MICRO-MACHINED GAS-PENDULUM DUAL-AXIS TILT SENSORS

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Abstract: This paper presents the elements of theory, principle, design, fabrication, and experimental results of micro-machined gas-pendulum dual-axis tilt sensors, which are used to measure the obliquity of moving carriers. This paper deduces gas-pendulum theory and characteristic under the continuous medium hypothesis [1], simulates the velocity vector distribution of hot airflow in the hermetic chamber by ANSYS software, and introduces the principle of micro-machined gas-pendulum dual-axis tilt sensors. This paper puts forward an original design scheme to improve the performances greatly through optimizing the chamber volume, distance between heater and temperature detectors and so on. Through signal conditioning and being compensated, this device has a response time of ≤ 80ms, a resolution of $\leq 0.01^{\circ}$, a small linearity error of <1% under full measurement range of $\pm 45^{0}$, a sensitivity of ≥30mv/°, and provides a shock survival up to 30000 g.

Key words: tilt sensors; micro-machined; gas-pendulum; device fabrication

1. INTRODUCTION

Tilt sensors are used to measure the gradient of the carrier, and acquire input signals of the automatic tracking and adjusting of the platform. Tilt sensors are applied in many fields, such as communication, consumer electronic products, toy, electro-mechanical equipment; and also applied in automobiles, tanks, ships, robots, stabilization system of radar and missiles [2]. Tilt sensors can be classified as solid pendulum tilt sensors, liquid pendulum tilt sensors, gas pendulum tilt sensors, micro-electro-mechanical system(MEMS) tilt sensors, compounding tilt sensors and so on, the micro-machined gas-pendulum dual-axis tilt sensor is a kind of gas pendulum tilt sensor fabricated by micro-system technology, it is different from conventional tilt sensors, have some outstanding advantages comparing with other tilt sensors.

1) The conventional inclinometers generally measure the displacement or the deformation of a proof mass (or seismic mass), the mobility is the principal disadvantage and they have low shock survival rating and fragility during very high accelerations.

The micro-machined gas-pendulum dual-axis tilt sensor is based on gas-pendulum principle, whose sensitivity mass is gas. Gas is the only moving object in the hermetic chamber, which has very little mass. The inertial force of gas is small when the sensor is concussed heavily and overloaded, so the sensor has excellent capacity restraining vibration and concussion.

2) This tilt sensor is manufactured with the micro-system technologies, whose volume is very small, whose capacity is steady, which is convenient to be used. Because micromachining technologies have been widely developed for the market of the tilt sensor, it permits to achieve low cost production, sensor miniaturization and mass manufacturing.

3) This paper puts forward original design scheme, makes use of newly technologies to improve the micro-machined tilt sensor performances greatly.

2. THEORY AND PRINCIPLE OF MICRO-MACHINED GAS-PENDULUM DUAL-AXIS SENSORS

2.1 Gas-pendulum Theory

Supposed that ideal gas is in the hermetic chamber, the axes of three-dimensional reference frame are respectively x, y and z. The velocity components along coordinate axes of a tiny gas agglomerate are respectively u, v and w. The pressure is p, and the density of the gas agglomerate is ρ. According to momentum conversation law, the momentum transformation gross of a fluid in random hermetic chamber is equal to the sum of the impulse of the force on all fluids in the circumscription and the impulse of the surface force on the fluid element on the circumscription surface [3][4], namely:

$$\frac{d}{dt}\iiint_V \rho v_i dV = \iiint_V [\frac{\partial}{\partial t}(\rho v_i) + \rho v_i \frac{\partial v_j}{\partial x_j}]dV$$

$$= \iiint_V \rho f_i dV + \oiint_S \sigma_{ij} n_{ij} dS \quad (1)$$

In the formula:

i the ith tiny gas agglomerate,
σ_{ij} stress tensor element.

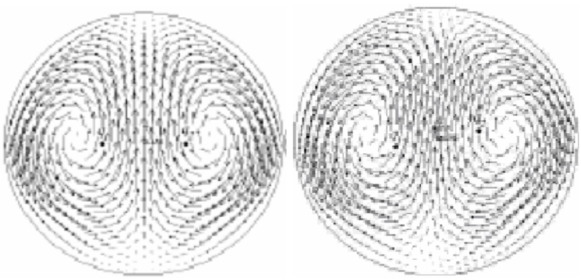
$$\frac{\partial}{\partial t}(\rho v_i)+\frac{\partial}{\partial x_j}(\rho v_i v_j)=\rho f_i+\frac{\partial \sigma_{ij}}{\partial x_j} \quad (2)$$

The formula above is changed according to continuity equation:

$$\frac{dv_i}{dt}=\frac{\partial v_i}{\partial t}+v_j\frac{\partial v_i}{\partial x_j}=f_i+\frac{1}{\rho}\frac{\partial \sigma_{ij}}{\partial x_j} \quad (3)$$

So the velocity field distribution is achieved according to formula (3).

