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Acoustic sealing of silicon MEMS microspeakers by the means of polymer films

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We present here a silicon MEMS microspeaker with an acoustic leakage reduction polymer sealing. The silicon MEMS microspeakeris formed by a silicon emissive surface suspended by thin silicon suspension beams. The high rigidity of the acoustic emissive surface is obtained thanks to the design of stiffeners located on its backside. Its displacement is obtained by an electrodynamic actuator, *i.e.* a micromachined planar coil manufactured onto the emissive surface and placed in the near vicinity of a permanent magnet. Out of plane displacements up to ±400 µm are possible without failure of the structure and 80 dB_{SPL} at 10 cm were obtained. The performances of silicon microspeakerscan be further improved by an optimized sealing between the static part and the emissive surface. The sealing requires high mechanical compliance and low mass to limit its impact on the microspeaker's characteristics. A thin polymer (PolyDiMethylSiloxane or dry resist film) seal has been designed with finite elements modelling. We demonstrate that the stiffness added by the seal can be reduced by a factor 10 compared to the same material seal with no forming. A fabrication process with a dedicated homemade vacuum forming set-up is presented.

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Keywords: MEMS, Microspeaker, Acoustic leakage, FEM, Polymer, PDMS, Seal, Dry resist film

1. Introduction

Ambient noise (office, locomotion and house) has been known as a source of disturbance for a long time. Recently, its effects on health have been quantified and a lot of effort has been put to reduce ambient noise on both scientific as well as on legal ways [1]. Different methods exist to enhance the acoustic comfort. The first one is the reduction at the source, *i.e.* reduction of vibrations of the surface that creates noise. It can be achieved by several means. The mostly uses ones are passive damping (using resilient layers stuck onto the structure or damping dashpots) and active vibration control (by the use of actuators stuck onto the structure to create counter-forces). Recently, specific structures (called acoustic black holes) were found to produce strong damping effects on flexural vibrations by the use of structure thinning, thus avoiding reflected waves at the boundary [2-3]. The second one is to reduce the acoustic noise level by the use of an acoustic liner, *i.e.* a device or a layer able to reduce the noise. The most extended passive acoustic linersaremultilayeredfoam that absorbs acoustic waves [4]. The main drawback of passive acoustic liner is the large thickness required for high absorption efficiency at low frequencies. A thinner liner can be obtained by the use of a perforated plate backed by a honeycomb structure and a plate, hence creating multiple Helmholtz resonators to produce a damping effect. However, this liner thickness still strongly dependent on the wavelength of the acoustic wave to be muffled.Another type of acoustic liner uses the interference of incident acoustic waves with the ones produced in phase opposition by an actuator. These acoustic noise reduction systems are called active acoustic liner. Several hybrid or active acoustic liners structures have been proposed. In [5] a duct with a passive absorber membrane (foam) is completed with a loudspeaker placed at the end of a duct. The loudspeaker is used to adjust the acoustic impedance of the duct, especially in the frequency ranges where the foam has less absorption efficiency.

The work presented in [6] deals with the quality of sound reproduction in rooms by reducing the effect of their natural resonances. For this enhancement, a small number of localized loudspeakers is used to adapt the apparent acoustic impedance of a small room. These works aim to reduce the undesirable noise in frequency ranges as wide as possible. Obviously, the performances obtained are conditioned by the characteristic parameters of the active transducer (loudspeaker) used in this type of application.

Another work about active acoustic liner [7] using an array of loudspeakers shows that the acoustic absorption coefficient can reach 0.7 for a wide frequency range. Lissek*et al.*present the limiting factors of this type of active acoustic liner, which are the moving mass, and the stiffness of the transducers used.

As our teams showed in [8], the efficiency of the electrical to acoustic transduction is a key factor for performance enhancement of microspeakers. These microspeakers can be used as active acoustic feedback control devices for active muffling of noise. An efficiency of $3.10^{-5}$of electrical to acoustic transduction acoustic, *i.e.* higher than typical valueswas reached. The high acoustic attenuation thus obtained could benefit toan use as an active sound absorber. Moreover, the small size of the microspeakerpaves the way towards a thin adaptive impedance layer by the use of distributed microspeakers.Despite its small size, such microspeaker allows a stroke up to ±400 µm of the emissive surface, whichwill be further increased by several means.

