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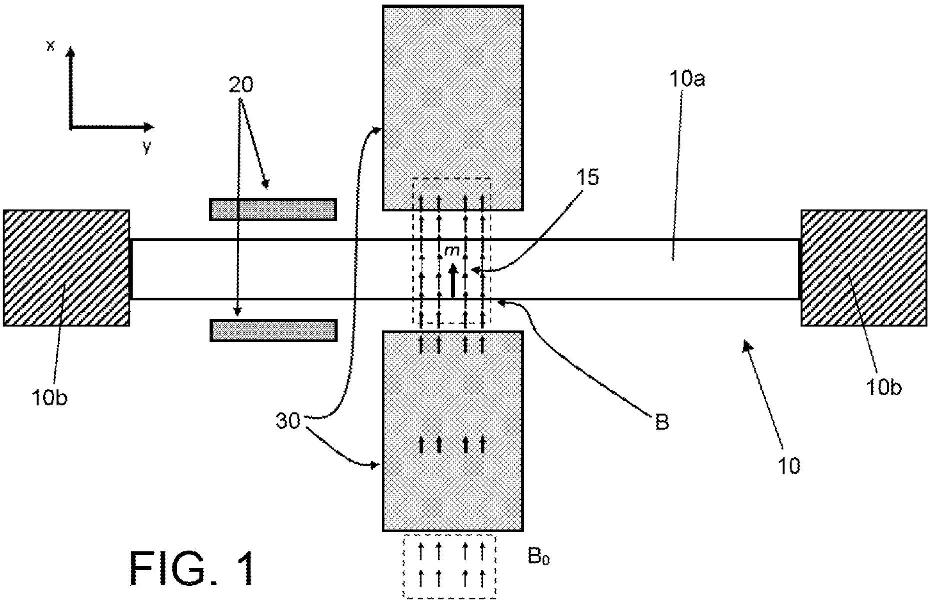

FIG. 1

(57) **Abstract:** Magnetic field sensor, comprising at least one magnetic field concentrator (30; 30, 30'), configured to amplify a magnetic field (B_0) to be measured, hereinafter external magnetic field, and produce a non- uniform magnetic field (B), hereinafter internal magnetic field, in a space close to the magnetic field concentrator, and an oscillating mechanical resonator (10) carrying at least one permanent magnet (15) arranged in space, the mechanical resonator having a resonance frequency that changes as a function of the external magnetic field, wherein the internal magnetic field has non-zero second derivative along a direction of oscillation of the mechanical resonator (10).

WO 2021/209891 A1

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A magnetic field sensor

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This invention relates in general to magnetic field sensors.

Magnetic field sensors are now present in all portable electronic devices, such as mobile phones and smart watches. By measuring the earth's magnetic field, magnetometers make it possible to use your mobile phone as a compass and, if properly combined with other inertial sensors (accelerometers, gyroscopes), are used for terrestrial navigation. Unlike accelerometers and gyroscopes, magnetometers do not use MEMS (micro-electro-mechanical systems) technology. In effect, the main technologies for the development of commercial magnetometers are: magnetic tunneling junction (MTJ), giant magnetoresistance (GMR), anisotropic magnetoresistance (AMR) and the Hall effect.

Each of these technologies has limitations: low resolution (Hall effect), complex process with deposition of different layers of magnetic materials (GMR, MTJ), low frequency noise and high temperature dependence (AMR); the latter plays a fundamental role in the stability of the sensor and in its use for navigation.

In order to overcome the limitations of existing technologies and allow a more efficient integration with the other inertial sensors (accelerometer, gyroscope), both in economic terms and in terms of performance, it is therefore appropriate to develop magnetometers in MEMS technology.

There are several examples of magnetometers in MEMS technology, which may be divided into three macro-categories: Lorentz force, magnetic moment, magnetoelectric.

The first group of devices exploits the Lorentz force generated by the passage of a current in suspended structures. This force produces measurable effects such as: (i) displacement of a movable structure, (ii) change of its resonance frequency. This type of device has several advantages, including the absence of magnetic materials, but requires a power consumption often not compatible with today's applications.

Magnetic moment magnetometers work like compasses on the microscale: a permanent magnet is integrated with a movable object, which orients itself according to the field applied. These objects offer low power consumption but often have limited bandwidth in order to have a sufficiently high sensitivity.

Lastly, magnetoelectric devices require the deposition of magnetostrictive materials, often accompanied by piezoelectric materials, making the integration with existing MEMS technology complicated.

Inomata Naoki et al: "Resonant magnetic sensor using concentration of magnetic field gradient by asymmetric permalloy plates," MICROSYSTEM TECHNOLOGIES, vol. 25, no. 10, 18 December 2018, pp. 3983-3989, describes a magnetometer comprising a magnetic field concentrator, a mechanical resonator supporting a permanent magnet, and a detector coupled with the mechanical resonator.

Pai Pradeep et al: "Fiber optic magnetometer with sub-pico Tesla sensitivity for magneto-encephalography," IEEE SENSORS 2014 PROCEEDINGS, 2 November 2014, pp. 722-725, describes a magnetometer comprising a magnetic field concentrator, an optical fiber supporting a permanent magnet, and a detector coupled to the optical fiber. The aforesaid magnetometer measures a magnetic force by means of a displacement induced by the force on the optical fiber acting as a moving element.

An object of this invention is to provide a magnetometer compatible with industrial MEMS processes, which allows for an improvement to the existing performance to be obtained, ensuring at the same time a reduced size and low power consumption.

With respect to this object, the subject of the invention is a flexible sensor comprising:

at least one magnetic field concentrator, configured to amplify a magnetic field to be measured, hereinafter an external magnetic field, and to produce a non-uniform magnetic field, hereinafter an internal magnetic field, in a space in the vicinity of said field concentrator, and

an oscillating mechanical resonator, which supports at least one permanent magnet disposed in said space, said mechanical resonator having a variable resonance frequency as a function of said external magnetic field, and

a detector coupled to the mechanical resonator,

wherein the internal magnetic field has a non-zero second derivative along an oscillation direction of the mechanical resonator, and

wherein the detector is configured to detect the resonance frequency of the mechanical resonator.

According to this invention it is possible to obtain a magnetometer compatible with industrial MEMS processes. Furthermore, from the simulations carried out it has emerged that this type of device may reach a resolution on the order of 1 nT/√Hz, with an area of less than mm^2 and the power consumption of a MEMS clock, i.e., on the order of a few µW. Lastly, the absence of resistive components and the encoding of the information through the sensor frequency offer a potentially high temperature stability.

Preferred embodiments of the invention are defined in the dependent claims, which are to be understood as an integral part of this description.

Further features and advantages of the device according to the invention will become apparent from the following detailed description of some embodiments of the invention, made with reference to the accompanying drawings, provided for illustrative and non-limiting purposes only, wherein

Fig. 1 is a schematic representation of a device according to the invention;

Fig. 2 shows: (A) a schematic representation of two square-shaped concentrators; (B) the trend of the second spatial derivative of the magnetic field within a gap between the concentrators;

Fig. 3-6 are schematic representations of further embodiments of the invention;

Fig. 7 represents the diagram of a circuit for actuating and reading a mechanical resonator of the device;

Fig. 8 is a graph representing the force-displacement transfer function calculated with field applied and with no field applied. Given a fixed frequency actuation force, the displacement changes as a function of the field applied;

Fig. 9-10 are schematic representations of further embodiments having a modular structure; and

Fig. 11a-11b show the steps of an example of a process for making a sensor according to the invention.

A possible embodiment of a sensor according to the invention is shown in Fig. 1.

The sensor comprises a mechanical resonator 10, comprising an oscillating structure 10a anchored to a fixed support (not shown) through one or more anchor points 10b. In the illustrated example, the oscillating structure 10a is made as a bridge, with two terminal anchoring points 10b. The mechanical resonator 10 is kept in oscillation along an x-axis with electrostatic actuation by means of a pair of capacitive electrodes 20. According to alternative embodiments, the mechanical resonator could be kept in oscillation by piezoelectric, optical, or magnetic actuation.

A permanent magnet 15 having magnetic moment *m* directed along the x-axis is integrated on the mechanical resonator 10, more precisely on the oscillating structure 10a. This orientation of the magnetic dipole moment is not essential for the purposes of the invention, as different orientations of the dipole may be provided. An external magnetic field B_0 to be measured is conveyed into the area of the permanent magnet 15 by means of a pair of magnetic field concentrators 30, which are arranged apart from each other in such a way as to define a gap between them in which the permanent magnet 15 is arranged. The magnetic field concentrators 30 allow the magnetic field B_0 to be amplified and at the same time a non-uniform field B to be generated in the aforementioned gap and therefore in the area of the permanent magnet 15. This field, which in the following will also be designated as "internal magnetic field," has a spatial non-zero second derivative defined along the direction of displacement of the device. In the figure, arrows of different thickness represent the gradient of the internal magnetic field.