Figure 1 is the velocity vector distribution of hot airflow in the rounded chamber simulated by Ansys software [5].



(a) Level *(b) Incline*

Figure 1: The velocity vector distribution of hot airflow.

Obviously, when the hermetic chamber is inclined, the velocity field and temperature of the hot airflow in which is swung, the character is like solid-pendulum and liquid-pendulum.

2.2 Principle of Micro-machined Gas-pendulum Dual-axis sensors

The principle of the micro-machined dual-axis tilt sensor reported is based on gas-pendulum. The device has a very simple device structure. Because the two sense directions X and Y have the same principle, only X direction is introduced here.

The device consists of a small silicon substrate with an etched chamber to provide thermal isolation. A suspended heater in the middle of the chamber heats up and lowers the density of the air surrounding it, and creates a symmetric temperature profile along the X axis of a hermetic chamber and two temperature detectors are symmetrically suspended on both sides of the heater. When the sensor is horizontal, the two detectors have the same temperature, while when obliquity is applied on the sensitive axis X, the convection heat transfer and the temperature profile become asymmetric and the differential temperature ΔT between the two detectors is proportional to the obliquity. Signal conditioning circuit can detects the change of the temperature detector resistance caused by the differential temperature ΔT, then the obliquity can be achieved.

3. FABRICATION OF MICRO-MACHINED GAS-PENDULUM DUAL-AXIS SENSORS

3.1 Device Fabrication

According to the characteristic of hot airflow and convection theory, finite element analysis result, character of microsystem technologies, the configuration of the sense organ of the micro-machined gas-pendulum tilt sensor and the micro-machined chip is designed. Based on the configuration of the sense organ and the characteristic of wafer in microsystem, this paper chooses singlecrystalline silicon as substrate; Based on the machining need of tiny chamber and the character of the corrosion technics, 100 orientation is chosen.

Based on the character of the electric material in microsystem such as conduct electricity and heat and electrode capability, Ti, Pt, Au is evaporated as the electrodes, and their size and technics configuration is confirmed. The designing and machining of the airflow chamber is very important for the efficient performance of sensor, the chamber is machined with bulk silicon micro-machining, and plasma-assisted etching and chemical corrosion is all adopted [6].

The chip fabrication sequence is illustrated in Fig. 2. Firstly, a 0.6 μm thick SiO_2 is formed on the silicon substrate by wet oxidation, a polysilicon film is deposited on the oxide layer by Low Pressure Chemical Vapor Deposition(LPCVD), a light P-doping the polysilicon is oxidized to provide an oxide-polysilicon-oxide sandwich structure shown in Fig. 2a. Secondly, the top oxide layer and polysilicon layer is patterned and etched for the polysilicon resistor bridge, temperature detector and the polysilicon contact, shown in Fig. 2b. Thirdly, the polysilicon sidewalls are oxidized to protect it from anisotropic etching with ethylene diamine-pyrocatechol(EDP) [7], after lithography and etching, the bonding pad and cavity windows are opened, shown in Fig. 2c. Fourthly, Ti, Pt and Au are evaporated through lithography (shown in Fig. 2d). Fifthly, after the photoresist is stripped, the electrode contact is formed, shown in Fig. 2e. Finally, the chamber is formed by EDP, shown in Fig. 2f.

In the end, the wafer is incised, the down-lead of electrode is welded; finally the chip is encapsulated [8].

3.2 Residual Stress Controlling and Releasing of thin films

The residual stress level of thin film depends on the character of thin film and substrate material, the technics condition in which thin film is thrown, and surroundings condition in which thin film is deposited [9]. It is necessary to found out the origin and character of residual stress of thin film for farther controlling residual stress. Through selecting proper material, changing facture method, technics parameters, heat treatment technology, film dimension (especially thickness), choosing different doping material and so on, the residual stress can be effectively controlled. This paper chooses evaporation not magnetic sputtering and ion beam sputtering to reduce the residual stress in micro-machined gas-pendulum dual-axis tilt sensors.