The aim of this work is to design a dedicated acoustic sealing able to take the performances of the microspeaker far beyond the state of the art in terms of electro-acoustic conversion efficiency. Some works have shown the interesting PDMS property, whichis its very high mechanical compliance, by using it as a highly deformable protection of large stroke actuators [9] andas 3D patterning [10] to obtain curved top membranes, with a static deformation up to some micrometers, we consider it as a suitable polymer. We propose here two solutions to obtain a thin polymer film (up to 15µm) with a millimetric out of plane solicitation as a post-process step of the microspeaker fabrication: afirst process of vacuum forming, applied to aresist polymer (dry resist film)commonly used for high resolution printed circuit boards patterning; and a second process with liquid PDMS spin-coatedover the wafer, to realize the acoustic sealing.

In the next paragraph, the transducer choice of our active acoustic liner and the manufacturing process are both explained. The FEM design of acoustic sealings and manufacturing processesare presented in chapter 4 and 5.

2.Transducer choice: advantages of a silicon MEMS microspeaker

2.1 Requirements for impedance matching

The mainrequirements of the active acoustic liner are a small thickness and high efficiencytransduction in the low frequency range around 500 Hz.To be efficient, the acoustic liner has to exhibit a purely resistiveacoustic impedance. In the case wherethis acoustic impedance is matched,there is no reflection of the acoustic wave on the acoustic liner surface.The best acoustic impedance matchingis obtained when the emissive surface of the transducer can reach the speedmovement of the air particles in front of it. This latter depends on the frequency and the displacement of the emissive surface that will be larger at low frequencies than at higherones.

Several transducers, based upon different technologies (electrostatic, piezoelectric and electrodynamic [11-14]), partially meet the requirements to allow a good impedance matching: small thickness (few centimeters) but in most cases a limited out of plane displacement.

A stroke up to ±400 µm was obtained with a silicon MEMS electrodynamicmicrospeaker [15]. This high stroke is obtained by silicon thin beams that were designed to have low stress as the emissive surface moves to a large out of plane distance; and the actuation of the emissive surface is obtained by a planar coil and one or two reported magnets for its actuation (Fig. 1.).

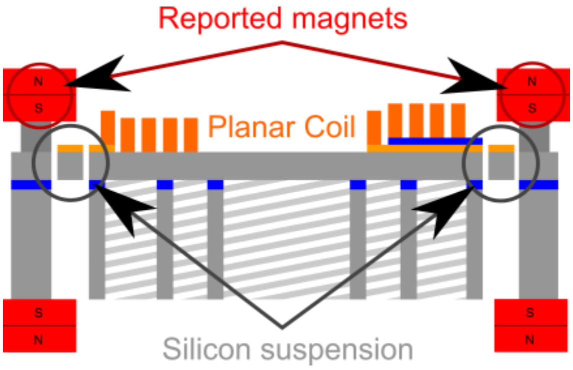


Fig. 1. Drawing of the main electrodynamic microspeaker part.

This type of microspeakerhas been targeted for nomad devices application in order toenable the rending of low frequency sounds [16]. Considering the size and the stroke of this microspeaker, the bandwidth ranges should be from 300 Hz, which is lower than the limit frequency for the acoustic liner planned for this work.

For a better understanding of the work developed in chapter 3 and 4, some important steps in the microspeaker process have to be presented.

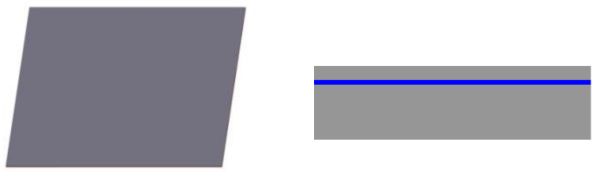
2.2 Microspeaker development

The silicon MEMS microspeakerpresented here is built on SOI (Silicon OnInsulator) wafers (Fig. 2.-a). This type of wafersare composed of three layers, the first one in silicon called "device" layer, the second of oxide layer is called "BOX" (Buried OXide) layer and the last one in silicon is called the "handle" layer.

