Efficiency optimization of an electrodynamic MEMS microspeaker

Iman Shahosseini, Elie Lefeuvre, Johan Moulin, Marion Woytasik, Emile Martincic, Guy Lemarquand

Efficiency optimization of an electrodynamic MEMS microspeaker

I. Shahosseini[a], E. Lefeuvre[a], J. Moulin[a], M. Woytasik[a], E. Martincic[a] and G. Lemarquand[b]

[a]Institut d'électronique fondamentale, bat. 220 Av Georges Clémenceau 91405 Orsay Cedex
[b]Laboratoire d'acoustique de l'université du Maine, Bât. IAM - UFR Sciences Avenue Olivier Messiaen 72085 Le Mans Cedex 9
elie.lefeuvre@u-psud.fr

This paper presents the optimization of a novel planar structure of MEMS electrodynamics microspeaker. The mobile part of the device is a microstructured silicon membrane suspended by a whole set of silicon springs. Its actuation principle relies on the Lorentz force, exactly like in conventional microspeakers broadly used in mobile electronics devices. The presented structure includes a planar coil electroplated on top of the silicon membrane, and a permanent magnet part based on magnet rings bonded onto the silicon substrate. Four different configurations of the permanent magnet part are studied. In each case, the dimensions of the planar coil are determined in order to maximize the electroacoustic conversion efficiency. The optimization method takes into account technological limits of microfabrication. Simulations based on analytical and finite element modeling show that the efficiency of optimized MEMS microspeaker could be up to ten times greater than that of conventional electrodynamics microspeakers used in mobile phones. The simulation results are confirmed by experimental measurements on MEMS microspeaker prototypes.

1 Introduction

Nowadays, miniaturized loudspeakers are commonly used in numerous electronic mobile devices, such as smart phones, handheld PCs, etc. Like conventional, large-dimensions loudspeakers, these microspeakers are electromagnetically actuated. However, scaling down of the loudspeaker dimensions faces the technological limits of conventional manufacturing processes. As a consequence, all the performances are degraded. For instance, imperfections of the sound radiator part and its suspension degrade the sound reproduction loudness, especially in low frequencies. Size reduction also degrades the electroacoustic conversion efficiency. Conventional microspeakers are actually very inefficient transducers. Large size loudspeakers have efficiency between 0.5% and 4%, but efficiency drops down to 0.001% in the case of microspeakers. The poor efficiency of the transducer has a direct impact on the overall efficiency: in portable multimedia devices, the audio system consumes up to 30% of the total power [1]. This, consequently, affects the device autonomy and the playback time. Such very low efficiency causes the battery undergo more recharging and discharging cycles, which decrease furthermore the batteries lifetime.

MicroElectroMechanical Systems (MEMS) technology can be a good alternative to overcome such drawbacks, thanks to its high precision manufacturing and batch processing potential to keep the final cost low. Moreover, it would be a good point for the microsystem industry to answer a demand of more than one billion microspeakers per year.

Though few works on the MEMS microspeakers report efficiency enhancements [2-5], rare elements about acoustic performances show that the sound quality and the sound intensity stay behind those of conventional microspeakers. The former is due to the use of a deformable diaphragm, whose nonlinear behavior and the numerous structural modes produce sound distortion; the latter stems from the low displaced air volume.

This paper presents the design and the electromagnetic optimization of a high performances MEMS microspeaker. The objectives are to improve the sound quality, the efficiency and to get wider frequency bandwidth. Regarding current trends of microspeakers applications, a sound pressure level (SPL) of 80 dB at 10 cm is aimed. This should be available from frequencies as low as 300 Hz. In comparison with the specifications of other non-MEMS microspeakers, 75 dB SPL from 700 Hz to 20 kHz, and other MEMS microspeakers, 70 dB SPL at 1 kHz, this is a real challenge. At the same time, an efficiency higher than 0.001% is targeted.

This paper is organized as follows: section two presents the global design of the microspeaker. In section three, the electromagnetic optimization is exhaustively investigated with the help of analytical model and finite element method (FEM). Then, theoretical results are compared to the experimental measurements in section four before the conclusion and perspectives.

