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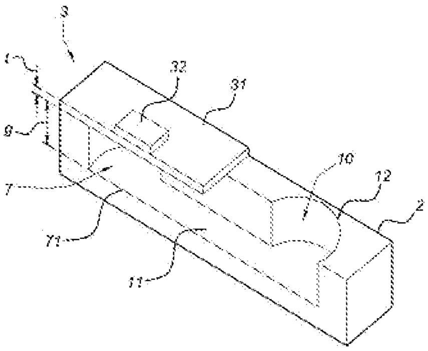
(54) MEMS-based microphone and microphone assembly

(57) A micro-electro mechanical systems, MEMS, -based microphone (1) for detecting sound signals. The MEMS-based microphone (1) comprises a body (2), a resonator (3) and a cavity provided in the body (2), the resonator (3) covering at least a part of the cavity (7). The cavity (7) comprises a gas volume. The MEMS-based microphone (1) further comprises a venting system (10) connecting the cavity (7) to an external environment, wherein the resonator (3) is arranged to vibrate at a mechanical resonance frequency higher than a characteristic equilibration frequency, the mechanical resonance frequency being variable in response to a pressure modulation of the gas volume in the cavity (7) caused by a sound signal in the external environment during operation. The characteristic equilibration frequency is dependent on the structure parameters of the cavity (7), and is equal or larger than a maximal frequency of the sound signal to be detected.



MEMS-based microphone and microphone assembly

Field of the invention

The present invention relates to a micro-electro-mechanical systems, MEMS, -based microphone for detecting a sound signal, comprising a body, a resonator, a cavity provided in the body and comprising a gas volume, and the resonator covering at least a part of the cavity.

Background art

EP patent application EP-A-2 700 928 discloses an integrated circuit apparatus with a membrane suspended over a cavity, where the membrane and cavity define a chamber. The membrane has a plurality of openings therein that passes gas into and out of the chamber. As the membrane is actuated, the volume of the chamber changes to generate a gas pressure inside the chamber that is different than a pressure outside the chamber. The integrated circuit apparatus includes a sensor to detect a frequency-based characteristic of the membrane that is responsive to the change in volume, and therein, it provides an indication of the gas pressure outside the chamber.

International patent publication WO2011/142637 discloses a MEMS-based microphone with a graphene membrane unit, and a back plate unit, opposite and spaced apart from the graphene membrane unit, so as to form an air gap between the back plate unit and the graphene membrane unit. The MEMS-based microphone operates at a high sensitivity and at a low voltage, and has a wide frequency domain, and therefore, can measure sound waves in an audio frequency domain and in a frequency domain that is lower or higher than the audio frequency domain.

Summary of the invention

The present invention seeks to provide a micro-electro-mechanical systems, MEMS-, based microphone for measuring e.g. sound waves.

According to the present invention, a MEMS-based microphone as defined above is provided, further comprising a venting system connecting the cavity to an external environment, wherein the resonator (e.g. a membrane) is arranged to vibrate at a mechanical resonance frequency higher than a characteristic equilibration frequency, the mechanical resonance frequency being variable in response to a pressure modulation of the gas volume in the cavity caused by a sound signal in the external environment during operation, wherein the characteristic equilibration frequency is dependent on structural parameters of the MEMS-based microphone and is equal to or larger than a maximal frequency of the sound signal to be detected.

The present invention embodiments have the advantage that the operation of the MEMS-based microphone for detecting e.g. sound waves is based on new physical principle, the so-called squeeze-film effect. This allows for a next step in the miniaturisation of MEMS-based microphones to a smaller scale, opening up new industrial application directions, such as, but not limited to, directional microphones, wireless hearing aids, presence detection, noise cancellation, stereo recording and medical applications.

In a further aspect, the present invention relates to a microphone assembly comprising a MEMS-based microphone, according to any one of the embodiments described herein.

Short description of drawings

The present invention will be discussed in more detail below, with reference to the attached drawings, in which

Fig. 1 shows a schematic, cross-sectional view of a micro-electro-mechanical systems, MEMS, -based microphone, according to an embodiment of the present invention.

Fig. 2 shows a schematic view of a micro-electro-mechanical-systems, MEMS, -based microphone, according to a 'bridge' structure embodiment of the present invention.

Fig. 3 shows a schematic view of a micro-electro-mechanical-systems, MEMS, -based microphone according to a 'beam' structure embodiment of the present invention,

Fig. 4 shows a schematic view of a micro-electro-mechanical-systems, MEMS, -based microphone according to further 'beam' structure embodiment of the present invention,

Fig. 5 shows a schematic view of a micro-electro-mechanical-systems, MEMS, -based microphone according to a 'trampoline' structure embodiment of the present invention,

Fig. 6A shows a schematic view of a micro-electro-mechanical-systems, MEMS, -based microphone according to further 'trampoline' structure embodiment of the present invention,

Fig. 6B shows a schematic, cross-sectional view of the 'trampoline' structure embodiment shown in Fig. 6A.

Fig. 7 shows a schematic view of a microphone assembly, according to an embodiment of the present invention.

Description of embodiments

In general, the operation of state-of-the-art micro-electro-mechanical systems, MEMS, -based microphones, for measurement of sound waves or pressure, is based upon a membrane suspended above a cavity in a substrate, wherein the cavity holds a gas volume. A pressure modulation in the external environment due to e.g. sound waves induces a pressure modulation in the external gas, which causes a pressure difference with respect to the gas in the cavity volume, which cannot rapidly respond to the change in the external gas pressure, since only very small holes are present in the membrane. This, in turn, induces a displacement or vibration of the membrane suspended across the cavity. This displacement or vibration of the membrane is usually measured by (piezo-)resistive, capacitive or optical means, whereby the measured signal is thereafter converted into an audio signal.

Although state-of-the-art partially-sealed MEMS-based microphones have been successful in measuring e.g. sound waves, their performance is limited. The main physical concept limiting the performance of state-of-the-art MEMS-based microphones is an effect called the back-cavity stiffening, that limits the sensitivity of the microphones. This occurs when the pressure modulation in the cavity gas volume is not entirely used to displace or vibrate the suspended membrane, but instead, part of the pressure modulation is used to compress the gas volume in the partially sealed (back-)cavity volume. Although this drawback can be mitigated by having larger cavities, this would increase the size and costs of a MEMS-based microphone.

Furthermore, state-of-the-art MEMS-based microphones tend to break when operating at large amplitudes or when exposed to sudden pressure changes, as the induced forces on the membrane become too large, causing the membrane to break or collapse. Although this can be mitigated by using small holes in or near the membranes, that has the drawback of deteriorating the sensitivity of these microphones at low sound frequencies. Consequently, the dynamic range and sensitivity of MEMS-based microphones is also limited.

In this respect, there is a need in the art to overcome these drawbacks. For many industrial fields and applications, it is highly desirable to miniaturize MEMS-based microphones to a smaller scale. This would enable further technological possibilities, such as, but not limited to, directional microphones, wireless hearing aids, presence detection, noise-cancellation, stereo recording, and, in particular, medical applications for e.g. membrane-based pressure sensing at audio or ultrasound frequencies in arteries. In addition, further miniaturization of MEMS-based microphones would also allow fabrication of MEMS-based microphone arrays with many elements on the same footprint of a single present state-of-the-art MEMS-based microphone.

The present invention embodiments provide a micro-electro-mechanical systems, MEMS, -based microphone, for detection of e.g. sound waves, where the operation principle is based on measuring the vibration of a resonator, and the so-called squeeze-film effect. This step would allow the fabrication of MEMS-based microphones to a smaller scale, e.g. at least an order of magnitude, thereby opening new industrial application directions, such as the examples described above.

Fig. 1 shows a schematic view of a micro-electro-mechanical systems, MEMS,-based microphone 1, according to an embodiment of the present invention. In this embodiment, the MEMS-based microphone 1 comprises a body 2. In general, the body 2 comprises a material known in the MEMS fabrication practices. For example, the body 2 may entirely comprise a single silicon material, a silicon nitride material, or a silicon base layer with a further material layer, e.g. silicon dioxide, on top.

For electrical readout and actuation purposes, it can be beneficial if the body 2 comprises an electrically conducting material. Further, the body 2 may comprise an actuating element for driving it into resonance.

In this embodiment, the MEMS-based microphone 1 further comprises a cavity 7 provided in the body 2 and comprising a gas volume. The cavity 7 may comprise many shapes, e.g. square, rectangular, circular or elliptical, and may be provided in the body 2 using e.g. an (dry) etching process. The gas volume in the cavity 7 comprises a fluid with a well-known compressibility behavior, for example air, such that it is possible to accurately monitor the compressibility of the gas volume as a function of e.g. pressure.

