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(54) **Microphone**

(57) A microphone comprises a planar substrate arrangement, an optical source provided over the substrate arrangement for emitting a light beam in a direction parallel to the substrate arrangement and a layer structure defining at least one optical cavity through which the light beam is directed, the cavity exposed to the sound pressure to be sensed. The light beam is directed to a target after passing through the cavity. Optical analysis is used for determining an optical property which is dependent on the pressure in the cavity.

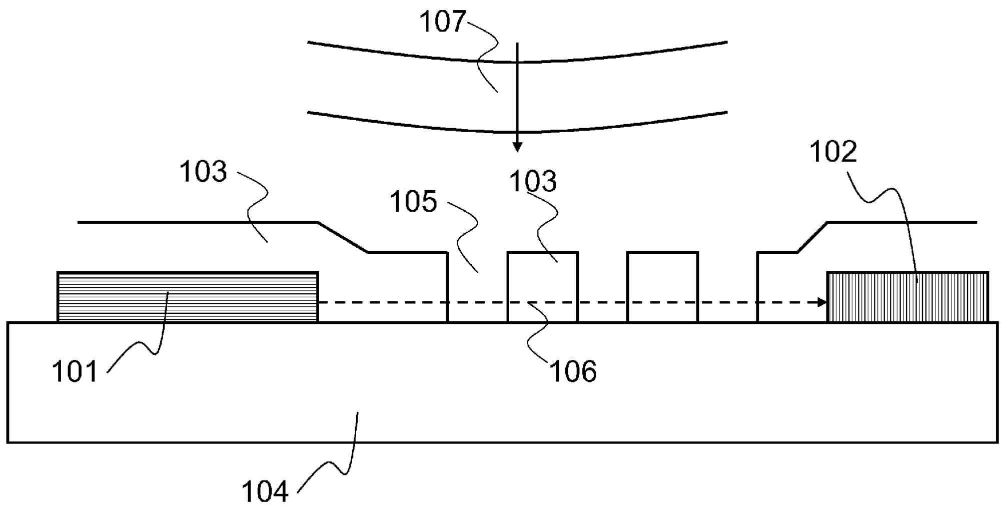

Fig. 1

EP 2 389 014 A1

Description

[0001] This invention relates to optical microphones.

[0002] Condenser microphones are commonly used for sound recording. They employ the principle of capacitive readout. One capacitor plate (the backplate) is perforated to allow the transmission of sound and the other plate (the membrane) is movable by the sound pressure. The movement of the membrane causes a change in capacitance, which can be sensed directly by electronic circuits.

[0003] The air flow between the plates causes dissipation and hence reduces the ultimate signal to noise ratio. The capacitance is furthermore very small, typically in the lower pF range, so that the noise from the readout electronics provides a limitation to the achievable signal to noise ratio.

[0004] Microphones using optical read-out have been proposed, for example using a laser reflected from a membrane. Essentially, the position of the membrane is detected by optical reflection from the membrane rather than by capacitive sensing. These designs can overcome some of the above disadvantages, but careful alignment of the optical source and detector with the membrane is required.

[0005] Microphone membranes are typically fragile because of their high compliance to achieve the required sensitivity. Therefore proposals exist to detect sound without moving parts by using optical interferometers. The refractive index of a medium through which the light in the interferometer passes is modulated by the sound pressure which results in a phase shift of the light waves. Alternatively, the change of the reflection coefficient between an optical fiber and the sound medium can be used, or the compressibility of fibers. These are mechanical or optical properties which vary in dependence on the sound pressure. These techniques are mainly useful for high sound pressures in gases and liquids.

[0006] All of these optical microphone configurations require very accurate alignment of the sound detection volume to the optical detection system. The required accuracy results in higher cost and inhibits miniaturization particularly if adjustment micromanipulators are needed. There is therefore a need for detection cells with higher tolerance against misalignment and/or for cost-effective accurate assemblies.

