A method of using a MEMS gyroscope is disclosed herein, wherein the MEMS gyroscope comprises a magnetic sensing mechanism. A magnetic field is generated by a magnetic source, and is detected by a magnetic sensor. The magnetic field varies at the location of the magnetic sensor; and the variation of the magnetic field is associated with the movement of the proof-mass of the MEMS gyroscope. By detecting the variation of the magnetic field, the movement and thus the target angular velocity can be measured.
FIG. 12

FIG. 13
Figure 14:

170
172
AF
F

FIG. 14

Temperature

FIG. 15

ΔT_{ref}
ΔT_{sig}
ΔT_{sig}
ΔT_{sig}
T
T_0

FIG. 16

174
176
178
180
Initialize the reference and signal sensors
Drive the proof-mass
Turn on the reference sensor
Lock the reference sensor

182
184
186
188
Turn on the signal sensor
Compare the outputs from the reference and signal sensors
Finished?
Set the states of the reference and signal sensors

Yes
No
174 Initialize the reference and signal sensors

175 Receive a trigger signal

176 Drive the proof-mass

178 Turn on the reference sensor

180 Lock the reference sensor

182 Turn on the signal sensor

184 Compare the outputs from the reference and signal sensors

186 Finished?

188 Set the states of the reference and signal sensors

FIG. 19
MEMS DEVICE AND A METHOD OF USING THE SAME

CROSS-REFERENCE


TECHNICAL FIELD OF THE DISCLOSURE

The technical field of the examples to be disclosed in the following sections is related generally to the art of operation of microstructures, and, more particularly, to operation of MEMS devices comprising MEMS magnetic sensing structures.

BACKGROUND OF THE DISCLOSURE

Microstructures, such as microelectromechanical (hereafter MEMS) devices (e.g. accelerometers, DC relay and RF switches, optical cross connects and optical switches, microlenses, reflectors and beam splitters, filters, oscillators and antenna system components, variable capacitors and inductors, switched banks of filters, resonant comb-drives and resonant beams, and micromirror arrays for direct view and projection displays) have many applications in basic signal transduction. For example, a MEMS gyroscope measures angular rate.

A gyroscope (hereafter “gyro” or “gyroscope”) is based on the Coriolis effect as diagrammatically illustrated in FIG. 1. Proof-mass \(100\) is moving with velocity \(V_p\). Under external angular velocity \(\Omega\), the Coriolis effect causes movement of the proof-mass \(100\) with velocity \(V_c\). With fixed \(V_p\), the external angular velocity can be measured from \(V_c\). A typical example based on the theory shown in FIG. 1 is capacitive MEMS gyroscope, as diagrammatically illustrated in FIG. 2.

The MEMS gyro is a typical capacitive MEMS gyro, which has been widely studied. Regardless of various structural variations, the capacitive MEMS gyro in FIG. 2 includes the very basic theory based on which all other variations are built. In this typical structure, capacitive MEMS gyro \(102\) is comprised of proof-mass \(100\), driving mode \(104\), and sensing mode \(102\). The driving mode \(104\) causes the proof-mass \(100\) to move in a predefined direction, and such movement is often in a form of resonance vibration. Under external angular rotation, the proof-mass \(100\) also moves along the \(V_c\) direction with velocity \(V_c\). Such movement of \(V_c\) is detected by the capacitor structure of the sensing mode \(102\). Both of the driving and sensing modes use capacitive structures, whereas the capacitive structure of the driving mode changes the overlaps of the capacitors, and the capacitive structure of the sensing mode changes the gaps of the capacitors.

Current capacitive MEMS gyros, however, are hard to achieve submicro-g/Hz because the capacitance between sensing electrodes decreases with the miniaturization of the movable structure of the sensing element and the impact of the stray and parasitic capacitance increase at the same time, even with large and high aspect ratio proof-masses.

Therefore, what is desired is a MEMS device capable of sensing angular velocities and methods of operating the same.

SUMMARY OF THE DISCLOSURE

In view of the foregoing, a method of measuring an angular velocity by using a MEMS gyroscope is disclosed herein, the method comprising: driving the proof-mass to move in a driving mode using a group of capacitors; measuring a background magnetic signal using a reference magnetic sensor; storing the measurement from the reference magnetic sensor; generating a target magnetic field that is associated with a movement of a proof-mass of the MEMS gyroscope; activating a signal magnetic sensor for measuring the background magnetic signal and the generated target magnetic signal; comparing the measurements from the reference and signal magnetic sensors so as to obtain the target magnetic field; and extracting the angular velocity from the target magnetic field.

