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微机械振动环陀螺

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摘要:为了减小振动环驱动模态和检测模态的频率差从而提高陀螺性能,提出了一种采用电磁驱动、电磁检测的全对称振动环陀螺结构。采用 MEMS 体硅工艺完成该微机械振动环陀螺的加工,其结构在保持镜像对称的同时,还保持了中心对称,因此整个结构高度对称,有利于减小模态频率差。为有效跟踪陀螺驱动模态的谐振频率并稳定驱动模态的幅值,设计了闭环驱动控制电路。该电路由低噪声前置放大器、相位调整环节以及自动增益放大器(VGA)组成。测试结果表明,该陀螺两个模态频率差为 0.27 Hz,实现了频率较好的匹配。在±200 °/s,测得陀螺灵敏度为 8.9 mV/(°/s),分辨力为 0.05 °/s,非线性度为 0.23%。

关　键　词:微机械陀螺;振动环陀螺;闭环控制
中图分类号:U666.12　　**文献标识码**:A

Micro-machined vibrating ring gyroscope

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Abstract: To reduce the frequency split of the drive mode and the sense mode of a vibrating ring gyroscope to improve the performance of the gyroscope, a novel symmetrical structure with electromagnetic driving and detection is proposed in this paper. The Micro-machined Vibrating Ring Gyroscope (MVRG) is fabricated in centro-symmetric and mirror-symmetric micro structures by MEMS bulk silicon processing with (100) oriented single-crystal silicon, which is conductive to reducing the frequency split. A closed-loop control circuit consisting of a low noise front-end amplifier, a phase shifter and a Variable Gain Amplifier (VGA) is developed to track the drive mode resonant frequency and to stabilize the vibration amplitude of the drive mode. The test results show that the frequency split of drive mode and the sense mode is about 0.27 Hz, which means the frequencies have been matched well. The sensitivity of this gyroscope is 8.9 mV/(°/s), the resolution is 0.05°/s and nonlinearity is about 0.23% in the rotation rate ranges of ±200 °/s.

Key words: micro-machined gyroscope; vibrating ring gyroscope; closed-loop control

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1 Introduction

Compared with other types of micro-machined gyroscopes, the vibrating ring gyroscope has lots of advantages, such as higher sensitivity, less sensitive to temperature and spurious vibrations[1]. The performance of the MVRG is markedly affected by the quality factor (Q-factor) and the frequency-split between drive and sense modes[2]. Several types of vibrating ring gyroscope have been reported[1-6], most of which are capacitive gyroscopes and use electronic tuning method to reduce the frequency split. In order to increase the capacitance to improve the sensitivity, it is necessary to fabricate high aspect ratio structure to reduce the air gap between the electrode planes[1,4], which inevitably increases the fabrication complexity. Furthermore, the capacitors are easily affected by parasitic capacitances, resulting in terrible co-channel interference. Thirdly, the electronic circuit used to tune the resonant frequencies is complicated.

A novel symmetric vibrating ring gyroscope structure is proposed in this paper. This highly symmetric structure is relatively easy to realize mode matching. The electromagnetic detection could effectively reduce the co-channel interface caused by parasitic capacitances, so the Signal Noise Ratio (SNR) of electromagnetic detection is higher than that of the capacitive detection, which provides the possibility to achieve high resolution. In addition, there's no high aspect ratio structure and the minimum air gap is about 30μm so as to simplify the fabrication processes. This gyroscope is fabricated through standard bulk MEMS processes. After being trimmed, the drive and sense modes could match well.

2 Principle and design

The MVRG consists of a vibrating ring with 100 μm in depth, 4 mm in radius and 40 μm in width and eight crab-leg support springs with 15 μm in width. The length of the radial support springs is about 600 μm and the tangential support springs about 3.4 mm. There are four drive metal electrodes (at 0, 90, 180, 270°) and four sense metal electrodes (the others), as shown in Fig. 1. Theoretical simulation shows that this highly symmetric layout provides better mode matching, which results in higher sensitivity and less sensitive to environmental vibrations and temperature change.

