第 17 卷　第 6 期
2009 年 6 月
光学 精密工程
Optics and Precision Engineering
Vol. 17　No. 6
Jun. 2009

文章编号　1004-924X(2009)06-1415-06

扇形梳齿驱动式体硅微机械隧道陀螺仪的设计与制备

王凌云，李文望，庄根煌，孙道恒
（厦门大学 机电工程系，福建 厦门 361005）

摘要：介绍了一种利用隧道效应所具有的高位移敏感特性来获得较高灵敏度的微机械隧道振动陀螺仪的设计和工艺制备，该陀螺仪分别采用扇形梳齿驱动和面外振动悬臂梁的方式实现质量块的振动和恒隧道电流的检测。介绍了扇形梳齿驱动的工作原理和隧道陀螺仪的设计。由于采用了硅玻键合和深反应离子蚀刻(DRIE)的 DDSOG 体硅制备工艺，因而可获得较大的敏感质量块，从而使陀螺仪具有较高的灵敏度和较大的动态响应范围。根据检测模态和驱动模态匹配的原则，利用有限元模型对隧道陀螺仪的结构尺寸进行了优化，仿真结果表明，该陀螺仪在常压下的灵敏度为 0.007 nm(°)/s。

关　键　词：隧道效应；陀螺仪；DDSOG；隧道传感器
中图分类号：U666.123；V241.5　　**文献标识码**：A

Design and fabrication of bulk micromachined tunneling gyroscope with fan-shaped comb drivers

WANG Ling-yun, LI Wen-wang, ZHUANG Gen-huang, SUN Dao-heng

(*Department of Mechanical and Electrical Engineering*, *Xiamen University*, *Fujian* 361005, *China*)

Abstract: A bulk micromachined vibratory tunneling gyroscope which employs the high displacement sensitivity of quantum tunneling to obtain the desired resolution has been developed. The device consists of fan-shaped comb drivers which can oscillate and an out-of-plane silicon cantilever linked up to a substrate suspended by springs. Because of adopting a solid-mass silicon structure to get the larger proof mass, the new ultracompact device can provide extremely high sensitivity and a wide dynamic range. Based on the modal analysis by a Finite Element Method(FEM), the structure dimensions are optimized according to resonant frequency matching of the driving mode and the sensing mode. Simulation results demonstrate that the gyroscope owns the sensitivity of 0.007 nm(°)/s at atmospheric pressure, which also shows the Deep Dry Silicon on Glass (DDSOG) process can be used to fabricate not only the micro-machined tunneling gyroscope but also other sensors and actuators.

Key words: tunneling effect; gyroscope; Deep Dry Silicon on Glass(DDSOG); tunneling sensor

---

Received date: 2008-12-24; **Revised date**: 2009-04-30.

Foundation item: Supported by Fujian Science and Technology Plan (Grant No. 2002H022)

1 Introduction

With the emergence of MEMS technology Since the late 1980s, the micromachined gyroscope as a rate sensor has received considerable attention for its applications in automotive and aerospace systems due to its low costs, low power consumption, low temperature drifts, small sizes, long lifetimes and exciting market demands [1]. Various MEMS gyroscope designs have been reported[2-4]. However, they failed to achieve performance levels compared to their optical and macro-mechanical counterparts in high-precision application such as space and tactical/inertial navigation. To achieve sub-deg/hr rate resolution, a vibratory gyroscope must adopt very sensitive detection means in detecting small defection caused by Coriolis force besides very high mechanical quality factors of both the driving and sensing modes, large proof mass, a small difference in the resonant frequencies of the two modes and large drive amplitude. This calls for innovative designs and radical advances in fabrication technology[5]. For the exponential dependence of the tunneling current with electrode gap separation, tunneling effect sensor has the advantage over the more common capacitive, piezoresistive, and piezoelectric displacement transducers in that the critical sensing area is greatly reduced. This allows the device to be scaled down to extremely small size, without sacrificing electronic signal-to-noise. Based on these characteristics of tunneling effect, many groups have recognized the utility of transforming the high displacement sensitivity of the tunneling effect into high sensitivity sensors, also including tunneling gyroscope[6-9]. However, these earlier devices were fabricated with surface process that was difficult to provide large proof mass and yielded failure primarily due to residual stress, thus limiting commercial development. In an effort to eliminate these disadvantages and improve the performance of microgyroscope, we have introduced an out-of-plane, solid-mass silicon tunneling gyroscope that incorporates large proof mass per unit area, large amplitude change of silicon tip per unit angular velocity and out-of-plane operation with fan-shaped comb drivers.