Another example, a method of detecting a target angular velocity is disclosed herein, comprising: providing a MEMS gyroscope that comprises a moveable proof-mass, a magnetic source, and a magnetic sensor, wherein the proof-mass is capable of moving in response to the target angular velocity under the Coriolis effect, and wherein the magnetic source is capable of generating a magnetic field that varies with the movement of the proof-mass, and wherein the magnetic sensor is capable of detecting the magnetic field from the magnetic source; detecting a background magnetic signal using a reference sensor; storing the detected background magnetic signal by the reference sensor; causing the proof-mass to vibrate using a group of capacitors; generating the magnetic field by the magnetic sensor; detecting a variation of the magnetic field by the magnetic sensor; and extracting the angular velocity from the variation of the magnetic field.

BRIEF DESCRIPTION OF DRAWINGS

FIG. 1 diagrammatically illustrates the Coriolis effect in a MEMS structure;

FIG. 2 is a top view of a typical existing capacitive MEMS gyroscope having a driving mode and a sensing mode, wherein both of the driving and sensing mode utilize capacitor structures;

FIG. 3 illustrates an exemplary MEMS gyroscope having a magnetic sensing mechanism;

FIG. 4 illustrates a top view of a portion of an exemplary implementation of the MEMS gyroscope illustrated in FIG. 3, wherein the MEMS gyroscope illustrated in FIG. 4 having a capacitive driving mode and a magnetic sensing mechanism;

FIG. 5 illustrates a perspective view of a portion of another exemplary implementation of the MEMS gyroscope illustrated in FIG. 3, wherein the MEMS gyroscope illustrated in FIG. 5 having a capacitive driving mechanism for the driving mode and a magnetic sensing mechanism for the sensing mode;

FIG. 6 illustrates an exemplary capacitive driving mechanism of the MEMS gyroscope in FIG. 5;

FIG. 7 illustrates an exemplary magnetic source of the MEMS gyroscope illustrated in FIG. 3;
FIG. 8 illustrates an exemplary magnetic sensing mechanism that can be used in the MEMS gyroscope illustrated in FIG. 3;

FIG. 9 shows an exemplary thin-film stack that can be configured into a CIP or CPP structure for use in the magnetic sensing mechanism illustrated in FIG. 8;

FIG. 10 illustrates an exemplary MEMS gyroscope that comprises multiple magnetic sensing structures;

FIG. 11 illustrates an exemplary operation for detecting and measuring an angular velocity using a MEMS gyroscope illustrated in FIG. 3;

FIG. 12 illustrates temperature dependence of the coercivity of a ferromagnetic thin film, wherein the ferromagnetic thin film can be used in the signal sensor illustrated in FIG. 3;

FIG. 13 illustrates temperature dependence of the coercivity of a ferromagnetic thin film, wherein the ferromagnetic thin film can be used in the signal sensor illustrated in FIG. 3;

FIG. 14 illustrates the temperature dependence of the magnetic exchange field between a pinning layer and a free layer, wherein the pinning layer and the free layer can be used in the signal sensor illustrated in FIG. 3;

FIG. 15 is a diagram showing an exemplary operation of the MEMS gyroscope of FIG. 3;

FIG. 16 is a flowchart showing the steps executed for operating the MEMS gyroscope of FIG. 3;

FIG. 17 is a diagram showing another exemplary operation of the MEMS gyroscope of FIG. 3;

FIG. 18 is a diagram showing another exemplary operation of the MEMS gyroscope of FIG. 3; and

FIG. 19 is a flowchart showing the steps executed for operating the MEMS gyroscope of FIG. 3.

Detailed Description of Selected Examples

Disclosed herein is a MEMS gyroscope and method of using the same for sensing an angular velocity, wherein the MEMS gyroscope utilizes a magnetic sensing mechanism. It will be appreciated by those skilled in the art that the following discussion is for demonstration purposes, and should not be interpreted as a limitation. Many other variations within the scope of the following disclosure are also applicable. For example, the MEMS gyroscope and the method disclosed in the following are applicable for use in accelerometers.

Referring to FIG. 3, an exemplary MEMS gyroscope is illustrated herein. In this example, MEMS gyroscope 106 comprises magnetic sensing mechanism 114 for sensing the target angular velocity through the measurement of proof-mass 112. Specifically, MEMS gyroscope 106 comprises mass-substrate 108 and sensor substrate 110. Mass-substrate 108 comprises proof-mass 112 that is capable of responding to an angular velocity. The two substrates (108 and 110) are spaced apart, for example, by a pillar (not shown herein for simplicity) such that at least the proof-mass (112) is movable in response to an angular velocity under the Coriolis effect. The movement of the proof-mass (112) and thus the target angular velocity can be measured by magnetic sensing mechanism 114.

