Novel Micro Gyroscope with High-Q Rotational Vibration Structure

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A rotational vibrating disk with a high Q value was proposed and applied to a micro gyroscope. This structure consists of a disk surrounded by four pendulums mounted at 90° increments. When rotationally resonant vibration is induced in the disk, there is an unmoving point on each arm of pendulums. When this point, is clamped, the vibratory energy loss was able to be reduced. This structure achieves a very high Q value of 85,000 in a vacuum. We used this rotational mode as a reference vibration for a vibratory gyroscope. The excitation of the vibration was induced by electrostatic forces. Electrodes were placed adjacent to the lower portion of the disk to measure the angular rate. The electrodes established a capacitance between themselves and the disk. The Coriolis force produces a displacement of the disk and this displacement varies the detection capacitance. Measuring the change in capacitance allowed for the measurement of the angular rate.

This paper describes the design and fabrication of the proposed device along with some results and observations.

Keywords : Gyroscope, MEMS, Rotational Vibration, Q value

1. Introduction

There has been increasing interest in the use of micro-electro-mechanical systems (MEMS) in vibratory gyroscopes in recent years⁽¹⁾⁻⁽⁸⁾.

Gyroscopes consisting of disk-shaped vibrating structure in 90° axially symmetric patterns are particularly useful, since these arrangements are able to detect two-axis angular velocity simultaneously⁽⁴⁾⁻⁽⁶⁾⁽⁸⁾. In order to obtain a sufficiently large reference vibration with a small energy input for reference vibration of such devices, the spring structure must be designed to ensure low vibratory losses. Some reports on disk shaped gyroscopes have described devices in which the springs support the disk from the exterior⁽⁴⁾⁽⁵⁾⁽⁸⁾ and where the springs support the disk from the interior⁽⁶⁾⁽⁷⁾. In each of these gyroscopes, one end of the spring was fixed, allowing the vibratory energy to leak from the structure to the substrate. Energy leakage reduces the Q value of a vibrating structure.

In this paper, a novel developed MEMS gyroscope is introduced that has the high Q value of the rotational vibration.

2. Basic Structure and Operation Principle of the Gyroscope

Figure 1 shows the structure of the gyroscope. A silicon structure is constructed on an etched glass substrate. Four electrodes are pre-formed on the lower substrate. Four measuring capacitances are formed between the disk and these electrodes.

Figure 2 shows some details of the silicon structure. The disk is on the center of the device and four pendulums are linked to the disk. Each pendulum consists of a flexible arm and a fan-shaped mass. The pendulums are positioned at 90° angles to each other. The arms of the pendulums are cantilevered from the bottoms of long notches in the disk.

Fig. 1. Structure of the gyroscope

The reference vibration of the gyroscope is driven at the rotational resonance mode of the disk. In this mode, when all of the pendulums rotate clockwise (counter clockwise), the disk itself rotates counter clockwise (clockwise). Outside of pendulums is a slit actuator that is able to drive the outer edge of the pendulums into this mode. When an angular rate Ω_x about the x-axis is applied, the generated Coriolis force causes the disk to vibrate about the y-axis. This vibration is the detection vibration. Displacement of the disk by the detection vibration causes a

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Fig. 2. Silicon vibrating structure

differential change in the capacitance pair (C_{x1} , C_{x2}) formed by the disk and the electrodes on the substrate beneath the disk. The angular rate can be determined by measuring this change. In the same way, if Ω_y is induced about the y-axis, this generates a disk vibration about the x-axis. Since two sets of mutually perpendicular differential-capacitors (C_{x1} , C_{x2} and C_{y1} , C_{y2}) are formed, angular rates along the two axes can be detected simultaneously.

3. Design and Performance Analysis

3.1 Design of Gyroscope The proposed device consists of a $10 \times 10 \text{ mm}^2$ chip with a $3 \times 3 \text{ mm}^2$ movable structure. The radius of the vibrating disk is 1 mm (Fig. 3(a)).

The reference resonance frequency must be low in order to increase the detection vibration amplitude of the gyroscope. Therefore, the disk is supported by high-compliance, long arms. These arms attach to the disk near its center at the bottom of deep notches, as shown in Fig. 3(b). In order to ensure the most effective storage of the rotational vibration energy, large fan-shaped pendulums are attached to the tips of the arms (Fig. 3(c)).