In the embodiment shown in Fig. 1, the MEMS-based microphone 1 further comprises a resonator 3, the resonator 3 covering at least a part of the cavity 7. In view of Fig. 1, the resonator

3 is placed on the body 2, such that the resonator 3 uses the body 2 as a platform to cover at least a part of the cavity 7, and such that the cavity 7 is beneath the resonator 3. Alternatively, the resonator 3 may be suspended over the cavity 7, such that the cavity 7 is beneath the resonator 3.

In a specific embodiment, the resonator 3 comprises a membrane having a mass per area less than 67 mg/m^2 e.g. 35 mg/m^2. In particular, a resonator 3 comprising a graphene-based membrane may be highly desirable, as graphene comprises a high surface-to-mass ratio, and has a very sensitive response to e.g. pressure modulations. Furthermore, a graphene-based membrane can be easily fabricated, by e.g. exfoliation from a graphite crystal using tape, or, alternatively, it can be easily grown via chemical vapour deposition. Similar fabrication techniques described herein can also be used to fabricate e.g. a MoS_2-based membrane. In general, the resonator 3 may comprise any material, assuming the operational principle, of the present invention embodiments described herein, may be carried out.

In the embodiment shown in Fig. 1, the MEMS-based microphone 1 further comprises a venting system 10 connecting the cavity 7 to an external environment. As a non-limiting example, the resonator 3, covers at least a part of the cavity 7 from the external environment, and, as such, there may be a remaining part of the cavity 7 that is not covered by the resonator 3 from the external environment. In this respect, the remaining, uncovered part of the cavity 7 can form the venting system 10 connecting the cavity 7 to the external environment.

In general, the venting system 10 allows the pressure, or a pressure modulation, of the external environment to be equal to the pressure, or a pressure modulation, respectively, of the gas volume in the cavity 7. In other wording, the venting system 10 regulates the pressure of the gas volume in the cavity 7 with respect to the (ambient) pressure of the external environment, and can be thought of as a 'transmission line' between the cavity 7 and the external environment.

When the (ambient) pressure of the gas in the external environment suddenly increases by an amount ΔP (e.g. due to a sound wave), the time it takes for the pressure of the gas volume in the cavity 7 to increase by an amount 0.63*ΔP, is defined as the characteristic equilibration time τ_c, whereby the factor 0.63 is equal to 1-1/exp(1), and exp(1) is the natural exponent. The characteristic equilibration frequency is thus defined as

$$f_c = \frac{1}{2\pi\tau_c} \tag{1}$$

In this respect, it is advantageous to have a sufficiently short enough 'transmission line' to allow the effects described herein to be achieved, e.g. allow the pressure of the gas volume inside the cavity 7 to respond sufficiently fast to the pressure modulations in the external environment by having characteristic equilibration time that is sufficiently small, and, accordingly, a characteristic equilibration frequency that is sufficiently large.

In the embodiment shown in Fig. 1, the resonator 3 is arranged to vibrate at a mechanical resonance frequency higher than a characteristic equilibration frequency, the mechanical resonance frequency being variable in response to a pressure modulation of the gas volume in the cavity 7 caused by a sound signal in the external environment during operation. The mechanical resonance frequency of the resonator 3 is a function of the pressure of the gas volume in the cavity 7. In this respect, contrary to state-of-the-art MEMS-based microphones, where the deflection or vibration of the membrane is measured, the present invention embodiments measure the 'compressibility' of the gas volume in the cavity 7 using the squeeze-film effect, whereby the 'compressibility' of a gas is strongly dependent on the pressure thereof.

In a non-limiting example of the MEMS-based microphone 1 that relate to the above present invention embodiments, sound waves of a certain characteristic, from the external environment, impinge on the MEMS-based microphone 1. This results in a pressure modulation of the external environment, and, via the venting system 10, also results in a pressure modulation of the gas volume in the cavity 7. As the mechanical resonance frequency of the resonator 3 is a function of the pressure of the gas volume in the cavity 7, the pressure modulation causes the resonator 3 to vibrate at a modulated mechanical resonance frequency associated with the pressure modulation, a result of the squeeze-film effect. If the relationship between the mechanical resonance frequency of the resonator 3 and the pressure of the gas volume in the cavity 7 is known, than the pressure modulation can be measured, and converted to an audio signal associated with the sound wave.

This operation principle, as described above, is based upon the resonator 3 being actively actuated at its mechanical resonance frequency, and it is the secondary relation between the pressure of the gas volume in the cavity 7, and the mechanical resonance frequency, that allows measurement of e.g. the frequency of the sound wave. This is also contrary to present state-of-the-art MEMS-based microphones, where the membrane therein is directly actuated by the sound waves.

The relation between the gas volume in the cavity 7 and mechanical resonance frequency is a by-product of an effect known as the squeeze-film effect. In general, the squeeze-film effect is a physiological phenomenon that traps gaseous or fluidic media underneath a resonator that is vibrating at high mechanical resonance frequencies, even in the absence of a seal. As such, in relation to the present invention embodiments, the gas volume in the cavity 7 is trapped under the resonator 3 vibrating at high mechanical resonance frequencies via the squeeze-film effect.

In this embodiment, the resonator 3 is arranged to vibrate at a mechanical resonance frequency higher than a characteristic equilibration frequency. In other wording, this is a condition to be satisfied for the assumption of the squeeze-film effect. If the condition is not satisfied, the planar flow of the gas volume (being squeezed) in the cavity 7 cannot be neglected, and the gas volume in the cavity 7 may no longer be trapped. As described herein and in equation (1), the characteristic equilibration frequency is inversely proportional of the time it takes for the pressure of the gas volume to equilibrate (i.e. become nominally equal) to the pressure of the external environment.

Furthermore, the characteristic equilibration frequency is dependent on structural parameters of the MEMS-based microphone 1 in this embodiment. The structural parameters of the MEMS-based microphone 1 comprises many (functional) features, including but not limited to, the physical dimensions of the cavity 7, the viscosity of the gas volume i.e. gaseous or fluidic medium in the cavity 7, a distance between the resonator 3 and a bottom of the cavity, physical dimensions of the resonator 3, and/or the physical dimensions of the venting system 10. In this regard, the structural parameters are determined by the geometry of the MEMS-based microphone 1; for example, if a MEMS-based microphone 1 has a circular geometry, then the characteristic equilibration frequency is determined by e.g. the radius of a circular resonator 3. Even further, in this embodiment, the characteristic equilibration frequency is equal or larger than a maximal frequency of the sound signal. In other wording, this is another condition for the operation of the present invention embodiments, where if the condition is not satisfied, the detected pressure of the gas volume in the cavity 7 is not representative of the pressure modulation(s) of the external environment. The structural parameters of the MEMS-based microphone 1 inter alia determine the maximal frequency of the sound waves to be detected by the MEMS based microphone 1 via the squeeze-film effect.

As described herein, the resonator 3 is not directly actuated by e.g. sound waves, an operation principle different to that found in state-of-the-art MEMS microphones. To elaborate, since the characteristic equilibration frequency is equal or larger than a maximal frequency of the sound signal, and the mechanical resonance frequency of the resonator 3 is also higher than the maximal frequency of the sound signal, the resonator 3 is not sufficiently actuated or physically displaced by e.g. sound waves in the form of the sound signal. As an exemplary embodiment, the lowest mechanical resonance frequency of the resonator 3 is at least 100 times higher than the maximal frequency of the sound signal to be detected.

In more general wording, the present invention embodiments as described above relate to a micro-electro-mechanical systems, MEMS, -based microphone 1 for detecting a sound signal, comprising a body 2, a resonator 3, a cavity 7 provided in the body 2 and comprising a gas volume, and the resonator 3 covering at least a part of the cavity 7. The MEMS-based microphone 1 further comprises a venting system 10 connecting the cavity 7 to an external environment, wherein the resonator 3 is arranged to vibrate at a mechanical resonance frequency, the mechanical resonance frequency being higher than a characteristic equilibration frequency and being variable in response to a pressure modulation of the gas volume in the cavity 7 caused by a sound signal in the external environment during operation, wherein the characteristic equilibration frequency is dependent on structural parameters of the MEMS-based microphone 1, and is equal to or larger than a maximal frequency of the sound signal. All the embodiments as described herein provide a MEMS-based microphone 1 using the squeeze-film effect as an alternative means for detecting sound signals. This is different to the operation of state-of-the-art MEMS-based microphones, allowing for further miniaturization of MEMS-based microphones to a smaller scale, thereby opening new industrial directions.

