Study on vacuum packaging reliability of micromachined quartz tuning fork gyroscopes

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Abstract. Packaging technology of the micromachined quartz tuning fork gyroscopes by vacuum welding has been experimentally studied. The performance of quartz tuning fork is influenced by the encapsulation shell, encapsulation method and fixation of forks. Alloy solder thick film is widely used in the package to avoid the damage of the chip structure by the heat resistance and hot temperature, and this can improve the device performance and welding reliability. The results show that the bases and the lids plated with gold and nickel can significantly improve the airtightness and reliability of the vacuum package. Vacuum packaging is an effective method to reduce the vibration damping, improve the quality factor and further enhance the performance. The threshold can be improved nearly by 10 times.

1. Introduction
Currently the design, processing and manufacturing technologies of the microelectromechanical systems (MEMS) are developing rapidly, but the development and application of MEMS devices are restricted because the packaging technology lags behind the processing technology. The service life of vacuum packaged MEMS devices depend on the vacuum level of the device cavity and the vacuum hold time. The real-time monitoring of the vacuum level in the cavity is a key technique for developing MEMS devices [1]. The packaging process of micromachined quartz tuning fork gyroscopes comprises the wire bonding, die attachment and seal cap. In order to ensure the packaging reliability of micromachined quartz tuning fork gyroscopes, the damping to the fork resonance caused by the air or inert gasses in the cavity must be reduced, so as to improve the sensitivity and comprehensive performance of gyroscopes. Even packaged in a high vacuum environment, the comprehensive performance of quartz tuning fork gyroscopes is not directly proportional to the vacuum level. If the damping is too small, “oscillation” occurs. Selecting an appropriate vacuum packaging process is important for isolating the effects of external interfering signals and obtain the highest quality factor (Q-factor), sensitivity and comprehensive accuracy [2, 3].

2. Bonding technology of micromachined quartz tuning fork gyroscopes
Packaging is a key process for the micromachined quartz tuning fork gyroscopes. The performance of gyroscope is influenced by the encapsulation shell, encapsulation method and fixation of forks. The quartz tuning fork is Z-cut crystal quartz wafer with a thickness of hundreds of microns, and its fabrication processes include grinding and polishing, photolithography, etching, evaporation coating of silver film electrodes, and packaging. Maintaining high vacuum for a long period of time is a necessary measure to control the noise level of micromachined quartz tuning fork gyroscopes, which
can directly affect the working stability, service life and shock resistance of quartz tuning fork. The single-point fixed packaging is good for stabilizing the working performance of quartz tuning fork. Main considerations for selecting the shell materials are elaborated as follows. (1) The iron-nickel alloy is one commonly used material, which comprehensively takes account of the strength, coefficient of thermal expansion (CTE) and airtightness. (2) The vacuum packaging process is utilized and the structure and dimension of the resonant cavity are determined according to the quartz tuning fork size. The tuning fork used in the experiment is 12mm long, 2.5mm wide and 0.4mm thick. The encapsulation shell base is 20mm long, 10mm wide and 8mm high and its size satisfies the packaging requirements of the forks. It is encapsulated with the vacuum level of $\leq 1 \times 10^{-2} \text{Pa} \cdot \text{m}^3 / \text{s}$. Refer to Table.1 for the material properties.

| Material          | Density $\rho$/gcm$^{-3}$ | Shear Modulus $G$/Gpa | Poisson’s ratio $\mu$ | Young’s modulus $E$/Gpa |
|-------------------|---------------------------|-----------------------|-----------------------|-------------------------|
| iron-nickel alloy | 8.1                       | 79.4                  | 0.3                   | 206.0                   |