Figure 4 shows the analytical results obtained with a finite-element method (FEM) where only of the center point of the disk is constrained to the fixed point. The resonance mode in Fig. 4 shows clockwise movement of the disk during counterclockwise movement of all of the pendulums. A stationary node (nodal point) occurred each arm in this mode. The node location varies with the beam length and the pendulum mass. Our design, the mass of each pendulum is set to be 1/4 of the disk mass and the beam length has been adjusted so that the nodal point is beyond the outer edge of the disk. Clamping the beams at these points allowed for the vibratory energy losses to be reduced. The beam with a one-meander serpentine spring makes a connection between this nodal point and substrate. Figure 5 shows the FEM results after the nodal point was clamped. The vibratory mode was nearly the same in this structure as in the unclamped one (Fig. 4). The resonance frequencies in the reference mode and the detection mode are 4861 Hz and 9680 Hz, respectively.

3.2 Performance Analysis For the reference vibration in gyro operation, the disk is driven by slit actuators located

Fig. 3. Design of structure. (a) Vibrating disk (b) Pendulum arms attached to the disk near its center. (c) Pendulum masses attached to the tips of the arms.

Fig. 4. FEM modal analysis for finding nodal point

around the periphery of the pendulums. Figure 6 shows the detail of this actuator. Alternately applying voltages to exterior driving electrodes (Electrode 1 and 2 in Fig. 6) induce left-right motion in the pendulums. Four slit actuators consist of 60 pairs of gaps for each direction of the motion. The driving force F generated by the electrostatic force in the actuator will now be described. F is given by the following expression, where ϵ is the dielectric constant in a

vacuum, d is the gap in the slit actuator, t is the structure thickness and V is the driving voltage:

$$F = \frac{1}{2} \epsilon \frac{t}{d} V^2 \quad (1)$$

The values for driving voltage, gap and structure thickness in the design were 8 V, 2 μm and 50 μm , respectively. These values resulted in a force of $F = 0.425 \mu\text{N}$.

Next, the reference vibration amplitude was derived using the FEM results. The previously calculated driving force F was used, and the mechanical Q value was estimated at 80,000 from the investigation of the prototype device. Harmonic FEM analysis indicated maximum vibration amplitudes of 22.2 μm and 4.35 μm

for the disk and the pendulums, respectively. The change in capacitances in the slit actuators due to that displacement was 57.8 fF.

Finally, Figure 7 shows the angular rate FEM results for the structure when a 1 rad/s angular rate was applied. The FEM analysis with Coriolis force was carried out by following. 1: the harmonic analysis for reference vibration was performed and the velocity vector of each element in FEM was calculated, 2: the mass of each element was calculated from density and volume of the element, 3: the Coriolis force for each element was estimated from mass, velocity and applied angular rate, and 4: with estimated Coriolis force as a boundary condition or force load for each element, harmonic analysis was performed again and the analysis was completed. This procedure was put together into "Coriolis macro" program for FEM Simulator⁽⁹⁾.

The displacement of the outer edge of the disk in the z-direction due to the Coriolis force was estimated to be 0.434 nm/rad/s, which corresponds to a capacitance change of around 1.01 fF according to the calculation method described in ref. (9). Table 1 provides a summary of the designed characteristics of this gyroscope.

Fig. 5. FEM modal analysis of the gyroscope

Fig. 7. FEM analysis using Coriolis macro

Table 1. Designed characteristics of the gyroscope

<i>Resonance frequency</i>	
Reference vibration [f_r]	4861 Hz
Detection vibration [f_d]	9680 Hz
<i>Amplitude of vibration</i> (Q value $Q=80,000$, driving voltage = 8V)	
The fringe of disk	22.2 μm
The fringe of pendulum	4.35 μm
ΔC for slit actuator [ΔC_s]	57.8 fF
<i>Displacement of disk by Coriolis force</i>	
The fringe of disk	0.434 nm/rad/s
ΔC for detector [ΔC_d]	1.01 fF/rad/s

Fig. 6. Detail of slit actuator

Fig. 8. Fabrication process

4. Fabrication Process

Figure 8 shows the processes for fabricating this device. A four-inch with 500 μm thick glass wafer and a four-inch with 250 μm thick bulk silicon wafer were prepared. A groove was etched into the glass wafer to allow the silicon structure to move. The detection electrodes were formed on the glass substrate. The silicon wafer was bonded to the glass substrate. Chemical mechanical polishing was employed to create a 50 μm layer of silicon. The silicon structure was then formed using Deep RIE.

Figure 9 shows photographs of the fabricated device. The chip size is $10 \times 10 \text{ mm}^2$ with thickness of 0.55 mm. The design gap of both the slit actuators and between the vibrating disk and the fixed electrodes on the glass substrate were 2 μm . However, in prototype device the gap of the slit actuators have been enlarged to around 8 μm due to loading effect and temperature distribution in Deep-RIE step.