The magnetic sensing mechanism (114) in this example comprises a magnetic source (116) and magnetic sensor (118). The magnetic source (116) generates a magnetic field, and the magnetic sensor (118) detects the magnetic field and/or the magnetic field variations that is generated by the magnetic source (116). In the example illustrated herein in FIG. 3, the magnetic source is placed on/in the proof-mass (112) and moves with the proof-mass (112). The magnetic sensor (118) is placed on/in the sensor substrate (120) and non-moveable relative to the moving proof-mass (112) and the magnetic source (116). With this configuration, the movement of the proof-mass (112) can be measured from the measurement of the magnetic field from the magnetic source (116).

Other than placing the magnetic source on/in the movable proof-mass (112), the magnetic source (116) can be placed on/in the sensor substrate (120); and the magnetic sensor (118) can be placed on/in the proof-mass (112).

It is also noted that the MEMS gyroscope illustrated in FIG. 3 can also be used as an accelerometer.

The MEMS gyroscope as discussed above with reference to FIG. 3 can be implemented in many ways, one of which is illustrated in FIG. 4. Referring to FIG. 4, the proof-mass (120) is driven by capacitive, such as capacitive comb. The sensing mode, however, is performed using the magnetic sensing mechanism illustrated in FIG. 3. For this reason, capacitive combs can be absent from the proof-mass (120).

An exemplary device structure is illustrated in FIG. 5. Referring to FIG. 5, the mass substrate (108) comprises a movable proof-mass (126) that is supported by flexure structures such as flexures 128, 129, and 130. The layout of the flexures enables the proof-mass to move in a plane substantially parallel to the major planes of mass substrate 108. In particular, the flexures enables the proof-mass to move along the length and the width directions wherein the length direction can be the driving mode direction and the width direction can be the sensing mode direction of the MEMS gyroscope.

The proof-mass (126) is connected to frame 132 through flexures (128, 129, and 130). The frame (132) is anchored by non-moveable structures such as pillar 134. The mass-substrate (108) and sensing substrate (110) are spaced apart by the pillar (134). The proof-mass (112) in this example is driving by capacitive driving mechanism, such as capacitive driving mechanisms 136 and 137. An exemplary capacitive driving mechanism is illustrated in FIG. 6.

Referring to FIG. 6, capacitive driving mechanism 136 comprises a group of capacitors arranged in parallel. Each capacitor comprises two plates, such as plates 141 and 143. A first set of plates of the capacitors is connected to a first comb bar (137) and a second set of plates of the capacitors is connected to a second comb bar 140. The first comb bar 137 is connected to the proof-mass; and the second comb bar is anchored such that the second comb bar does not move with the proof-mass. By applying a voltage to the capacitors, the first comb bar moves so as to push the proof-mass to move accordingly.

The magnetic source (114) of the MEMS gyroscope (106) illustrated in FIG. 3 can be implemented in many ways, one of which is illustrated in FIG. 7. Referring to FIG. 7, conductive wire (142) is placed on/in proof-mass (112). In one example, conductive wire (142) can be placed on the lower surface of the proof-mass (112), wherein the lower surface is facing the magnetic sensors (118 in FIG. 3) on the sensor substrate (110, in FIG. 3). Alternatively, the conductive wire (142) can be placed on the top surface of the proof-mass (112), i.e. on the opposite side of the proof-mass (112) in view of the magnetic sensor (118). In another example, the conductive wire (142) can be placed inside the proof-mass, e.g. laminated or embedded inside the proof-mass (112), which
will not be detailed herein as those examples are obvious to those skilled in the art of the related technical field.

The conductive wire (142) can be implemented in many suitable ways, one of which is illustrated in FIG. 7. In this example, the conductive wire (142) comprises a center conductive segment 146 and tapered contacts 144 and 148 that extend the central conductive segment to terminals, through the terminals of which current can be driven through the central segment. The conductive wire (142) may have other configurations. For example, the contact tapered contacts (144 and 148) and the central segment (146) may be U-shaped such that the tapered contacts may be substantially parallel but are substantially perpendicular to the central segment, which is not shown for its obviousness.