[0007] According to the invention, there is provided a microphone comprising:

- a planar substrate arrangement;
- an optical source provided over the substrate arrangement for emitting a light beam in a direction parallel to the substrate arrangement;
- a layer structure defining at least one optical cavity through which the light beam is directed, the cavity exposed to the sound pressure to be sensed; and
- optical analysis means for determining an optical property which is dependent on the pressure in the cavity.

[0008] This arrangement provides an optical analysis arrangement that can be integrated onto the chip of the optical source. This provides accurate alignment as part of the semiconductor manufacturing process. The detection is based on interferometric principles. The arrangement enables cost savings, for example horizontally emitting solid state lasers such as distributed feedback lasers can be used. The invention enables the use of cavities without requiring membranes or other moveable parts.

[0009] A target can be provided to which the light beam is directed after passing through the cavity. The target can comprise a light sensor so that an optical property can be measured which varies in dependence on the sound pressure. For example the optical analysis means can determine an amplitude and/or phase of the light beam reaching the target.

[0010] Instead of detection at the target, the optical analysis means can determine the electrical parameters of the light source.

[0011] The cavity can be formed as an opening in a layer over the substrate arrangement. Thus, layer patterning can be used to define the cavity. Alternatively, the cavity can be formed as a micromachined opening in the substrate arrangement.

[0012] Preferably, the light source and the target are formed over the substrate arrangement.

[0013] In one implementation, an array of cavities is provided, and which implements a photonic bandgap resonator. This provides a higher tolerance against misalignment and can also improve the sensitivity.

[0014] The cavities can be interconnected and defined as the spacing between an array of posts. This provides an inverted photonic bandgap structure. A cover layer can be provided over the posts, which has air pressure access openings.

[0015] The microphone can comprise an ultrasound microphone.

[0016] The invention also provides a method of detecting an acoustic input in a microphone, comprising:

- using an optical source provided over a planar substrate arrangement to emit a light beam in a direction parallel to the substrate arrangement;
- directing the light beam through an optical cavity defined by a layer structure, the cavity having an open top exposed to the sound pressure to be sensed; and
- determining an optical property which is dependent on the pressure in the cavity.

[0017] An example of the invention will now be described in detail with reference to the accompanying drawings, in which:

- Figure 1 is a schematic drawing of a first example of microphone design of the invention.
- Figure 2 shows how the design of Figure 1 can im-

plement a fabry perot interferometer sensor

Figure 3 is a schematic drawing of a second example of microphone design of the invention; and

Figure 4 shows the design of Figure 3 in plan view.

[0018] The invention provides an optical microphone design in which an optical source emits a light beam in a direction parallel to the substrate arrangement. The light beam passes through at least one optical cavity which is exposed to the sound pressure to be sensed. An optical property is sensed which is dependent on the pressure in the cavity. This sensing is based on interferometric sensing principles.

[0019] As shown in Figure 1, the microphone comprises a planar substrate arrangement 104. An optical source 101 is provided over the substrate arrangement for emitting a light beam 106 in a direction parallel to the substrate arrangement.

[0020] A layer structure defines at least one optical cavity 105 through which the light beam 106 is directed, the cavity having an open top exposed to the sound pressure 107 to be sensed.

[0021] The light beam is directed to a target 102 after passing through the cavity. Optical analysis means is provided for determining an optical property which is dependent on the pressure in the cavity, thereby to detect the sound pressure level and hence reconstruct the sound information.

[0022] In the example of Figure 1, a series of optical cavities 105 is shown. The cavities can be formed in a cover layer 103 or in the substrate itself 104 - either option providing the cavity in a substrate arrangement.

[0023] In the example of Figure 1, the target is a light sensor 102 which detects changes in the signal due to the sound waves 107 which change the pressure in the cavities 105.

