

**METHOD FOR PRODUCTION OF A MECHANICAL RESONATOR WITH A
PLANAR MONOLITHIC VIBRATING STRUCTURE MACHINED IN A
CRYSTALLINE MATERIAL AND RESONATOR PRODUCED THUS**

5 The present invention relates to improvements made in the field of gyroscopic devices based on mechanical resonators with a planar monolithic vibrating structure machined in a crystalline material.

10 Gyroscopic devices are devices for measuring a speed of rotation or an angle of rotation about one or more particular axes.

At the present time, there are many techniques used for
15 producing gyroscopic devices, but currently there is a need to have very compact devices (with a size of less than a few cubic centimeters) that can be achieved in high volume for low cost, that can withstand sudden accelerations of high level, and are capable of
20 delivering accurate measurements within a wide range of rotation speeds. Among potential fields of application for such devices, mention may especially be made of the navigation and guiding of small spin-controlled missiles (for example short-range antitank missiles) or
25 spin-controlled munitions (shells or mortars), that is to say projectiles rotating about the roll axis at a high permanent speed of rotation, typically a few revolutions per second in the case of spin-controlled missiles or fin-controlled projectiles, and a few
30 hundred revolutions per second in the case of gyro-controlled projectiles.

To meet this requirement, the technology of vibrating gyroscopes, combined with fabrication of micromachined
35 structures, is particularly suitable. However, although several formulations have emerged and reached a relatively advanced stage of development and industrialization, none of them allows the problem

posed by the abovementioned applications to be correctly solved, for which a rotation measurement about the roll axis is necessary. This inability of such formulations to correctly meet the needs stems
5 from the combination of two causes:

- the first cause is that they are intrinsically suited to gyrometer-type feedback control (measurement of angular velocity);

- the second cause is that the dynamics of the
10 speed of rotation about the roll axis are too fast for gyrometric feedback control to offer sufficient precision and/or result in saturating the sensor electronics used.

15 Consequently, it is known that the only possible general solution to the problem posed consists in using the devices intrinsically adapted to gyroscopic feedback control (measurement of the angle of rotation). Furthermore, as specified in document
20 FR 2 756 375, the gyroscopic feedback control of a vibrating mechanical resonator placed along the roll axis of a carrier allows high scale-factor precision to be obtained. In combination with resonators feedback-controlled in gyrometer mode about the transverse axes
25 of the carrier, it is thus possible to produce a high-performance system for which the bias errors of the transverse resonators cancel out over one revolution of the carrier about its roll axis.

30 In the case of devices based on vibrating gyroscope technology, the condition of optimum gyroscopic feedback control involves searching for structures whose frequency anisotropy between the two useful modes coupled through the effect of Coriolis forces is
35 intrinsically zero. The frequency anisotropy may be decomposed into three main terms:

$$\Delta f = \Delta f_m + \Delta f_g + \Delta f_s$$

where

Δf is the overall frequency anisotropy,

- Δf_m is the frequency anisotropy introduced by the material of the resonator,
 Δf_g is the frequency anisotropy introduced by the geometry of the resonator and
5 Δf_s is the frequency anisotropy introduced by the suspension or attachment of the resonator.

Other terms could be added, such as for example the anisotropies introduced by the electronics used, but
10 these terms are assumed to be of second order compared with the terms mentioned here.

Thus, in order for the overall frequency anisotropy Δf to be zero, it is sufficient for the three components
15 Δf_m , Δf_g and Δf_s all to be zero. Other sufficient conditions are possible, but they necessarily imply compensations between the Δf_m and/or Δf_g and/or Δf_s components, which ends up increasing the complexity of the definition of the structure of the resonator and
20 makes this structure particularly sensitive to the variations of any parameter. It therefore seems fundamental to seek structures for which each term Δf_m , Δf_g and Δf_s is zero. However, it is found that the design approach usually adopted consists, in the case
25 of micromachined resonator structures, in taking into account only the geometrical aspects, whereas it is just as fundamental to consider the constituent material of the resonator through its intrinsic symmetries or its symmetries resulting from the cut
30 plane in which the wafer supporting the resonator structure will be cut.