The magnetic sensor (118) illustrated in FIG. 3 can be implemented to comprise a reference sensor (150) and a signal sensor (152) as illustrated in FIG. 8. Referring to FIG. 8, magnetic sensor 118 on/in sensor substrate 120 comprises reference sensor 150 and signal sensor 152. The reference sensor (150) can be designated for dynamically measuring the magnetic signal background in which the target magnetic signal (e.g. the magnetic field from the conductive wire 146 as illustrated in FIG. 7) co-exists. The signal sensor (152) can be designated for dynamically measuring the target magnetic signal (e.g. the magnetic field from the conductive wire 146 as illustrated in FIG. 7). In other examples, the signal sensor (152) can be designated for dynamically measuring the magnetic signal background in which the target magnetic signal (e.g. the magnetic field from the conductive wire 146 as illustrated in FIG. 7) co-exists, while the signal sensor (150) can be designated for dynamically measuring the target magnetic signal (e.g. the magnetic field from the conductive wire 146 as illustrated in FIG. 7).

The reference sensor (150) and the signal sensor (152) preferably comprise magneto-resistors, such as AMRs, giant-magneto-resistors (such as spin-valves, hereafter SV), or tunneling-magneto-resistors (TMR). For demonstration purpose, FIG. 9 illustrates a magneto-resistor structure, which can be configured into CIP (current-in-plane, such as a spin-valve) or a CPP (current-perpendicular-to-plane, such as TMR structure). As illustrated in FIG. 9, the magneto-resistor stack comprises top pin-layer 154, free-layer 156, spacer 158, reference layer 160, bottom pin layer 162, and substrate 120. Top pin layer 154 is provided for magnetically pinning free layer 156. The top pin layer can be comprised of IrMn, PtMn or other suitable magnetic materials. The free layer (156) can be comprised of a ferromagnetic material, such as NiFe, CoFe, CoFeB, or other suitable materials or the combinations thereof. The spacer (158) can be comprised of a non-magnetic conductive material, such as Cu, or an oxide material, such as Al2O3, MgO or other suitable materials. The reference layer (160) can be comprised of a ferromagnetic magnetic material, such as NiFe, CoFe, CoFeB, or other materials or the combinations thereof. The bottom pin layer (162) is provided for magnetic pinning the reference layer (160), which can be comprised of a IrMn, PtMn or other suitable materials or the combinations thereof. The substrate (120) can be comprised of any suitable materials, such as glass, silicon, or other materials or the combinations thereof.

In examples wherein the spacer (158) is comprised of a non-magnetic conductive layer, such as Cu, the magneto-resistor (118) stack can be configured into a CIP structure (i.e. spin-valve, SV), wherein the current is driven in the plane of the stack layers. When the spacer (158) is comprised of an oxide such as Al2O3, MgO or the like, the magneto-resistor stack (118) can be configured into a CPP structure (i.e. TMR), wherein the current is driven perpendicularly to the stack layers.

In the example as illustrated in FIG. 9, the free layer (156) is magnetically pinned by the top pin layer (154), and the reference layer (160) is also magnetically pinned by bottom pin layer 162. The top pin layer (154) and the bottom pin layer (162) preferably having different blocking temperatures. In this specification, a blocking temperature is referred to as the temperature, above which the magnetic pin layer is magneticallydecoupled with the associated pinned magnetic layer. For example, the top pin layer (154) is magnetically decoupled with the free layer (156) above the blocking temperature Tp, of the top pin layer (154) such that the free layer (156) is “freed” from the magnetic pinning of top pin layer (154). Equal to or below the blocking temperature Tp of the top pin layer (154), the free layer (156) is magnetically pinned by the top pin layer (154) such that the magnetic orientation of the free layer (156) is substantially not affected by the external magnetic field. Similarly, the bottom pin layer (162) is magnetically decoupled with the reference layer (160) above the blocking temperature Tp of the bottom pin layer (162) such that the reference layer (160) is “freed” from the magnetic pinning of bottom pin layer (162). Equal to or below the blocking temperature Tp of the bottom pin layer (162), the reference layer (160) is magnetically pinned by the bottom pin layer (162) such that the magnetic orientation of the reference layer (160) is substantially not affected by the external magnetic field.

The top and bottom pin layers (154 and 162, respectively) preferably have different blocking temperatures. When the free layer (156) is “freed” from being pinned by the top pin layer (154), the reference layer (160) preferably remains being pinned by the bottom pin layer (162). Alternatively, when the free layer (156) is still pinned by the top pin layer (154), the reference layer (160) can be “freed” from being pinned by the bottom pin layer (162). In the later example, the reference layer (160) can be used as a “sensing layer” for responding to the external magnetic field such as the target magnetic field, while the free layer (156) is used as a reference layer to provide a reference magnetic orientation.