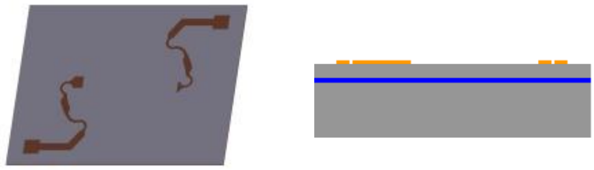
The microspeaker process can be divided into six main steps. Some of these steps concern the electrical part of the microspeakercomposed of two electrical tracks (Fig. 2.-b), an electroplated planar coil (Fig. 2.-e) and an insulator part for the internal connection on the planar coil (Fig. 2.-c) , which are developed on the device layer. The silicon device layer is also used for the suspension by etching it(Fig. 2.-c). During the etching process, the box layer is used like a stop layer for the etching suspension step and the etching stiffeners step (Fig. 2.-f), thanks tothis layer the thickness beams are always the same and gives the same stiffness to each beams that compose the suspension.

The use of silicon suspension beams imposes some requirements because this material is relatively fragile. A localized stress could break the suspension beamswhen the emissive surface moves. Silicon material has a low elastic limit around 160MPa compared to the steel one (around 300 MPa). In the aim to limit this constraint localization, some simulations have been performed to define an optimized suspension design, which allows the large displacement of the emissive surface.

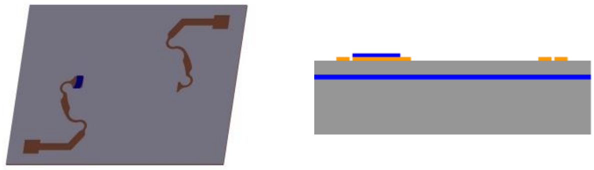
a-SOIWafer



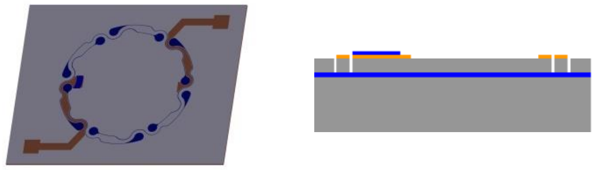
b-Conductive copper for the coil access tracks



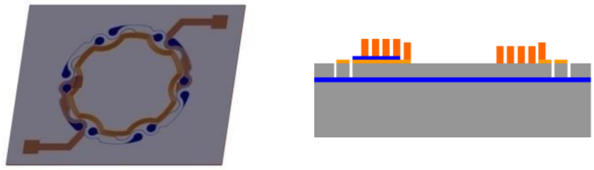
c-Local insulatordeposition



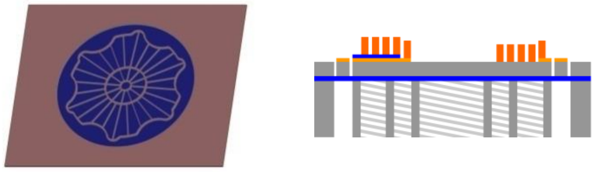
d-Etching of the suspension beams in the "device" layer



e-Electroplated coil



f-Etching of the back side of the microspeaker



g-Etching the isulator layer to release the emissive surface

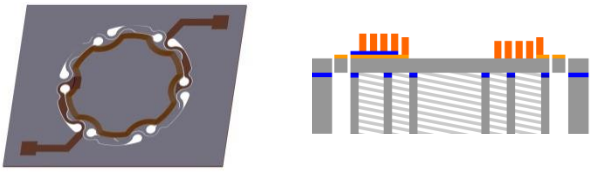


Fig.2. Microfabrication process for silicon MEMS microspeaker

In a previous work, Shahosseini*et al.* proved that an optimized shape decrease the stress concentration from 320 MPa to less than 50 MPa with this advanced design [17].

As we can see on the figure 3, the optimized design limits the stress localization and gives a maximum stress of 50 MPa (in red).