In another embodiment shown in Fig. 1, the resonator 3 comprises a membrane 31 sealed to the body 2 over the cavity 7 and a resonator actuator 32 linked to the membrane 31. The resonator actuator 32 is arranged to actuate the membrane 31 into a vibration at one of its mechanical resonance frequencies, for example the lowest mechanical resonance frequency owing to its highest sensitivity by e.g. periodically forcing the resonator actuator 32 into actuation. The resonator actuator 32 may use any possible actuation mechanism, including but not limited to mechanical actuation, (piezo-)electrical actuation, capacitive actuation, laser/light induced actuation, etc. In general, the type of actuation mechanism used by the resonator actuator 32 is dependent on the material properties of the membrane 31. As a non-limiting example, if a laser/light induced or capacitive actuation mechanism is used by the resonator actuator 32, then the membrane 31 would have e.g. high reflectivity or conductive properties, respectively.

It is noted that to sufficiently drive the resonator actuator 32, the mechanical resonance frequency of the membrane 31 needs to be known. For this purpose, a readout system, for example, can be used and the resonator 32 can be driven in a closed loop system, similar to the operation found in e.g. electrical oscillators or clocks. Alternatively, a phase-locked loop feedback system can be used to drive the resonator 32, whereby the resonator 32 is phase-locked to e.g. a voltage controlled oscillator.

The present invention embodiments allow for a measurement of e.g. sound signals, with frequencies up to a maximum frequency f_{max}, defined as:

$$f_{max} = \frac{f_{res}}{Q}, \tag{2}$$

whereby f_{res} is the mechanical resonance frequency of the resonator 3 and Q is the corresponding quality factor. Assuming a fixed quality factor, if the mechanical resonance frequency of the resonator 3 is of sufficient high frequency, the maximum frequency may be above audible frequencies i.e. frequencies higher than 20 kHz.

The sensitivity of the invention is set by the following equation:

$$\omega_{res}{}^2 = \omega_0{}^2 + \frac{P_{acoustic}}{g\,\rho_m\,t}, \tag{3}$$

wherein

$$\omega_{res} = 2\pi\,f_{res}, \tag{4}$$

$$\omega_0 = 2\pi\,f_0. \tag{5}$$

ω_0 is the unperturbed mechanical resonance frequency i.e. in the absence of any external effects, g is a distance between the resonator 3 and a bottom of the cavity 71, t is a thickness of the resonator 3, and ρ_m is the mass density of the membrane 3.

In a further embodiment shown in Fig. 1, a thickness t of the resonator 3 is less than 1 nm, e.g. 0.335 nm. In view of equation (3) and (4), since the mechanical resonance frequency f_{res} of the resonator 3 is inversely proportional to the thickness t of the resonator 3, it is desirable to reduce the thickness t of the resonator 3, i.e. fabricate the resonator 3 to be as thin as possible as to increase the dynamic range of the MEMS-based microphone 1.

In other wording, it is advantageous to reduce the thickness t of the resonator 3 as to increase the mechanical resonance frequency f_{res} of the resonator 3. This allows the mechanical resonance frequency f_{res} to be higher than the characteristic equilibration frequency as to satisfy the condition for the assumption of the squeeze-film effect (as described above). In addition, it is also advantageous to reduce the thickness t of the resonator 3 as to increase the responsivity of the resonator 3, the responsivity being defined as change in mechanical resonance frequency f_{res} per Pascal of change in pressure of the gas volume in the cavity 7.

In an even further embodiment shown in Fig. 1, a distance g between the resonator 3 and a bottom 71 of the cavity 7 opposite the resonator 3 is less than 500 nm, e.g. 50 nm. Similarly, in view of equation (3) and (4), since the mechanical resonance frequency f_{res} of the resonator 3, is inversely proportional to the distance g between the resonator 3 and a bottom 71 of the cavity 7 opposite the resonator 3, it is desirable to reduce the distance g, as to increase the dynamic range of the MEMS-based microphone 1. It is advantageous to reduce the distance g for the similar reasons, e.g. increased responsivity. as described above for reducing the thickness t of the resonator 3.

As a non-limiting example that relates to the present invention embodiments described herein, if the lowest sensitivity level to the human ear of 20 μPa is to be obtained, by taking a thickness t of the resonator 3 to be e.g. 0.335 nm, a distance g between the resonator 3 and a bottom 71 of the cavity 7 opposite the resonator 3 to be e.g. 50 nm, and assuming an estimate of the mass density ρ_m of the resonator 3 of e.g. 2000 kg m^{-3}, this results in a measurable mechanical resonance frequency shift of 0.75 Hz. As such, given the parameters describe above i.e. the thickness t and distance g, it is possible to fabricate a MEMS-based microphone 1 that can detect the lowest sensitivity level to the human ear of 20 μPa.

In an exemplary embodiment, the resonator 3 is pre-tensioned. By applying a pre-tension, the stress and/or strain in the resonator 3 is increased, and, in turn, this increases the mechanical resonance frequency f_{res} of the resonator 3. The stress and/or strain can be induced in the resonator 3 by using a variety of techniques. One possible technique to induce stress is to change the parameters during the fabrication of the resonator 3; for example, if the resonator 3 comprises a graphene material, the graphene material can be grown e.g. on a copper plate at high temperature, whereby the graphene material experiences an expansion or shrinking upon cooling down to room temperature, thereby introducing stress and/or strain in the graphene material, and thus, the resonator 3.

Moreover, the resonator 3 comprises a membrane main element 34 and at least one membrane connecting element 35A-B, according to another embodiment of the present invention. The at least one membrane connecting element 35A-B may be placed on the body 2 such that it allows the membrane main element 34 to be suspended across the cavity 7, and thus, also cover at least a part of the cavity 7.

In an advantageous embodiment, the resonator 3 has a widest dimension of less than 9 µm, e.g. 5 µm. For example, if the resonator 3 is circular, than the resonator 3 has e.g. a diameter of less than 9 µm, e.g. 5 µm. In this respect, if the widest dimension of the resonator 3 is taken to be e.g. equal to the widest dimension of the MEMS-based microphone 1, than a MEMS-based microphone 1 with a widest dimension of 9 µm, e.g. 5 µm, is significantly smaller than the size of state-of-the-art MEMS-based microphones, which have a diameter of e.g. 700-1100 µm. From this perspective, further miniaturization of MEMS-based microphones to a smaller scale, of more than an order of magnitude, is possible.

In a further embodiment (as shown in Fig. 1), the venting system 10 comprises a venting channel 11. In view of Fig. 1, although the cavity 7, as provided in the body 2, is 'fully' covered by the resonator 3, the venting channel 11, which can be seen as a 'transmission pipe/channel', connects the (enclosed) gas volume in the cavity 7 to the external environment. Similar to the cavity 7, the venting channel 11 can be provided in the body 2 using e.g. a (dry) etching process. In an exemplary embodiment, in view of Fig. 1, the venting channel 11 may connect the cavity 7 to a venting cavity 12, whereby the venting cavity 12 is exposed, and, thus, is also connected to the external environment. In other wording, the venting cavity 12 can be thought of as a secondary cavity open to the external environment, whereby a venting channel 11 connects the venting cavity 12 to the (main) cavity 7. The venting cavity 12 can also be provided in the body 2 via e.g. a (dry) etching process.

In another specific embodiment, the venting system 10 comprises at least one pore 36 in the resonator 3. The at least one pore 36 comprises an 'open area' in the resonator 3, whereby the at least one pore 36 is open to the external environment, and thus, the at least one pore 36 connects the cavity 7 to the external environment. Alternatively stated, the at least one pore 36 can be thought as a 'hole-punch' in the resonator 3. The at least one pore 36 may comprise many shapes or forms e.g. a hole, square or rectangular shaped, and can also be provided in the resonator 3 using e.g. a (dry) etching process.

In view of the above, the features explained in any of the embodiments described above can be used to describe multiple embodiments of the present invention MEMS-based microphone 1, wherein several structures can be envisaged.

Fig. 2 shows a schematic view of the MEMS-based microphone 1, according to a non-limiting embodiment of the present invention, whereby Fig. 2 relates to a 'bridge'-like structure of the MEMS-based microphone 1. In this non-limiting embodiment, a cavity 7 is provided in a body 2, wherein the cavity 7 and body 2 both comprise a rectangular shape; the cavity 7 provided in the body 2 can be thought of as a trench-like structure. Further, in this non-limiting embodiment, the resonator 3 also comprises a rectangular shape, whereby the resonator 3 is placed on the body 2 such that it covers a least a part of the cavity 7. In view of Fig. 2, the rectangular-shaped resonator 3 may have the same width dimension as the rectangular-shaped body 2, but a smaller length dimension than the rectangular-shaped body 2, and thus, the rectangular-shaped resonator 3 may be placed in the middle of the body 2 such that there are two, remaining, uncovered parts of the cavity 7. In this respect, the two uncovered parts of the cavity 7 form the venting system 10, and the MEMS-based microphone 1 therefore may operate as according to the description provided herein.