The quartz tuning fork must be fixed to the encapsulation shell base after being processed. Common fixed packaging methods include single-point or two-point package. The latter method is employed for the quartz tuning fork. Because the quartz and shell have different CTEs, the stresses generated from external vibrations and temperature protection are prone to affect the tuning fork performance. The performance of the single-point package of resonant nodes of quartz tuning fork is better than the two-point package. The structure is shown in Figure 1. The nickel and gold films are plated on the bonding regions of the quartz tuning fork by means of sputtering, evaporation or electroplating, and the anodic bonding is achieved by using the vacuum packaging machine [4]. The gold-plated bonding region of quartz tuning fork is attached to the convex surface of the encapsulation shell base and placed on the worktable in the vacuum furnace. A certain pressure is applied. When the vacuum and heating reach the set values, apply a voltage of $800 \text{DC V}$, the bonding region of quartz tuning fork is connected to the high voltage anode and the shell base connects with the cathode. Heat the bonding region to the gold-silicon eutectic temperature ($363^\circ\text{C}$). The gold-silicon inter-diffuses on the bonding interface and forms the eutectic mixture. When the temperature exceeds the eutectic point, a strong eutectic bonding layer is shaped as the time increases. The electrodes of quartz tuning forks are welded by gold wires with the encapsulation pin through the gold wire ball bonding or hot bonding process. The gold wire ball bonding is characterized by the big contact surface, corrosion resistance, high tensile strength, good reliability and easy automatic or semi-automatic operation [5,6].

![Figure 1. Quartz tuning fork by single-H single-point package.](image)

The Q-factor of quartz tuning fork is related not only to the quartz material, electrode distribution, tine size, and shape, but also to the packaging vacuum level of the tuning fork. If the Q-factor is very high, the damping coefficient can be used for assessing the quality factor of tuning forks. The $Q$-value and...
the damping coefficient $\alpha$ have the following approximate relationship: $Q \cdot \alpha = 1/2$. It is packaged in an atmospheric environment and in the vacuum state. The impedance analysis test is conducted for the drive line of quartz tuning forks. The main test data include the equivalent motional capacitance $R_i$, equivalent motional inductance $L_i$, equivalent shunt capacitance $C_0$, equivalent motional capacitance $C_i$ and resonant frequency $f$. The quality factor $Q$ may be calculated by the equation below:

$$Q = \frac{1}{2\pi f C_i R_i} \quad (1)$$

The damping coefficient $\alpha$ can be obtained by Eq.(1) after calculating the quality factor $Q$. When the sample packaging experiment is conducted in an atmospheric environment, the lower the quality factor $Q$ of the quartz tuning fork, the larger the damping coefficient $\alpha$, and the motional capacitance $R_i$ reflecting the mechanical loss also becomes larger. The resonant frequency of the quartz tuning fork can be calculated through the equivalent motional capacitance $C_i$ and the equivalent motional inductance $L_i$:

$$f = \frac{1}{2\pi \sqrt{L_i C_i}} \quad (2)$$

The experimental results show that the damping coefficient becomes larger, the equivalent motional capacitance becomes smaller, the equivalent motional inductance becomes larger and the resonant frequency of the tuning fork decreases. The vacuum level has a significant impact on the performance of the quartz tuning fork. It can reduce the damping coefficient and improve the quality factor. Therefore, if the vacuum package is employed, the damping coefficient of gasses in the shell is greatly reduced and the quality factor of the micromachined quartz tuning fork gyroscope can be significantly improved.

In the packaging process of micromachined quartz tuning fork gyroscopes, the quartz tuning fork must first be attached to the convex support of the shell substrate by the welding or bonding process. The bonding technology generally adopts the integral heating, which is time-consuming. The high temperature is easy to cause thermal damage to the sensitive element and circuit. The mismatch of the CTEs of the two kinds of bonding materials leads to the increasing thermal stress in the bonding region as well as the poor device reliability. In order to reduce the adverse factors of thermal bonding, two technical approaches are usually taken: first, the low-temperature solder and low-temperature bonding technology; second, the localized induction heating packaging technology, for the package of devices containing temperature sensitive chip and structure when the temperature difference is greater than 200 ℃. It can be sealed in the air or achieve the vacuum hermetic package at a low cost and the localized heating of the electromagnetic induction bonding region. The microsystem electromagnetic induction local-heating packaging equipment is shown in Figure 2.

**Figure 2.** Electromagnetic induction localized-heating and bonding packaging equipment.
3. Vacuum packaging process of micromachined quartz tuning fork gyroscopes

The shell of micromachined quartz tuning fork gyroscope can adsorb gasses. The airtight materials in a high-temperature environment release the adsorbed gasses and thus affecting the packaging vacuum level. Before packaging, adsorbed gasses of the shell must be removed to ensure the reliability of the gyroscope vacuum packaging. Experiments show that the average vacuum level of the unbaked shell is \(9 \times 10^9\) Pa after vacuum package, but that of the baked device is about \(5\) Pa. The vacuum level is nearly doubled and beneficial to improve the gyroscope precision [7].