2 Microspeaker structure

In the MEMS literature, different actuation principles can be found. Among them, the principal ones used in former MEMS microspeakers are electrostatic, piezoelectric, and electromagnetic. Electrostatic and piezoelectric loudspeakers appear more amenable to miniaturization and to MEMS fabrication. Nevertheless, because of high driving voltage for electrostatic actuation, and non-linear behavior of piezoelectric materials, electromagnetic actuation presents the best properties, regarding the objectives of this work. Though its principle, which involves moving coil and magnet, makes the microfabrication process a challenge, it is still the best choice as it has quite linear behavior and yields high driving force.

To generate sound waves, a surface movement, which creates air pressure, is necessary. To do so, former electrodynamic MEMS microspeakers used the drum-like deformation of polymer diaphragms clamped to rigid frame [2-5]. Despite polymers lightness and flexibility advantages, the existence of numerous structural modes for the radiator surface and its nonlinear elasticity hinders the sound reproduction quality and the acoustic intensity.

Here, the sound radiator is a rigid and light membrane, whose structural eigenvalues are shifted out of the frequency bandwidth. The needed large displacement is enabled by a series of very soft springs [6-7]. Both parts are made of silicon, as this material presents a high young's modulus and low mass density. Moreover, many micromachining processes are available for this material. Fig. 1 depicts a schematic view of the microspeaker with its circular membrane, the planar microcoil, and a ring shape magnet around. The mobile part is attached to the fix part of the microspeaker by curved shape suspension beams. To feed the microcoil, two conductor tracks on top of the suspensions lead the electric current from the fix part to the mobile part, and inject it to the coil's interior and exterior ends.

For this device configuration, the driving force, known as Lorentz force $F_{Lorentz}$, can be written as:

$$F_{Lorentz} = I.2\pi.\sum_{i=1}^{N} R_i.B_r(R_i) \qquad (1)$$

where I is the injected current, R_i is the radius of the i^{th} coil turn and $B_r(R_i)$ the radial component of magnetic flux density in the coil plane observed by the i^{th} turn. The magnetic field is assumed symmetrical to the membrane center axis. Thus, the sum of elementary forces is perpendicular to the coil-membrane plane.

This force is actually responsible to give enough acceleration to the membrane in order to generate the necessary sound pressure. For a spherical acoustic radiation, the acoustic power $P_{acoustic}$ at distance a from the source can be computed by (2).

$$P_{acoustic} = 10^{\frac{L_{dB}}{10}} \times 10^{-12} \times 4\pi \times a^2 \qquad (2)$$

For L_{dB} =80 SPL, the microspeaker should radiate an acoustic power of 12.6 µW. In the proposed design, for the sake of sound quality, the sound generation is resulted from the piston movement of the membrane. For such structure, (3) defines the produced acoustic power at frequency f.

$$P_{acoustic} = 0.25 d^4 f^4 x_{peak}^2 \qquad (3)$$

In (3), d and x_{peak} are respectively the membrane diameter and out-of-plane displacement. The $(d^2.x_{peak})$ product is the volume of air that the radiator surface should displace. Fig. 2 shows the volume of displaced air as a function of frequency. The lower the frequency is, the higher the air volume should be. If setting the objectives to meet the majority of today's non-MEMS and MEMS microspeakers acoustic power, at maximum SPL and for the lowest working frequency, a volume of 8 and 3 mm^3 should be displaced respectively. In the same way, for this work a total air volume of 75 mm^3 must be displaced. Setting the membrane diameter and displacement for displacing 9 times bigger air volume than non-MEMS speakers is a real challenge. This point is described more in details in Table 1, which summarizes the necessary membrane out-of-plane displacement for various membrane diameters to meet specifications of different microspeaker categories. Going toward small diameters asks for very high displacements, which are difficult to reach for either MEMS or conventional technologies. On the other hand, going toward large membranes diameters makes difficult the integration and increases the costs. A membrane diameter of 15 mm and a displacement of 350 µm were chosen as a nice trade-off.

3 Electromagnetic optimization

To optimize the electromagnetic motor of the microspeaker, both the microcoil and the magnet components should be considered. For this purpose, the electroacoustic conversion efficiency should be taken into account. Eq. (4) gives the relation between the electrodynamic force factor, $\Sigma\, l_i\, Br(R_i)$, the mobile mass M, and the microcoil resistance R.