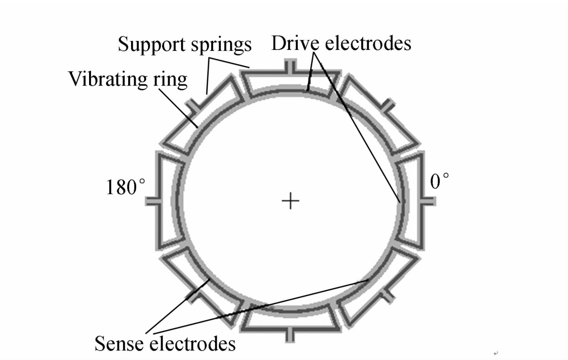
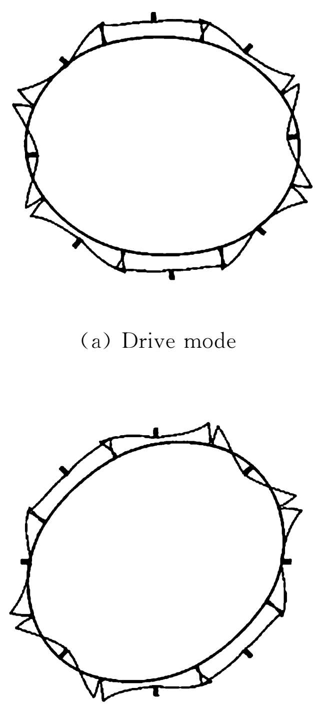


Fig. 1 Diagrammatic sketch of the gyroscope



(a) Drive mode

(b) Sense mode

Fig. 2 Flexural modes of the MVRG

The ring has two identical elliptically-shaped flexural modes with equal natural frequencies[7]. The first mode is primary mode (or drive mode), as shown in Fig. 2(a). And the second mode (or sense mode) is located 45 degree apart from the drive mode, as shown in Fig. 2(b). The ring is vibrated into the drive mode with a fixed amplitude which will generate electromagnetic force with the help of magnetic field when drive current flow through the drive electrodes. When the device is subject to rotation around its normal axis, energy is transferred from the drive mode to the sense mode caused by Coriolis force. Therefore, oscillation amplitude proportional to the rotation rate is built up in sense mode, which will generate induced voltage among the sense electrodes.

According to reference [8], when the resonant frequencies for both modes are same, the vibration amplitude of sense mode is given by

$$q_s = 4A_g \frac{Q}{\omega_0} q_d \Omega_z , \quad (1)$$

where q_d and q_s represent the drive amplitude and sense amplitude respectively; A_g is angular gain of the gyroscope; Q is quality factor; ω_0 angular frequency for both modes; Ω_z is input rotation rate.

The induced voltage in one sense electrode is

$$U = \int_0^{\pi/4} B \times r \times \dot{q}_s \times \sin(2\theta) \mathrm{d}\theta , \quad (2)$$

where B is magnetic flux density; r is radius of the ring; θ is radian of the electrode. Then the sensitivity of one electrode is

$$S = 2\sqrt{2} B r A_g \frac{Q}{\omega_0} \dot{q}_d . \quad (3)$$

3 Fabrication

The vibrating ring gyroscope adopts a single-wafer technology which uses a (100) oriented single-crystal silicon and DRIE process to release the main structure.