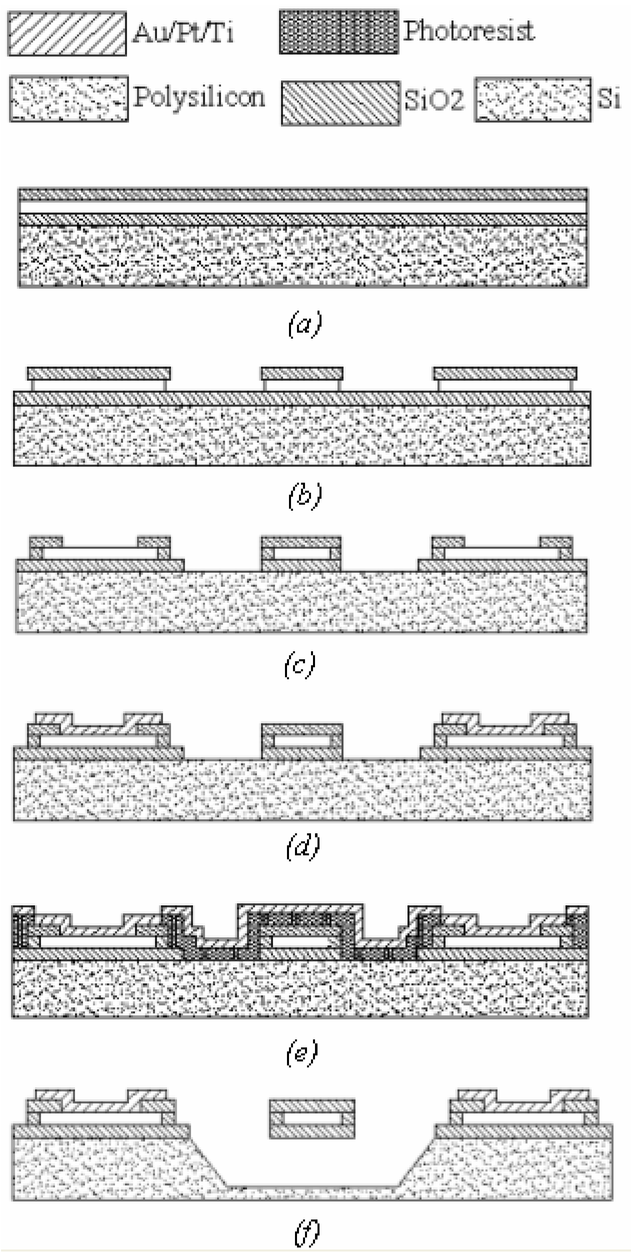


Fig. 2 Device fabrication process

According to the balance relationship when stress is released, and the configuration of the elastomer, ageing treatment is necessary to release residual stress [10]. Natural ageing treatment is unfit, because it is slow, and the period is long. The method adopted by this paper is prompt annealing treatment, tired pulsating treatment and resonance is also fit. So the residual stress is released greatly, the capability of thin films is steadier.

The Scanning Electron Microscopy (SEM) photos of one electrode are shown in Fig. 3.

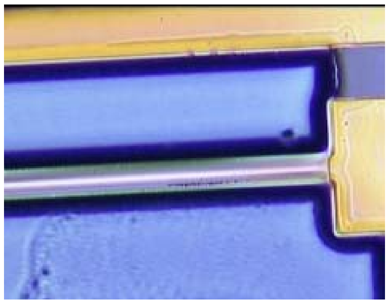


Fig. 3 SEM photo of one of the electrodes

3.3 Design of Detection Circuit

For detecting the change of the temperature detector resistance, this paper adopts Wheatstone bridge circuit which is composed of two temperature detectors described above paragraphs and two identical resistance R_{1X} and R_{2X}. Fig. 4 is the detection circuit sketch map. The two identical hot wires r_{1X} and r_{2X} mean two temperature detectors in the chip above. The differential temperature ΔT between the two detectors cause the change of the two detectors, then the output voltage V_{outx} of the bridge circuit can be acquired. So the obliquity θ is received through signal conditioning [11][12].

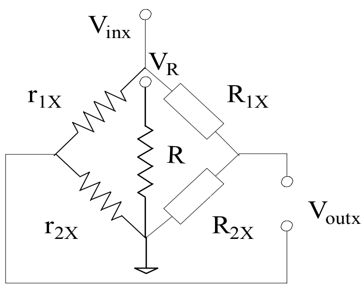


Fig. 4 X-axis detection circuit

4. EXPERIMENT AND DISCUSSION

This paper simulates and tests two micro-machined gas-pendulum dual-axis tilt sensor chips. As is illustrated in Fig. 5, the output of the device responds nearly linearly to the applied tilt angle. This result is achieved before the signal of the tested devices is conditioned and compensated. After signal conditioning and compensating, a small linearity error of <1% under full measurement range of $\pm 45^0$ and a sensitivity of ≥30mv/° can be achieved. At the same time, this device has a response time of $\leq$ 80ms, a resolution of $\leq 0.01^{\circ}$, and provides a shock survival up to 30000 g.