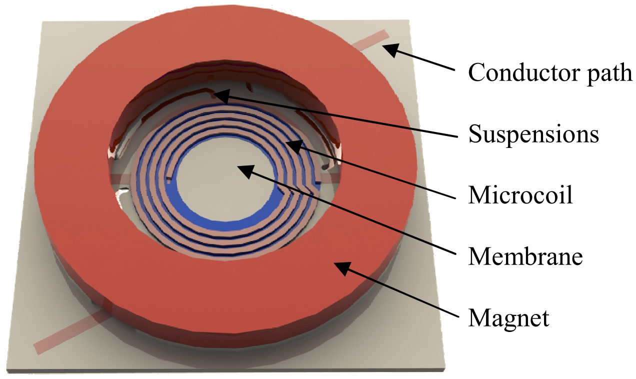

Figure 1: Schematic view of the MEMS microspeaker and its components

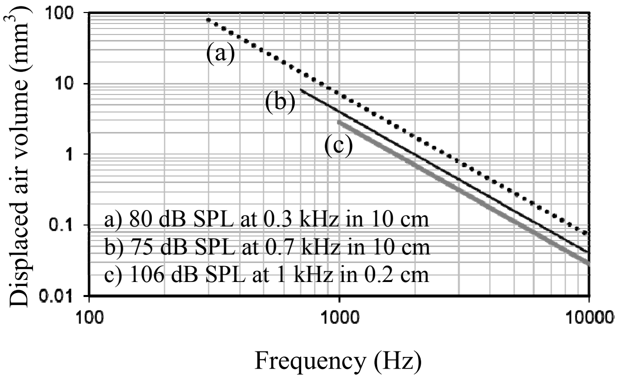

Figure 2: Displaced air volume as a function of frequency to meet the objectives of this work (a), achieved by conventional microspeakers (b), achieved by former MEMS microspeakers (c)

Table 1: Out-of-plane displacement for various membranes diameters, to meet the specifications of other conventional microspeakers and former MEMS microspeakers, and the specifications of this work.

Membrane diameter (mm)	Membrane displacement (µm)		
	Non-MEMS	Other MEMS	This work
5	1030	113	3155
10	260	30	790
12	180	20	545
15	115	13	350
18	80	9	240
20	64	7	200

$$\eta = \frac{\rho.\pi.r^4}{4c}.\frac{1}{R}.\left(\frac{\sum_{i=1}^{N} l_i.B_r(R_i)}{M_{coil}+M_{membrane}}\right)^2 \quad (4)$$

Here c is the sound speed, ρ the air density, and r the membrane radius.

Eq. (4) shows that the three coil characteristics (mass, resistance, and length) intervene in the efficiency. For this work, the resistance was set at 10 Ω to be compatible with the electronic amplifier circuit, but either the mass or the length of the coil was free to be varied. Since c, ρ, and r are constant, the only way to increase the efficiency is to increase the force factor and/or to reduce the mobile mass ($M_{membrane}$ + M_{coil}). Since the preset membrane mass, $M_{membrane}$, is 28 mg, the coil mass, M_{coil}, should be kept as low as possible.

Four different configurations of magnets were modeled using FEM. These models were used to calculate the radial component of magnetic flux density in the coil plane. Then, with help of (4), the microcoil turn width was analytically determined in order to maximize the efficiency. Optimal dimensions of the microcoil were calculated for each configuration.

Fig. 3 illustrates the microspeaker in cut view with ring-shape magnets. For each case, the same total volume of magnetic material and the same remanent magnetization of 1.5 T were considered. For magnetic flux density calculations and coil optimization, the membrane was assumed to be in the rest position. This hypothesis was made because, for frequencies higher than 1 kHz, the membrane remains close to its rest position, as sown in Fig 4. Fig. 5 shows the variation of the radial component of the magnetic flux density in the membrane plane. The configuration of two parallel magnets with axial magnetization gives the strongest B_r within 1.5 mm distance from the magnets. One ring magnet with axial magnetization yields the second strongest B_r in the magnet vicinity. By going beyond 1.5 mm distance, *Br* stays almost in the same level for all configurations, near to 0.1 T. This shows how important it is to minimize the magnet(s)-coil distance. Ideally, the coil turns should be concentrated on the membrane perimeter. However, with today's technological limits, the maximum thickness for the copper microcoil is 30 µm, with 20 µm minimum spacing between each coil turn.