2 Design and simulation of gyroscope

2.1 General description of tunneling gyroscope

A simple schematic diagram of the vibratory tunneling microgyroscope, which senses x-axis rotation, is shown in Fig. 1. The microgyrsocope is based on silicon-on-glass compound structure through silicon-glass anodic bonding technique. The DRIE technique is used for comb driving finger etching. The anchor bonded with the glass substrate supports the silicon cantilever and comb drivers by sensing beam, which are floating 4 μm above the substrate and free for sensing and driving vibration. The deflection electrode under the proof mass, which is fabricated by spurting gold on the glass substrate, could deflect cantilever into the tunneling position. The silicon tip at the end of the cantilever is used to sense the vibration of the silicon frame at Z direction. The undeflected gap spacing between the silicon tip and detected electrode is typical about 1 μm. During the operation, alternating electrostatic forces on the movable fan-shaped driving fingers induce vibration of the proof mass along Y direction, which is called driving mode. If there is an angular velocity along the X direction, the proof mass will experience an alternating Coriolis′ force along Z direction. This in turn will excite the cantilever to vibrate along Z direction, which is called sensing mode. The tunneling gap between silicon tip and detected electrode will be changed due to the sensing vibration along Z direction. By measuring the tunneling current change, we can get the value of the angular velocity.

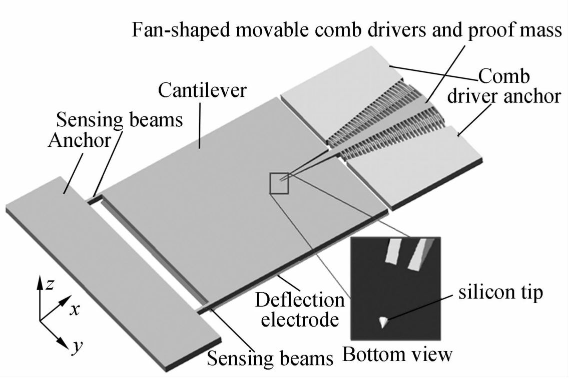

Fig. 1 Schematic diagram of bulk- micromachined tunneling gyroscope

2.2 Electrostatic driving in fan-shaped comb drivers

Many choices are available for microgyroscope driving. Among them, fan-shaped electrostatic driving is the most attractive for its large allowed displacement at the out of the radius and constant driving moment unrelated to the vibration angle. As shown in Fig. 2, Movable driving fingers extrude from the edge of the proof mass. Electrical driving voltage V is applied between fixed and movable fingers. Assume the overlap of finger angle as θ, finger gap as g, finger width as w, device thickness as h, the first inner finger radius as R_1, and there are n number of movable fingers in each side of proof mass. The electrostatic driving moment is:

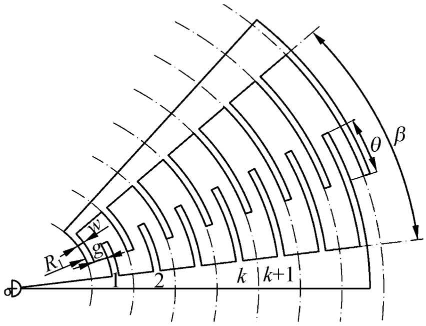

Fig. 2 Schematic diagram of fan-shaped electrostatic driving

$$M_g = \sum_{k=1}^{n} \frac{\varepsilon h V^2}{2g}[2R_1 + (4k-3)(w+g) + 2w] . \tag{1}$$