The different blocking temperatures can be accomplished by using different magnetic materials for the top pin layer (154) and bottom pin layer (162). In one example, the top pin layer (154) can be comprised of IrMn, while the bottom pin layer (162) can be comprised of PtMn, vice versa. In another example, both of the top and bottom pin layers (154 and 162) may be comprised of the same material, such as IrMn or PtMn, but with different thicknesses such that they have different blocking temperatures.

It is noted by those skilled in the art that the magneto-resistor stack (118) is configured into sensors for sensing magnetic signals. As such, the magnetic orientations of the free layer (156) and the reference layer (160) are substantially perpendicular at the initial state. Other layers, such as protective layer Ta, seed layers for growing the stack layers on substrate 120 can be provided. It is further noted that the magnetic stack layers (118) illustrated in FIG. 9 are what is often referred to as “bottom pin” configuration in the field of art. In other examples, the stack can be configured into what is often referred as “top pinned” configuration in the field of art, which will not be detailed herein.
In some applications, multiple magnetic sensing mechanisms can be provided, an example of which is illustrated in FIG. 10. Referring to FIG. 10, magnetic sensing mechanisms 116 and 164 are provided for detecting the movements of proof-mass 112. The multiple magnetic sensing mechanisms can be used for detecting the movements of proof-mass 112 in driving mode and sensing mode respectively. Alternatively, the multiple magnetic sensing mechanisms 116 and 164 can be provided for detecting the same modes (e.g., the driving mode and/or the sensing mode).

By using the different blocking temperatures of the sensors as discussed above with reference to FIG. 9, the reference sensor (150) and signal sensor (152) can be dynamically activated or deactivated for sensing the target magnetic field. For demonstration purpose, FIG. 11 shows an exemplary operation method of measuring a target magnetic field (e.g., from the wire 146 as illustrated in FIG. 7) by using the magnetic sensor (118 as illustrated in FIG. 8).

With reference to FIG. 7, FIG. 8, and FIG. 11, the wire can be set to the OFF state by not driving a current through the wire at the initial time $T_1$. The reference sensor can be set to the ON state. The ON state of the reference sensor can be achieved through “freezing” the free layer of the reference sensor by raising the temperature of the pin layer that pins the free layer of the reference sensor above its blocking temperature (e.g., by applying a series of heating pulses or current pulses) and driving a current through the reference sensor so as to measure its magneto-resistance. The signal sensor at this time can be set to the ON or any other suitable state, even though it is preferred that the signal sensor can be set to the OFF state to avoid the magnetic field generated by the current driven through the signal sensor for setting the signal sensor to the ON state. Because the wire is set to the OFF state and no current is driven through the wire, the reference sensor measures the instant magnetic signal background at time $T_1$. After the reference sensor finished the measurement, it locks its instant state at time $T_1$ by for example, lowering the temperature of its top pin layer (used for pinning the free layer) below its blocking temperature such that the free layer is magnetically coupled to (thus pinned by) the top pin layer. The reference sensor at this state is referred to as the “Lock” state.

At time $T_1$, the wire remains OFF and the signal sensor can be set to any state. When the reference sensor is stabilized at the “Lock” state (e.g. finishes “locking” the state of its free layer), the wire is set to the ON state at time $T_2$, by driving current with pre-defined amplitude through the wire so as to generate magnetic field. The current can be DC or AC. After the magnetic field generated by the wire is stabilized, the signal sensor can be set to the ON state. Setting the signal sensor to the ON state can be accomplished by raising the temperature of the pin layer used for pinning the free layer of the signal sensor above its blocking temperature so as to free the free layer. A current is driven through the signal sensor so as to measure its magneto-resistance.

After the signal sensor finished the measurement, it locks its instant state at time $T_2$ by for example, lowering the temperature of its top pin layer (used for pinning the free layer) below its blocking temperature such that the free layer is magnetically coupled to (thus pinned by) the top pin layer. The signal sensor at this state is referred to as the “Lock” state.

When the signal sensor finishes its locking at time $T_2$, the reference sensor and the signal sensor can output their measurements to so to obtain the magnetic field from the magnetic source attached to the proof-mass, thus extract the information of the movement of the proof-mass.

