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On-Chip Temperature-Control Technology for Silicon Micro-Gyroscope

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Abstract. A micro-heater is used inside silicon micro-gyroscope to keep the working temperature of gyroscope constant so as to minimize the effect of environment temperature on performances of gyroscope. The structure of gyroscope package is first given. With a heater inside, the characteristics of gyroscope, such as frequency, coupled vibrations, temperature distribution and thermal equilibrium time, are predicted with the aid of ANSYS, a finite element tool. Finally, surfaces of the package are optimized with anti-radiation shields covering. As a result, when gyroscope is subjected to an ambient temperature of 20ºC, the temperature of itself could reach the equilibrium state of about 84ºC within 2 minutes with a temperature difference of about 2ºC between the anchor and the proof mass. Besides, if ambient temperature increases from -40ºC to 80ºC, heating power consumption is degraded from 1.27625W to 0.09712W. However, this design needs further improvement to decrease its heating power consumption and equilibrium time.

Introduction

Silicon micro-gyroscope is a typical MEMS instrument which has been widely used in military and commercial products. Driven by the rapid development of fabrication and signal processing, performances of MEMS gyroscope have improved a lot. However, many of these performances are influenced by ambient temperature [1,2], which changes the pressure inside the package, dimensions of the structure and material properties e.g. Young's Modulus. Presently, there are two methods to minimize the temperature influence and they are temperature compensation and temperature controlling. Nevertheless, the former, which is specific to a certain gyroscope, has limited usage and weak repeatability, and the latter needs high power consumption with the temperature inside the package unknown. Compared with these two methods, the on-chip temperature-control technology has the advantage of low power consumption [3] and extensive applicability. Thus, an on-chip heater is designed in this paper inside the package of gyroscope to make the gyroscope's performances uninfluenced by ambient temperature.

Structure

In Fig.1, (a),(b),(c) and (d) illustrate the structure of the packaged gyroscope, which has five major components; (I) the Kovar alloy substrate, (II) the PCB attached on the Kovar alloy substrate, (III) the micro-gyroscope supported on the PCB, (IV) the heater and the cap used for fixing the heater, (V) the cap used for vacuum encapsulation.

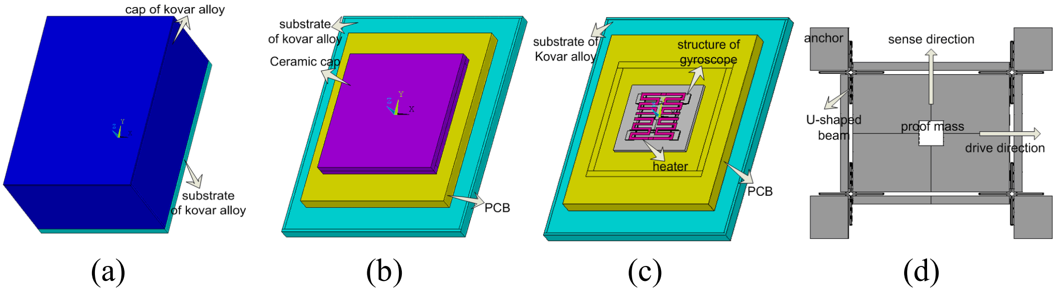

Fig.1: Structure of the packaged gyroscope: (a) the vacuum cap and the substrate which are both made of Kovar alloy; (b) the heating cap made of ceramic, PCB and Kovar alloy substrate; (c) heater made of alloy of Ti and Pt, gyroscope made of Si and glass, PCB and Kovar alloy substrate; (d) Schematic illustration of the silicon structure of the gyroscope [4].

Thermal Characteristics

In the prototype, gyroscope is heated to be above 80ºC and below 90, higher than the maximum ambient temperature, so it doesn't need to be equipped with heat sink. Besides, temperature difference between anchor and proof mass always exists, which means different parts of gyroscope have different Young's Modulus and thermal expansion causes deformation and stress.