The variable force produced by the interaction between the permanent magnet 15 and the internal magnetic field induces a shift in the resonance frequency of the mechanical resonator 10. This variation may be easily read in order to trace the magnetic field B_0 to be measured.

As mentioned above, the magnetic field concentrators 30 have two functions: to amplify the magnetic field B_0 to be measured and to produce a non-uniform magnetic field inside the gap between the magnetic field concentrators 30.

In this gap, the second derivative of the internal magnetic field must be: (i) non-zero, (ii) directed mainly along the direction of movement of the resonator 10 (x-axis in the example illustrated).

The magnetic field concentrators 30 are made of a soft magnetic material (e.g., Permalloy), magnetize linearly when subjected to a magnetic field, and have low remanence.

The non-uniform magnetic field generated inside the gap may be estimated by applying some simplifications in the system: (i) assuming the concentrator is uniformly magnetized with magnetization M, (ii) equating the magnetic behavior of the thin film concentrator to that of a flattened spheroid, (iii) assuming the sides of the concentrator are greater than the thickness g of the gap (see Fig. 2A).

Given the equations provided in [1],[2] and the conditions listed above, the value of the second derivative at the center of the gap has the following dependence on the applied field:

$$\frac{\partial^2 B_x}{\partial x^2} \approx \beta \frac{c}{g^3} B_0 \qquad \beta = \frac{\mu_r - 1}{1 + N_x\,(\mu_r - 1)} \frac{2}{\pi} \qquad (1)$$

where μ_r is the relative magnetic permeability of the material, N_x the demagnetizing tensor and c the thickness of the film.

Fig. 2A shows a diagram of two square-shaped concentrators, and Fig. 2B shows the trend of the second derivative in the gap estimated both with a finite element simulation and with the analytical model reported in [1]. As may be seen, the analytical model provides a sufficiently accurate estimate of the value of the second derivative and may be used for evaluating the sensitivity of the device.

The use of square-shaped concentrators simplifies the estimation of the second derivative; nevertheless, concentrators of other shapes may be used, for example trapezoidal, rectangular, etc. The shape of the concentrator may be varied in order to optimize the relationship between the amplification of the field and the maximum amplifiable field (saturation of the concentrator). The concentrator may be single or multiple, in order to maintain a compact area but keep a well-defined aspect ratio (see Fig. 3, where two pairs of concentrators are respectively indicated with 30 and 30’). Lastly, the concentrator may be chosen to read out-of-plane fields and convey them in the direction of the sensor, offering the possibility of implementing a triaxial magnetic field sensor.

The permanent magnet 15 is used to apply a force of magnetic origin on the mechanical element 10. The permanent magnet 15 is manufactured by depositing suitably patterned hard magnetic materials (such as Neodymium-Iron-Boron, Platinum-Iron or Samarium-Cobalt alloys) on the resonator 10. The magnet 15 is given shape and/or magnetocrystalline anisotropy in such a way that its average magnetization in remanence is aligned with the component of the internal magnetic field which has a non-zero (and possibly greater) second derivative in the direction of displacement. Preferably, and for the structures illustrated in this description, the magnetization of the magnet 15 is aligned along the axis of movement of the resonator 10 and of variation of the gradient. Due to the anisotropy and a magnetization process, the magnet 15 maintains a magnetic dipole (m). The appropriate orientation of the axis of magnetocrystalline anisotropy may be obtained by increasing the magnetic film with a magnetic field applied along the desired magnetization axis.

The magnet 15 is positioned inside the internal magnetic field so as to be subjected to a magnetic force gradient ∇F proportional to the external field:

$$\frac{\partial F_x}{\partial x} = \mu_0 V \frac{\partial^2 (M \cdot H)}{\partial x^2} = \mu_0 m \left(\frac{\partial^2 H_x}{\partial x^2} + \frac{\partial^2 H_y}{\partial x^2} + \frac{\partial^2 H_z}{\partial x^2} \right) \quad (2)$$

Assuming that ($\frac{\partial^2 H_x}{\partial x^2} \gg \frac{\partial^2 H_y}{\partial x^2}$ e $\frac{\partial^2 H_x}{\partial x^2} \gg \frac{\partial^2 H_z}{\partial x^2}$), the equation (2) may be simplified as follows:

$$\frac{\partial F_x}{\partial x} \approx m_x \frac{\partial^2 B_x}{\partial^2 x} \approx \overbrace{m_x \, \beta \frac{c}{g^3}}^{G_{mm}} B_0 = k_{mag} \qquad (3)$$

The derivative of the magnetic force thus generated acts on the resonator 10 on which the magnet is arranged and is equivalent to a mechanical elastic constant (k_{mag}), which induces a change in the resonance frequency of the electro-mechanical device. This elastic constant may be rewritten as a function of the applied field by combining the geometric terms into a single coefficient that may be defined as magneto-mechanical gain (G_{mm}).

As in the case of concentrators, the permanent magnet may be replaced by a series or matrix of magnets (Fig. 4). In this way, the necessary shape anisotropy is maintained to obtain an average magnetic moment in remanence oriented according to the desired axis on each magnetic element with dimensions compatible with the shape of the mechanical resonant element on which it is made without reducing the total magnetic volume and thus the dipole (m).

In the embodiments described above, at least one pair of concentrators is provided, between which the permanent magnet of the mechanical resonator is positioned. This configuration has the advantage of producing an area where the second derivative of the magnetic field is sufficiently flat, increasing the linearity of the sensor. The invention, however, also comprises embodiments in which there are individual concentrators, such as the one represented in Fig. 5 (the same numerical references have been assigned to elements corresponding to those of the foregoing embodiments).

In effect, the key concept is the use of an element that converts a uniform field of space (the field to be measured, which we assume to be uniform in the sensor area) into a non-uniform field with a non-zero gradient and in particular of which the second derivative has a non-zero component in the direction of movement of the mechanical resonator. Similar to Fig. 1, in Fig. 5, the field gradient is represented by arrows of different thickness.

The object of the resonator 10 is to translate the magnetic force into a measurable signal. The resonator 10 may have different geometries and different mechanical features. An example of geometry is the so-called Tang-type resonator (Fig. 6). In Fig. 6, 10c indicates suspension springs for the oscillating structure 10a. This type of resonator has the advantage of being implemented through capacitive comb electrodes 20, 20’ with surface variation. This type of actuation allows for obtaining a displacement linearly proportional to the applied voltage and a pure translational movement along the x-axis. Other possible architectures are cantilever resonator or tuning fork, in addition to the bridge architecture represented in Fig. 1 and 3-5.

During operation of the sensor, the resonator 10 is kept in oscillation at its resonance frequency $f_0 = \sqrt{\frac{k_{eff}}{m_{eff}}}$ through an electronic circuit 40, shown in Fig. 7. m_{eff} is the effective mass of the resonator, k_{eff} is the effective constant of the mechanical system given by the sum of the mechanical elastic constant (k_m) and the magnetic constant induced by the concentrators 20 and by the permanent magnet 15, whereby:

$$f_0 = \sqrt{\frac{k_m + k_{mag}}{m_{eff}}} = \sqrt{\frac{k_m + G_{mm}B_0}{m_{eff}}} = \qquad (4)$$

As the magnetic field (B_0) applied varies, so does the resonance frequency of the device:

$$\frac{\partial f_0}{\partial B_0} = \frac{f_0}{2k_{eff}} G_{mm} = f_0 \frac{G_{mm}}{2k_m\left(1 + \frac{k_{mag}}{k_m}\right)} \approx f_0 \frac{G_{mm}}{2k_m} \qquad (5)$$

where k_m is assumed to be much greater than k_{mag}. For a sensor with f_0 = 200 kHz, G_{mm} = 10 and k_m = 10 N/m, the scale factor is approximately 100 kHz/T.

For the sake of simplicity, a resonator with a bridge architecture such as that of Fig. 1 is shown coupled to the circuit of Fig. 7. It is however understood that the electronic circuit of Fig. 7 is not conditioned by the specific architecture and may be coupled to sensors with different architecture.

All the considerations made so far are also valid for a resonator that moves out of the plane or in the direction perpendicular to the field, as long as there is a significant component of the second derivative of the magnetic field produced by the concentrator in the direction of motion.

The readout of the frequency variation may be operated in different ways. Two main methods are mentioned:

- Electronic measurement
- Optical readout

As previously mentioned, during operation, the resonator 10 is kept in oscillation by means of a positive-feedback loop (Fig. 7) or by the use of a phase-locked loop. The oscillation will occur at a frequency close to the resonance frequency of the MEMS device (ideally the same). When a magnetic field is applied, the resonance frequency of the resonator 10 varies, and the feedback loop follows this variation by shifting the new working frequency coherently. By acquiring the periodic current/voltage signal generated by the oscillating loop with a counter, it is possible to translate the electrical signal into a frequency value and measure the applied magnetic field. In order to perform a differential measurement, it is also possible to calculate the difference between the measured frequency of the oscillator 10 of the magnetometer and an oscillator identical thereto, but not equipped with permanent magnets (thus insensitive to the applied field).