Fig. 3 shows a schematic view of the MEMS-based microphone 1, according to further non-limiting embodiment of the present invention, whereby Fig. 3 relates to ‘beam’-like structure of the MEMS-based microphone 1. In this non-limiting embodiment, a cavity 7 is provided in a body 2, and the resonator 3 comprises a membrane main element 34 and at least one membrane connecting element 35A. In view of Fig 3, the at least one membrane connecting element 35A is placed on the body 2, such that, via the at least one membrane connecting element 35A, the membrane main element 34 is suspended across at least a part of the cavity 7. In this regard, the membrane main element 34 also covers at least a part of the cavity 7, and, as such, the remaining, uncovered parts of the cavity 7 form the venting system 10. The MEMS-based microphone 1 may then may operate as according to the description provided above.

Fig. 4 shows a schematic view of the MEMS-based microphone 1, according to further non-limiting (example) embodiment of the present invention embodiments, whereby Fig. 4 relates to further ‘beam’-like structure of the MEMS-based microphone 1. In the embodiment shown in Fig. 4, the features of the MEMS-based microphone 1 are similar to the embodiment described above for Fig. 3, with the exception that the resonator 3 comprises two membrane connecting membrane elements 35A-B. Specifically, in view of Fig. 4, the membrane main element 34 comprises a square shape, whereby the two membrane connecting elements 35A-B are on the same side of the square-shaped membrane main element 34, such that the main membrane element 34 is suspended from one side. Alternatively stated, the two membrane connecting elements 35A-B connect one side of the membrane main element 34 to the body 2, wherein the two membrane connecting elements 35A-B are placed on the body 2. In this regard, the membrane main element 34 and two membrane connecting elements 35A-B cover at least a part of the cavity 7, whereby the remaining, uncovered parts of the cavity 7 form the venting system 10.

For the embodiments described in Figs. 3 and 4, they have the advantage that only a small proportion of the resonator 3 i.e. the at least one membrane connecting element 35A-B, are placed on the body 2, and this allows the resonator 3 to vibrate with further ease.

Fig. 5 shows a schematic view of the MEMS-based microphone 1, according to further exemplary embodiment of the present invention embodiments, whereby Fig. 5 relates to a 'trampoline’-like structure of the MEMS-based microphone 1. In this non-limiting example, a cavity 7 is provided in a body 2, and the resonator 3 comprises at least one pore 36. In view of the non-limiting embodiment shown in Fig. 2, the resonator 3 comprises two rectangular-shaped pores 36. The resonator 3 is placed on the body 2 such that the resonator 3 covers at least a part of the cavity 7, and via the rectangular-shaped pores 36, the remaining, uncovered parts of the cavity 7 form the venting system 10.

Figs. 6A-B show a schematic view of the MEMS-based microphone 1, according to an even further exemplary embodiment of the present invention embodiments, whereby Fig. 6 relates to a further ‘trampoline’-like structure of the MEMS-based microphone 1. In the non-limiting example shown in Fig. 6, a circular cavity 7 is provided within a body 2, and the resonator 3 comprises four pores 36a-d (see Fig. 6A), whereby the four pores 36 form the venting system 10. The ‘trampoline’-like structure shown in Figs. 6A-B can be realized by e.g. first covering the entire circular cavity 7 with a circular resonator 3, and thereafter etching four circular patterns such that the etching takes place on the parts of the body 2 and resonator 3. The etched parts of the resonator 3, then become the pores 36, wherein the cavity 7 is beneath the resonator 3 (see Fig. 6B)

One further example of an implementation of the resonator 3 and cavity 7 is a comb-like membrane structure suspended above the cavity. The voids between teeth of the comb-like structure can act as the venting system 10, and the structural and dimensional characteristics of the teeth of the comb like membrane structure can be chosen to obtain the desired functional characteristics of the MEMS-based microphone 1.

It is re-iterated that the alternative structures of the MEMS-based microphone 1 described above are non-limiting examples, and alternative implementations of the features described are also possible. For example, different shapes may be envisaged for the resonator 3 and cavity 7.

Furthermore, a MEMS-based microphone 1, in any of the embodiments describe herein, can operate at very low sound frequencies or constant pressure, i.e. there is no lower frequency limit. Similarly, the gas volume in the cavity 7 may be of a high compressibility, such that there is no maximum (dynamic) pressure limit at which the MEMS-based microphone 1 would stop working. Consequently, the MEMS-based microphone 1 has a large dynamic range of operation, and this is advantageous in comparison to state-of-the-art MEMS-based microphones, where, as described above, the membranes of state-of-the-art MEMS-based microphones may tend to break or collapse at high gas dynamic pressures.

In addition, the MEMS-based microphone 1, in any of the embodiments describe above, may also be arranged to detect other parameters, e.g. pressure of the external environment in which the MEM based microphone 1 is placed within. In this respect, a MEMS-based microphone 1 that may simultaneously detect sound waves and pressure provides many advantages over state-of-the-art MEMS-based microphones.

Fig. 7 shows a schematic view of a microphone assembly, according to a further aspect of the present invention. In this further aspect, the microphone assembly comprises a MEMS-based microphone 1 and a processing unit 12 connected to the resonator 3 and arranged for processing an output signal of the resonator 3. The processing unit 12 may comprise e.g. an optical unit or electrical device, e.g. a lock-in amplifier, for processing the output signal of the resonator 3.

In an exemplary embodiment, the processing unit 12 is further arranged to actuate the resonator 3 into resonance. The processing unit 12 may be arranged to actuate the resonator 3 at a specific mechanical resonance frequency, e.g. by controlling the membrane actuator 32, as described in one of the embodiments above. In this respect, the processing unit 12 may comprise an optical unit with a blue laser light to apply an alternating heat flux to the resonator 3, whereby the resonator 3 is actuated owing to thermal expansion effects. Alternatively, the processing unit 12 may comprise a waveform generator to generate an actuation signal to be applied, via the resonator actuator 32, to the resonator 3.

In an further exemplary embodiment, the processing unit 12 comprises a detection system 100 arranged to measure an instant mechanical resonance frequency of the resonator 3, thereby allowing the measurement of impinging sound waves via the mechanical resonance frequency of the resonator 3, as described herein. In a specific embodiment, the detection system 100 is arranged to measure the instant mechanical resonance frequency using an optical detection technique, a capacitive detection technique, a piezo resistive detection technique or a trans conductance technique. As a non-limiting example, the optical detection technique may comprise directing red laser light at the resonator 3, whereby the red laser light is reflected off the resonator 3 i.e. the resonator 3 acts as a mirror, and the intensity of the reflected laser light can thereafter be processed to determine the mechanical resonance frequency of the resonator 3. Alternatively, in another non-limiting example, the capacitive detection technique may comprise e.g. a set of capacitive sensors located on the resonator 3, whereby the capacitance of the set of capacitive sensors can be calibrated as a function of the mechanical resonance frequency of the resonator 3.

These detection techniques described herein can determine e.g. the position of the resonator 3 as a function of time. This is then used to determine the resonance frequency of the resonator 3 as a function of time. Since the mechanical resonance frequency of the resonator 3 is modulated by impinging sound waves, its modulation amplitude will be a measure of the amplitude of the sound waves, whereas the modulation frequency is a measure of the frequency of the sound waves.

Furthermore, the detection system 100 may be located away from the resonator 3, i.e. in an external location, to measure the instant resonance frequency using e.g. an optical detection technique. Alternatively, the detection system 100 may be located close to the resonator 3 i.e. directly connected to and on the resonator 3, to measure the instant resonance frequency using e.g. a capacitive detection technique.

In an even further exemplary embodiment, the processing unit 12 comprises a phase-locked loop arrangement. In this embodiment, the phase-locked loop arrangement is arranged to reconstruct the output signal from the resonator 3 i.e. the mechanical resonance frequency, into a sound signal by translating the phase error, due to a change of the mechanical resonance frequency of the resonator 3, into a required frequency changed needed to remedy the phase error. This measured frequency change is then enacted to bring the phase error to zero. From this perspective, the phase-locked loop arrangement is also arranged to follow the variable mechanical resonance frequency of the resonator 3 owing to impinging sound waves, thereby allowing full reconstruction of the output signal from the resonator 3, into an audio signal. The phase-locked loop arrangement is faster measurement methodology (i.e. 20 kHz signals) than e.g. an arrangement relating to sweeping the frequency to acquire the magnitude-plot and search for the frequency at the maximal amplitude, allowing quick reconstruction of the output signal. The control system for the phase-locked loop arrangement can be processed to obtain the frequency and amplitude of the sound signal, but other methods for down mixing the modulated high-frequency signal of the resonator 3 to determine the sound signal can also be used.