The main procedures are shown in Fig. 3. This technology starts with the growth of a 0.1

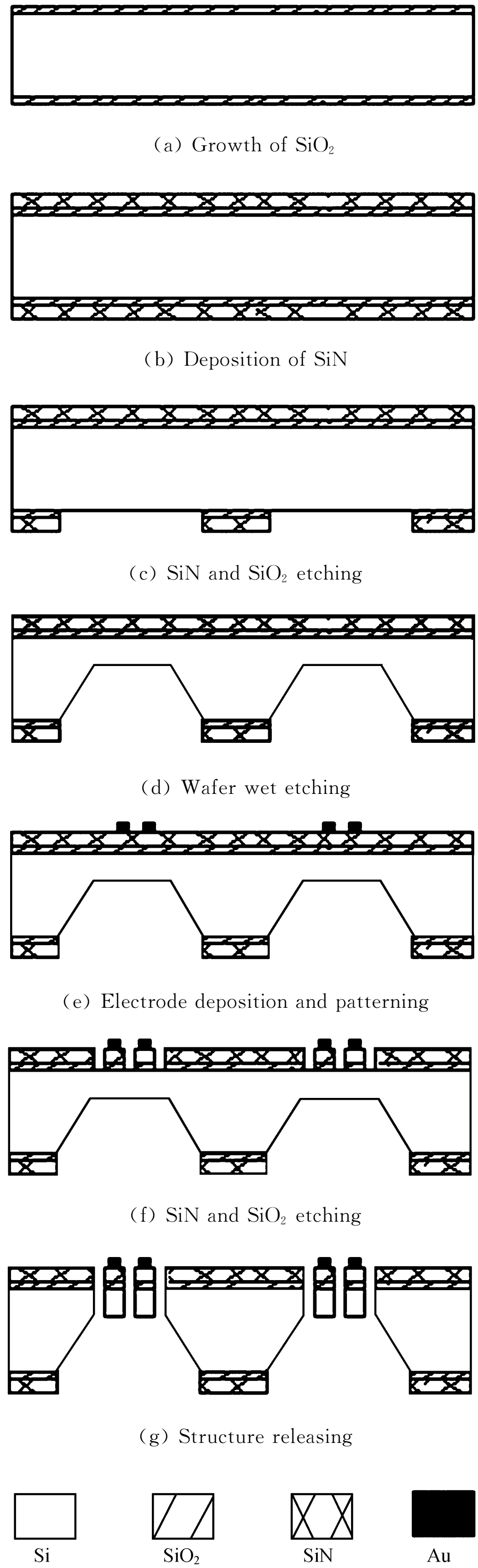


Fig. 3 Fabrication procedure

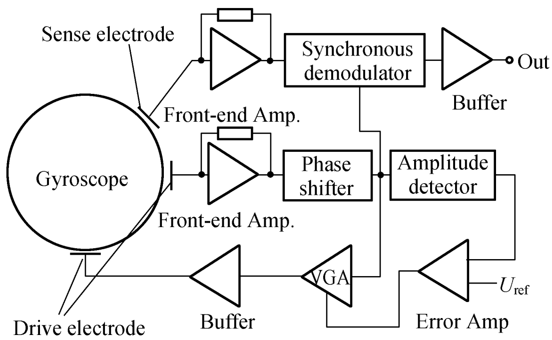
μm thick thermal SiO_2 layer on the silicon substrate as the transition layer. Then an insulation layer of 0.5 μm thick SiN is deposited by low pressure chemical vapor deposition (LPCVD). The photoresist is patterned to define the structure areas on the back of the wafer and the SiN within these areas is removed by reactive ion etching (RIE). And the SiO_2 layer is removed using buffer HF (BHF). Then the structure areas in the wafer are thinned down to 100 μm by KOH solution. The Au electrodes are deposited and patterned on the front side of the wafer. The photoresist is then patterned and the SiN layer is etched by RIE. DRIE is adopted to release the whole structure. Finally, any asymmetry introduced by silicon wafer or fabrication processes is trimmed. The processed wafer is then diced and packaged.