In the case of good welding quality, the shell leakage mode is the approximate molecular flow mode. The vacuum cavity volume is \(V\) and the vacuum pressure of the vacuum cavity of encapsulation shell is \(P\). Assume that the air pressure is \(P_{\text{air}}\), the vacuum pressure in the buffer cavity is \(P_1\) and the buffer cavity volume is \(V_1\). Gasses may only pass the outside of the sealed cavity through the first welding rib into the vacuum buffer cavity, where the gas pressure rises. Then gasses pass through the second welding rib into the vacuum cavity. According to the molecular flow theory, if the leakage permeance is identical for inner and outer welding ribs, assume that the air leakage permeance is \(C\), and the equation is as follows:

\[
V_1 \frac{dP}{dt} = C(P_{a} - P) - C(P_1 - P)
\]

(3)

\[
V \frac{dP}{dt} = C(P_1 - P)
\]

(4)

Assume that the pressure in the initial buffer cavity and the vacuum cavity is \(P_0\) and solve the two equations, we obtain the change of vacuum cavity pressure \(P\) with time:

\[
P = \frac{r_2}{r_1 - r_2} \left( P_{\text{air}} - P_0 \right) e^{\frac{r_1}{r_2}} - \frac{r_1}{r_1 - r_2} \left( P_{\text{air}} - P_0 \right) e^{\frac{r_1}{r_2}} + P_{\text{air}}
\]

(5)

Meanwhile, the change of pressure in the buffer cavity with time can be obtained:

\[
P = \frac{1}{r_1 - r_2} \left( C \frac{1}{V_1} + r_2 \right) e^{\frac{r_1}{r_2}} - \frac{r_1}{r_1 - r_2} \left( C \frac{1}{V_1} + r_1 \right) e^{\frac{r_1}{r_2}} + P_{\text{air}}
\]

(6)

Where: \(r_1 = \frac{-b + \sqrt{b^2 - 4c}}{2} ; r_2 = \frac{-b - \sqrt{b^2 - 4c}}{2} ; b = 2(CV + CV_1) \); \(c = \frac{C^2}{V \cdot V_1}\)

The encapsulation shell has no buffer cavity suitable for the equation:

\[
V \frac{dP}{dt} = C(P_{a} - P)
\]

(7)

The change of pressure with time is:

\[
P = P_{a} - \left( P_{a} - P_0 \right) e^{\frac{r_1}{V}}
\]

(8)

After improving the welding quality, the leak rate usually reaches \(10^{-9} \sim 10^{-13} \text{ Pa} \cdot \text{m}^3 / \text{s}\). Assume that the vacuum failure criterion is the change of vacuum level by 50%. By using Eqs.(5) and (8), a rough calculation of the vacuum hold time is obtained for the vacuum package with and without buffer cavity, at least extended by over 20 times. Generally, the vacuum packaged devices are required to hold for more than 8 years. The existing getter has limitations in its application in the vacuum package of micromachined quartz tuning fork gyroscopes. The encapsulation shell with buffer cavity
can reduce the leak rate. Its structural design is shown in Figure 3. The key to the design of the encapsulation shell is to ensure that all the gas leakage pathways pass through the buffer cavity, the shell buffer cavity and the vacuum cavity must have the same initial vacuum while being packaged, and the buffer cavity is directly formed by the resistance welding of the inner and outer welding ribs [8, 9].

Figure 3. Design of vacuum package shell with vacuum buffer cavity.

According to the welding process characteristics, at the squeeze stage the shell cap is in close contact with the base and then the welding current is connected. Due to the restriction in the accuracy of the shell fabrication process, the roughness is not uniform for the contact surface between the seal cap and the base, resulting in too large contact resistance at the welding position. The excessive joule heat will burn the contact surface when the current passes, so the preliminary squeeze is needed. If without sufficient squeeze or pressurization, the uneven current may lead to a lot of solder splash or local burn. After the squeeze stage, the passage of current generates heat, and plastic deformation occurs with broken grains at the interface under pressure and heat. The broken grains are recrystallized at a high temperature so that common crystal grains are formed between weld pieces through the mutual crystallization to complete the welding in the plastic state. As the temperature rises, the plastic area extends around and there is a melting area in the center. Since the melting area is surrounded by the plastic area, the liquid molten core will not splash under pressure and the molten solder will not be oxidized by external air. However, if the temperature is too high, the melting area expands to the edges of the weld seam and causes an outflow of the molten metal. The gold-tin solder is molten, then the power is cut off and the welding pressure is held. The molten gold-tin solder gradually cools under the normal temperature and becomes solidified and crystallized to form alloy. The rapid cooling of liquid gold-tin solder must be avoided to prevent the formation of a brittle alloy structure and a small strength at the welding position that is brittle and especially easy to leak.