The present invention has been described above with reference to a number of exemplary embodiments and with reference to the drawings. The invention embodiments can also be described by the following numbered and interrelated embodiment clauses:

Embodiment 1. Micro-electro-mechanical systems, MEMS, -based microphone (1) for detecting a sound signal, comprising

a body (2),

a resonator (3),

a cavity (7) provided in the body (2) and comprising a gas volume, the resonator (3) covering at least a part of the cavity (7), and

a venting system (10) connecting the cavity (7) to an external environment,

wherein the resonator (3) is arranged to vibrate at a mechanical resonance frequency higher than a characteristic equilibration frequency, the mechanical resonance frequency being variable in response to a pressure modulation of a gas volume in the cavity (7) caused by a sound signal in the external environment during operation,

wherein the characteristic equilibration frequency is dependent on structural parameters of the MEMS-based microphone (1) and is equal to or larger than a maximal frequency of the sound signal to be detected.

Embodiment 2. MEMS-based microphone (1) according to embodiment 1, wherein the resonator (3) comprises a membrane having a mass per area of less than 67 milligrams per square meter.

Embodiment 3. MEMS-based microphone (1) according to embodiment 1 or 2, wherein a thickness t of the resonator (3) is less than 1 nm, e.g. 0.335 nm.

Embodiment 4. MEMS-based microphone (1) according to any one of embodiments 1-3, wherein a distance g between the resonator (3) and a bottom (71) of the cavity (7) opposite to the resonator (3) is less than 500 nm, e.g. 50 nm.

Embodiment 5. MEMS-based microphone (1) according to any one of embodiments 1-4, wherein the venting system (10) comprises a venting channel (11).

Embodiment 6. MEMS-based microphone (1) according to any one of embodiments 1-4, wherein the venting system (10) comprises at least one pore (36) in the resonator (3).

Embodiment 7. MEMS-based microphone (1) according to any one of embodiments 1-6, wherein the resonator (3) is pre-tensioned.

Embodiment 8. MEMS-based microphone (1) according to any one of embodiments 1-7, wherein the resonator (3) comprises a membrane main element (34) and at least one membrane connecting element (35A-B).

Embodiment 9. MEMS-based microphone (1) according to any one of embodiments 1-8, wherein the resonator (3) further comprises a membrane (31) sealed to the body (2) over the cavity (7) and a resonator actuator (32) linked to the membrane (31).

Embodiment 10. Microphone assembly comprising a MEMS-based microphone (1) according to any one of embodiments 1-9, and a processing unit (12) connected to the resonator (3) and arranged for processing an output signal of the resonator (3).

Embodiment 11. Microphone assembly according to embodiment 10, wherein the processing unit (12) is further arranged to actuate the resonator (3) into resonance.

Embodiment 12. Microphone assembly according to embodiment 10 or 11, wherein the processing unit (12) comprises a detection system (100) arranged to measure an instant mechanical resonance frequency of the resonator (3).

Embodiment 13. Microphone assembly according to embodiment 12, wherein the detection system (100) is arranged to measure the instant mechanical resonance frequency using an optical detection technique, a capacitive detection technique, a piezo resistive detection technique or a transconductance technique.

Embodiment 14. Microphone assembly according to any one of embodiments 10-13, wherein the processing unit (12) comprises a phase-locked loop arrangement.

The present invention has been described above with reference to a number of exemplary embodiments as shown in the drawings. Modifications and alternative implementations of some parts or elements are possible, and are included in the scope of protection as defined in the appended claims.

Conclusies

1. Op micro-elektro-mechanisch systeem, MEMS, gebaseerde microfoon (1) voor detecteren van een geluidssignaal, omvattend

een lichaam (2),

een resonator (3),

een holte (7) die voorzien is in het lichaam (2) en een gasvolume omvat, waarbij de resonator (3) ten minste een deel van de holte (7) afdekt, en

een ontluchtingssysteem (10) dat de holte (7) verbindt met een externe omgeving,

waarbij de resonator (3) is ingericht om te vibreren op een mechanische resonantiefrequentie die hoger is dan een karakteristieke evenwichtsfrequentie, waarbij de mechanische resonantiefrequentie variabel is in reactie op een drukmodulatie van een gasvolume in de holte (7) die tijdens bedrijf veroorzaakt wordt door een geluidssignaal in de externe omgeving,

waarbij de karakteristieke evenwichtsfrequentie afhankelijk is van structurele parameters van de MEMS-gebaseerde microfoon (1) en gelijk is aan of groter is dan een maximale frequentie van het te detecteren geluidsignaal.

2. MEMS-gebaseerde microfoon (1) volgens conclusie 1, waarbij de resonator (3) een membraan omvat met een massa per oppervlakte van minder dan 67 milligram per vierkante meter.

3. MEMS-gebaseerde microfoon (1) volgens conclusie 1 of 2, waarbij een dikte t van de resonator (3) minder is dan 1 nm, bijvoorbeeld 0,335 nm.

4. MEMS-gebaseerde microfoon (1) volgens één van de conclusies 1-3, waarbij een afstand g tussen de resonator (3) en een bodem (71) van de holte (7) tegenover de resonator (3) minder is dan 500 nm, bijvoorbeeld 50 nm.

5. MEMS-gebaseerde microfoon (1) volgens één van de conclusies 1-4, waarbij het ontluchtingssysteem (10) een ontluchtingskanaal (11) omvat.

6. MEMS-gebaseerde microfoon (1) volgens één van de conclusies 1-4, waarbij het ontluchtingssysteem (10) ten minste één porie (36) in de resonator (3) omvat.

7. MEMS-gebaseerde microfoon (1) volgens één van de conclusies 1-6, waarbij de resonator (3) voorgespannen is.

8. MEMS-gebaseerde microfoon (1) volgens één van de conclusies 1-7, waarbij de resonator (3) een hoofdmembraan (34) omvat en ten minste één membraanverbindingselement (35A-B).

9. MEMS-gebaseerde microfoon (1) volgens één van de conclusies 1-8, waarbij de resonator (3) verder een membraan (31) omvat dat over de holte afgedicht is aan het lichaam (2) en een resonatoractuator (32) die verbonden is met het membraan (31).

10. Microfoonsamenstel dat een MEMS-gebaseerde microfoon (1) volgens één van de conclusies 1-9 omvat, en een verwerkingseenheid (12) die verbonden is met de resonator (3) en is ingericht voor het verwerken van een uitgangssignaal van de resonator (3).

11. Microfoonsamenstel volgens conclusie 10, waarbij de verwerkingseenheid (12) verder is ingericht om de resonator (3) in resonantie te bekrachtigen.

12. Microfoonsamenstel volgens conclusie 10 of 11, waarbij de verwerkingseenheid (12) een detectiesysteem (100) omvat dat is ingericht om een instantane mechanische resonantiefrequentie van de resonator (3) te meten.

13. Microfoonsamenstel volgens conclusie 12, waarbij het detectiesysteem (100) is ingericht om de instantane mechanische resonantiefrequentie te meten met gebruik van een optische detectietechniek, een capacitieve detectietechniek, a piëzoresistieve detectietechniek of een transconductantietechniek.

14. Microfoonsamenstel volgens één van de conclusies 10-13, waarbij de verwerkingseenheid (12) een fasevergrendelde-lusopstelling omvat.