2.3 Dynamic analysis of the microgyroscope

Assume α and γ are the rotation angle of proof mass I_Z and I_Y and are the moment of inertia along Z and Y directions separately. D_Z and D_y are the damping ratio of the driving and sensing modes separately, k_Z and k_Y are the spring constants of the driving and detection modes separately. M_g is the amplitude of the driving moment. ω is the frequency of the driving force. The angular velocity Ω is along X direction. Assuming linear springs and damping, for a MEMS vibratory microgyroscope, the mathematical model can be represented by the following two differential equations[9]:

$$I_Z\ddot{\alpha} + D_Z\dot{\alpha} + k_Z\alpha = M_g \sin \omega t \ , \tag{2}$$

$$I_Y\ddot{\gamma} + D_Y\dot{\gamma} + k_Y\gamma = 2I_Y\Omega\dot{\alpha}(t) \ . \tag{3}$$

Assume the vibration max angle of the driving mode is α_M. Solving above differential equations we can have the vibration angle γ_s of the sensing mode as:

$$\gamma_s = \frac{2\Omega\alpha_M\omega_d}{\omega_s^2\sqrt{\left[1-\left(\frac{\omega_d}{\omega_s}\right)^2\right]^2 + \frac{1}{Q_s^2}\cdot\left(\frac{\omega_d}{\omega_s}\right)^2}} \ , \tag{4}$$

Where ω_d and ω_s are the resonant frequencies of the driving and sensing modes separately. Q_s is quality factor of the driving mode.

For the tunneling current sensing structure, when there is a displacement change A_s in the Z direction, the detected tunneling current will be[9]

$$\Delta I = \lambda V_{tun}\sqrt{\Phi}e^{-\lambda d_0\sqrt{\Phi}}A_s \ , \tag{5}$$

Where V_{tun} is tunneling bias voltage across the electrode, λ is a constant, d_0 is the original tunneling gap, and Φ is the tunneling barrier height. The tunneling current ΔI is proportional to the value of vibration amplitude A_s in the Z direction as well as the input angular velocity Ω. Therefore the angular velocity Ω can be measured by determining the tunneling current. Assume L is the distance of tunneling tip to the anchor. So the sensitivity of the vibration tunneling microgyroscope S_d, which is an important feature of all sensors, can be described as:

$$S_d=\frac{d\Delta I}{d\Omega}=\frac{2\lambda V_{tun}L\alpha_M\omega_d\sqrt{\Phi}}{\omega_s^2\sqrt{\left[1-\left(\frac{\omega_d}{\omega_s}\right)^2\right]^2+\frac{1}{Q_s^2}\cdot\left(\frac{\omega_d}{\omega_s}\right)^2}}e^{-\lambda d_0\sqrt{\Phi}}. \tag{6}$$

This equation indicates that in order to ensure enough sensitivity, it is very vital to precisely match the resonant frequencies of driving and sensing modes. Increasing quality factors of the vibration can also help to improve the sensitivity.

2.4 Performance of the gyroscope

The mechanical behavior of the microgyroscope was analyzed using a lumped-mass and FEM models simultaneously. According to above analysis, an optimized design for the mcirogyroscope is proposed. ANSYS simulation is used to extract the resonant frequencies of driving and sensing modes. The resonant frequencies of the driving and sensing modes are 7 019 Hz and 9 730 Hz separately for optimized design gyroscope. We intentionally set sensing frequencies to be 27.8% larger than driving frequencies to tolerate the electrostatic softening stiffness effect of sensing beams and expect a proper bandwidth[10]. The frequency of the third mode is 25 718 Hz, three times larger than the former modes. As shown in Fig. 3, the amplitude of silicon tip deflection produced by a distributed Coriolis force is linear with angular velocity input. The simulated device performance parameters at the atmosphere pressure are listed in Tab. 1. These results demonstrate that the gyroscope has the sensitivity of 0.007 ℃ (°)/s, which is larger than that fabricated by surface process[11].