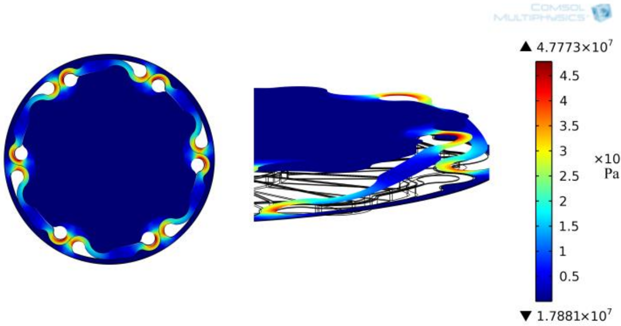


Fig. 3.:Stress repartition in the suspension springs obtained by FEMfor a 300 µm displacement

This suspension beams design for the emissive surface displacement implies the creation of empty zones along the moving parts. As a counterpart of the high stroke obtained, anair connection appears between the front and the back sides of the device, thus creating acoustic leaksthatdramatically impact on the sound level produced by the microspeaker.

2.3 First investigated acoustic sealing

As presented in the previous part, the design of the microspeakercreates acoustic leaks thatare accentuated by the large stroke of the emissive surface.The out of plane movement (Fig. 4.) creates the main contribution to the acoustic leakage.

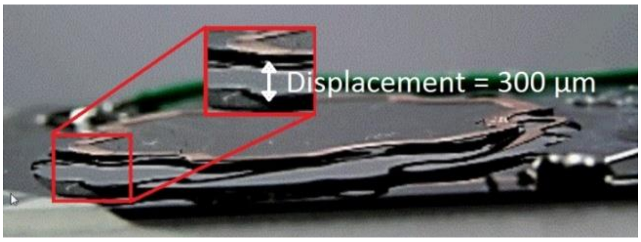


Fig. 4. Out of plane movement

For a traditional loudspeaker, the emissive surface displacement produces over pressure on its front side and an under pressure on its back side. The pressure variationon the emissive surface produces sound that is radiated in the air environment. The displacement needed, for the sound radiation,is higher at low frequencies than at high frequencies. For our design of microspeaker,the out of plane movement creates acoustic leaksthat reduce dramatically the over pressure produced. In this situation, the sound produced by the microspeaker is no longer audible. To solve this problem, an acoustic sealing must be applied.

A first solution with a stretchedlatex filmwas glued on the backside of the microspeaker (Fig. 5.).

Fig. 5. Latex film glued on the microspeaker backside

This acoustic sealing solved the acoustic leakage problem and with this modification, the microspeaker produces sound with a mean level of 80 dB_{SPL} (ref 20 µPa) at a distance of 10 cm with an electric power of 0.5 W.

Although the stretchedlatex film solves the acoustic leakage problem, it adds mass to the emissive surface and significantly increases the suspensions stiffness, thus reducing the overall microspeakers' efficiency. It also increases the low frequency limit that reaches a value of 600 Hz. The next chapter will present anotherdesign of acoustic sealing which should solve this problem.

2.4 Acoustic sealing design

Theseal conception must fulfil three main requirements: minimize the added mass to the emissive surface; minimize the added stiffness to the suspension beams andlimit its impact on the emissive surface stroke.

For the acoustic sealing design, several parameters must be studied likethe material andthe shape. This chapter presents in a first time a material study followed by the FEM simulations to define an optimized sealing shape.

2.5 Elastic Materials

As presented in chapter 3, a previous study of anacoustic sealing used a latex film. However,much mass and stiffnesswere added that changed dramatically the stroke and shiftedthe first eigen-frequency of the microspeaker.Most of theadded mass came from the method used to fix the latex film on the backside of the microspeaker. To overcome theeffect ofadded mass by gluing,a new application method must be developed. In order to minimize the acoustic sealing impact on both the $330\,\mathrm{mg}$mass of the emissive surface and the$6.4\,\mathrm{N.m^{-1}}$stiffness of the suspension beams, several materials were investigated. Their properties are summarized in Table 1.

Table 1. List of materials used in micro-fabrication

Materials	**Latex**	**Dry film**	**PDMS (10:1)**	**Parylene D**
Thickness (µm)	50	15	20	0.5
Volumic mass (kg/m^3)	≈ 3600	≈ 1400	950	1418
Elastic modulus (MPa)	36	2100	1-4	2500
Temperature Range (°C)	[0;140]	[0;100]	[-40;200]	[-200;200]

Amongst them, the dry film is a photo-resist film commonly used for high resolution printed circuit boards patterning, available in 15 µm thickness. The PDMS (PolyDiMethylSiloxane),before polymerization, is a liquid polymer that can be spin-coated to make a film of 10 to 50 µm thickness on a plane surface. Compared to the latex film, both dry film and PDMS offer superior qualities regarding the requirements described previously. Both of them show a lower density than latex film.Thedry film has a higher elastic modulus, so a higher impact on suspension beams stiffness can be expected. Parylene D seems also convenient, but the fabrication of a seal with this material has not been investigated yet.