In order to improve the weld strength, the secondary pulse method can be used to change the brittle alloy structure. With the secondary pulse current, the gold-tin solder alloy is directly annealed into the void-free alloy structure with good ductility and fine grains. The weld strength can achieve satisfactory results after good control of the annealing current and time, adjustment of the parameters of welding pressure, current and time according to the secondary pulse process, and consideration of other factors such as weld strength. The packaging process of micromachined quartz tuning fork gyroscopes directly affects the vacuum level inside the shell, thus influencing the gyroscope performance. In order to optimize the vacuum package process of micromachined quartz tuning fork gyroscopes, the process parameter optimization test of the vacuum end cap by using the empty shell is employed to test the vacuum package reliability. It is tested on the vacuum packaging machine developed by Huazhong University of Science and Technology. The vacuum seal cap utilizes the reflow soldering of Au-Sn solder with the process as follows:

(1) The Au-Sn plated base and shell for the package of micromachined quartz tuning fork gyroscopes are cleaned for 10 minutes by using the ultrasonic acetone, so as to remove the oil dirt and ensure the surface cleanliness of the package;
(2) The packaging material and gasses adsorbed on the component surface are removed and it is baked in an 80°C vacuum drying oven for 8h;

(3) The package base, solder material, and seal cap are placed in the special clamp of the vacuum packaging machine. The vacuum extraction system on the vacuum packaging machine is started and vacuumed to $10^{-2}$ Pa so as to observe the vacuum level. The optimized parameters are used for resistance welding and the vacuum is held for a period of time;

(4) The packaged device is taken out when it cools off to the normal temperature, and the gross leak detection and the fine leak detection of the packaged shell and welding quality are carried out.

Six groups of optimization experiments using different process parameters are designed for the packaging process of micromachined quartz tuning fork gyroscopes. The metal ring on the Kovar metal base and shell has good flatness and density. Its surface must be plated with nickel and gold-tin and the thickness should be greater than 1.25 μm.

The factors influencing the airtightness of the vacuum seal cap of micromachined quartz tuning fork gyroscopes during the optimization of its process parameters are as follows:

(1) The applied pressure is not uniform, the shell is deformed, the hot molten gold-tin solder flows between the seal cap and the shell base and the solder is deficient in local areas, so the seal-tightness is poor and the welding strength is bad.

(2) The applied pressure is too large, the gold-tin solder flows out of the welding position after squeeze and thus the shell appearance is affected. The gold-tin solder is attached to the inside and outside of the shell and leads to the wire short circuit and device failure.

(3) The welding temperature is too high for the package of micromachined quartz tuning fork gyroscopes, the surface tension of the gold-tin solder becomes weaker, it is boiling between the seal cap and the base, and holes easily form in the weld layer and affect the airtightness of shell after vacuum package. Cracks easily develop in the holes of the weld layer and shorten the gyroscope’s service life.

The interface and welding effect in the vacuum resistance welding area of the micromachined quartz tuning fork gyroscope are shown in Figure 4, where the gold in the Kovar base and shell spreads towards the solder layer and forms a layer of dense eutectic mixtures between the Kovar alloy base and the shell solder layer. There is no crack in the weld interface layer, so the airtightness can be maintained for long.