By setting the coil turns thickness and spacing, the only coil parameter which can be varied is the coil turn width. Modifying the turn width influences the efficiency via changes in the coil length, so the coil mass. Fig. 6 shows the efficiency variation for a 30 µm thick coil and a pair of magnet rings, with 1.0 and 1.5 T axial remanent magnetization. A microcoil with 35 µm wide turns gives the maximum efficiency of 10^{-4} with two magnets having axial remanent magnetization of 1.5 T. The optimized coil has 14 turns and 6 mg mass. In the case of 1 T remanent magnetization, the efficiency drops down to 0.4×10^{-4}. This point highlights the strong impact of the magnets properties on efficiency.

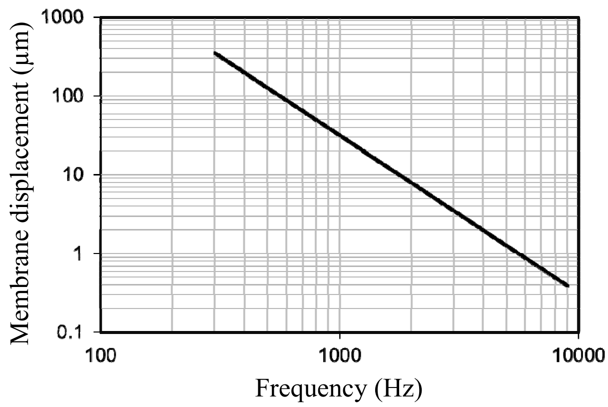

Figure 4: Membrane displacement as a function of frequency to produce 80 dB SPL at 10 cm

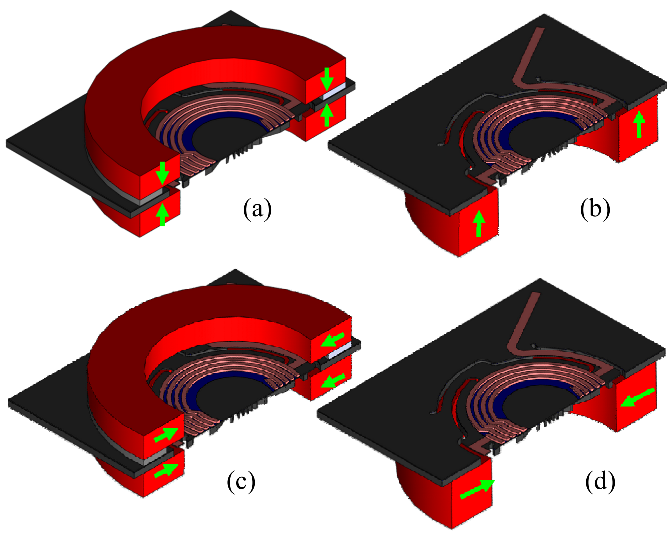

Figure 3: Four investigated configurations of ring-shape magnets with the same total volume, two magnets with axial magnetization (a), one magnet with axial magnetization (b), two magnets with radial magnetization (c), one magnet with radial magnetization (d)

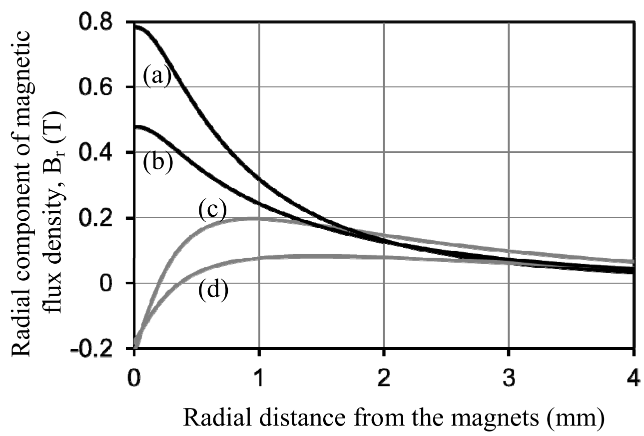

Figure 5: Radial component of magnetic flux density as function of distance from the edge of the 1.5 T magnets, for two magnets with axial magnetization (a), one magnet with axial magnetization (b), two magnets with radial magnetization (c), one magnet with radial magnetization (d)