2.6 Mechanical design

At the first time, we considered two positions for the acoustic sealing: the front side of the microspeaker or the back side. Each position has its own advantages and drawbackssummarized in the table 2.

Table 2: Constraint on placement of the acoustic sealing

	Advantages	Drawbacks
Front side integration	Could be integrated in the microspeaker process before the release of the emissive surface	Thickness of the coil Place of the magnet in the vicinity of the planar coil
Back side integration	The electrical part does not affect the acoustic sealing integration	Problem to fix the center part of the acoustic sealing on the emissive surface with the stiffeners

Although the front side holds the planarcoil with a thickness of 35 µm,we have chosen to place the acoustic sealing on it in order to optimize the contact area between the emissive surface and the acoustic sealing. Figure 6 shows the microspeaker (A) with the acoustic leakage and the toroidal sealing shape (B) that will be bonded onto the front side surface.

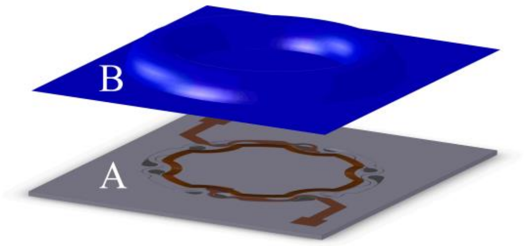


Fig. 6. Split-view (Part A: microspeaker; Part B: polymer film).

The main inconvenient when bonding the seal on this side is the coil that is 35 µm high. The seal design must therefore take into account the coilconstraint but also keep the maximum space around the emissive surface to have the magnet as near as possible of the coil to enhanceelectrodynamicactuation.

To define the optimal design, some FEM calculations have been done with COMSOL Multiphysics® software.

2.6.1 Finite Element Method calculation

As the shape of the film over the suspensions and the coilwill influence the added stiffness, a study was carried out in order to find an optimal shape. The use of COMSOL Multiphysics® enabled the modelling of the assembled structure comprising the microspeaker and the acoustic seal. As the microspeaker shape is quite complex due to the suspension beams shapes, a 3D model of a thin (20 µm) but large (several centimeters) structure may lead to a very large number of DOF. A 2D-axi-symmetrical modellingwas therefore chosen in order to save computation time. Previous 3D modelling results of the structure required more than1 million of DOFas, with the simplified 2D-model only 50 thousand of DOF were needed.

2.6.2 Modelparameters definition

A toroidal shape has been chosen for the acoustic seal. Its parameters (film thickness [h_{film}], film bridge length [l_{bridge}], and tangent angle [θ]) are described on Fig. 7. These two latter parameters will define the mould shape used for the seal forming. For the dry film, the forming method (shaping onto a mould under vacuum) induces a film thinning on the deformed part. This has to be taken into account in the FEM modelling. A simple model gives the thinning factor as a function of the toroidal shape parameters:

$$h_{film\_bridge} = h_{film}\frac{l_{bridge}}{l_{arc}} \quad (1)$$

with:

$$l_{arc} = 4\pi\left(\frac{l_{bridge}}{2\sin\theta}\right)\frac{\theta}{360} \quad (2)$$

For the PDMS film, no noticeable thinning was measured as it is obtained by a conformal spin-coating of the liquid PDMS onto the mould.

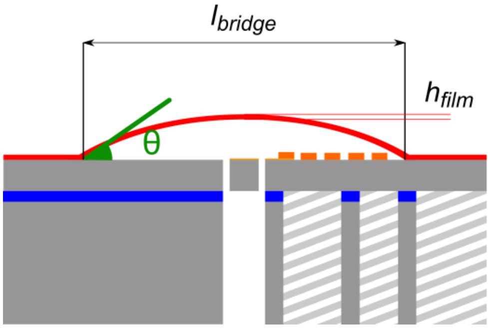


Fig. 7. Modelparameters depending on the process and the material (h_{film}: thickness; l_{bridge}: "bridge" length; θ:tangent to the "bridge")

2.6.3 FEM simulation results

The deformed shape computed for a seal stuck onto a microspeakeris depicted on figure 8. All simulations presented in this paperhave been done for a displacement X of 600 µm that is the maximum displacementby forced actuation of the emissive surface.