The reference sensor and the signal sensor can be connected by a Wheatstone bridge, or can be connected directly to an amplifier or other electrical circuits to obtain the target magnetic field, which not be detailed herein.

In the example discussed above, the reference sensor and/or the signal sensor can be configured to “lock” the status (e.g. the detected magnetic signal). This locking capability can be accomplished in many ways. In the following, such locking capability will be discussed with reference to signal sensor, and the reference sensor can be implemented in substantially the same ways.

In one example, the signal sensor can be configured to be comprised of a storage layer that comprises a ferromagnetic layer. The storage layer is connected to electrical leads such that electrical current can be applied through the storage layer. When current is applied, the storage layer is heated, and its temperature can be elevated.

The material, as well as the geometry (e.g. the thickness) of the storage layer can be configured such that at the elevated temperature above a threshold temperature, such as the Currie temperature, the storage layer is capable of being magnetized by the target magnetic signal so as to accomplish the detection of the target magnetic signal. When the temperature of the storage layer is dropped to a temperature below the threshold temperature, the storage layer “freezes” its magnetization states so as to accomplish its “locking” operation. FIG. 12 illustrates such operation.

Referring to FIG. 12, the vertical axis plots the coercivity of the storage layer (e.g. the ferromagnetic layer of the storage layer); and the horizontal axis plots the temperature. The coercivity of the storage layer (ferromagnetic layer) decreases with increased temperature. At room temperature RT, the storage layer has a coercivity that is higher than the target magnetic signal $H_{\text{target}}$, therefore, the storage layer is unable to detect the target magnetic signal. As the temperature of the storage layer increases, the coercivity of the storage layer decreases. At the storing temperature (or the blocking temperature wherein the signal storage layer transits from ferromagnetic to paramagnetic or super-paramagnetic), the coercivity of the storage layer is equal to or less than the target magnetic signal $H_{\text{signal}}$ such that the storage layer is capable of being magnetized and thus detecting the target magnetic signal. After the detection, the temperature of the storage layer can be decreased, by for example, removing the current applied through the storage layer (e.g. the ferromagnetic layer of the storage layer). When the temperature of the storage layer is decreased to a temperature below the storing temperature, the magnetization state of the ferromagnetic layer (storage layer) is “locked” because the coercivity of the storage layer is higher than the target magnetic field. With this mechanism, the storage layer accomplishes the “locking process.”

The coercivity of a magnetic thin-film (layer) also varies with its thickness, as diagrammatically illustrated in FIG. 13. The storage layer can have a thickness such that the coercivity of the signal-storage layer is in the vicinity of the target magnetic field $H_{\text{target}}$, such as within a range of ±0.5%, ±1%, ±1.5%, ±2%, ±2.5%, ±3%, ±4%, ±5%, ±6%, ±10% of $H_{\text{target}}$. Especially when the storage layer has a thickness such that its coercivity is higher than $H_{\text{target}}$, a thermal layer can be provided to adjust the coercivity of the storage layer.

In addition to utilizing the temperature dependence of coercivity of a ferromagnetic layer, a magnetic coupling
structure can be utilized to accomplish the “locking” process, as illustrated in FIG. 14. Referring to FIG. 14, the signal sensor comprises free layer 172 and pinning layer 170. The free layer (172) is a ferromagnetic layer, and is provide for responding to the target magnetic field to be detected. The pinning layer (170) is an antiferromagnetic layer, and is provided for magnetically pinning the free layer (172) through the exchange magnetic field \( H_{exch} \). It is known in the art that the magnetic exchange field \( H_{exch} \) changes with temperature. When the temperature is higher than the blocking temperature \( T_{b} \) that characterizes the magnetic exchange field between the free layer (172) and pinning layer (170), the magnetic exchange field between the free layer (172) and pinning layer (172) is broken, e.g. reduced to a level such that the free layer (172) and pinning layer (172) are magnetically decoupled. The free layer (172) is not pinned by the pinning layer (172) at this temperature. By utilizing such magnetic-couple (pinning) and magnetic-decouple (unpinning), the signal sensor comprising the free layer (172) and pinning layer (170) can accomplish the state locking process.

For example, when it is desired to detect the target magnetic field signal, the signal sensor may elevate its temperature above the blocking temperature \( T_{b} \) by, for example, applying current through the free layer (172) and/or the pinning layer (170). The free layer (172) is thus "free" and can be used for picking up the target magnetic field signal. When it is desired for the signal sensor to lock its detection, for example, after the detecting the target magnetic signal, the signal sensor can decrease its temperature below the blocking temperature \( T_{b} \). At a temperature below \( T_{b} \), the free layer (172) is magnetically pinned by the pinning layer (172). The magnetic states of the free layer (172), which corresponds to the target magnetic field signal, is thus "frozen" in the free layer (172).