![Figure 4. Welding effects at different vacuum resistance welding positions.](image)

### 4. Testing and analysis of packaging effects

Aetrium model 6000 bubble leak detector is used for the gross leak detection of airtightness of the packaged micromachined quartz tuning fork gyroscopes. The perfluorotributylamine solution (FC-43, boiling point: 165-185°C) is poured into the leak detector and heated to about 90°C. Then the gyroscope resonant cavity is immersed in the solution. Observe from the observation window of the high magnifying glass if there are bubbles released around the weld seam. The gross leak detector and the experimental effects are shown Figures 5(a) and (b). The experimental results indicate no bubbles at the weld seam. Compared with previous experimental data, it was demonstrated that the vacuum
packaged micromachined gyroscope maintains a relatively stable output value after five years, the vacuum package has minor leaks and the airtightness of the devices is kept well [10]. Due to the limitation of experimental conditions, the fine leak detection of the sample hasn’t been completed. A helium mass spectrometer is used for the fine leak detection. In this process, the packaged micro-gyroscope device is placed into a pressurization device filled with helium gas for a period of time. Then the leak rate is detected by putting it in a leak rate detection cavity connected with the helium mass spectrometer [11].

The solder material selection is very important for the miniaturization of micromachined quartz tuning fork gyroscopes and high-precision and high-reliability welding pad on the welding surface micro-area of vacuum package. The thermal conductivity is 57w/m·K for the eutectic AuSn2O with the highest thermal conductivity among solders. The gold content in the eutectic AuSn2O is 80wt% and the eutectic point is 280℃, so it is an ideal vacuum resistance welding material without the need of flux. The vacuum resistance welding process is, in essence, the reasonable match of three factors, namely pressure, current and time, so as to melt and cool off the gold-tin solder to be alloy. Different heating and melting rates and cooling rates form different alloy structures with big differences in the weld strength. The welding effects indicate that:

1. The vacuum resistance welding needs no flux and the mechanical strength is high. Gold accounts for a large proportion of the alloy (80%), and the surface oxidation of the material is low. The yield strength of the gold-tin alloy is very high. Even at the temperature of 250~260℃, its strength can meet the airtightness requirements.
2. The vacuum resistance welding has a low viscosity and a good wettability. The liquid gold-tin alloy has a very low viscosity, thus being able to fill the gap generated by the welding process and having good density.

![Figure 5](image1.png)  (a) gross leak detector  (b) no bubble indicated by the gross leak detection.

After the quartz tuning fork is packaged, if the drive circuit is the same as the sense circuit, the change of gyroscope threshold is only related to the damping change. The damping is determined by the airtightness of the vacuum cavity. The detection of threshold change of micromachined quartz tuning fork gyroscopes can be used to characterize the vacuum package airtightness[12]. The threshold is generally smaller than 0.01°/s and can be determined by measuring the relationship of the bias voltage output and the angular rate input. The measurement method is measuring the noise after the gyroscope starts and outputs stably. From the input rate of 0.001°/s, with an increment of 0.001°/s, the output curve is recorded and the mean is calculated. When the noise to signal ratio of the output value reaches 63%, the input angular rate is the identifiable sensitivity limit, called threshold. Figure 6 shows the output curve of one minute when the input rate of the micromachined quartz tuning fork gyroscope is 0.005°/s. It can be determined that the threshold is 0.005°/s. The tuning fork gyroscope has no dead band caused by friction or other reasons, so the relationship between threshold and noise output is especially obvious. The main source of irregular fluctuation noise is electrical noise, which is caused by the high gain operational amplifier. Another source of
noise is generated by the drive motion coupling in output. This effect can be minimized if the gyroscope works at the mechanical zero point by the frequency modulation process.

![Figure 6. Threshold test of micromachined quartz tuning fork gyroscopes.](image)

5. Conclusion

The vacuum level of micromachined quartz tuning fork gyroscopes should be kept at 1 Pa to meet the requirements of long-term stability of quartz tuning fork resonance. Resistance welding has the advantages of high yield, short welding time and less material outgassing during welding. The welding surface of alloy solder is characterized by high strength, small thermal resistance, and good stability. The source of gases in the sealed cavity are mainly gases leaked from the cavity or released by materials in the vacuum cavity. The internal outgassing is primary compared with the external leakage. The processing of shell material and alloy solder is a key technology for keeping the airtightness. Real-time monitoring of the vacuum level inside small device cavities is a technical problem. Due to the individual differences of quartz tuning forks, the vacuum measurement system outputs different values and needs to be calibrated before online measurement. The online monitoring of resonant resistance of the quartz tuning fork in the small device cavity and the damping coefficient of gases are related to the measurement of vacuum level, which is of great significance for the optimization of the packaging process of micromachined quartz tuning fork gyroscopes.

6. References

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