4 Package and circuitry

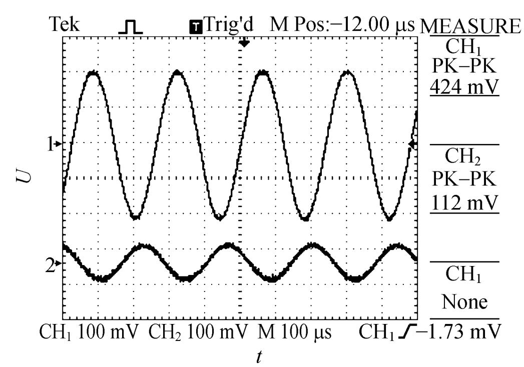
The gyroscope chip and a SmCo permanent magnet are assembled together and then packaged in a 18-pin sealed case, as shown in Fig. 4. The SmCo permanent magnet can create a 0.3 T magnetic field vertical to the vibration plane, and the magnetic field of SmCo magnets is stable with respect to temperature change.

Fig. 4 Photo of the packaged gyroscope

Fig. 5(a) shows the schematic diagram of the closed-loop drive and readout circuit. In order to track the resonant frequency of the drive mode automatically and stabilize the vibration at fixed amplitude, a self-oscillation circuit is designed, which mainly consists of a low noise front-end amplifier, a phase shifter and a variable gain amplifier (VGA). The phase shifter is used to ensure that the whole phase shifting is $2n\pi$. And the VGA can change its gain according to the output voltage of the error amplifier, so as to stabilize the vibration. The waveform of drive signal (CH_1) and vibration amplitude detection signal (CH_2) are shown in Fig. 5(b). The readout circuit consist of a low noise front-end amplifier, a synchronous demodulator and a buffer. The reference signal of the demodulator is from the drive signal, and a multiplier plus a low pass filter is used to perform the demodulation.



(a) Schematic diagram of the drive and sense circuit

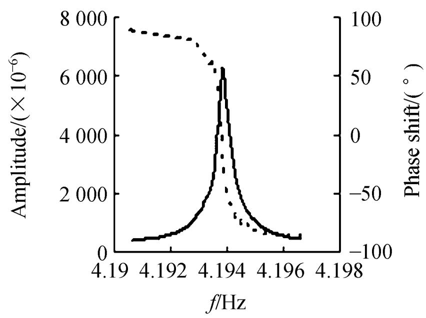


(b) Drive signal (CH_1) and vibration amplitude detection signal (CH_2)

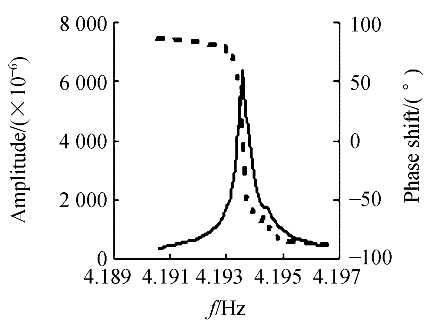
Fig. 5 Schematic diagram of the circuit and the signal curves

5 Test results

The resonant frequencies and Q-factors for drive and sense modes of the gyroscope are tested at about 1 Pa pressure using Dynamic Signal Analyzer (HP3562A). The resonant frequencies of drive and sense modes are 4.193 87 kHz and 4.193 6 kHz respectively, the frequency split is 0.27 Hz (see Fig. 6). The -3 dB bandwidth of both modes is 0.3 Hz. Therefore, the Q-factors for both modes are same about 14 000.



(a) Response of the drive mode



(b) Response of the sense mode

Fig. 6 Frequency responses of the MVRG

Fig. 7 shows the measured rate output of the gyroscope in open-loop detection mode in a range of ±200 °/s, which is carried out at room temperature and atmospheric pressure. The gyroscope has a sensitivity of about 8.9 mV/(°/s). The measured nonlinearity is about 0.23% in the ±200 °/s measurement range, which can be improved by operating the sensor in force-to-rebalance mode. The resolution of this gyroscope is about 0.05 °/s.