The band limit of this type of readout is linked to the ability of the actuation circuit to lock onto the frequency variation of the oscillator 10. In a PLL implementation this may be the most stringent limit (from tens of Hz to a few kHz).

The second band limit is imposed by the magnetic concentrators which are limited to frequencies clearly lower than the ferromagnetic resonance frequency (fR), on the order of MHz, but also suffer from phenomena of viscous relaxation due to the granular structure and defects of the film that limit the band to frequencies lower than fR.

The optical readout may be done via an external apparatus or may be directly integrated on a chip. The optical measurement system uses a different type of readout than the electronic measurement.

The resonator 10 is kept in oscillation at its resonance frequency in the absence of an applied field, and its displacement is measured by means of an optical system (for example an interferometer).

As the resonance frequency of the device varies, its displacement is reduced as the operating point changes within the force transfer/displacement function as shown in Fig. 8.

In this implementation, the bandwidth limits are linked to the response of the concentrators.

For both methods presented, the resolution may be limited by the noise of the readout apparatus. The intrinsic measurement limit, a limit common to all readout types, of this type of sensor is shown here.

A resonator is subject to fluctuations in its oscillation frequency due to the thermal agitation of the oscillating element. This fluctuation may be described through a phase noise S_Φ or a frequency noise S_f, which is directly proportional to the phase noise through the following relationship, derived from [3]:

$$S_f = S_\phi \frac{\omega_0}{4\pi Q} = \underbrace{\frac{\sqrt{\frac{4k_bTQ}{k_{eff}\,\omega_0}}}{x_{rms}}}_{S_\phi}\frac{\omega_0}{4\pi Q} \qquad (6)$$

where k_b is the Boltzmann constant, T is the temperature, Q is the quality factor, ω_0 is the resonance frequency in rad/s and x_{rms} is the rms displacement of the resonant device.

Considering the values proposed heretofore and assuming $Q = 15000$, $x_{rms} = 200$ nm, the frequency noise is on the order of 100 µHz/√Hz.

The last sensor readout limit may then be calculated by dividing this noise value by the previously calculated scale factor.

Fig. 9 and 10 show further embodiments of the sensor, having a modular structure. Elements corresponding to those of the foregoing embodiments have been assigned the same numerical references.

In these embodiments, the oscillating structure 10a of the mechanical resonator 10 has a reticular shape and carries a plurality of magnets 15, or groups of magnets 15, arranged according to an ordered array, for example a matrix. A plurality of concentrators 30 correspondingly arranged in an ordered array are associated with the magnets 15. The direction of movement of the oscillating structure 10a is indicated by the arrow SX. The geometry shown may be used to increase the magnetic sensitivity of the device. The object in the figure in effect has more than one column of concentrators and magnets, thus increasing the total magnetic volume present on the device. In Fig. 9, 10c indicates suspension springs for the oscillating structure 10a. Similar to the embodiment of Fig. 6, the suspension springs allow a pure translation movement of the oscillating structure 10a in the SX direction to be obtained. There is therefore a decoupling between the geometry of the magnets and the mechanical properties of the resonator, unlike configurations, such as cantilevers and bridges, in which the entire structure is generally deformed, and therefore the displacement of the single magnet is influenced by the specific position thereof on the oscillating structure. Still similar to the embodiment of Fig. 6, the resonator of Fig. 9 is implemented by means of capacitive comb electrodes 20 with surface variation. This type of actuation allows a displacement linearly proportional to the applied voltage.

It should also be noted that in the oscillating reticular structure of Fig. 9 there is an ordered array of openings 31 suitable for receiving the respective concentrators 30, whereby each individual magnet 15, or each individual group of magnets 15, is interposed between a pair of concentrators 30.

Fig. 10 shows the same geometry of Fig. 9, to which a switching system 50 is additionally coupled, configured to reverse the magnetization of the permanent magnets 15.

The system 50 comprises a plurality of parallel tracks aligned with the permanent magnets 15, and which may be supplied with a current I_{switch}. In the illustrated example, these tracks are arranged under the mechanical resonator, but may potentially also be manufactured above it, for example on a cap of the device.

By making a sufficiently high current flow through, a circular magnetic field is generated around each track. This field magnetizes the permanent magnet according to the direction of the current (instant t1, represented in the box on the right of Fig. 10).

After the magnetization procedure, the frequency shift of the device, due to the external field, is measured.

The magnetization is then reversed, making current flow in the opposite direction (instant t2, box on the right of Fig. 10).

The frequency shift measurement of the device is then repeated and the difference between the first and second measurement is calculated.

Since the shift depends on the orientation of the magnetic dipole with respect to the gradient (the magnetic elastic constant may be positive or negative), by rapidly changing (much faster than the signal to be measured) the magnetization of the permanent magnet it is possible to perform a differential-type measurement, thus eliminating all common mode disturbances (such as the temperature drift of the device).

This technique allows for the drift effects of the device to be compensated.

Fig. 11a and 11b show the main steps of an example of a process for manufacturing a sensor according to the invention, in particular the sensor represented in Fig. 1 and 3-5. These steps may be integrated into an already existing MEMS process on an industrial level. The steps necessary for the manufacture of the electrical contacts are not shown, these steps usually taking place through a polysilicon layer placed under the sacrificial oxide, which connects directly to the MEMS conductive silicon layer through vias. Similarly, a complete process involves hooding the sensor inside a vacuum cavity in order to obtain high quality factors for the resonator, which results in better performance.

In the process of Fig. 11a-11b, in step (1) a support wafer 100 is represented, on which an insulating layer 101, for example of SiO_2, and a layer 102 of conductive silicon are deposited. In step (2) a resist layer 103 is deposited through a mask, and subsequently a layer 104 of magnetic material for the permanent magnet 15. In a lift-off step (3) the sacrificial layer 103 is removed. The layer 104 of magnetic material therefore remains in the areas that were not covered by the resist layer 103. In step (4) a layer 106 of material for the concentrators 30 is deposited, after depositing—by means of a mask—a second sacrificial layer 105. In a second lift-off step (5) the second sacrificial layer 105 is removed. The layer 106 made of material for the concentrators therefore remains in the areas that were not covered by the second resist layer 105. A protective layer 107 (step (6)) is then applied by means of a mask. In step (7) an ionic etching of the silicon is carried out (deep reactive ion etching) which removes the conductive silicon in the areas that were not covered by the protective layer 107, exposing the underlying insulating layer 101. The conductive silicon layer 102 is therefore interrupted between the permanent magnet region 104 and each of the regions 106 of magnetic material. Lastly, in step (8) a chemical wet-etching is carried out, which removes the insulating layer in the exposed areas. A cavity 108 is also formed below an area 102’ of conductive silicon, underneath the magnetic material 104. The conductive silicon area 102’ underlying the magnetic material 104 makes up the movable part of the resonator 20, while the areas 106 arranged on opposite sides of the magnetic material 104 make up the concentrators 30.

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CLAIMS

1. A magnetic field sensor, comprising

at least one magnetic field concentrator (30; 30, 30'), configured to amplify a magnetic field (B_0) to be measured, hereinafter external magnetic field, and produce a non-uniform magnetic field (B), hereinafter internal magnetic field, in a space close to said magnetic field concentrator,

an oscillating mechanical resonator (10) carrying at least one permanent magnet (15) arranged in said space, said mechanical resonator having a resonance frequency that changes as a function of said external magnetic field, and

a detector (40) coupled to the mechanical resonator (10),

wherein the internal magnetic field has non-zero second derivative along a direction of oscillation of the mechanical resonator (10),

characterized in that the detector (40) is configured to detect the resonance frequency of the mechanical resonator (10).

2. The sensor according to claim 1, wherein the detector (40) comprises an optical or electronic readout circuit.

3. The sensor according to one of the preceding claims, wherein said mechanical resonator is configured to be maintained in oscillation by electrostatic, piezoelectric, optical, or magnetic actuation.

4. The sensor according to one of the preceding claims, wherein said concentrator is of soft magnetic material whereby the concentrator has low hysteresis and is capable of linearly amplifying the magnetic field to be measured.

5. The sensor according to one of the preceding claims, wherein said permanent magnet is made of hard magnetic material deposited on the mechanical resonator (10).

6. The sensor according to claim 5, wherein said permanent magnet has a net permanent magnetic dipole moment oriented parallel to a component of the internal magnetic field that

has non-zero second derivative in the direction of oscillation of said mechanical resonator.

7. The sensor according to claim 6, wherein said net permanent magnetic dipole moment is oriented parallel to the component of the internal magnetic field that has the second derivative of the highest absolute value in the direction of oscillation of said mechanical resonator.