****

Fig. 1

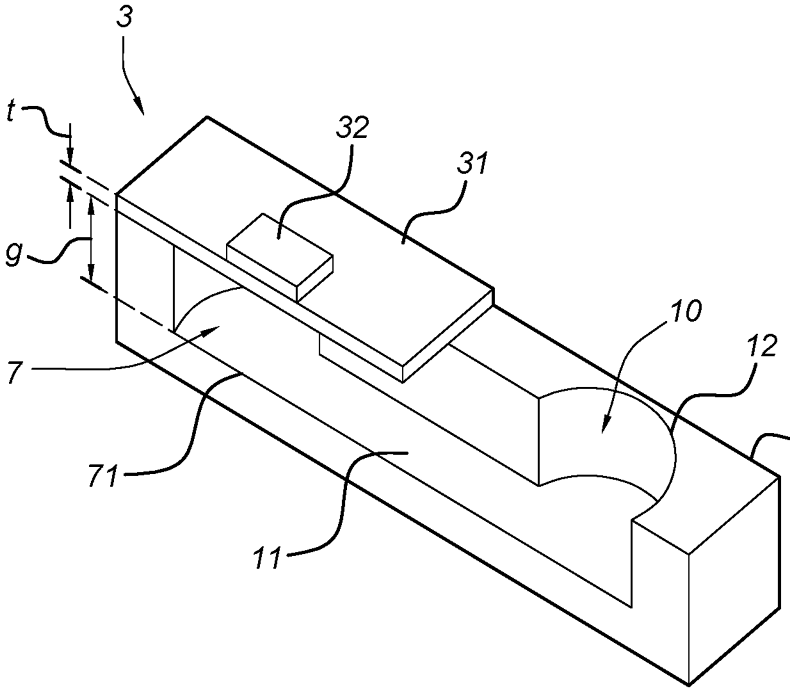


Fig. 2

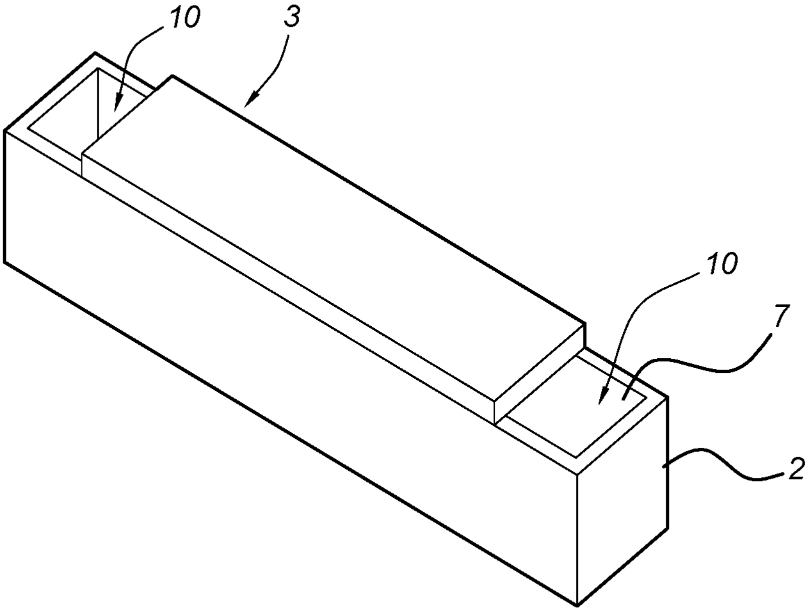


Fig. 3

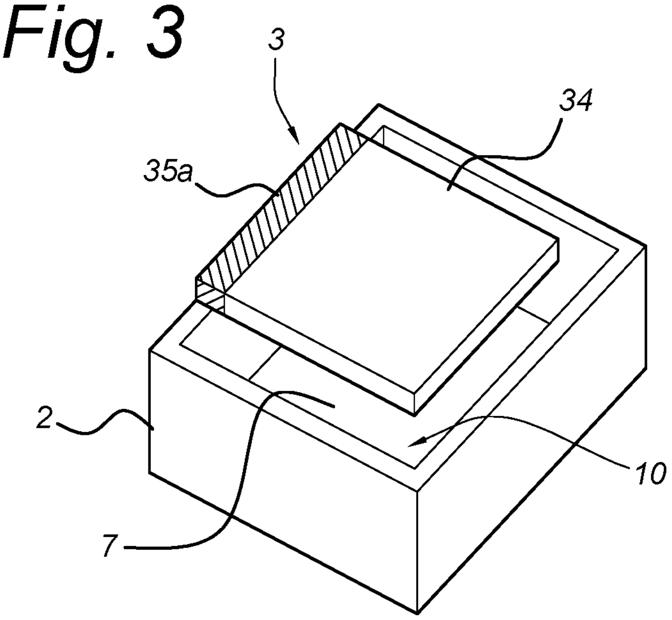


Fig. 4

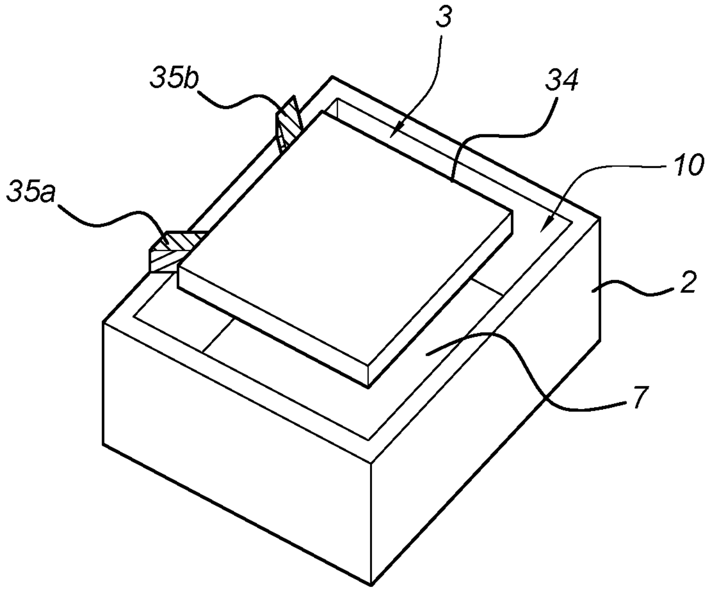


Fig. 5

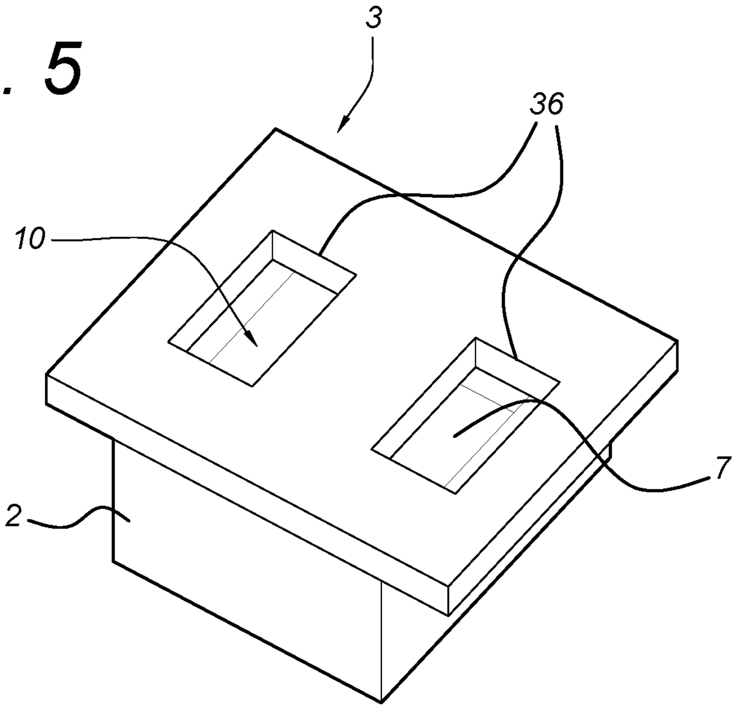


Fig. 6A

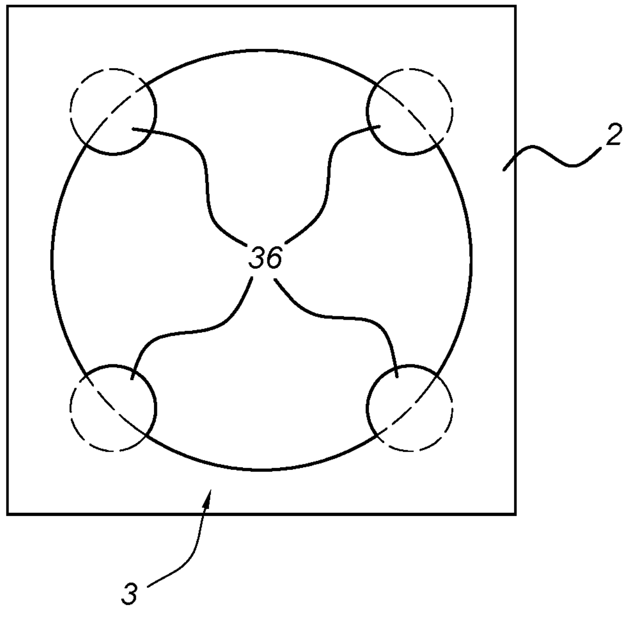


Fig. 6B

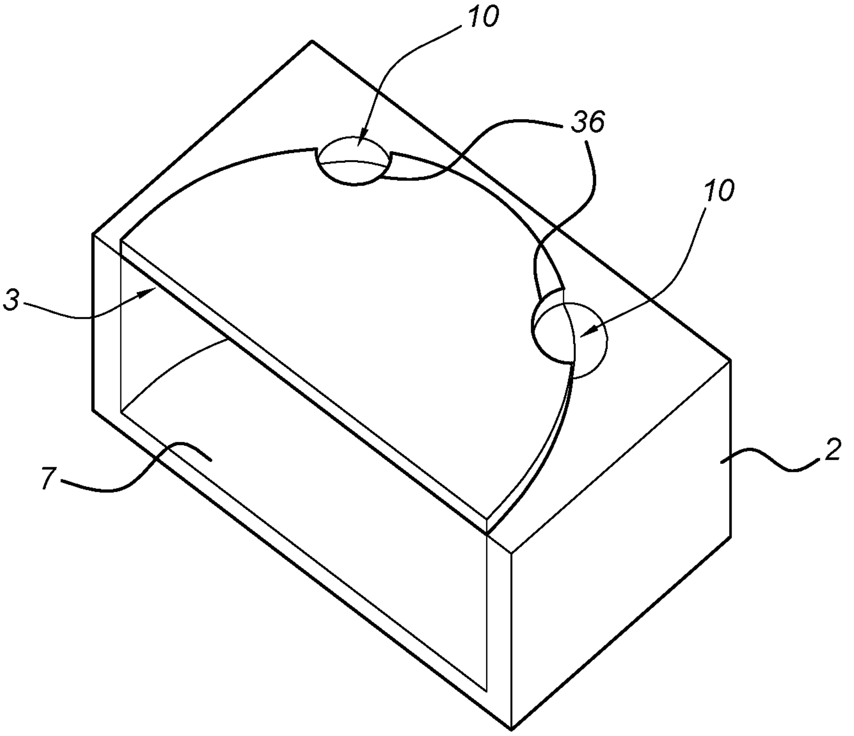
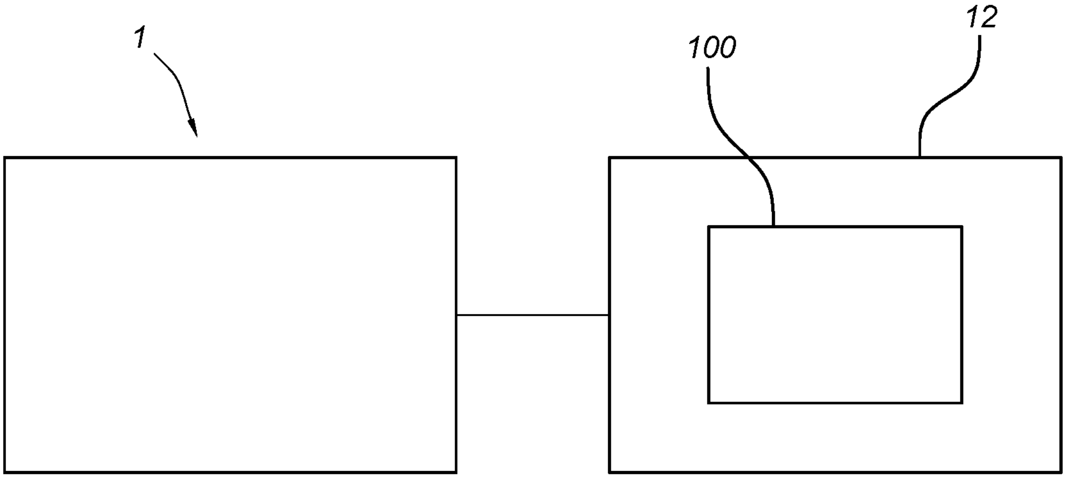


Fig. 7



SAMENWERKINGSVERDRAG (PCT)

RAPPORT BETREFFENDE NIEUWHEIDSONDERZOEK VAN INTERNATIONAAL TYPE

IDENTIFICATIE VAN DE NATIONALE AANVRAGE	**KENMERK VAN DE AANVRAGER OF VAN DE GEMACHTIGDE**
Nederlands aanvraag nr. **2026284**	Indieningsdatum **18-08-2020**
	Ingeroepen voorrangsdatum
Aanvrager (Naam) **TECHNISCHE UNIVERSITEIT DELFT**	
Datum van het verzoek voor een onderzoek van internationaal type **10-10-2020**	Door de Instantie voor Internationaal Onderzoek aan het verzoek voor een onderzoek van internationaal type toegekend nr. **SN77034**

I. CLASSIFICATIE VAN HET ONDERWERP (bij toepassing van verschillende classificaties, alle classificatiesymbolen opgeven)

Volgens de internationale classificatie (IPC)

Zie onderzoeksrapport

II. ONDERZOCHTE GEBIEDEN VAN DE TECHNIEK

	Onderzochte minimumdocumentatie
Classificatiesysteem	Classificatiesymbolen
IPC	**Zie onderzoeksrapport**

Onderzochte andere documentatie dan de minimum documentatie, voor zover dergelijke documenten in de onderzochte gebieden zijn opgenomen

III. ☐ **GEEN ONDERZOEK MOGELIJK VOOR BEPAALDE CONCLUSIES** (opmerkingen op aanvullingsblad)

IV. ☐ **GEBREK AAN EENHEID VAN UITVINDING** (opmerkingen op aanvullingsblad)

Form PCT/ISA 201 A (11/2000)

ONDERZOEKSRAPPORT BETREFFENDE HET RESULTAAT VAN HET ONDERZOEK NAAR DE STAND VAN DE TECHNIEK VAN HET INTERNATIONALE TYPE

Nummer van het verzoek om een onderzoek naar de stand van de techniek
NL 2026284

A. CLASSIFICATIE VAN HET ONDERWERP
INV. H04R19/00
ADD. G01L9/00

Volgens de Internationale Classificatie van octrooien (IPC) of zowel volgens de nationale classificatie als volgens de IPC.

B. ONDERZOCHTE GEBIEDEN VAN DE TECHNIEK

Onderzochte miminum documentatie (classificatie gevolgd door classificatiesymbolen)
H04R G01L

Onderzochte andere documentatie dan de mimimum documentatie, voor dergelijke documenten, voor zover dergelijke documenten in de onderzochte gebieden zijn opgenomen