To get the effect of temperature difference on natural frequency, mode analysis is made while temperature of the proof mass is 84ºC and that of the anchor increases from 64ºC to 104ºC and the result, as shown in Fig.2, is that the drive frequency and the sense frequency decrease by nearly 2Hz. However, if temperature of gyroscope varies along with ambient temperature from -40ºC to 80ºC, these two frequencies decrease by nearly 12Hz, as shown in Fig.3. Therefore, the frequency characteristic of gyroscope is improved when a heater is built-in.

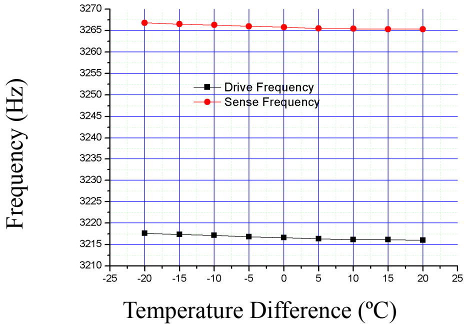

Fig.2 Dependency of drive frequency and sense frequency on temperature difference between anchor and proof mass.

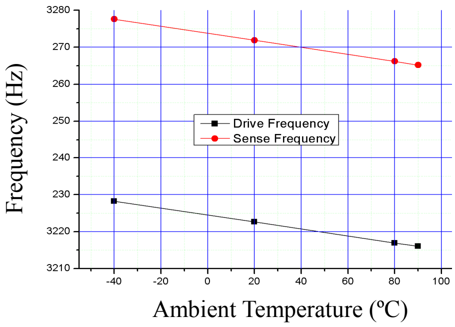

Fig.3 Dependency of drive frequency and sense frequency on ambient temperature when no heater is built in.

As stated above, temperature difference would cause different thermal expansions in parts of U-shaped beams. As a result, beams would become asymmetric and drive vibration is coupled with sense vibration, which is not desired in the gyroscope. There are two coupling modes, the parallel coupling and the orthogonal coupling. As shown in Fig.4 and Fig.5, when temperature difference between anchor and proof mass increases from -20ºC to 20ºC, orthogonal coupling ratio of the unwanted sense vibration caused by drive vibration to drive vibration has a descending trend while parallel coupling ratio of that has the ascending trend, and orthogonal coupling ratio of the unwanted drive vibration caused by sense vibration to sense vibration has a ascending trend and so it is with parallel coupling ratio of that. The ratios in Fig.5 are much higher but have less impact on performances of the designed gyroscope than those in Fig.4. Therefore, compromise is made to set temperature difference a little above 0ºC.

Finally, when voltage of 4.5V is applied to the heater and ambient temperature is 20ºC, the temperature of proof mass is about 84ºC and that of anchor is about 87ºC. And when the voltage applied to the heater is as shown in Fig.6, temperature of the gyroscope can reach its equilibrium state of about 84ºC in two minutes, during which the largest temperature difference between the anchor and the proof mass is less than 3ºC, which is shown in Fig.7.

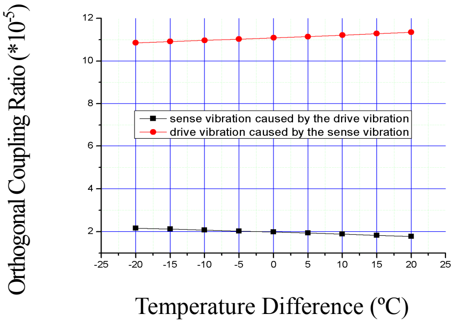

Fig.4 Comparison of the two kinds of orthogonal coupling ratio.

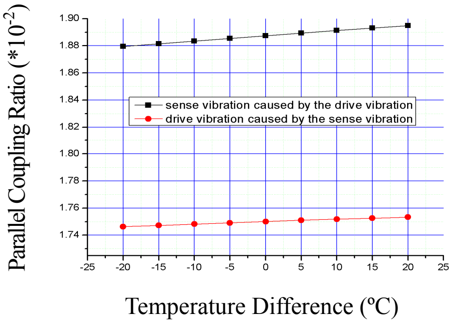

Fig.5 Comparison of the two kinds of parallel coupling ratio.