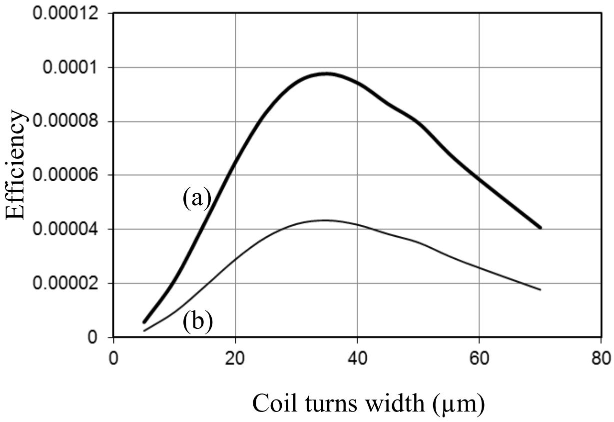

Figure 6: Efficiency as a function of the coil turn width for a 30 µm thick coil with 20 µm spacing between turns, 10 Ω resistance, and two parallel magnets with axial magnetization field of 1.5 T (a), 1.0 T (b)

Fig. 7, which shows the variation of efficiency, confirms the optimal coil geometry and shows the force factor as a function of coil turns number. This figure also shows that above the optimal number of turns which gives the maximum efficiency, additional turns keep increasing the force factor. However, this augmentation is not sufficient to compensate the effect of the additional mass. The additional turns are actually farther from the magnets, so they are subjected to a lower magnetic flux density.

Table 2 summarizes the optimized coil properties (mass, turns width, and turns number) for each of the four configurations. The second highest efficiency is rated for one magnet with axial magnetization. In this case, the maximum efficiency is a half that of the previous configuration. The two magnet configurations with radial remanent magnetization produce lower radial component of magnetic flux density, and thus their efficiencies are lower.

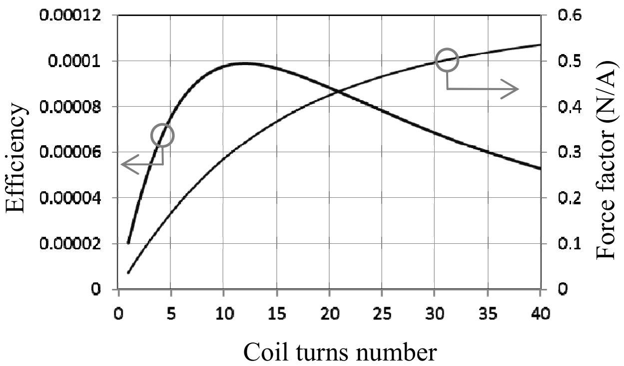

Figure 7: Efficiency and force factor as a function of the coil turns number, 30 µm thick coil with 20 µm spacing between turns, and two magnets with 1.5 T axial magnetization

Table 2: Optimized coil characteristics for each magnets configuration

Magnet configuration	(a)	(b)	(c)	(d)
Turns width (µm)	35	40	65	70
Turns number	14	16	29	33
Mass (mg)	6	8	20	23
Efficiency	10^{-4}	0.5×10^{-4}	9×10^{-6}	1.5×10^{-6}

4 Electroacoustic characterizations

The MEMS microspeaker prototype was fabricated in clean room using classic silicon micromachining processes. One ring-shape magnet with axial remanent magnetization of 1.5 T was bonded onto the device substrate. For acoustic tests, the sample and a B&K 4938 microphone set at 10 cm from the membrane were installed in an anechoic chamber. The measured SPL response for a frequency range between 100 Hz to 20 kHz is shown in Fig. 8. The microspeaker showed it was able to generate 80 dB SPL at frequencies as low as 330 Hz. This confirms the expected capability to produce high sound intensity at low frequencies. Despite the existence of some little peaks and dips in the SPL spectrum, between 330 Hz and 20 kHz, the SPL response stays more or less close to 80 dB. These measurements were carried out with an electrical RMS input power of 0.5 W. This corresponds to an efficiency of 0.003%, that is to say a little lower than the 0.005% efficiency predicted by the simulations (Table 2). Although this value remains behind the objective of this work, it is still three times better than typical efficiency of conventional microspeakers. Moreover, according to these experimental results, the best magnet configuration (Fig. 3-a) should raise the efficiency near the 0.01% theoretical value.