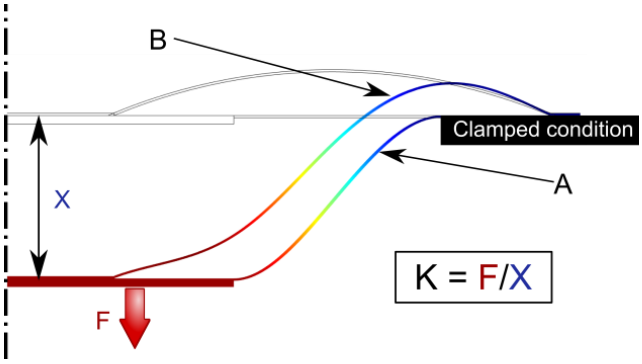


Fig.8. 2D Simulation of the film effect on the stiffness

The different results presented figure 9 come from the simplified 2D-model with the different parameters describe in paragraph b). The parameters that minimize the acoustic sealing effect on the beams stiffness are θ = 6° and l_{film} = 8 mm, which are imposed by the micro – fabrication process. The minimum added stiffness calculatedis25 N.m^{-1}for thedry film material whereas it is less than 0.1 N.m^{-1} for the PDMS. The interest to realize a toroidal seal shape is the low participation of the tensile strength thatis conditioned by the parameters θ and l_{film}.

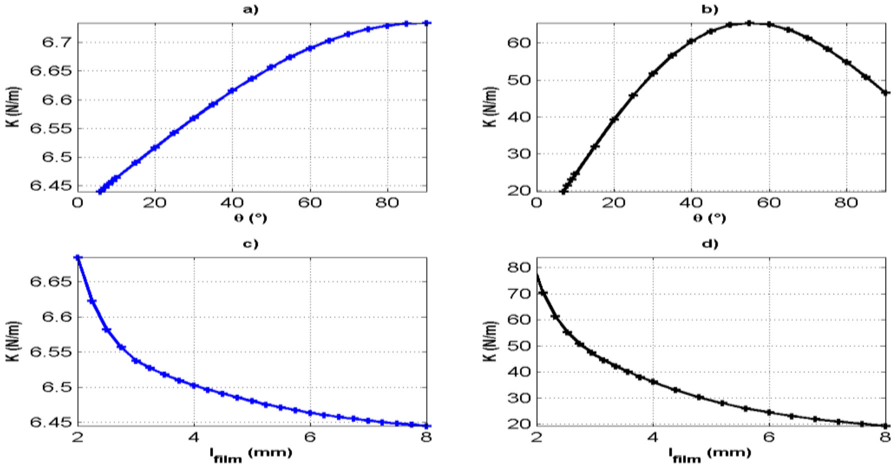


Fig. 9. Simulation results on the stiffness variation in function of the tangent angle (θ) and the bridge length (l_{film}): dry film (a) and c)) and PDMS (b) and c)

2.7 Micro-fabrication

As the dry film and the PDMS are available in different states, (respectively solid and liquid) two micro-fabrication processes were developed.

2.8 Vacuum forming process

For this process a dedicated mould and a vacuum support have been built(Fig. 10.): a Teflon® plate with the dug shape of the sealing and small holes (diameter of 500 µm) for vacuum forming and an aluminium support (with a n O-ring) to connect vacuum. To realize the step of vacuum forming (Fig. 11.-3) the aluminium part with Teflon® plate mounted on it are connected to a pump.

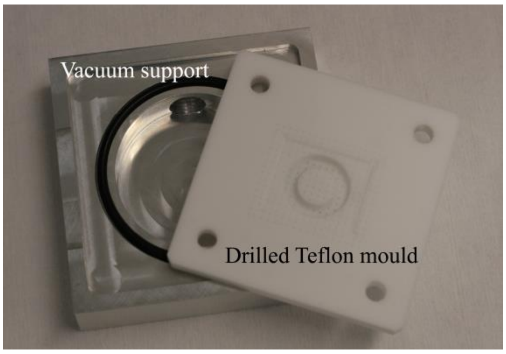


Fig. 10.: Teflon® mould with the vacuum support.