8. The sensor according to claim 6 or 7, wherein said permanent magnet has a net permanent magnetic dipole obtained by crystalline and/or shape anisotropy and is made of hard magnetic material that allows the dipole to be maintained for a time interval greater than a readout interval of the sensor.

9. The sensor according to any of the preceding claims, comprising a plurality of said permanent magnets supported by the mechanical resonator (10) and arranged according to an ordered array and a plurality of said magnetic field concentrators arranged according to an ordered array.

10. The sensor according to claim 9, wherein the mechanical resonator (10) comprises an oscillating structure (10a) anchored to a fixed support through a plurality of anchoring points (10b), and a plurality of suspension springs (10c) that connect the oscillating structure (10a) to the anchoring points (10b), whereby the oscillating structure (10a) is capable of completing a pure translation movement along said direction of oscillation.

11. The sensor according to claim 10, wherein said oscillating structure has a reticular shape with an ordered array of apertures (31) adapted to receive the respective concentrators (30), whereby each individual permanent magnet (15) is interposed between a pair of adjacent concentrators (30).

12. The sensor according to claims 9 to 11, further comprising a switching system (50) controllable to invert the magnetization of said permanent magnets.

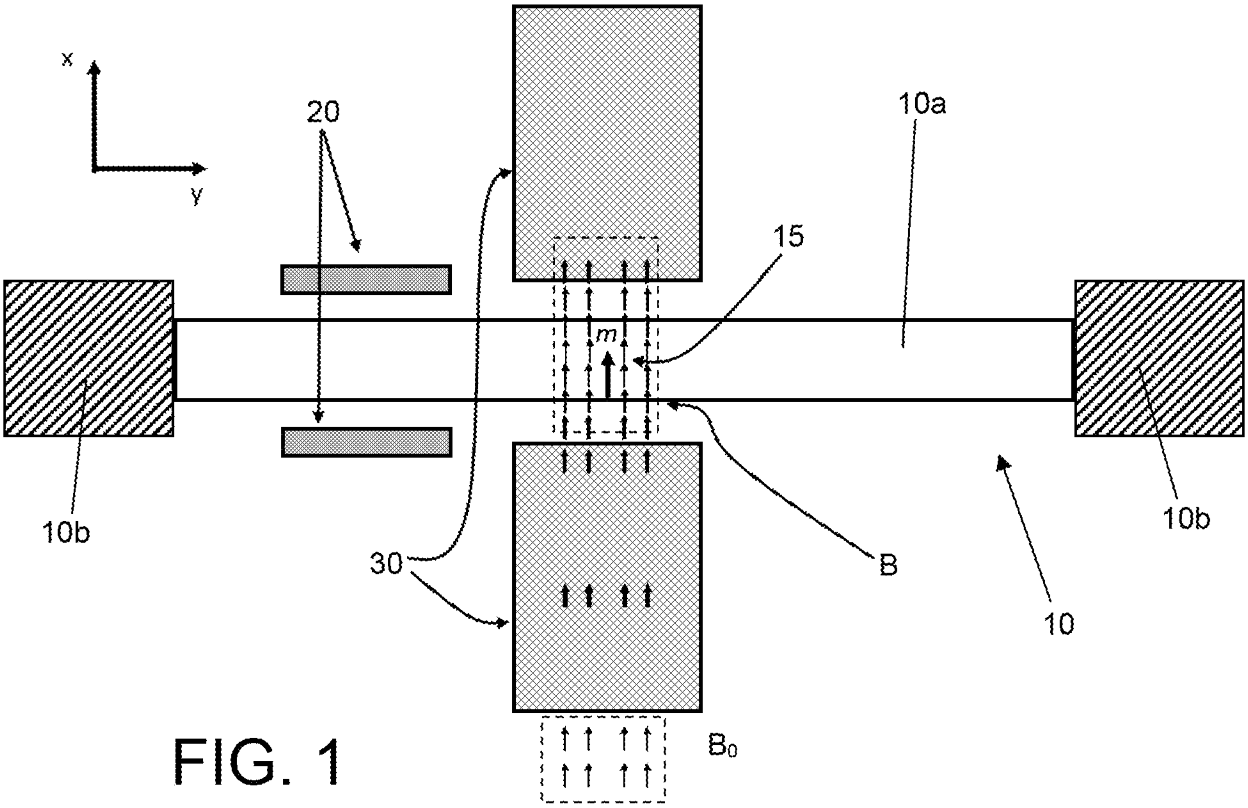
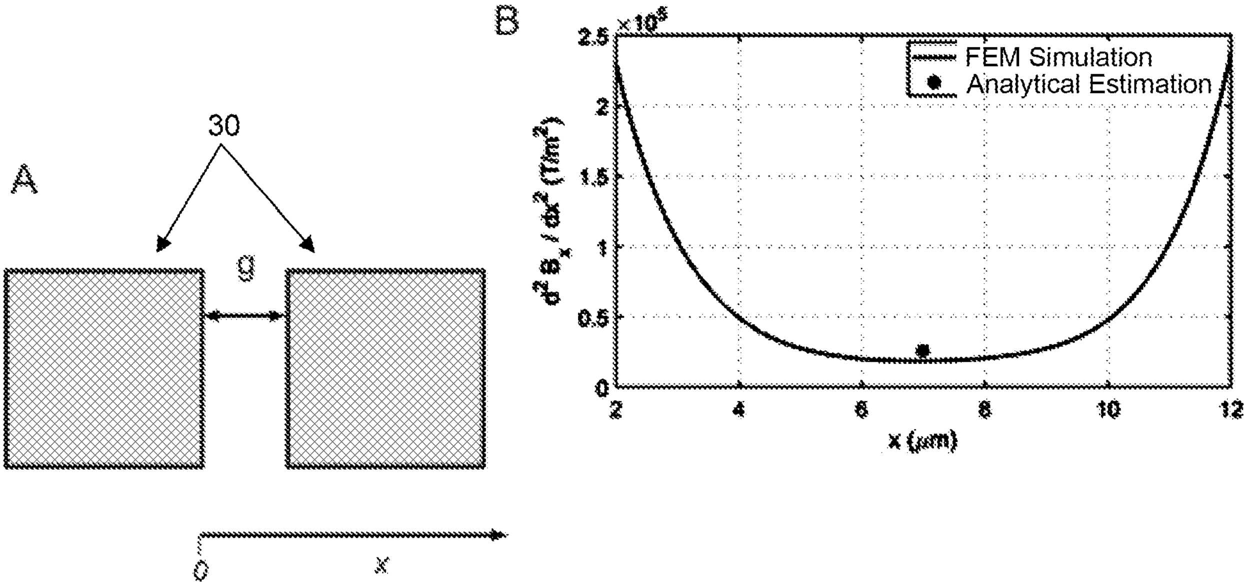

x
y
20
10a
15
m
10b
10b
30
B
10
B₀

FIG. 1


A
30
g
0
x
B
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2
1.5
1
0.5
0
2
4
6
8
10
12
d²Bₓ / dx² (T/m²)
x (μm)
FEM Simulation
Analytical Estimation