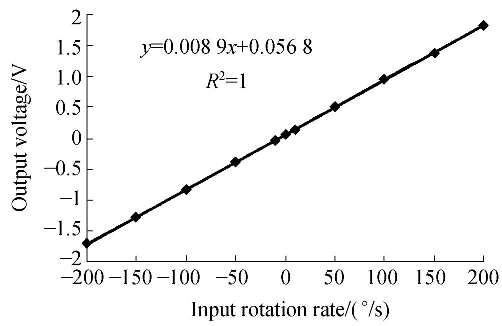


Fig. 7 Input *vs.* output

6 Conclusions

A novel highly symmetrical vibrating ring gyroscope has been designed, fabricated and measured. Initial test shows that the resonant frequencies of the drive and sense mode can match well. The Q-factors for two modes measured at 1 Pa low vacuum are both about 14 000. This sensor has a sensitivity of 8.9 mV/(°/s) in a range of ± 200°/s. The measured nonlinearity is about 0.23% and resolution is 0.05 °/s.

References:

[1] AYAZI F, NAJAFI K. A HARPSS polysilicon vibrating ring gyroscope [J]. *Journal of Microelectromechanical Systems*, 2001,10:169-179.

[2] KIM D J. A systematic method for tuning the dynamics of electrostatically actuated vibratory gyros [J]. *IEEE Trans. of Control Syst. Technology*, 2006,14:69-81.

[3] WENG J H, CHIENG W H, LAI J M. Structural design and analysis of micromachined ring-type vibrating sensor of both yaw rate and linear acceleration [J]. *Sensors and Actuators A*, 2005,117:230-240.

[4] AYAZI F, CHEN H H, KOCER F, *et al.*. A high aspect-ratio polysilicon vibrating ring gyroscope [C]. *Solid-State Sensor and Actuator Workshop*, *Hilton Head*, *SC*, 2000:289-292.

[5] JIANG M, HE X Y. Optical testing of dynamic characteristic of vibrating wheel micromechanical

gyroscope [J]. *Opt. Precision Eng.*, 2008, 16(2): 295-299. (in Chinese)

[6] LI J L, FANG J C, SHENG W, *et al.*. Calculation and simulation of silicon MEMS gyroscope with dual-mass resonant output [J]. *Opt. Precision Eng.*, 2008, 16(3): 484-491. (in Chinese)

[7] TIMOSHENKO S, YOUNG D H. *Vibration Problems in Engineering* [M]. 3rd ed. New York: D. Van Nostrand Company Inc., 1955: 427-430.

[8] PUTTY M W. *A micro-machined vibrating ring gyroscope* [D]. Michigan: Univ. Michigan, 1995.

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●下期预告

利用复合磨粒抛光液的硅片化学机械抛光工艺

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为了提高硅片的抛光速率，利用复合磨粒抛光液对硅片进行化学机械抛光。分析了 SiO_2 磨粒与聚苯乙烯粒子在溶液中的 ζ 电位及粒子间的相互作用机制，观察到 SiO_2 磨粒吸附在聚苯乙烯及某种氨基树脂粒子表面的现象。通过向单一磨粒抛光液中加入聚合物粒子的方法获得了复合磨粒抛光液。对硅片传统化学机械抛光与利用复合磨粒抛光液的化学机械抛光进行了抛光性能实验研究，提出了利用复合磨粒抛光液的化学机械抛光技术的材料去除机理，并分析了抛光工艺参数对抛光速率的影响。实验结果表明：利用单一 SiO_2 磨料抛光液对硅片进行抛光的抛光速率为 180 nm/min；利用 SiO_2 磨料与聚苯乙烯粒子或某氨基树脂粒子形成的复合磨粒抛光液对硅片进行抛光的抛光速率分别为 273 nm/min 和 324 nm/min。利用复合磨粒抛光液对硅片进行抛光提高了抛光速率，并可获得 *Ra* 为 0.2 nm 的光滑表面。