The MEMS gyroscope with the above discussed status locking mechanism can be operated in many ways for detecting the target angular velocity, an example of which is diagrammed in FIG. 15. Referring to FIG. 15, \( \Delta T_{ref} \) refers to the time period used for detecting the background signal by the reference sensor, and \( \Delta T_{target} \) refers to the time period used for detecting the target magnetic field signal by the signal sensor. \( \Delta T_{delay} \) refers to the time period when the reference sensor and signal sensor are not responding to the background magnetic field signal or the target magnetic field signal.

A detecting time period from time \( T_{0} \) to time \( T \) comprises a \( \Delta T_{target} \) and may or may not comprise \( \Delta T_{ref} \). In examples wherein \( \Delta T_{ref} \) exists, \( \Delta T_{ref} \) can be at any time location between detecting time period from \( T_{0} \) to time \( T \). In particular, \( \Delta T_{ref} \) can be at the beginning of the detecting time period. In another example, \( \Delta T_{ref} \) can be at the immediate front of \( \Delta T_{target} \). In an alternative example, \( \Delta T_{target} \) can be immediately followed by \( \Delta T_{target} \). The detecting time period from \( T_{0} \) to \( T \) may also comprise one or more delay time periods \( \Delta T_{delay} \). The delay time period(s) can be at any time location in the detecting time period from \( T_{0} \) to \( T \), as shown in FIG. 15. In one example, \( \Delta T_{delay} \) can be immediately after the completion of \( \Delta T_{target} \).

FIG. 16 shows a flow chart having steps executed by the MEMS gyroscope according to the operation discussed above with reference to FIG. 16. Referring to FIG. 16, the MEMS gyroscope can be initialized (step 174). During the initialization, the MEMS gyroscope device can perform self-test, self-calibration, stabilization of its functional operations (e.g. establishing a stable voltage and/or current). After the initialization, the proof-mass is driven to move in the drive mode, such as vibrating with its own mechanical resonant frequency (step 176). As discussed above, the proof-mass can be driven by capacitors.

When the movement of the proof-mass in the drive mode is established and preferably stabled, the reference sensor can be turned on to measure the magnetic signals in the background in which the target magnetic field signal exists (step 178). When the reference sensor completes the measurement, it is turned to the “lock” state, at the state of which the instant measurement is locked in the reference sensor (180). The signal sensor can then be turned on (step 182). Before or substantially simultaneously turning on the signal sensor, the magnetic source of the proof-mass can be activated so as to generate the target magnetic field, especially when the magnetic source comprises a conducting wire or a super-paramagnetic nanoparticle. In these examples, the target magnetic signal appears after the measurement of the reference sensor (measures the background magnetic signal) and is measured by the signal sensor. As a consequence, the measurement from the reference sensor comprises the instant background magnetic signal, and the measurement from the signal sensor comprises both of the instant background magnetic signal and the target magnetic signal. By differentiating the measurements from the reference and signal sensors, the target magnetic field can be extracted. This configuration and measurement process can be of great importance in applications when the background comprises complex magnetic signals.

When the signal sensor completes the measurement, it may lock its measurement by entering into a lock state, even though it is not required. After both of the reference and signal sensors complete their measurement, the measurement results from the reference and signal sensors can be compared (step 184) so as to extract the target magnetic field. The movement of the proof-mass, and thus the target angular velocity can be determined.

After obtaining the target magnetic field at step 184, it is determined if the entire measurement is finished (step 186). If so, the measurement process can be stopped. Alternatively, the reference and signal sensors can be set, for example, to their initial states for the next measurement (step 188). If the entire measurement is not finished (e.g. according to the scheme shown in FIG. 15) at step 186, the process flows back to step 176, and the process continues.

In addition to the scheme shown in FIG. 15, other measurement schemes can be utilized. For example as shown in FIG. 17, multiple \( \Delta T_{ref} \) periods can be provided in the scheme for measuring the instant background magnetic signals. This can be advantageous especially when the entire measurement period is long or the background comprises fast varying magnetic signals. By increasing the number of \( \Delta T_{ref} \) period, the instant background magnetic field can be more accurately measured.