5. Experimental Result

The predicted change in capacitance of 1.01 fF/rad/s is extremely low (Table 1). In order to detect such low capacitance changes, the C/V converter circuit as shown in Fig. 10 was used for measurements. The circuit consists of an oscillator, an I/V converter, amplifiers, and a synchronous demodulator. The figure also shows the gain at each stage. This circuit can be applied not only to the detection of the rate signal but also the monitoring of the amplitude of the reference vibration.

The detection capacitor electrodes were attached as shown in Fig. 10. The differential capacitors were driven by the two opposite polarity signals (carrier signals) from the oscillator. A current was generated due to changes in the capacitance of the differential

Fig. 9 Photographs of fabricated device. (a) Overall chip. (b) Slit actuator. (c) Nodal point clamped by thin beam. (d) one-meander serpentine spring. (e) Pendulum arm attached to bottom of notch in the disk

capacitors, which was then converted to a voltage by the I/V converter. This voltage was amplified, synchronous demodulated with the carrier signal and measured by the lock-in amplifier. With the parameter from Fig. 10 and carrier signal of 100 kHz 1 V_{p-p} AC signal, the relationship between the output voltage V_{out} and ΔC can be expressed as follow:

$$V_{out} = 6.72 \times 10^{12} \times \Delta C \dots\dots\dots (2)$$

Table 2 shows the calculated relationship between the differential changes in capacitance and the output of the C/V converter for the reference vibration and the detection vibration, using Table 1 and eq. (2).

5.1 Resonance curve of the Reference Vibration The slit actuators were driven with a 1 to 8 V_{p-p} AC signal with a DC offset of 4 V. Figure 11 shows the characteristics of the resonance curve in a vacuum. The vertical axis is the voltage output from the C/V converter and the calculated displacement of the slit actuators,

Fig. 10. Block diagram of measuring circuit

Table 2. Output of C/V converter

Reference output ($\Delta x = 4.35 \mu\text{m}$)	
ΔC of slit actuator [ΔC_r]	57.8 fF
C/V converter output	388 mV
Detection output	
ΔC of Detector [ΔC_d]	1.01 fF/rad/s
C/V converter output	6.76 mV/rad/s

Fig. 11. Resonance curve of the reference vibration

Fig. 12. Q value of the reference vibration.
Solid line shows fitting result

Fig. 13. Output for applied angular rate

where the gap d is regarded as the actual value of $8 \mu\text{m}$. Asymmetrical characteristics were observed under high driving voltages due to the hard-spring effect.

Figure 12 shows the resonance curve under a driving voltage of $1 V_{p-p}$. This curve was symmetrical in this low range. Calculations using numerical fitting indicate a resonance frequency and a Q value of 3656.3 Hz and 85,000, respectively.

Some of MEMS resonators, especially the devices based on torsion bars and tuning forks show extremely high Q values of $10^4 - 10^6$ (1)(10). However, Q values for disk resonators are usually not so high; according to reports up to the present, the Q values have been around $10^2 - 10^3$ (4)(7)(8). Thus, the proposed structure shows an extremely high Q value for a disk resonator.

5.2 Detection of Angular Rate Figure 13 shows the output signal from the system for applied angular rates. Since the driving signal was mixed with the output, this was subtracted to obtain the values in the figure. The applied angular rate was varied from 0 rad/s to -7 rad/s, then changed to +7 rad/s, and finally reduced to 0 rad/s. The voltage applied to the slit actuators was a $30 V_{p-p}$ AC signal with a DC offset of 15 V. The output was about 0.38 mV/rad/s. This output was about 1/18 of the output level

shown in Table 2. The noise in the output was analyzed under the assumption of a normal distribution. The standard deviation, or RMS noise level, was calculated to be $8.7 \times 10^{-5} \text{ V}$, or an equivalent resolution of about 0.2 rad/s.

In this stage, sensitivity is not so high comparing to the designed values. The deterioration in the sensitivity and S/N ratio (resolution) was blamed on two factors: (1) The actual slit actuator gap of $8 \mu\text{m}$, rather than the $2 \mu\text{m}$ design gap, due to overetching in RIE step reduces the amplitude of the reference vibration; and (2) The Q value decreases due to poor vacuum maintenance by our vacuum package. Thus, it seems likely that the resolution can be upgraded by improving the RIE conditions and the vacuum

packaging.

6. Conclusion

A novel disk-shaped gyroscope was designed, fabricated and tested. The newly developed disk generated a high Q value of 85,000 due to the clamping of the resonance nodes. The disk was also shown to be capable of measuring angular rates.

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