[0024] The sound pressure wave 107 changes the refractive index of air. This leads to a modulation (amplitude or phase) of the light signal 106 in the cavities 105. The modulation can be detected in the separate detector 102 as shown, but it may also be detected as a change in the power consumption or other electrical parameters of the light source 101. In this case, the target 102 can be an absorber or reflector.

[0025] The modulation is detected based on interferometric effects. In particular, the path between the light source and the detector has an optical transfer function which is dependent on the refractive index in the cavities.

[0026] For the example of the detection of changes in the electrical parameters of the light source, the sensitivity of the light source to changes is highest if the light beam is reflected back into the laser cavity. This is partially effected by the sensing cavities. The target 102 must then be matched to the interferometer transfer function so that sensitivity is optimal. In one example, a dielectric reflector can be used that is matched to the sensing cavities.

[0027] However, if reflection is too high, the laser can become unstable. Using many sensing cavities typically avoids this problem and the target can be omitted, because the light is attenuated enough by the many cavities. The large pattern of cavities can form a photonic crystal.

[0028] The refractive index of air depends only slightly on the wavelength, except if close to an absorption line. Therefore, the light source should be chosen that can be most easily integrated or that is close to an absorption line. The lithographic requirements are typically more relaxed for longer wavelengths, so that a typical laser will have a wavelength between 300nm and 4000nm. Edge emitting lasers require less reflecting mirrors due to the longer amplification path parallel to the wafer surface and are therefore best suited for the sound pressure sensing. A preferred example is a distributed feed-back laser that is integrated together with the cavities, or the cavities can be etched after the active laser area is processed. Covers and reflecting layers of the laser can be used to form the cavities.

[0029] The laser can be operated continuously. If the power consumption is to be reduced or if high signals are wanted, e.g., for using the phase matching of harmonic distortions for detecting the refractive index of air, the laser can be pulsed, as outlined in Roberto Macovez, Marina Mariano, Sergio Di Finizio, and Jordi Martorell, Measurement of the dispersion of air and of refractive index anomalies by wavelength-dependent nonlinear interferometry, OPTICS EXPRESS August 2009 / Vol. 17, No. 16 / pp. 13881- 13888.

[0030] The pulse repetition rate should be much higher than the typical 48kHz sampling rate for audio frequency to allow averaging and noise reduction.

[0031] Continuous operation, however, results in simpler circuitry because the audio signal can be directly picked up from the detector without demodulation. In some cases it might nevertheless be useful to modulate the laser wavelength. If for example optical resonators with high Q-factors are used, then the wavelength should be adapted to the highest sensitivity, i.e., when the interferometer output amplitude changes most strongly with variations of the refractive index of the air. The laser can be slightly tuned by the supply power of the laser. It can also be modulated to build a heterodyne detector as described in J.-P. Monchalin, Optical Detection of Ultrasound, IEEE Tran. UFFC, vol. 33, no. 5, 1986, pp. 485-499.

[0032] The mechanism by which sensing takes place will now be described in greater detail. The refractive index of a gas normally increases with higher pressure. A higher pressure leads to more molecules in the cavity, which each adds to the susceptibility (Lorentz-Lorenz equation). This means that a pressure change modulates the speed of the light within a cavity as well as the reflectivity of the interfaces of the cavity. Both effects can be used for detection of the pressure change.

[0033] In an interferometric set-up, the first effect (of varied refractive index) is more often used. Both effects can also be multiplied by using more cavities in series.

[0034] The dependence of the index of refraction n on the air pressure P causes a phase shift $\Delta\phi$ of the light beam that travels a distance through air:

$$n = 1+aP \text{ with } a \approx 2.7\times10^{-9}/\text{Pa}$$

$$\Delta\phi = \Delta n\ 2\pi l/\lambda$$

λ denotes the wavelength. This results in:

$$\Delta\phi/(l\Delta P) = a\ 2\pi/\lambda \approx 1\ \text{deg}/(\text{Pa m})\ .$$

[0035] It can be seen that the optical path length *l* through air should be as long as possible. This can be achieved by multiple reflections such as in a Fabry-Perot interferometer or by a meandered light path. A typical length of a cavity creating by surface micromachining is in the order of a micrometer. This means that many cavities should be used in series.