Tijdens het onderzoek geraadpleegde elektronische gegevensbestanden (naam van de gegevensbestanden en, waar uitvoerbaar, gebruikte trefwoorden)

EPO-Internal, WPI Data

C. VAN BELANG GEACHTE DOCUMENTEN

Categorie °	Geciteerde documenten, eventueel met aanduiding van speciaal van belang zijnde passages	Van belang voor conclusie nr.
A	ROBIN J DOLLEMAN ET AL: "Graphene Squeeze-Film Pressure Sensors", ARXIV.ORG, CORNELL UNIVERSITY LIBRARY, 201 OLIN LIBRARY CORNELL UNIVERSITY ITHACA, NY 14853, 23 oktober 2015 (2015-10-23), XP081347792, DOI: 10.1021/ACS.NANOLETT.5B04251 * het gehele document * -----	1-14
A,D	EP 2 700 928 A2 (NXP BV [NL]) 26 februari 2014 (2014-02-26) in de aanvraag genoemd * alinea [0012] - alinea [0054]; figuren 1-2, 10 * ----- -/--	1-14

☒ Verdere documenten worden vermeld in het vervolg van vak C.

☒ Leden van dezelfde octrooifamilie zijn vermeld in een bijlage

° Speciale categorieën van aangehaalde documenten

"A" niet tot de categorie X of Y behorende literatuur die de stand van de techniek beschrijft

"D" in de octrooiaanvrage vermeld

"E" eerdere octrooi(aanvrage), gepubliceerd op of na de indieningsdatum, waarin dezelfde uitvinding wordt beschreven

"L" om andere redenen vermelde literatuur

"O" niet-schriftelijke stand van de techniek

"P" tussen de voorrangsdatum en de indieningsdatum gepubliceerde literatuur

"T" na de indieningsdatum of de voorrangsdatum gepubliceerde literatuur die niet bezwarend is voor de octrooiaanvrage, maar wordt vermeld ter verheldering van de theorie of het principe dat ten grondslag ligt aan de uitvinding

"X" de conclusie wordt als niet nieuw of niet inventief beschouwd ten opzichte van deze literatuur

"Y" de conclusie wordt als niet inventief beschouwd ten opzichte van de combinatie van deze literatuur met andere geciteerde literatuur van dezelfde categorie, waarbij de combinatie voor de vakman voor de hand liggend wordt geacht

"&" lid van dezelfde octrooifamilie of overeenkomstige octrooipublicatie

Datum waarop het onderzoek naar de stand van de techniek van internationaal type werd voltooid

22 april 2021

Verzenddatum van het rapport van het onderzoek naar de stand van de techniek van internationaal type