FIG. 2

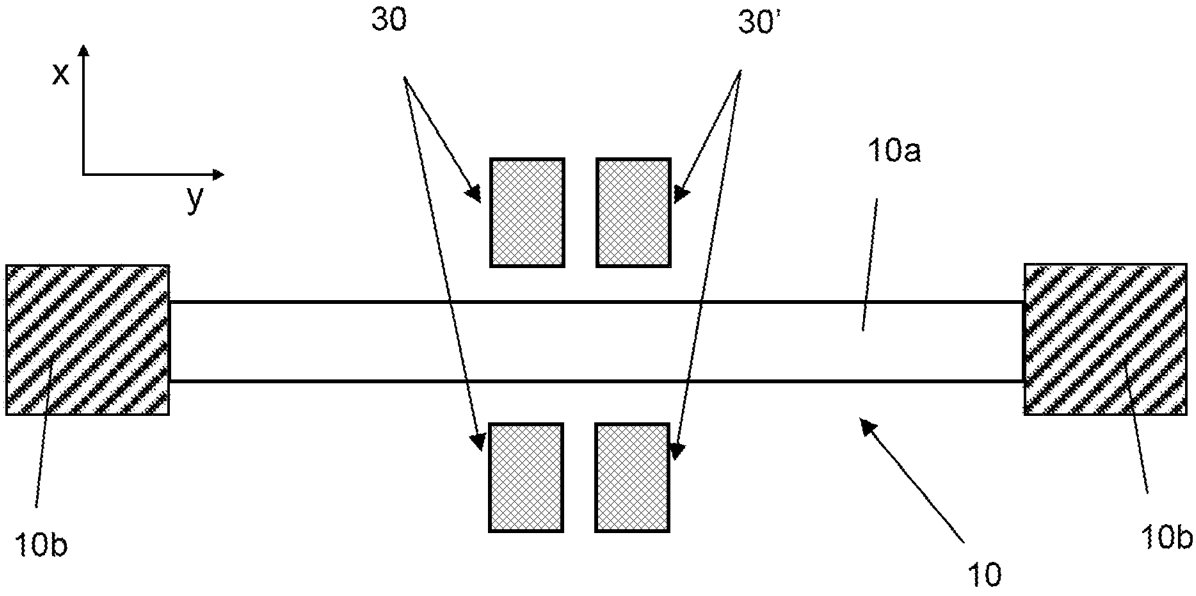


FIG. 3

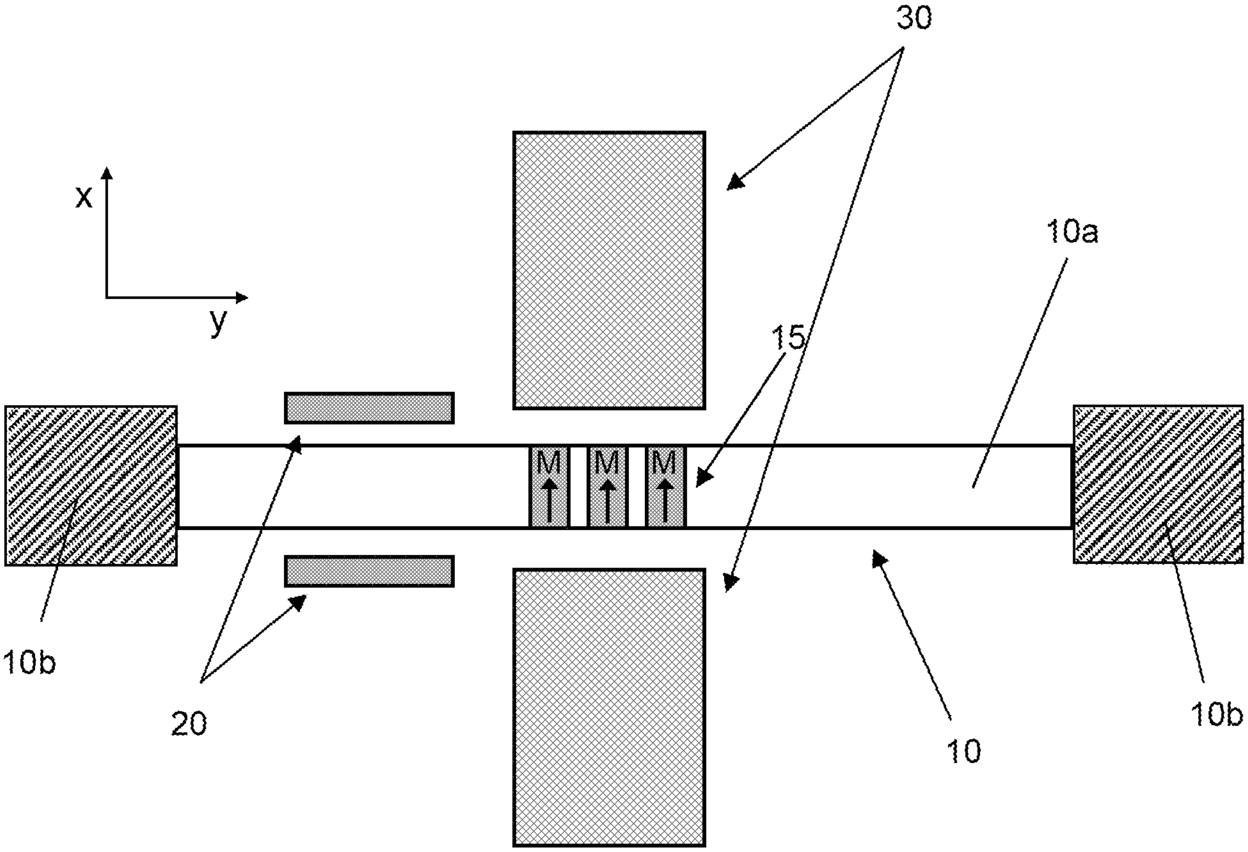


FIG. 4

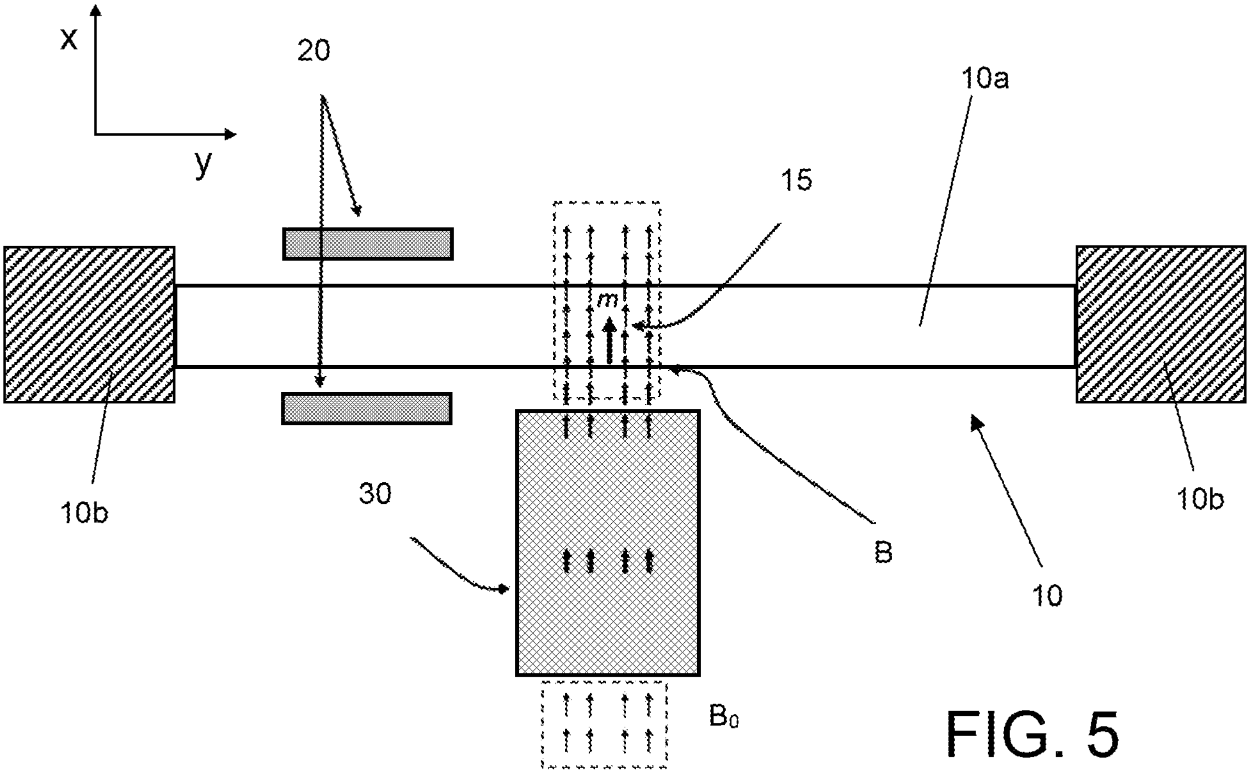


FIG. 5

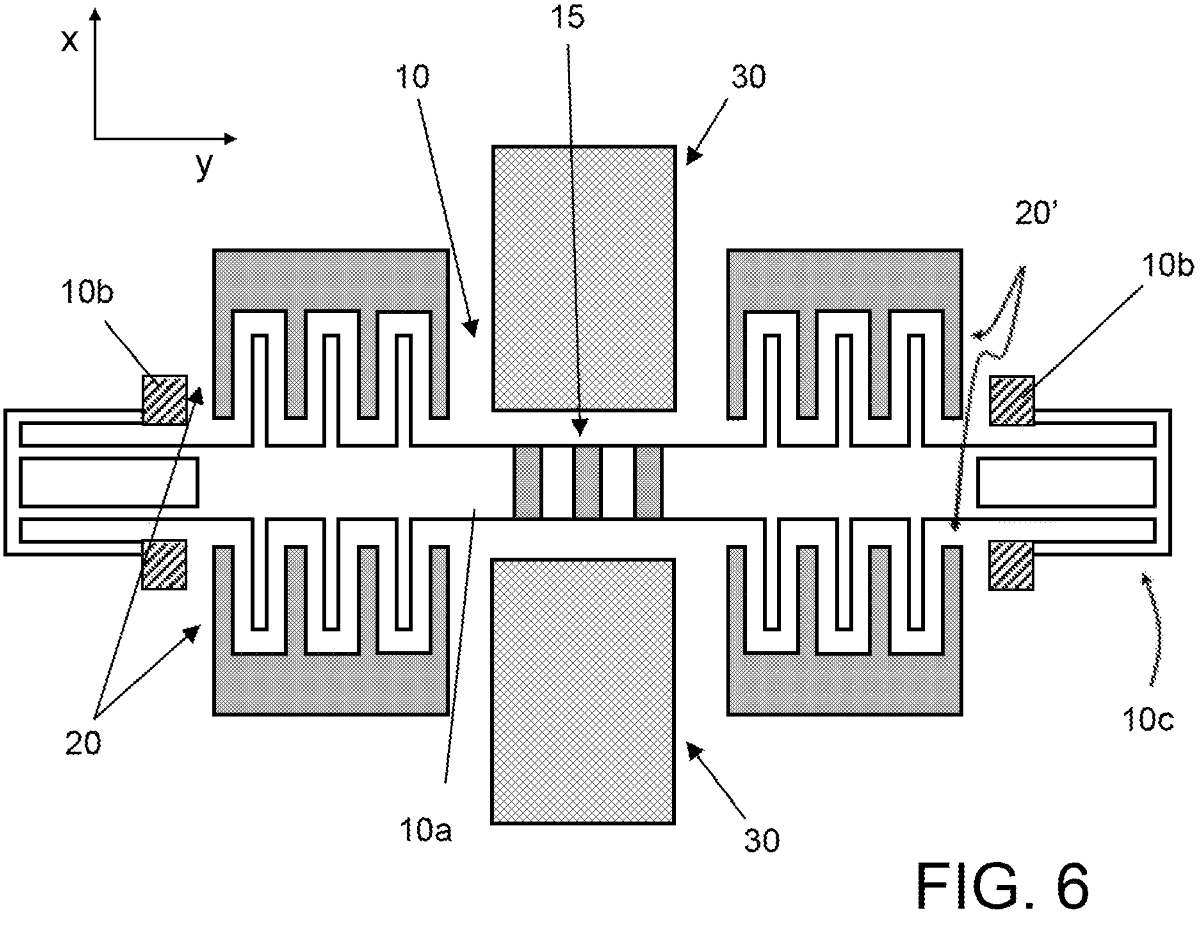
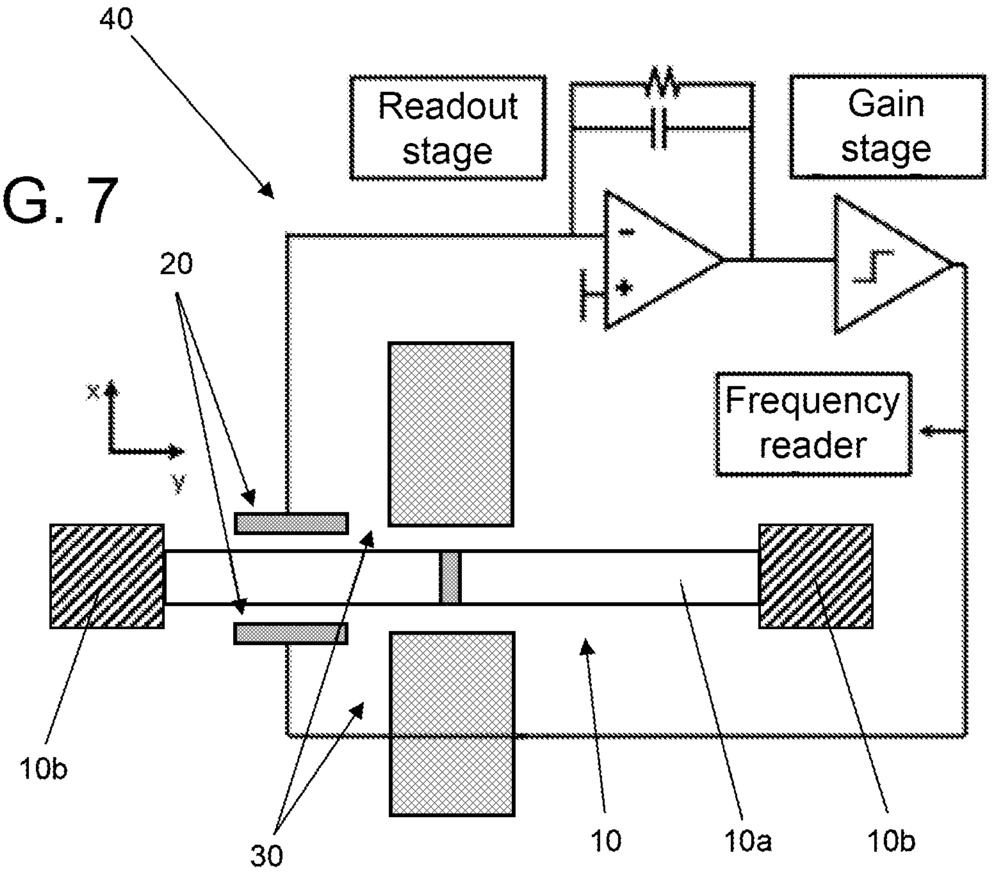


FIG. 6

FIG. 7


40
Readout stage