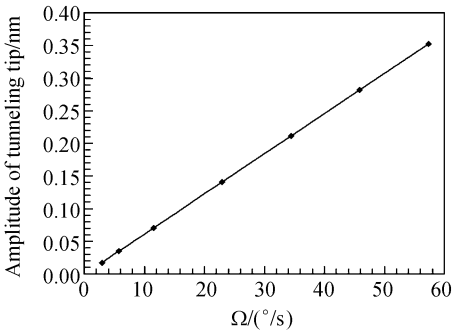

Fig. 3 Calculated amplitude of tip at different angular velocity

Tab. 1 Simulated performance for gyroscope

Performance parameters	Values
Driving mass	46.4 μg
Sensing mass	70.6 μg
Rotary stiffness of driving mode	2.45×10^6 μN · μm
Spring constant of sensing mode	260.9 μN/μm
Driving mode resonant frequency	7 019 Hz
Sensing mode resonant frequency	9 730 Hz
Displacement sensitivity	0.007 nm(°)/s

3 Fabrication

This microgyroscope fabrication is based on DRIE of single crystal silicon on glass substrate. It is different from other groups using surface process due to small Hooke's constant in the out-of-plane direction, but the DRIE process, which has the distinct advantages of large proof mass, lower residual stress and single silicon structure, has been used for an out-of plane tunneling gyroscope[12-14]. The deep dry silicon on glass (DDSOG) process, which includes silicon etching, electrodes on the glass, anodic bonding, the silicon thickness reduction and silicon deep etching on the back side, has finally been utilized to fabricate the tunneling microgyroscope. SEM picture of gyroscope and silicon tip are shown in Fig. 4 and Fig. 5 and a close-up view of fan-shaped comb drivers in Fig. 6.

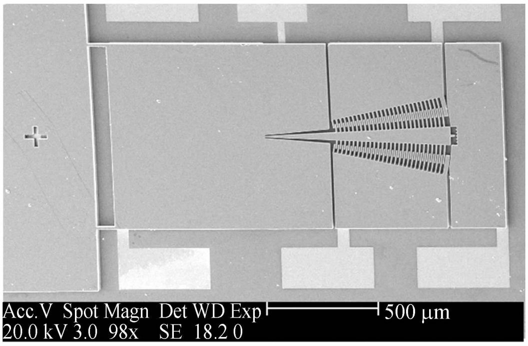

Fig. 4 SEM photo of a micromachined tunneling gyroscope

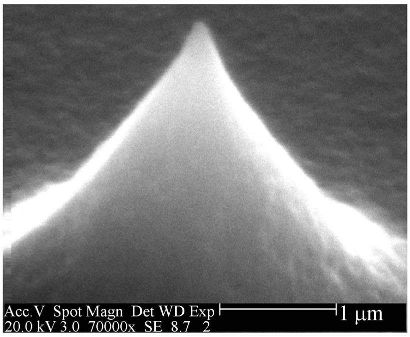

Fig. 5 Silicon tip

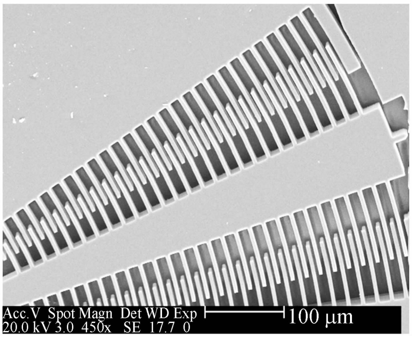

Fig. 6 Close-up view of fan-shaped comb drivers

4 Conclusions

In this paper, a novel bulk-micromachined tunneling vibratory microgyroscope with fan-shaped comb drivers is designed and fabricated. The gyroscope uses electrostatic comb driving for its driving mode, and tunneling current sensing for signal detection. Because of adopting the fan-shaped comb drivers to get larger proof mass amplitude, the new ultracompact devices can provide extremely high sensitivity. The working principle and performance of this tunneling microgyroscope are analyzed in detail. Based upon the analysis, an optimized microgyroscope design is proposed. Simulation results demonstrate that the gyroscope has the sensitivity of 0.007 nm(°)/s, which is much larger than that fabricated by surface process. The device is based on silicon-on-glass structure. The deep dry silicon on glass (DDSOG) process, which is a bulk micromachined process, has been successfully used to fabricate this tunneling gyroscope. We have measured the basic mechanical performance. All of fabricated gyroscopes can be driven to oscillate along two directions in air environment, and resonant frequencies are matched very well. The gyroscopes are for vacuum packaging now, and other performance will be further tested and investigated.