By way of an example illustrating what has just been explained, the known example of a vibrating ring whose
35 geometry is perfectly suited to obtaining gyroscopic feedback control may be considered. By producing this structure in a silicon wafer (by wet etching) cut in the [001] plane and by using the two plane modes of elliptical deformation as principal mode and as

secondary mode, $\Delta f_g = 0$ is of course obtained, but Δf_m is very much greater than 1 Hz. In practice, for a ring with a mean frequency of 400 Hz, having a diameter of 5 mm and a thickness of 100 μm , $\Delta f_m = 250$ Hz is
5 obtained, so that in the end, by neglecting the frequency anisotropy introduced by the attachment or other elements, an overall frequency anisotropy Δf of about 250 Hz is obtained. This result is incompatible with effective gyroscopic feedback control and clearly
10 illustrates the problem raised in the case of resonators obtained using microelectronics technologies.

This is because micromachined resonator structures use,
15 as support materials, crystalline materials that are naturally anisotropic and consequently lend themselves particularly well to micromachining by chemical etching, as is carried out for collective processes in microelectronics. However, offset against the advantage
20 associated with the collective aspect of the machining operations there is the major drawback of the anisotropy of the material. This anisotropy, when no selection rule for the symmetries of the material consistent with the symmetry of the modes used is
25 respected, irremediably results in a nonzero term Δf_m .

The object of the invention is therefore to propose a technological solution (method and device) which achieves, with certainty, frequency isotropy introduced
30 by the crystalline material from which the vibrating resonator with a planar structure is cut, it being understood that the present invention is aimed solely at providing the means for obtaining frequency isotropy introduced by the material ($\Delta f_m = 0$) and that the
35 problems of obtaining frequency isotropies due to the geometry (Δf_g) and to the suspension (Δf_s) are to be solved elsewhere for the purpose of obtaining overall frequency isotropy ($\Delta f = 0$) capable of constituting an

intrinsically gyroscopic device (see for example document FR 01/02498).

5 It should be understood that, if the material of the resonator is isotropic, then the intrinsic pulses of the two k th-order modes become equal, this being so whatever k , namely $\omega_1 = \omega_2 = \omega$.

10 Moreover, the shapes of the two k th-order eigenmodes are identical by rotation of the reference frame through an angle of $\pi/2k$. Thus, the 2nd-order modes of the vibrating ring correspond to elliptical shapes offset one with respect to the other by an angle of $\pi/4 = 45^\circ$. Likewise, the 3rd-order modes of the
15 vibrating ring correspond to trilobate shapes offset one with respect to another by an angle of $\pi/6 = 30^\circ$.

The cut plane of the crystalline material is defined by the position of its normal vector $\bar{V}$, which is itself
20 defined by its coordinates $[x, y, z]$ in an orthonormal coordinate system Oex, ey, ez . Thus, the sole datum of the three information items $[x, y, z]$ allows the normal vector $\bar{V}$, and therefore the cut plane, to be uniquely defined. For example, the $[001]$ datum gives the
25 coordinates of the normal vector and the plane is parallel to the (ex, ey) plane.

Moreover, it is known that currently known crystalline materials can be divided up into 32 classes distributed
30 in nine families from the standpoint of the representation of rigidity and flexibility matrices: mention may especially be made of the tetragonal (1), tetragonal (2), trigonal (1), trigonal (2), hexagonal and cubic families.

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Finally, it should be pointed out that only the vibration modes of order $k = 2$ and $k = 3$ of the vibrating resonators may at the present time be exploited in a practical fashion, whereas the

exploitation of vibration modes of higher order ($k = 4, 5, \text{etc.}$) would require very complex electronics to be used (increasing the number of excitation/detection electrodes would be incompatible with production of a
5 gyroscopic device of small, or even very small, size).

Admittedly, document WO 01/55675 mentions, just for a silicon crystal, the possibility of a 2nd-order vibration mode with a silicon crystal cut in the [111]
10 plane and a 3rd-order mode with a silicon crystal cut in the [100] plane. However, this is one specific item of information that does not provide a person skilled in the art with any indication, in the case of 2nd- and 3rd order vibrations, as regards the other possible cut
15 planes for silicon, or as regards possible cut planes for other crystalline materials with a cubic structure, or more generally as regards possible cut planes for other crystalline materials.

20 Having mentioned this, the invention, in a first of its aspects, proposes a method for producing a mechanical resonator with a planar monolithic vibrating structure machined in a crystalline material, characterized in that:

- 25 - when the crystalline material is chosen from crystalline materials of trigonal (1) or trigonal (2) or hexagonal structure, this material is cut in the [001] plane or, when it is chosen from materials of cubic structure
30 (silicon excluded), it is cut in the [111] plane, and the 2nd-order vibration mode is then used,
 or else
- when the crystalline material is chosen from
35 crystalline materials of tetragonal (1) or tetragonal (2) or hexagonal structure, this material is cut in the [001] plane, or, when it is chosen from materials of cubic structure, it is cut in the [001] or [100] plane (silicon

excluded) or [010] plane, and the 3rd-order vibration mode is then used, whereby the resonator exhibits natural material-based frequency isotropy ($\Delta f_m = 0$).