Gain stage
-
+
Frequency reader
20
x
y
10b
30
10
10a
10b

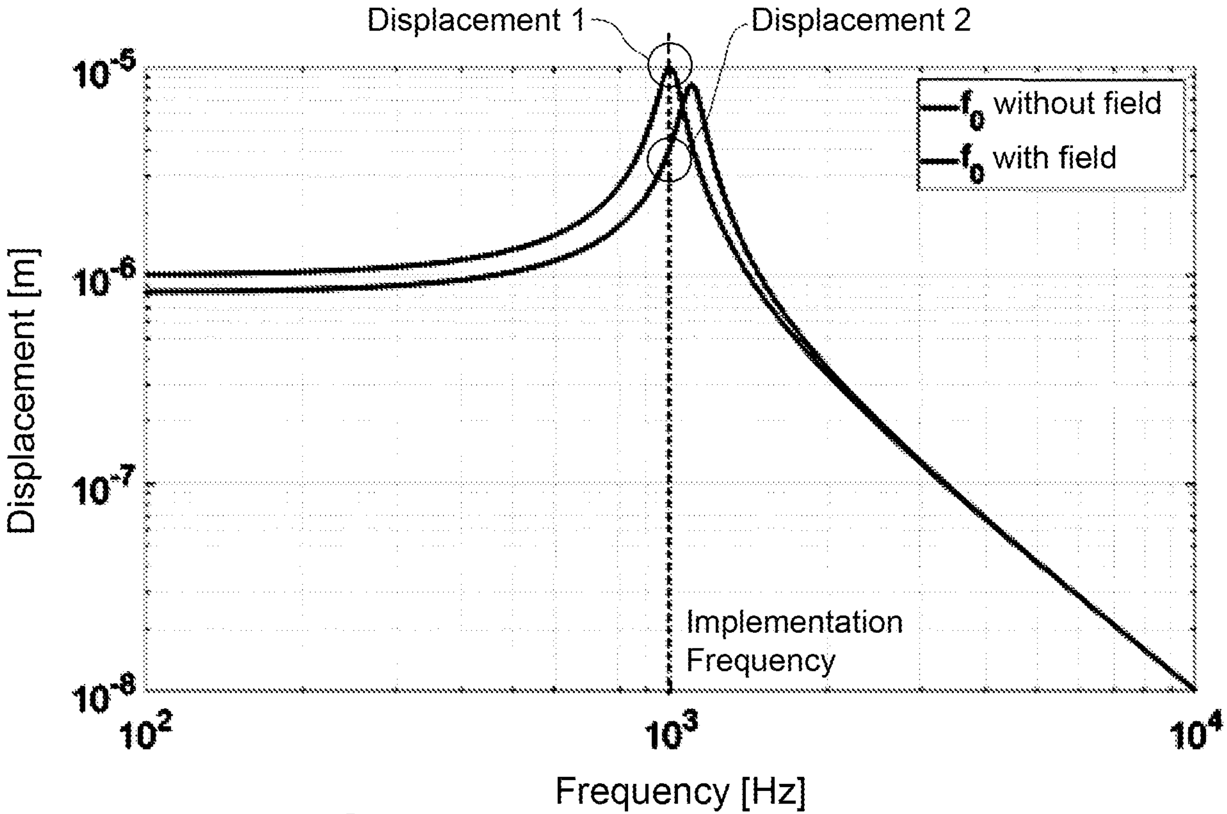

Displacement 1
Displacement 2
f_0 without field
f_0 with field
10^{-5}
10^{-6}
10^{-7}
10^{-8}
Displacement [m]
Implementation Frequency
10^2
10^3
10^4
Frequency [Hz]