[0036] This approach is shown schematically in Figure 2, in which multiple reflections are shown in each cavity 105, each functioning as a Fabry Perot interferometer 201.

[0037] The interference within each interferometer 201 gives rise to transmission peaks which are dependent on the refractive index of the cavity medium, and therefore dependent on the sound pressure. Thus, the path between the source 101 and the detector 102 has a transfer function which is dependent on the refractive index, and the detection of peaks at specific frequencies in the light output can be used to derive the refractive index and therefore sound pressure level. If the light source emits an essentially single frequency, then the output amplitude is modulated by the audio signal. The operation is typically at the steep edge of a transmission line (peak in transmission if the frequency would be swept) of the interferometer. As described above, the light source can also be modulated and the heterodyne signal can be detected in the target. In most cases, the amplitude is detected, and the phase is recovered by using the interferometer principle.

[0038] A positive optical feedback increases the light intensity in the laser cavity and hence lowers the laser threshold power. As the ratio between spontaneous emission and stimulated emission changes, the light output changes, the power consumption and the voltage across the laser for a given current. Many effects further modulate the electrical laser properties. For example the temperature changes by changing the light output, which in turn shift the I(V) characteristic of the laser diode.

[0039] An example for a detector system that monitors the voltage for a constant current (proportional to the electrical power) is given in paper D. Heinis, C. Gorecki, S. Bargiel and B. Cretin, Feedback-induced voltage change of a Vertical-Cavity Surface-Emitting Laser as an active detection system for miniature optical scanning probe microscopes, OPTICS EXPRESS, Vol. 14, No. 8, Apr. 2006, pp. 3396-3405.

[0040] The laser 101 can be a separate device mounted on the substrate 104, or it can be manufactured on the substrate 104 at the same time as the sensor 102. When separate devices are used, the detector and laser can be on separate wafers, which are wafer-bonded or assembled onto another substrate. For the more integrated approach, the microphone structure can be integrated onto a single substrate. The substrate 104 can be used for the light path instead of a separate layer.

[0041] However, this invention does not concern the details of the manufacturing of the light source (DFB) or detector. For example, an existing edge-emitting laser process (on-wafer) can be used, followed by post-processing to form the cavities and sensing structures on it.

[0042] The aspect ratio between the depth of the cavity and the smallest diameter of the cavity should be high enough to avoid too much signal loss, for example the cavity depth should be greater than its smallest lateral dimension.

[0043] In a modification, several cavities 105 can be combined in regular or irregular patterns with well-defined distances to form a photonic bandgap. For this purpose, at least one of the lateral widths of the cavity 105, which corresponds to the path length of light across the cavity, should be most conveniently in the order of a wavelength, typically below ½ wavelength. This allows guiding of the light beam and implementation of photonic bandgap structures or gratings. For bulk micromachining, the structures can also be larger, especially in the direction normal to the substrate surface (thickness direction), approaching more the designs of macroscopic interferometers such as Fabry-Perot as outlined above.

[0044] In surface micromachining, the depth of the cavities is limited and hence the width if the light losses are to be limited. The cavities are arranged in this case best in a photonic bandgap structure that channels or focuses the light. Otherwise the optical path length will be effectively shorter or the light will be lost and the signal at the detector weaker, causing more noise. Since the light should travel mostly through the air for maximum pressure sensitivity, an inverted photonic bandgap structure may be best suited. This means that the light is not concentrated in the layer with the higher dielectric constant, but in the air. The cavities then become interconnected and dielectric posts guide the light.

[0045] Figure 3 shows an example of inverted photonic band gap with a cover.