The dry film is set-up over the micro-perforated mould (Fig.11.-b). A primary vacuum is made between the film and the mould; the atmospheric pressure then pushes the film into the mould shape (Fig. 11.-c). Vacuum is hold as the dry-film is UV-exposed, hence freezing its shape (Fig. 11.-d). A photo-resist spray-coating (Fig. 11.-e) will ensure the film sticking onto the micro-speaker (Fig. 11.-f) before the vacuum release (Fig. 11.-g).

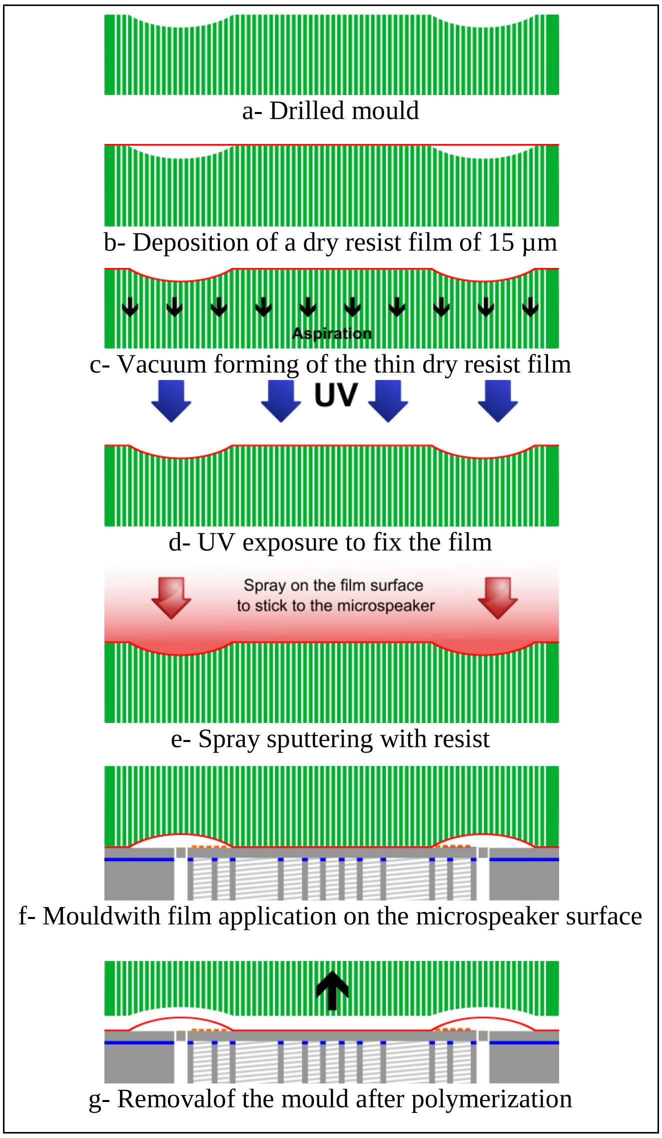


Fig. 11. Principal steps in the dry film seal fabrication process.

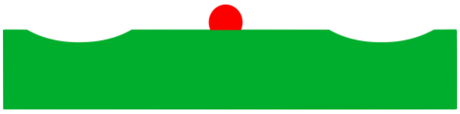
Fig. 12. Dry film applied on silicon MEMS microspeaker

A drawback of this process is the use of a gluelayer to stick the acoustic sealing onto the microspeaker thatadds mass to the emissive surface (result Fig. 12.).A second method has been developed to reduce even more the added mass on the emissive surface.

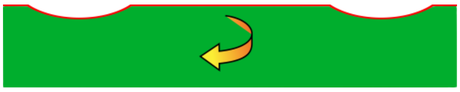
2.9 Spin-coating process

This process uses the spin-coating of liquid PDMS on the mould (Fig.13.-a to c). Then, the micro-speaker is reported onto the film before curing (Fig 13.-d). A pressure plate holds the microspeaker in place during curing in an oven (Fig.13.-e), before the removal of the micro-speaker with the PDMS film bonded onto it (Fig. 13.-f).