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These features may be summarized as follows:

for k = 2	family: trigonal (1)	→	plane: [001]
	trigonal (2)	→	[001]
	hexagonal	→	[001]
	cubic (Si excluded)	→	[111]
for k = 3	family: tetragonal (1)	→	plane: [001]
	tetragonal (2)	→	[001]
	hexagonal	→	[001]
			[001]
	cubic	→	[100] (Si excluded) [010]

Of course, the use of the provisions presented may
10 accompany a construction of axisymmetric structure, resulting in geometry-based isotropy $\Delta f_g = 0$.

According to a second of its aspects, the invention
proposes a mechanical resonator with a planar
15 monolithic vibrating structure machined in a crystalline material, characterized in that, for the resonator to exhibit material-based frequency isotropy ($\Delta f_m = 0$), the crystalline material is chosen from the following:

- 20 a) a crystalline material of tetragonal (1) or tetragonal (2) structure cut in the [001] plane, the resonator then exhibiting material-based frequency isotropy in the 3rd-order vibration mode;
- 25 b) a crystalline material of trigonal (1) or trigonal (2) structure cut in the [001] plane, the resonator then exhibiting material-based frequency isotropy in the 2nd-order vibration mode;
- 30 c) a crystalline material of hexagonal structure cut in the [001] plane, the resonator then

exhibiting material-based frequency isotropy in both the 2nd- and 3rd-order vibration modes; and

d) a crystalline material of cubic structure

5 - cut in the [111] plane (silicon excluded), the resonator then exhibiting material-based frequency isotropy in the 2nd-order vibration mode

or

10 - cut in the [001], [100] (silicon excluded) or [010] planes, the resonator then exhibiting material-based frequency isotropy in the 3rd-order vibration mode.

15 As a consequence of this, a resonator produced in accordance with the invention by a suitable choice of the constituent crystalline material, of the cut plane of said crystalline material and of the kth-order vibration mode exhibits material-based frequency
20 isotropy ($\Delta f_m = 0$) and, provided that overall frequency isotropy $\Delta f = 0$ is obtained (for example with $\Delta f_g = 0$ and $\Delta f_s = 0$, or with $\Delta f_g + \Delta f_s = 0$), such a resonator may constitute the core for a gyroscopic device of optimum design.

CLAIMS

1. A method for producing a mechanical resonator with a planar monolithic vibrating structure machined in a crystalline material, characterized in that:

- when the crystalline material is chosen from crystalline materials of trigonal (1) or trigonal (2) or hexagonal structure, this material is cut in the [001] plane or, when it is chosen from materials of cubic structure (silicon excluded), it is cut in the [111] plane, and the 2nd-order vibration mode is then used, or else
- when the crystalline material is chosen from crystalline materials of tetragonal (1) or tetragonal (2) or hexagonal structure, this material is cut in the [001] plane, or, when it is chosen from materials of cubic structure, it is cut in the [001] or [100] plane (silicon excluded) or [010] plane, and the 3rd-order vibration mode is then used,

whereby the resonator exhibits natural material-based frequency isotropy ($\Delta f_m = 0$).

2. A mechanical resonator with a planar monolithic vibrating structure machined in a crystalline material, characterized in that, for the resonator to exhibit material-based frequency isotropy ($\Delta f_m = 0$), the crystalline material is chosen from the following:

- a) a crystalline material of tetragonal (1) or tetragonal (2) structure cut in the [001] plane, the resonator then exhibiting material-based frequency isotropy in the 3rd-order vibration mode;
- b) a crystalline material of trigonal (1) or trigonal (2) structure cut in the [001] plane, the resonator then exhibiting material-based

frequency isotropy in the 2nd-order vibration mode;

5 c) a crystalline material of hexagonal structure cut in the [001] plane, the resonator then exhibiting material-based frequency isotropy in both the 2nd- and 3rd-order vibration modes; and

10 d) a crystalline material of cubic structure
- cut in the [111] plane (silicon excluded), the resonator then exhibiting material-based frequency isotropy in the 2nd-order vibration mode

or

15 - cut in the [001], [100] (silicon excluded) or [010] planes, the resonator then exhibiting material-based frequency isotropy in the 3rd-order vibration mode.