[0046] The sound pressure wave is again shown as 107. Dielectric or metal posts 301 are provided over the substrate 104 with cavity resonators 302 defined between the posts. A cover with an air access hole 303 is provided over the posts, and the light path 304 is beneath the cover.

[0047] The cavity resonators 302 are defined by leaving out posts, in order to form microresonators or waveguides that can be used to act as cavities. This can be seen in Figure 4, which is a plan view of the arrangement of Figure 3 using the same reference numerals.

[0048] J.D. Joannopoulos, S.G. Johnson, J.N. Winn, R.D. Meade, Photonic Crystals - Molding the flow of light, Princeton University Press, 2008 provides a description of photonic bandgap structures, e.g, beam-splitters, resonators and waveguides. Photonic bandgap structures can be designed in such a way that light can only travel in certain directions, causing a collimation of the beam. This effect can be used together with the construction of diffractive lenses (see, e.g., I. V. Minin, O. V. Minin, Y. R. Triandaphilov and V. V. Kotlyar, Subwavelength Diffractive Photonic Crystal Lens, Progress In Electromagnetics Research B, Vol. 7, 2008, pp. 257-264) to couple the light source in and still have a well defined light path even if the light source is slightly misaligned, e.g., if it is not directly processed on the same substrate, but is wafer-bonded.

[0049] The advantage of using multiple cavities or photonic bandgap structures is a higher signal modulation or a higher tolerance against misalignment.

[0050] In all examples, the invention enables the use of a solid-state, horizontally emitting laser (e.g., DFB), which has a better stability than a solid state vertical emitting laser (VCSEL). The arrangement can be smaller than existing devices without membranes. The use of small cavities allows the detection of a wide range of frequencies without acoustic interference.

[0051] The additional possibility of creating photonic bandgaps as explained above can allow better tolerance against misalignment or can be designed for less spurious signals.

[0052] If used for high (ultrasound) frequencies, a pressure gradient microphone can be implemented by splitting the optical beam and using two light paths. The phase difference between the two paths depends on the pressure at the location of the paths (see above equations). In this way, the laser beam can be split in multiple paths, comprising a reference path.

[0053] An interferometric set-up that combines the two light beams will only sense the phase difference between the paths, so that the output signal is proportional to the pressure difference at both path locations. If a sound pressure field is homogeneous over the substrate, both paths will experience the same phase shift and hence the resulting phase shift will be zero, so that no output signal is detected. Only if there is a pressure gradient along the substrate, the resulting phase shift will be non-zero. If only one of the paths is exposed to the sound field, "normal" omnidirectional sound sensing will occur in the exposed path. However, if multiple paths are exposed, only the pressure gradient along the substrate surface is sensed. This can be used, e.g., for making directional ultrasound microphones.

[0054] The invention is not limited to any particular detection process, as several interferometer principles can be implemented such as Fabry-Perot, Sagnac, Mach-Zender or Michelson.

[0055] The invention can be used as a microphone in mobile phones, headsets, voice recorders, ultrasound receivers or sound power meters. It may also be used in sonar applications in liquids. If enough stability is achieved, it might also be used as sensor for slow pressure changes.

[0056] The microphone of the invention is particularly suited for fast, high intensity ultrasound receivers. It may also be used in photoacoustic applications as acoustic detector and as modulator as well. The source wavelength could be set to the absorption line of a gas that is to be detected by photoacoustic spectroscopy.

[0057] Other variations to the disclosed embodiments can be understood and effected by those skilled in the art in practicing the claimed invention, from a study of the drawings, the disclosure, and the appended claims. In the claims, the word "comprising" does not exclude other elements or steps, and the indefinite article "a" or "an" does not exclude a plurality. The mere fact that certain measures are recited in mutually different dependent claims does not indicate that a combination of these measured cannot be used to advantage. Any reference signs in the claims should not be construed as limiting the scope.