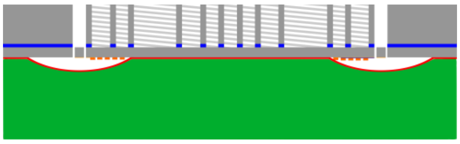
a- Mould



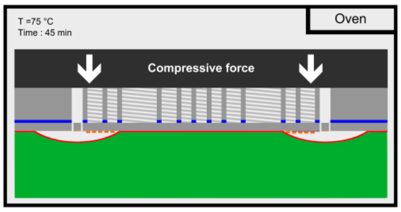
b- Mould with a drop of liquid PDMS



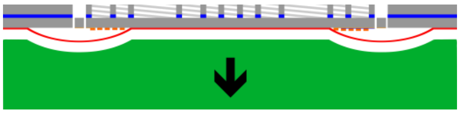
c- Spin-coating of PDMS on the mould



d- Application of the microspeaker on the non-reticulated PDMS



e- Reticulation of the PDMS



f- Removal of the mould

Fig.13.: Principal steps in the PDMS seal fabrication process

An advantage of this process is that the bonding step and the polymerization of the PDMScan be processed at the same time. At this step, the PDMS sticks to the microspeaker.Glue is no longer required, so the added mass is minimized.

2.10 Comparison of the two sealswith the latex one

The two seals developed and presented in this papershow different characteristics (added stiffness and added mass), which are compared to the latex filmones in Table 3. We have reduced the stiffness impact by 10 for the dry film seal and the PDMS seal has almost no influence in this configuration.

Table 3: Chosen parameters for each seal fabricated

Materials	Side place-ment	Θ (°)	l_{film} (mm)	h_{film} (mm)	Added Stiffness (N/m)	Added mass (mg)
Latex	Back	0	0	50	131.60	40 (incl. glue)
PDMS	Front	10	8	20	0.05	3.80
Dry film	Front	10	8	15	12.90	4.20 + spray resist

Another point that is worth to be noted, is the temperature resistance:microspeaker with PDMS seal can be used in an environment from -40°C up to +200°C whereas the dry film does not withstand temperatures below 0°C and higher than 100°C. Although the PDMS seems be better to meet the requirements of acoustic sealing than the dry film, the fabrication process can be applied on a full wafer for the dry film, which is not the case for the PDMS as it is spin-coated. This factor is very important in industry where the fabrication cost is a critical parameter.

3. Conclusion and future work

The microspeaker designed previously designed [11] showed aninteresting stroke of its emissive surface. This particularityis allowed by the use of silicon suspension beams. Although this silicon suspension design allows a large stroke, it creates large acoustic leaks between the front and the backside of the emissive surface thatdramatically affect the microspeakers'performance.To solve this drawback a first acoustic sealing has been applied onto the microspeaker backside but this widely modifies the microspeaker characteristics.

In the aim to solve the acoustic leakage problem and enhance the microspeakeracoustic performance, two acoustic sealshave been developed which solve acoustic leakageproblem and limit their impactsonthe large stroke of the stiff emissive surface. The designs of each acoustic sealing have been numericallymodelled in order to lower their impacts on the microspeaker suspension stiffness. Several materials were investigated and two of them (dry film and PDMS) were chosen for their properties and ease of use. For their applications to the microspeaker, two dedicated micro-fabrication processes have been developed, a vacuum forming process for the dry resist film and a spin-coating process for the liquid PDMS.

The two seals developed exhibit different properties, that one can take advantage of regarding the condition of use of the microspeaker. For indoor uses,microspeaker does not need a resistance to high temperature variation whereas outdoor uses will require a specific sealing like PDMS, which resists from -40°C to 200°C.

The next work on acoustic sealing will be the characterization of the added stiffness and added mass on the mechanical microspeaker characteristics. A characterization of the seal's fatigue that is also required to determine the lifetime of the polymer.Today's microspeaker suspension beams resist to a solicitation of 1 billion cycles with a displacement condition in the limit of the silicon elasticity domain. The acoustic sealing should also resist to the same solicitations.

Acknowledgements

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