FIG. 8

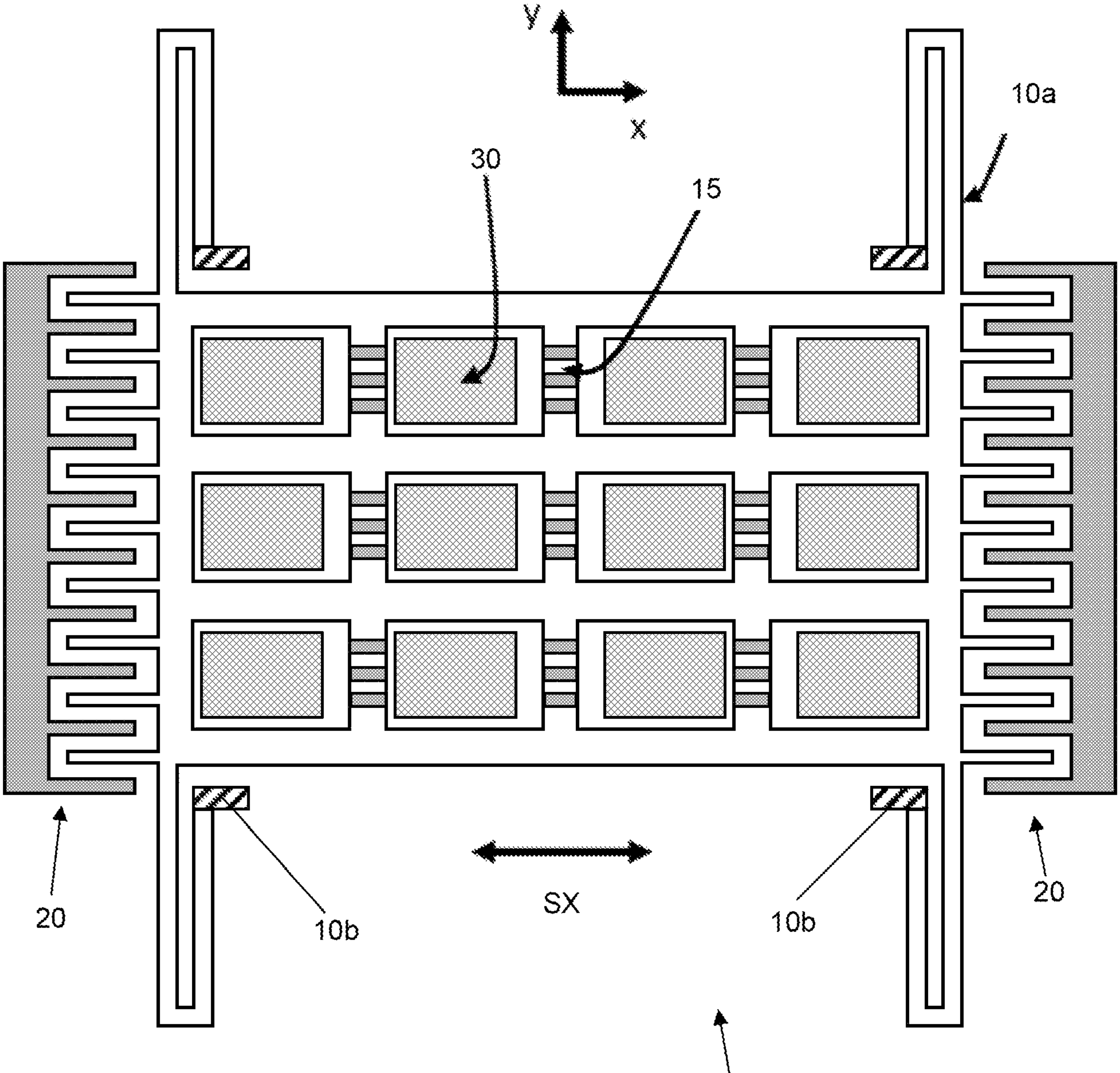


FIG. 9

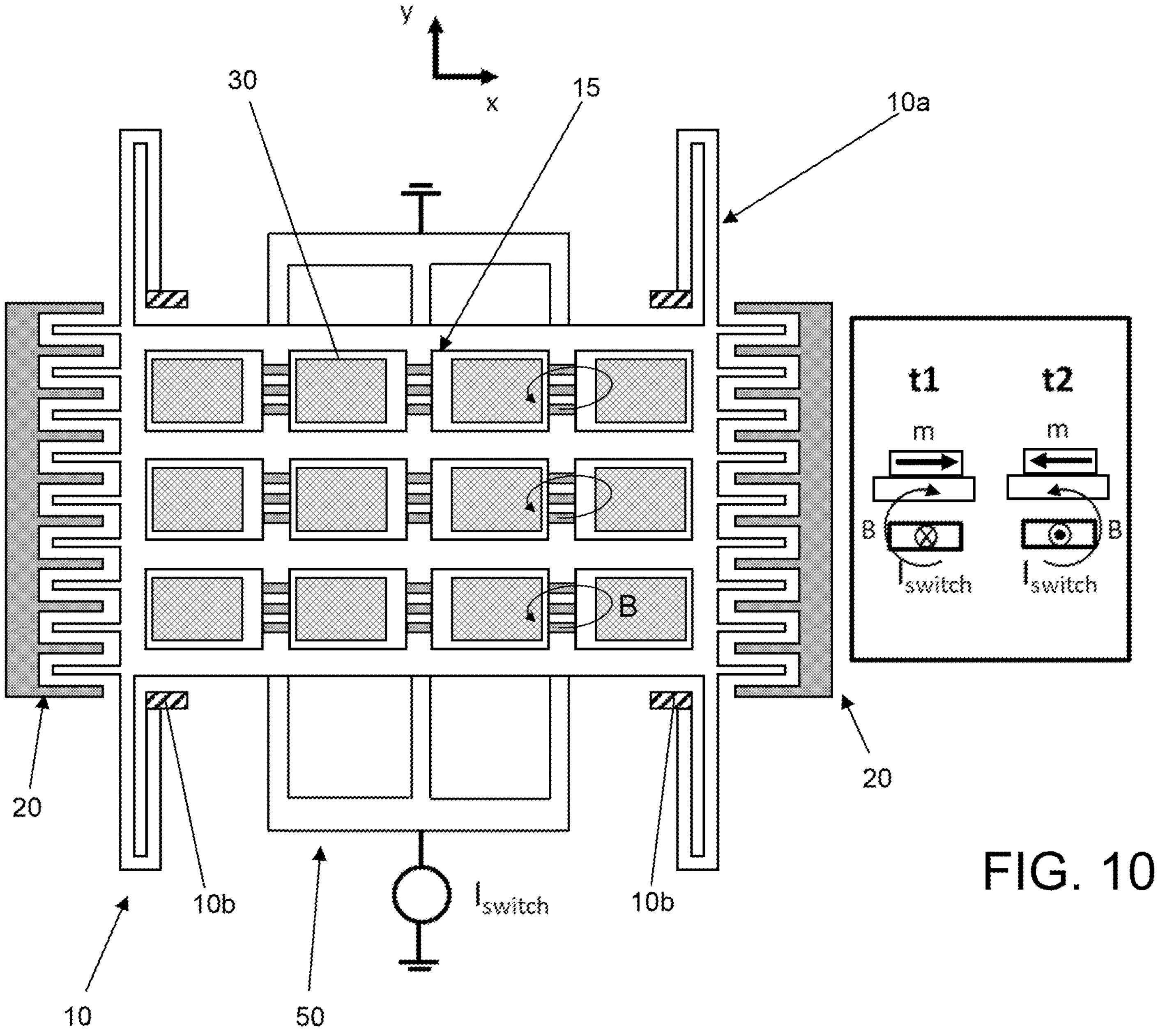

y
x
30
15
10a
t1
t2
m
m
B
B
I_{switch}
I_{switch}
B
20
20
10b
10b
I_{switch}
10
50