Claims

1. A microphone comprising:

a planar substrate arrangement (104);
an optical source (101) provided over the substrate arrangement (104) for emitting a light beam (106) in a direction parallel to the substrate arrangement;
a layer structure (103) defining at least one optical cavity (105) through which the light beam is directed, the cavity (105) exposed to the sound pressure (107) to be sensed; and
optical analysis means for determining an optical property which is dependent on the pressure in the cavity (105).

2. A microphone as claimed in claim 1, further comprising a target (102) to which the light beam is directed after passing through the cavity.

3. A microphone as claimed in claim 2, wherein the target (101) comprises a light sensor.

4. A microphone as claimed in claim 3, wherein the optical analysis means determines an amplitude and/or phase of the light beam reaching the target

(101).

5. A microphone as claimed in claim 1, wherein the optical analysis means determines an electrical parameter of the light source (101).

6. A microphone as claimed in any preceding claim, wherein the cavity (105) is formed as an opening in a layer (103) over the substrate arrangement.

7. A microphone as claimed in any one of claims 1 to 5, wherein the cavity (105) is formed as a micromachined opening in the substrate arrangement (104).

8. A microphone as claimed in any preceding claim, wherein the optical source (101) and the target (102) are formed over the substrate arrangement (104).

9. A microphone as claimed in any preceding claim, wherein the light source (101) comprises a laser.

10. A microphone as claimed in claim 9, wherein the laser (101) comprises a horizontally emitting solid state distributed feedback laser.

11. A microphone as claimed in any preceding claim comprising an array of cavities (105) which define a photonic bandgap resonator.

12. A microphone as claimed in claim 11, wherein the cavities (302) are interconnected and defined as the spacing between an array of posts (301).

13. A microphone as claimed in claim 12, comprising a cover layer over the posts (301), which has air pressure access openings (303).

14. A microphone as claimed in any preceding claim comprising an ultrasound microphone.

15. A method of detecting an acoustic input in a microphone, comprising:

    using an optical source (101) provided over a planar substrate arrangement (104) to emit a light beam (106) in a direction parallel to the substrate arrangement (104);
    directing the light beam (106) through an optical cavity (105) defined by a layer structure (103), the cavity exposed to the sound pressure (107) to be sensed; and
    determining an optical property which is dependent on the pressure in the cavity.