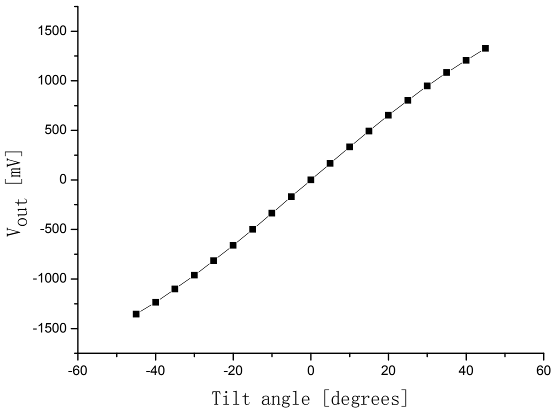


Fig. 5 Measured performances of one axis of the tilt sensor before being compensated

Research turns out that the response of the micro-machined gas-pendulum dual-axis tilt sensor is proportional to the obliquity, the heater temperature rise, the square of gas pressure, the chamber volume, and inversely proportional to the square of the gas thermal diffusivity. The micro-machined gas-pendulum dual-axis tilt sensor has low cost, high reliability and high Sensitivity, the main disadvantages of the sensor is their power consumption and the room temperature dependence of their sensitivity, but they can be reduced respectively by adopting relevant measures according to effecting factors.

5. CONCLUSION

This paper introduces the theory of gas-pendulum, simulates the gas flow under the continuous medium hypothesis, it is necessary for the comprehension of the thermal accelerometer principle and its design optimization. An original design scheme and fabrication is applied to the tilt sensor, the performances of the micro-machined gas-pendulum dual-axis tilt sensor is improved by optimizing the chamber volume, distance between heater and temperature detectors and so on.

REFERENCES

[1] Fuxue Zhang 2005 Natural convection gas pendulum and its application in accelerometer and tilt sensor Progress in Natural Scienc vol. 15, no. 9, pp.857-860

[2] Jordan G.R. 1985 Sensor technology for the future J.Phys. E: Sci.Instrum vol.18, pp.729-735

[3] M.Emmengger, S. Taschini, J. G. Korvink and H. Baltes 1998 Simulation of a Thermomechanically Actuated Gas Sensor *Proc.IEEE MEMS-98* pp.184-189 (Heidelberg, Germany)

[4] Wiggert D.C. 2003 Fluid Mechanics pp.163-201 (China Machine Press)

[5] Linhua Piao, Lu Lin, Wei Zhang and Fuxue Zhang 2006 Analysis of the sensitive mechanism of the gas pendulum tilt sensor by finite element method Electronic Components & Materials vol.22, no.3, pp.1-3

[6] Stephen D. Senturia, 2004 Microsystem Design pp213-220 (Publishing House of Electronics Industry Press)

[7] H. Seidel 1987 The mechanism of anisotropic silicon etching and its relevance for micromaching *Digest Tech. Papers, 4' Int. Conf. Solid-state Sensors and Actuators (Transducers '87)*, June 2-5 120-12 (Tokyo, Japan)

[8] A. Singh, D. Horsely, M., M. Cohn, A. Pisano and R. Howe 1999 Batchtransfer of microstructures using flip-chip solder bonding *J. of Microelectromech. Systems* Vol. 8, No. 1

[9] Pruessner Marcel W., King Todd T., Kelly Daniel P. et al. 2003 Mechanical property measurement of InPbased MEMS for optical communications *Sensors and Actuators* A: Physical vol. 105, Iss. 2, pp. 190-200

[10] Townsend P H, Barnett D M, Brunner T A 1987 Elastic relationship in layered composite media withapproximation for the case of thin films on a thick substrate *Journal of Applied Physics* vol. 62, iss.11, pp. 4438-4444

[11] Robinson A M, Haswell P, Lawson R P W et.al. 1992 A thermal conductivity microstructrual pressure sensor fabricated in standard complementary metal-oxide semiconductor *Rev Sci Instrun* 63(3):2026

[12] Veljko Milanovi, Edwin Bowen and Nim Tea 1998 Convection-based Accelerometer and Tilt Sensor Implemented in Standard CMOS *International Mechanical Engineering Conference and Exposition* (MEMS Symposia, Anaheim, CA,) Vol.18, No.11