a permanent magnet interacts with a fixed voice coil, which caused generating of sound. A schematic illustration of this approach is shown in Fig. 4.

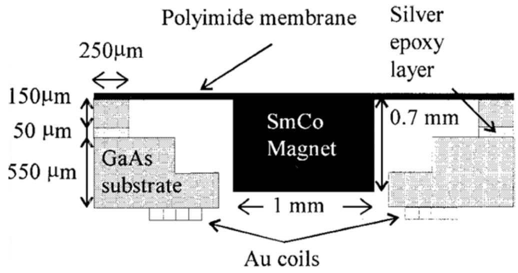

Fig. 4: Cross section showing the electrodynamic MEMS-speaker of Harradine et. al [6].

A MEMS speaker with electrostatic drive system was introduced by Neumann and Gabriel in 2002 [15]. Sound is generated by their system by the interaction of a movable membrane electrode and a fixed stator electrode. A photograph of their demonstrator is depicted in Fig. 5.

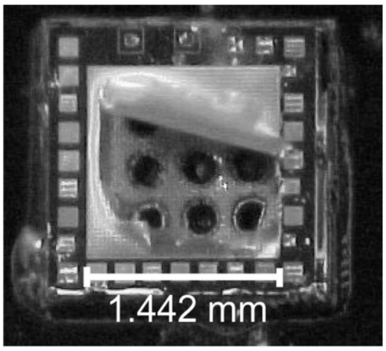

Fig. 5: Photograph of the electrostatic MEMS-speaker by Neumann et. al [15].

All recent MEMS speakers are more or less based on well known and well established principles from the field of common loudspeakers. Even exotic concepts like magnetostrictive drive systems are adapted to MEMS speaker approaches [1]. A more elaborate but still incomplete list of MEMS speaker related literature is given by Maennchen et al. [13].
In addition to these academic publications many patents and patent applications have been published by companies like Bosch [18], Infineon [4], Goertek [20] and AudioPixels [11]. In the meantime none of these companies have made any public demonstrations.

2.3. Todays MEMS Speakers

The following discourse is meant as short overview of the present MEMS speakers. A detailed view cannot be given in this frame. For further information on technical details or characterization results, please refer to the references provided. Due to the continuously growing demand for miniaturization of loudspeakers for headphone based applications, new approaches have been published in recent years:

USound is an Austria-based startup and provides the only MEMS speaker available on the market at now. Multiple MEMS based cantilevers act as piezoelectric drive system. Attached to this is a plate that acts as piston-like membrane. Because the membrane is attached in a non-semiconductor-technology processing step, it is a MEMS hybrid [19]. The MEMS based drive system and the entire MEMS speaker is depicted in Fig. 6.

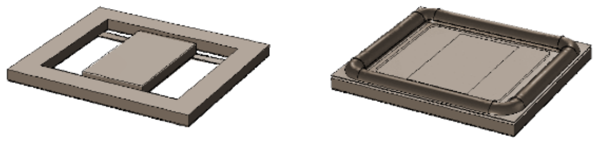

Fig. 6: Schematic illustration of the USound loudspeaker [19].

Fraunhofer ISIT introduced a piezoelectric MEMS speaker consisting of four triangular cantilevers which are separated by narrow gaps. This speaker is hence called piezoelectric narrow gap MEMS (PNG-MEMS) [13]. Related to the drive signal, the cantilevers act as bending actuators for the reproduction of sound. Because of the narrow gaps, the acoustic short-circuit is avoided and large excursions are enabled. Functionality was proven by public demonstrations of an In-Ear Headphone demonstrator several times, at first at the Conference of the German Acoustic Society DAGA in 2018. In order to optimize its performance, the In-Ear Headphone was designed and equipped with dedicated signal processing by Fraunhofer IDMT. The basic principle of the PNG-MEMS is shown in Fig. 7.

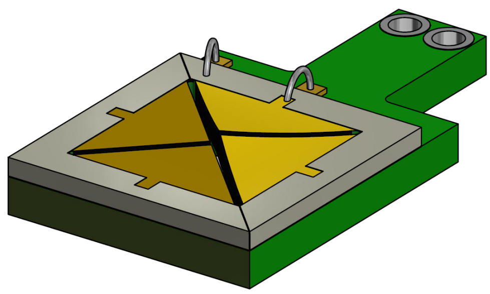

Fig. 7: Working principle of the ISIT loudspeaker [13].

Fraunhofer IPMS developed an electrostatic MEMS speaker with a drive system called Nano-Electrostatic-Drive (NED). The working principle differs from that of conventional electrostatic speakers and is based on electrostatic actuated bimorph bending actuators moving in-plane [5, 9]. Within the chip, several actuators move in pairs towards and away from each other. In that way air is pushed out of one speaker side and sucked in on the other. Some experts may recall the Air Motion Transformer from Oskar Heil [7]. Functionality was proven by demonstrations of an In-Ear Headphone in the project team of Fraunhofer IPMS and Fraunhofer IDMT. The basic principle of the NED is shown in Fig. 8.

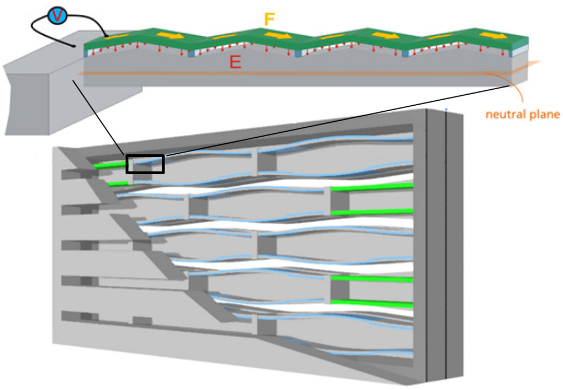

Fig. 8: Working principle of the IPMS loudspeaker [5].

3. Outlook

The first developments of MEMS loudspeakers presented in this paper provide high potential for headphone based applications. Further considerations regarding performance and new actuator designs are required.

3.1. Conclusion

More than any other technology, MEMS technologies provide a high potential to fulfill the current need and to effectively address the current challenge of miniaturized speakers considering high acoustical performance and low prices for portable audio applications like headphones, hearables, hearing aids, and AR respectively VR glasses. The technology ensures simple, high volume production of speakers, which are more light weighted, less divergent and easier to assemble than conventional technologies. Especially the high integration density of actuators, sensors and signal processing and the high-precision manufacturing make MEMS loudspeakers highly attractive. All components can be easily interconnected and adjusted to each other. This enables sufficient versatility to cope with various application scenarios. Regarding headphone system functions like adaptive control to compensate deviations between left and right channels, automated installation of user-oriented listening experiences and similar are possible.

3.2. Future Work

MEMS speaker technology follows a paradigm change in the value chain of headphone based solutions. As a result, headphones are not manufactured anymore by a single manufacturer, but represent a combination of headphone manufacturers, chip manufacturers, and design and software developers. The increase in production can also reduce manufacturing costs. As more and more systems are being developed by wireless means, the problem with impedance loads is becoming irrelevant, which means that the power consumption of mobile devices is reduced. Further development will prove to what extent MEMS loudspeakers can also be used as mobile loudspeakers in mobile devices, as headphones with over-ear or even as free-field loudspeakers.

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