Naam en adres van de instantie

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De bevoegde ambtenaar

Duffner, Orla

1

ONDERZOEKSRAPPORT BETREFFENDE HET RESULTAAT VAN HET ONDERZOEK NAAR DE STAND VAN DE TECHNIEK VAN HET INTERNATIONALE TYPE

Nummer van het verzoek om een onderzoek naar de stand van de techniek
NL 2026284

C.(Vervolg). VAN BELANG GEACHTE DOCUMENTEN

Categorie °	Geciteerde documenten, eventueel met aanduiding van speciaal van belang zijnde passages	Van belang voor conclusie nr.
A	WO 2019/220103 A1 (SINTEF TTO AS [NO]; SAMUELS ADRIAN JAMES [GB]) 21 november 2019 (2019-11-21) * bladzijde 6, regel 31 - bladzijde 39, regel 25; figuur 2 * -----	1-14
A,D	WO 2011/142637 A2 (KOREA MACH & MATERIALS INST [KR]; HUR SHIN [KR] ET AL.) 17 november 2011 (2011-11-17) in de aanvraag genoemd * het gehele document * -----	1-14

1

Formulier PCT/ISA/201 (vervolg tweede blad) (Januari 2004)

ONDERZOEKSRAPPORT BETREFFENDE HET RESULTAAT VAN HET ONDERZOEK NAAR DE STAND VAN DE TECHNIEK VAN HET INTERNATIONALE TYPE

Informatie over leden van dezelfde octrooifamilie

Nummer van het verzoek om een onderzoek naar de stand van de techniek
NL 2026284

In het rapport genoemd octrooigeschrift	Datum van publicatie	Overeenkomend(e) geschrift(en)	Datum van publicatie
EP 2700928 A2	26-02-2014	CN 103630286 A	12-03-2014
		EP 2700928 A2	26-02-2014
		US 2014053651 A1	27-02-2014
WO 2019220103 A1	21-11-2019	CN 112470493 A	09-03-2021
		EP 3794842 A1	24-03-2021
		KR 20210020910 A	24-02-2021
		WO 2019220103 A1	21-11-2019
WO 2011142637 A2	17-11-2011	KR 101058475 B1	24-08-2011
		WO 2011142637 A2	17-11-2011

WRITTEN OPINION

File No. SN77034	Filing date *(day/month/year)* 18.08.2020	Priority date *(day/month/year)*	Application No. NL2026284
International Patent Classification (IPC) INV. H04R19/00 ADD. G01L9/00			
Applicant TECHNISCHE UNIVERSITEIT DELFT			

This opinion contains indications relating to the following items:

☒	Box No. I	Basis of the opinion
☐	Box No. II	Priority
☐	Box No. III	Non-establishment of opinion with regard to novelty, inventive step and industrial applicability
☐	Box No. IV	Lack of unity of invention
☒	Box No. V	Reasoned statement with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement
☐	Box No. VI	Certain documents cited
☐	Box No. VII	Certain defects in the application
☒	Box No. VIII	Certain observations on the application

	Examiner Duffner, Orla

WRITTEN OPINION

Box No. I Basis of this opinion

1. This opinion has been established on the basis of the latest set of claims filed before the start of the search.
2. With regard to any **nucleotide and/or amino acid sequence** disclosed in the application and necessary to the claimed invention, this opinion has been established on the basis of:

   a. type of material:

   ☐ a sequence listing

   ☐ table(s) related to the sequence listing

   b. format of material:

   ☐ on paper

   ☐ in electronic form

   c. time of filing/furnishing:

   ☐ contained in the application as filed.

   ☐ filed together with the application in electronic form.

   ☐ furnished subsequently for the purposes of search.

3. ☐ In addition, in the case that more than one version or copy of a sequence listing and/or table relating thereto has been filed or furnished, the required statements that the information in the subsequent or additional copies is identical to that in the application as filed or does not go beyond the application as filed, as appropriate, were furnished.
4. Additional comments:

Box No. V Reasoned statement with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement

1. Statement

Novelty	Yes:	Claims	1-14
	No:	Claims	
Inventive step	Yes:	Claims	1-14
	No:	Claims	
Industrial applicability	Yes:	Claims	1-14
	No:	Claims	

2. Citations and explanations

   see separate sheet

WRITTEN OPINION

Box No. VIII Certain observations on the application

see separate sheet

Re Item V

Reasoned statement with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement

1 Reference is made to the following documents:

D1 ROBIN J DOLLEMAN ET AL: "Graphene Squeeze-Film Pressure Sensors",
ARXIV.ORG, CORNELL UNIVERSITY LIBRARY, 201 OLIN LIBRARY CORNELL UNIVERSITY ITHACA, NY 14853, 23 oktober 2015 (2015-10-23), XP081347792,
DOI: 10.1021/ACS.NANOLETT.5B04251

D2 WO 2019/220103 A1 (SINTEF TTO AS [NO]; SAMUELS ADRIAN JAMES [GB]) 21 november 2019 (2019-11-21)

D3 WO 2011/142637 A2 (KOREA MACH & MATERIALS INST [KR]; HUR SHIN [KR] ET AL.) 17 november 2011 (2011-11-17) in de aanvraag genoemd

D4 EP 2 700 928 A2 (NXP BV [NL]) 26 februari 2014 (2014-02-26) in de aanvraag genoemd

2 D1 is regarded as being the prior art closest to the subject-matter of claim 1, and discloses

- a MEMS sensor comprising a body, a resonator, a cavity provided in the body and a gas volume, wherein the resonator covers at least part of the cavity and a venting system connecting the cavity to an external environment (p. 1 2nd column, Fig. 1),

- the resonator being arranged to vibrate at a mechanical resonance frequency that is higher than a characteristic equilibrium frequency (p. 1 2nd column),

- the mechanical resonance frequency being variable in response to a pressure modulation of a volume of gas in the cavity caused during operation by a sound signal in the external environment (implicit for a squeeze film pressure sensor),

- the characteristic equilibrium frequency being dependent on structural parameters of the MEMS-based sensor (implicit).

2.1 The subject-matter of claim 1 therefore differs from this known MEMS sensor in that claim 1 describes a MEMS microphone for detecting a sound signal and not a MEMS pressure sensor, and is therefore new. Furthermore, D1 does not describe the characteristic equilibrium frequency as being equal to or greater than a maximum frequency of the sound signal to be detected.

2.2 The problem to be solved by the present invention may be regarded as measuring a sound signal using gas volume pressure modulation

2.3 The solution to this problem proposed in claim 1 of the present application is considered as involving an inventive step for the following reasons:

2.3.1 D2 describes a pressure sensor that can be combined with a MEMS microphone (par. 54), with a membrane that includes a plurality of openings. The membrane is actuated at or below a resonant frequency (par. 13), where a change in the resonant frequency is used to detect an indication of pressure in the chamber. The resonance frequency may shift upwards due to the compressibility of the gas inside the volume (par. 15, 17).

However, there is no clear teaching in D2 to apply the principles used in the pressure sensor of D1 to the microphone sensor in D2. Furthermore, even when starting from D2, there is no incentive for the resonator or membrane to vibrate at a mechanical resonance frequency higher than a characteristic equilibrium frequency, where the mechanical resonance frequency is equal to or higher than a maximal frequency of the sound signal to be detected.

D3 describes a MEMS optical microphone. The squeeze film effect is described in the application as being undesirable as it can cause noise (p. 23 lines 13-27), therefore D3 describes ensuring a large enough gap to minimize the squeeze film noise.

D4 describes a MEMS microphone with a graphene membrane. D4 describes graphene as having a large resonance frequency, so sound wave far wider than the audio frequency band can be measured. However, D4 does not mention the resonance frequency of the resonator or membrane, or anything about the squeeze film effect.

2.4 No prior art document could be found that describes a MEMS microphone where the resonator vibrates at a mechanical resonance frequency higher than a characteristic equilibration frequency, in order to measure pressure modulations of a gas volume in the cavity caused by a sound signal.

There is no incentive to apply the teachings known from the MEMS pressure sensor in D1 to any previously known MEMS microphone, since the known MEMS microphone literature teaches away from such a combination.

2.5 Claims 2-14 are dependent on claim 1 and as such also meet the requirements of novelty and inventive step.

Re Item VIII

Certain observations on the application

3 Independent claim 1 refers to the characteristic equilibration frequency. However, this feature is not a well recognised term and the meaning of this feature is not clear from the claim. Consequently, the meaning of this technical feature is not clear to the skilled person from the wording of the claim.

Description page 4 lines 24-29 provide a definition of this feature, which is essential to the definition of the invention.

Since independent claim 1 does not contain this feature it does not meet the requirement of clarity that any independent claim must contain all the technical features essential to the definition of the invention.