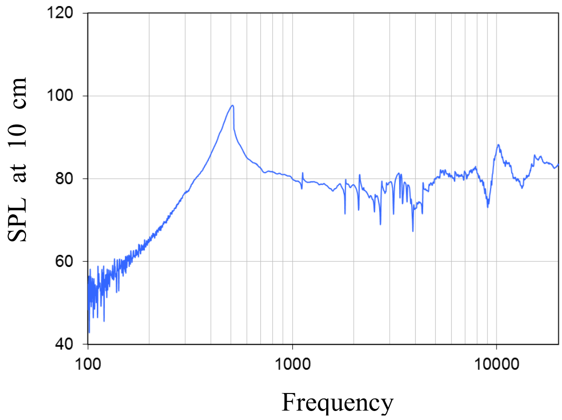

Figure 8: SPL response as a function of frequency measured at 10 cm distance from the microspeaker with one magnet, and 0.5 W input power.

5 Conclusion and perspectives

This paper proposed a new microspeaker structure based on MEMS technology. The high sound intensity and high electroacoustic conversion efficiency were two main targets to make the device an appropriate transducer for high fidelity mobile audio systems.

To obtain high sound intensity and guarantee the sound quality, a rigid circular membrane vibrating with piston-like displacement was used as radiator surface. The interaction between the planar microcoil on the membrane and the annular magnet on non-mobile part of the device created the electromagnetic driving force, which displaced the membrane up to 350 µm out-of-plane.

Four different configurations of magnets were analyzed. For each configuration, the microcoil was optimized using a coupled analytical and FEM models. For this purpose, the technological limits of the fabrication process were taken into account. The best magnet configuration, composed of two magnets rings with axial remanent magnetization of 1.5 T, associated to an optimized planar copper microcoil yielded 0.01% efficiency in theory, that is to say ten times higher than that of conventional microspeakers.

The membrane diameter of the experimental prototype was set to 15 mm. The device microfabrication took place in clean room using classic silicon micromachining processes. After integrating one annular magnet, electroacoustic characterizations were carried out in an anechoic chamber.

Measurements showed that 80 dB SPL was produced at 10 cm from frequencies as low as 330 Hz. This first performance makes an important distinction of this work with other MEMS and non-MEMS existing microspeakers.

The second achievement concerns the electroacoustic efficiency. Indeed, experimental results showed three times higher efficiency than that of non-MEMS microspeakers.

In the near future, the two-ring structure will replace the one-ring magnet one, in order to confirm the theoretical value of 0.01% efficiency, that is to say ten times higher than that of conventional microspeakers. The electroacoustic performances of the transducer with various membrane diameters will be also investigated to get a broader view of the device integration potential.

Acknowledgments

This work has been financially supported by the French Agence Nationale pour la Recherche (ANR).

The authors would like to thank the staff of the University Technological Center IEF-MINERVE for their help and technical support.

References

[1] K. Lee, Y. Cho, and N. Chang, "High-level power management of audio power amplifiers for portable multimedia applications", in *Proc. IEEE/ACM/IFIP Workshop on Embedded Sys. for Real Time Multimedia*, 41-46 (2006)

[2] Y. C. Chen, and Y. T. Cheng, "A low-power milliwatt electromagnetic microspeaker using a PDMS membrane for hearing aids application", in *Proc. MEMS*, 1213-1216 (2011)

[3] S. S. Je, F. Rivas, R. E. Diaz, J. Kwon, J. Kim, and B. Bakkaloglu, “A compact and low-cost MEMS loudspeaker for digital hearing aids”, *Trans. Biomed. Circ. and Syst.*, 3(5), 348-358 (2009)

[4] S. H. Yi and E. S. Kim, "Micromachined piezoelectric microspeaker", *Jap. J. of App. Phys.*, 44(6A), 3836-3841 (2005)

[5] M. C. Cheng, W. S. Huang, and S. R. S. Huang, “A silicon microspeaker for hearing instruments”, *J. Micromech. Microeng.*, 14, 859-866 (2004)

[6] I. Shahosseini, E. Lefeuvre, M. Woytasik, J. Moulin, X. Leroux, S. Edmond, E. Dufour-Gergam, A. Bosseboeuf, G. Lemarquand, and V. Lemarquand, “Towards high fidelity high efficiency MEMS microspeakers,” in *Proc. IEEE Sensors*, 2426-2430 (2010)

[7] I. Shahosseini, E. Lefeuvre, E. Martincic, M. Woytasik, J. Moulin, S. Megherbi, R. Ravaud, and G. Lemarquand, "Design of the silicon membrane of high fidelity and high efficiency MEMS microspeaker", in *Proc. DTIP conference*, 258-262 (2011)