In some examples, a measurement scheme can be divided into multiple sections and each section may have different schemes, an example of which is illustrated in FIG. 18. Referring to FIG. 18, T0 to T1 and T1 to T2 are different or independent measurement sections. “Independent sections” refers to that the measurement of the two sections are independent, a measurement in one section does not affect the measurement of another section regardless of their sequence. Each section may or may not have the same scheme. For example, the section from T0 to T1 may comprise the measurement scheme discussed above with reference to FIG. 5,
and the section from T1 to T2 comprises the measurement scheme discussed above with reference to FIG. 17. In other examples, the measurement of the background magnetic signal by the reference sensor can be activated dynamically based upon the actual or projected variation of the background magnetic signal. For example, a measurement from the signal sensor can be compared to the previous measurement by the same signal sensor. If the difference is above a predefined threshold, the reference sensor can be activated for measuring the instant background magnetic field signal. This step is preferably accomplished by turning off the magnetic source (e.g. the conducting wire) and then measuring the background magnetic field signal using the reference sensor.

[0068] It will be appreciated by those of skilled in the art that a new and useful MEMS gyroscope and a method of operating the same have been described herein. In view of the many possible embodiments, however, it should be recognized that the embodiments described herein with respect to the drawing figures are meant to be illustrative only and should not be taken as limiting the scope of what is claimed. Those of skill in the art will recognize that the illustrated embodiments can be modified in arrangement and detail. Therefore, the devices and methods as described herein contemplate all such embodiments as may come within the scope of the following claims and equivalents thereof. In the claims, only elements denoted by the words "means for" are intended to be interpreted as means plus function claims under 35 U.S.C. §112, the sixth paragraph.

We claim:

1. A method of measuring an angular velocity by using a MEMS gyroscope, the method comprising:
   - driving the proof-mass to move in a driving mode using a group of capacitors;
   - measuring a background magnetic signal using a reference magnetic sensor;
   - storing the measurement from the reference magnetic sensor;
   - generating a target magnetic field that is associated with a movement of a proof-mass of the MEMS gyroscope;
   - activating a signal magnetic sensor for measuring the background magnetic signal and the generated target magnetic signal;
   - comparing the measurements from the reference and signal magnetic sensors so as to obtain the target magnetic field;
   - and extracting the angular velocity from the target magnetic field.

2. The method of claim 1, wherein the step of measuring the background magnetic signal comprises:
   - raising the temperature of the reference magnetic sensor above a blocking temperature of the reference sensor such that the reference sensor is capable of detecting the background magnetic field signal.

3. The method of claim 2, wherein the reference sensor comprises a free layer for detecting the background magnetic field signal, wherein the free layer is magnetically pinned by an antiferromagnetic layer when the temperature is below the blocking temperature.

4. The method of claim 2, wherein the step of generating the magnetic field comprises:
   - driving a current through a conductive wire so as to generating the magnetic field.

5. The method of claim 4, wherein the magnetic sensor comprises a spin-valve structure.

6. The method of claim 4, wherein the magnetic sensor comprises a tunneling-magneto-resistor structure.

7. A method of detecting a target angular velocity, comprising:
   - providing a MEMS gyroscope that comprises a movable proof-mass, a magnetic source, and a magnetic sensor, wherein the proof-mass is capable of moving in response to the target angular velocity under the Coriolis effect, and wherein the magnetic source is capable of generating a magnetic field that varies with the movement of the proof-mass, and wherein the magnetic sensor is capable of detecting the magnetic field from the magnetic source;
   - detecting a background magnetic signal using a reference sensor;
   - storing the detected background magnetic signal by the reference sensor;
   - causing the proof-mass to vibrate using a group of capacitors;
   - generating the magnetic field by the magnetic source;
   - detecting a variation of the magnetic field by the magnetic sensor; and
   - extracting the angular velocity from the variation of the magnetic field.

8. The method of claim 7, wherein the step of measuring the background magnetic signal comprises:
   - raising the temperature of the reference magnetic sensor above a blocking temperature of the reference sensor such that the reference sensor is capable of detecting the background magnetic field signal.

9. The method of claim 8, wherein the reference sensor comprises a free layer for detecting the background magnetic field signal, wherein the free layer is magnetically pinned by an antiferromagnetic layer when the temperature is below the blocking temperature.

10. The method of claim 8, wherein the step of generating the magnetic field comprises:
    - driving a current through a conductive wire so as to generating the magnetic field.

11. The method of claim 8, wherein the magnetic sensor comprises a spin-valve structure.

12. The method of claim 8, wherein the magnetic sensor comprises a tunneling-magneto-resistor structure.