References:

[1] FRANCIS E H T, LIANG Y C, LOGEESWARAN V J. Design and fabrication of a micromachined resonant gyroscope[J]. *International Journal of Electronics*, 1999,86(10):1179-1191.

[2] SONG C, SHINN M. Commercial vision of silicon-based inertial sensors [J]. *Sensors and Actuators*: *Physical*, 1998,66(1-3):231-236.

[3] XIE H, FEDDER G K. Fabrication, characterization, and analysis of a DRIE CMOS-MEMS gyroscope [J]. *IEEE Sensors Journal*, 2003,3(5):622-631.

[4] ZHAO Y, SU Y. Influence of drive modes on output signals of micro-fluidic gyroscope [J]. *Opt. Precision Eng.*, 2008,16(5):889-893. (in Chinese)

[5] TANAKA K, MOCHIDA Y, OHWADA K, *et al.*. A micromachined vibrating gyroscope [J]. *Sensors and Actuators A*: *Physical*, 1995,50:111-115.

[6] AYAZI F, NAJAFI K. A HARPSS polysilicon vibrating ring gyroscope [J]. *IEEE/ASME JMEMS*, 2001(6):169-179.

[7] PARTRIDGE A, KURTH R J, JOHA D G, *et al.*. An integrated controller for tunnel sensors [J]. *IEEE Journal of Solid-State Circuit*, 1999, 34(8):1099-1106.

[8] 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)

[9] LI J L, FANG J CH, DONG H F, *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)

[10] SHI Q, QIU A P, ZHU X H, *et al.*. Mechanical coupling error of silicon microgyroscope [J]. *Opt. Precision Eng.*, 2008, 16(5):598-602. (in Chinese)

[11] KUBENA R L, VICKERS-KIRBY D L, FREDERICK P, *et al.*. A new tunneling-based sensor for inertial rotation rate measurements [J]. *Journal of Microelectromechanical system*, 1999, 8(4): 439-447.

[12] CHEN Y, JIAO J W, WANG Y L, *et al.*. Design and noise analysis of a micromachined gyroscope working at atmospheric pressure [J]. *Chinese Journal of Semiconductors*, 2005, 26(11): 148-152.

[13] FU L, MIAO J M, LI X X, *et al.*. Study of deep silicon etching for micro-gyroscope fabrication [J]. *Applied Surface Science*, 2001, 177:78-84.

[14] LI Z H, YANG Z C, WANG Y Y, *et al.*. A bulk micromachined vibratory lateral gyroscope fabricated with wafer bonding and deep trench etching [J]. *Sensor and Actuators*, 2000, 83:24-29.

Authors' biographies:

WANG Ling-yun (1978—), Ph. D., received his B. S. and M. S. degrees in mechanical and electrical engineering from Xiamen University. His current research interests include the design, fabrication, characterization and control of microelectromechanical systems and inertial sensors. **E-mail**: rabitwangly@yahoo. com. cn

LI Wen-wang, Ph. D. candidate, teacher of the Xiamen University of Technology, his primary researches are related to the design of traditional micromechanical gyroscopes, accelerometers and FEM analysis. **E-mail**: xmlww@xmut. edu. cn

ZHUANG Gen-huang (1984—), M. S. candidate of the Xiamen University, his current research interests include data acquisition and analysis, sensors, instruments and system design, electronics architecture development, test and evaluation, error modeling and signal processing. **E-mail**: 021130zgh@163. com

SUN Dao-heng, professor of the Xiamen University, received his Ph. D., M. S. and B. S. from Northeastern University in 1997, 1990 and 1987 respectively. His research fields include MEMS/NEMS, flexible/printable electronics and electrospinning and its applications. **E-mail**: Sundh @ xmu. edu. cn