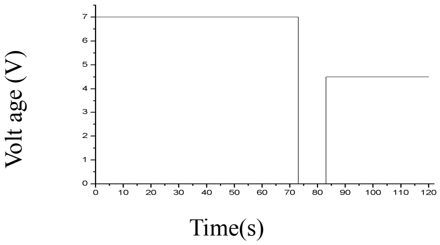

Fig.6 Variation of volt applied to the heater with time.

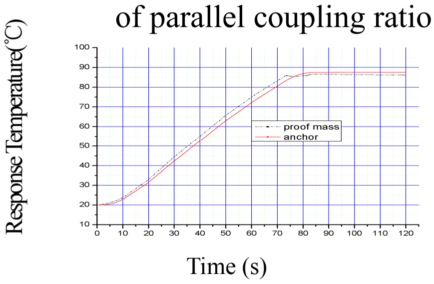

Fig.7 Variation of temperatures of proof mass and anchor with time under normal radiation.

Optimization

In the design, two heat transfer paths are considered, one of which is conduction through cap and PCB and the other is radiation among the surfaces inside the package. When the surfaces are covered with anti-radiation shields, heat transfer through radiation would be very little. The corresponding heat transfer path at equilibrium state is shown in Fig.8, in which heat is generated from heater and then passes through ceramic cap, PCB, and the substrate and cap of Kovar alloy to air, where air convection takes place, and the heating power consumption expression is Eq.1, in which s_h and z_h are respectively the depth of PCB and the thickness of the Kovar alloy package, A_s and A_z are respectively areas of PCB and Kovar alloy package, λ_s and λ_z are respectively the heat conductivities of PCB and Kovar alloy, h is the coefficient of air convection ,P is the power consumption of heater and T_{su} is assumed to be equal to 84ºC, the temperature of gyroscope [5].

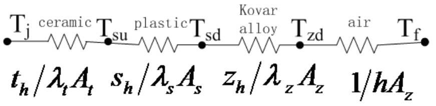

Fig.8 Graph of thermal resistance in the heat transfer path: T_j, T_{su}, T_{sd}, T_{zd} and T_f are respectively the temperatures of heater, upper surface and lower surface of PCB, the exterior temperature of the Kovar alloy package and ambient temperature.

Besides, thermal simulation is made on two conditions of normal radiation and low radiation. With gyroscope heated to be about 84ºC, Eq.2 is the linear fitting expression between heating power consumption and ambient temperature when radiation is low. Similarly, Eq.3 shows the dependency of heating power consumption on ambient temperature when radiation is normal.

Based on the above equations, heating power consumptions are compared under different radiation conditions, which is shown in Fig.9. It is found that heating power consumption is less when heat transfer by radiation is reduced, so the design can be optimized by anti-radiation shields.

$$\left(T_{su}-T_f\right)\Big/\left(s_h/\lambda_s A_s+z_h/\lambda_z A_z+1/hA_z\right)=P\,. \tag{1}$$

$$P_l=-0.00993T_{fl}+0.83938\,. \tag{2}$$

$$P_n=-0.00984T_{fn}+0.86528\,. \tag{3}$$

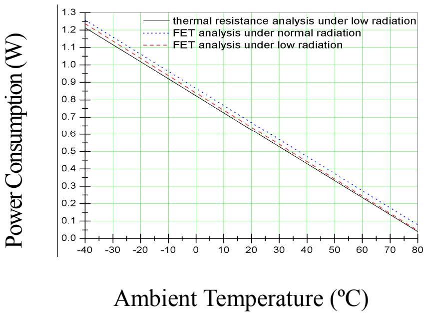

Fig.9 Comparison of heating power consumption under normal radiation and low radiation by FET and thermal resistance.

Conclusion

In this paper, an on-chip heater is built inside the gyroscope and the temperature of gyroscope is controlled around 84ºC by applying appropriate voltages when environment temperature is varied. When ambient temperature is 20ºC, gyroscope can reach its equilibrium state in 2 minutes. With a built-in heater, ambient temperature has less impact on the natural frequencies of gyroscope and the coupling vibrations are reduced. The surfaces of the package are optimized with anti-radiation shields, leading to lower heating power consumption. However, it is found that the power consumption is high because of the weak thermal isolation between the heater and the substrate, which needs further improvement in the future work.

Acknowledgments

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