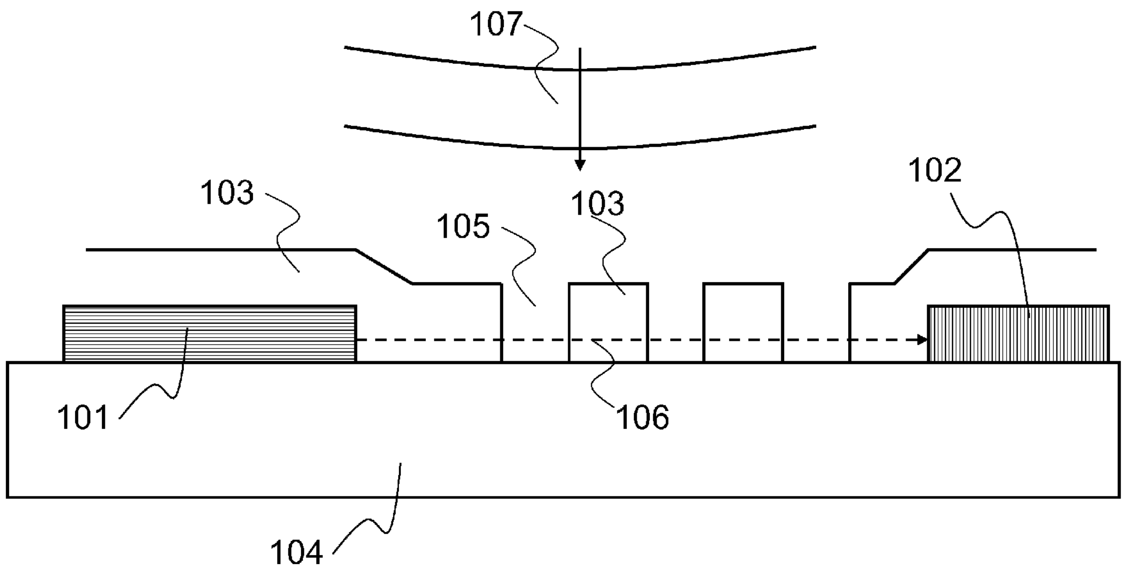

Fig. 1

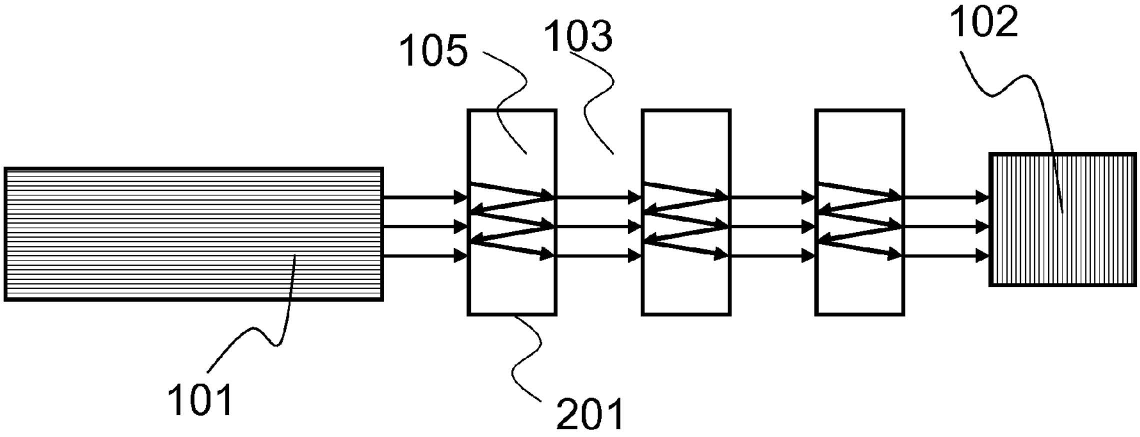

Fig. 2

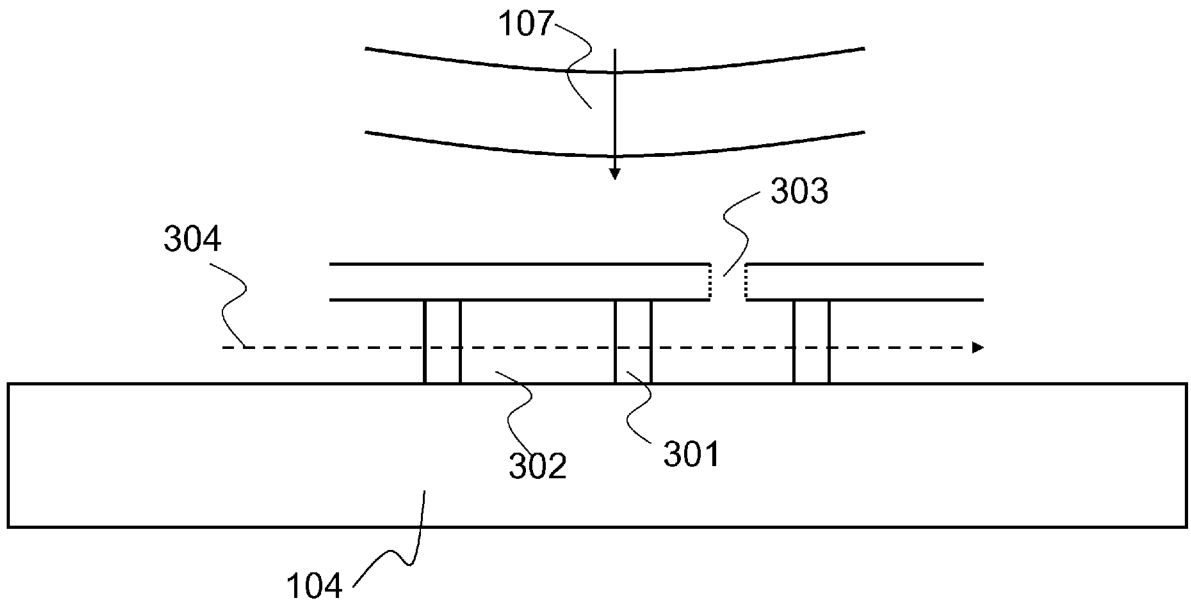

Fig. 3

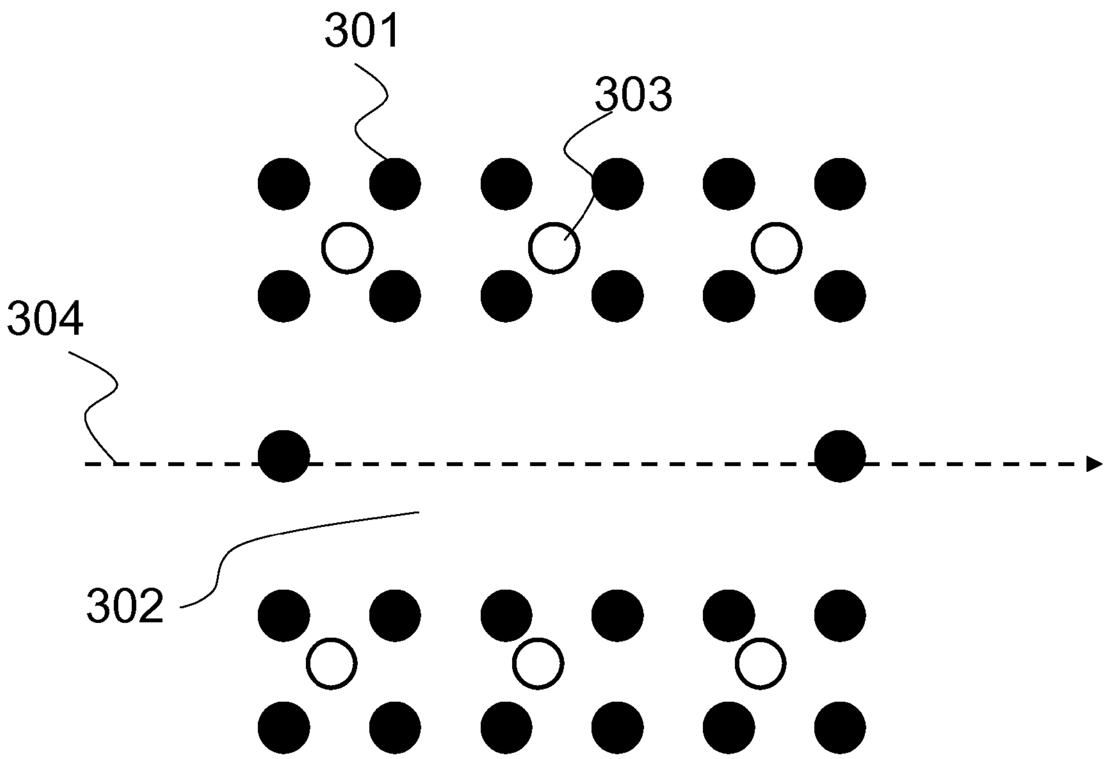

Fig. 4

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EUROPEAN SEARCH REPORT

Application Number
EP 10 16 3441

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The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
Munich	3 November 2010	Heiner, Christoph

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
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For more details about this annex : see Official Journal of the European Patent Office, No. 12/82

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