FIG. 10

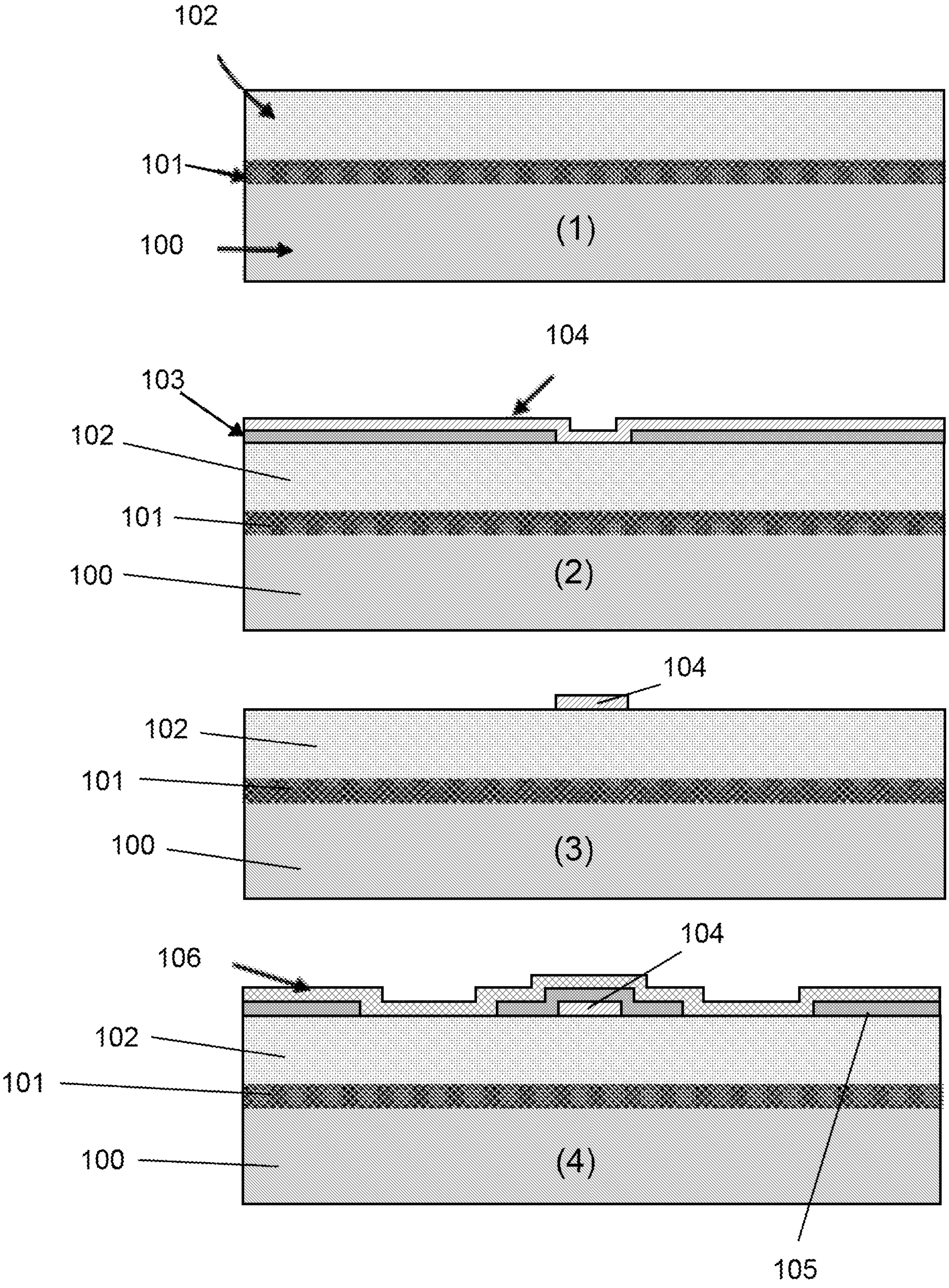

102
101
100
(1)
104
103
102
101
100
(2)
104
102
101
100
(3)
104
106
102
101
100
(4)
105

FIG. 11a

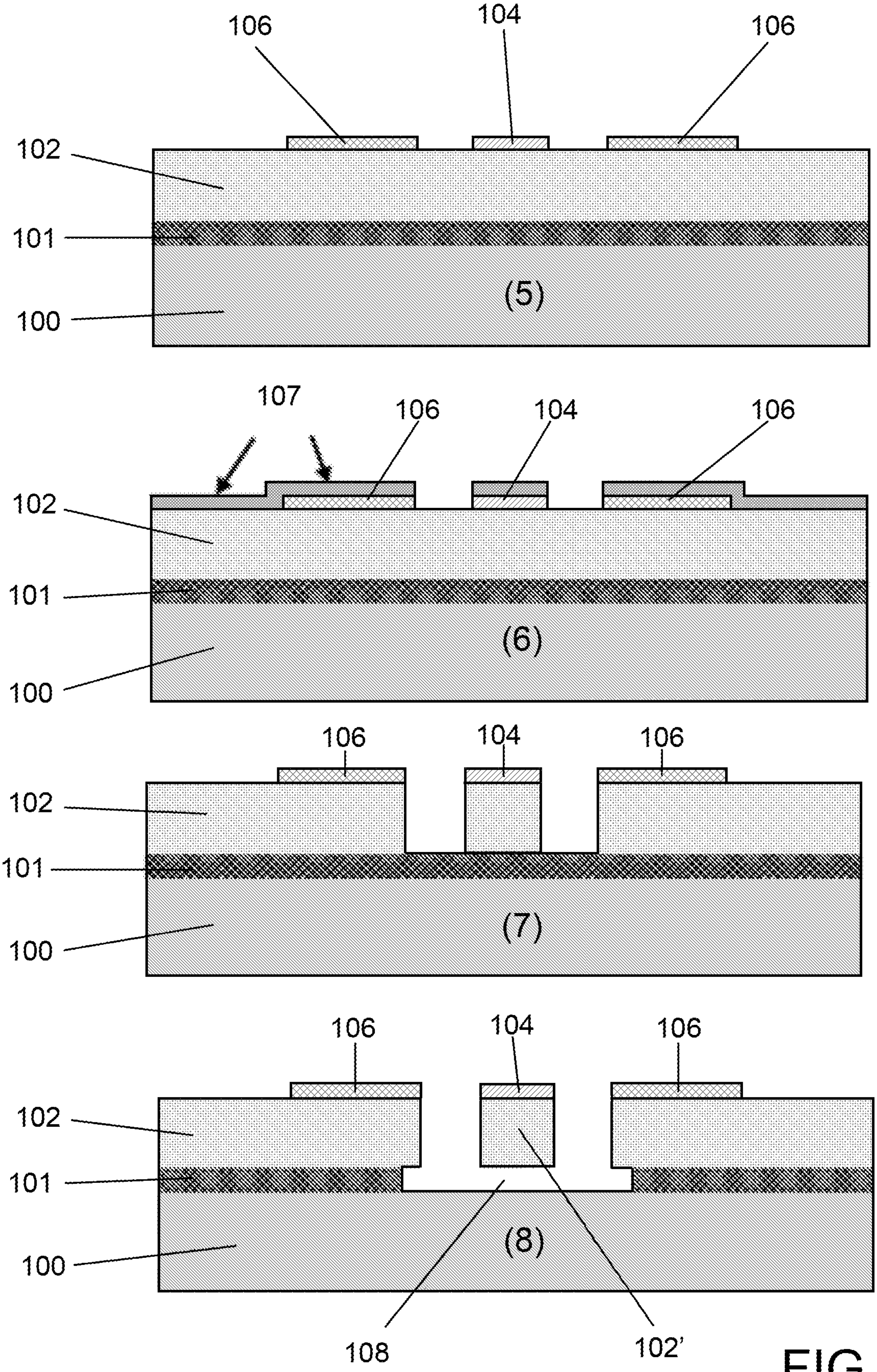

106
104
106
102
101
100
(5)
107
106
104
106
102
101
100
(6)
106
104
106
102
101
100
(7)
106
104
106
102
101
100
(8)
108
102'

FIG. 11b

INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2021/053032

A. CLASSIFICATION OF SUBJECT MATTER
INV. G01R33/00 G01R33/028 B81B3/00
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G01R B82B H02N B81B H01L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	INOMATA NAOKI ET AL: "Resonant magnetic sensor using concentration of magnetic field gradient by asymmetric permalloy plates", MICROSYSTEM TECHNOLOGIES, BERLIN, DE, vol. 25, no. 10, 18 December 2018 (2018-12-18), pages 3983-3989, XP036889919, ISSN: 0946-7076, DOI: 10.1007/S00542-018-4257-8 [retrieved on 2018-12-18]	1-8
Y	Abstract, Section 2-4;	9,10
A	figures 1-4 ----- -/--	11,12

☒ Further documents are listed in the continuation of Box C.

☐ See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search 22 July 2021	Date of mailing of the international search report 05/08/2021
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Authorized officer Philipp, Peter

2

INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2021/053032

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	PAI PRADEEP ET AL: "Fiber optic magnetometer with sub-pico Tesla sensitivity for magneto-encephalography", IEEE SENSORS 2014 PROCEEDINGS, IEEE, 2 November 2014 (2014-11-02), pages 722-725, XP032705358, DOI: 10.1109/ICSENS.2014.6985101 figures 1, 7 -----	9,10
A	KIM HOE JOON ET AL: "Piezoelectric/magnetostrictive MEMS resonant sensor array for in-plane multi-axis magnetic field detection", 2017 IEEE 30TH INTERNATIONAL CONFERENCE ON MICRO ELECTRO MECHANICAL SYSTEMS (MEMS), IEEE, 22 January 2017 (2017-01-22), pages 109-112, XP033069472, DOI: 10.1109/MEMSYS.2017.7863352 figure 2 -----	1-12
A	SAÃOL M DOMINGUEZ-NICOLAS ET AL: "Signal Conditioning System With a 4 20 mA Output for a Resonant Magnetic Field Sensor Based on MEMS Technology", IEEE SENSORS JOURNAL, IEEE SERVICE CENTER, NEW YORK, NY, US, vol. 12, no. 5, 1 May 2012 (2012-05-01), pages 935-942, XP011440778, ISSN: 1530-437X, DOI: 10.1109/JSEN.2011.2167012 figures 1-4 -----	1-12

2