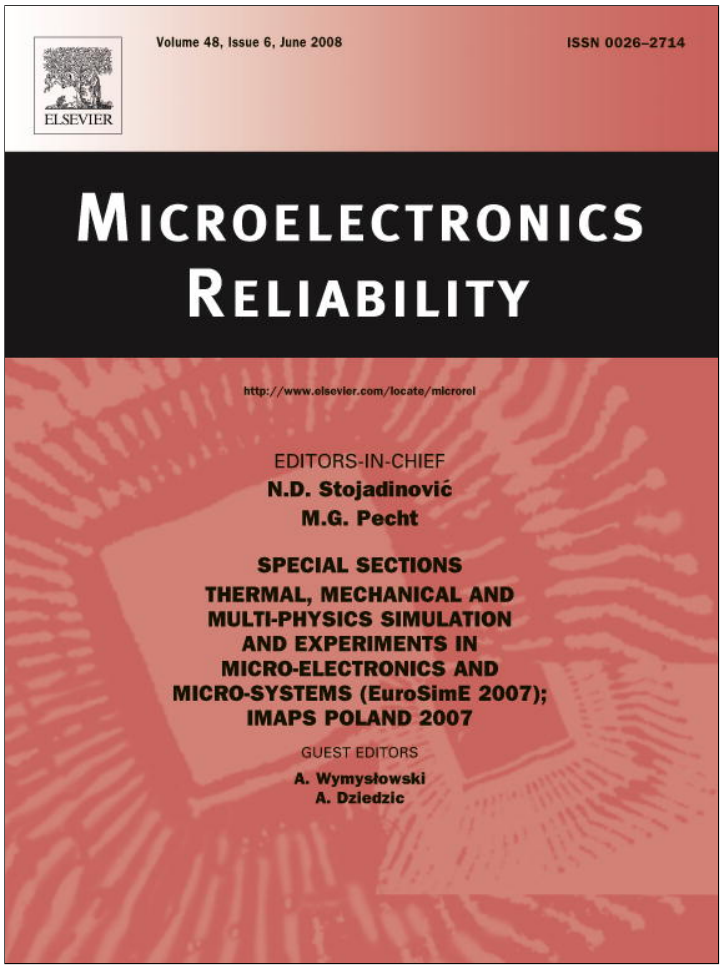

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Quality factor measurement of micro gyroscope structure according to vacuum level and desired Q-factor range package method

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ABSTRACT

A micro-machined gyro chip of gyroscope is normally packaged in specific vacuum level to get the specific quality factor(Q-factor). If the Q-factor is too high, frequency tuning and the approximate matching between driving and sensing comb structure become difficult, and if the Q-factor is too low, its sensitivity decreases. The optimum Q-factor of our gyro chip design is 4000 range. To get this range, we measured the drive mode Q-factor as vacuum level of our gyro chip and we found that the vacuum level of the desired Q-factor 4000 is in the range of 740 mTorr. Based on this data, we fabricate the wafer level package gyro chip of the desired Q-factor by controlled the basic pressure of package bonding chamber just prior to the bonding process. After wafer level package process, we measured Q-factor of whole samples. Among 804 samples, 502 packaged gyro chips are worked and the Q-factor of 67% samples is between 3500 and 4500 range.

1. Introduction

As the accelerometer and pressure sensor based on MEMS technology become increasingly commercialized, more attention has been given to the development of low cost MEMS gyroscopes. Especially, they have been applied to automobiles, camcorders and mobile phones. Many papers about development of micro-machined gyroscopes have been reported last decades [1]. And a variety of silicon gyroscopes employing different excitation and detection mechanisms have been presented [2–5].

In order to improve the sensitivity of a vibratory gyroscope, it is necessary to match the resonant frequency of driving and sensing mode, and operate it in vacuum for sensitivity amplification by amount of Q-factor of driving and sensing mass [6].

The high Q-factor in the driving mass allows a large resonating displacement at a low voltage and a stable resonance because the driving mass of vibratory gyroscopes operates as a resonator. However, the excessive Q-factor in the sensing mass has an effect on the resonant peak in the frequency response of the gyroscopes. The magnitude of the resonant peak is related to the transient response of gyroscopes such as the overshoot and the settling time as well as the vibration immunity due to unwanted shock. This means that a high driving mass Q-factor and an adequate sensing mass Q-factor can improve the performances of the gyroscopes. On the other hand, the quality factors of the two mass change simultaneously according to a change in the vacuum level. This means that the sensing system Q-factor restricts the vacuum level within a narrow range [7]. In our design, an adequate driving mass Q-factor is around 4000 and sensing mass Q-factor is 280 at that time. If we know the driving or sensing mass Q-factor as vacuum level of our design, we can fabricate the wafer level package gyro-chip of the desired Q-factor by controlled the basic pressure of package bonding chamber just prior to the bonding process. For these reason, we organize the system and measure the driving mass Q-factor as vacuum level of our gyro chip. We also measure the Q-factor distribution of packaged whole gyro chip in the wafer.

2. Experimental

2.1. Overview of MEMS gyroscope

Fig. 1 shows the SAIT (Samsung Advanced Institute of Technology) gyroscope structure. It has a laterally oscillating comb structure, which consists of driving springs that suspend the entire mass; sensing springs; driving comb electrodes; and driving–sensing comb electrodes. To avoid the coupling effect caused by the mechanical interference between the driving and the sensing modes, the gyroscope has a 'decoupled' design – independent springs for driving and sensing modes. Fig. 2 shows the cross-sectional view of the fabricated gyro chip. Structures are made of SOI

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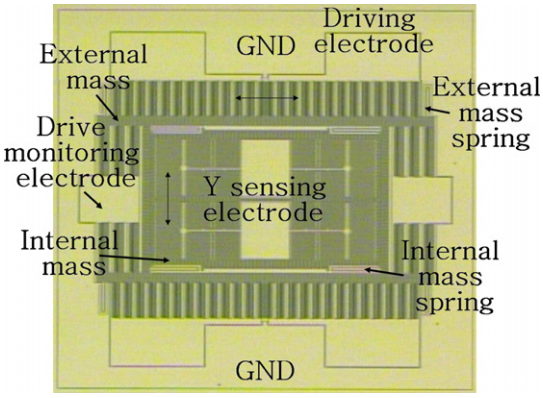

Fig. 1. Fabricated gyro structure.

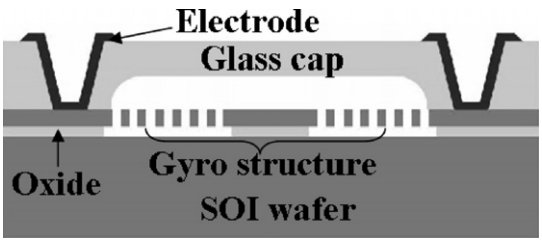

Fig. 2. Cross-sectional view of packaged micro gyro chip.

(silicon on insulator) wafer and anodically bonded with glass cap wafers for packaging.

Fig. 3 shows that the assembly is finished gyroscope sensor. It is consist of packaged gyro chip, ASIC chip which process the detected signals and the case. The size of this gyroscope sensor is approximately 8 mm(D) × 15.8 mm(W) × 4.9 mm(H) in dimensions. The gyro sensor has a nominal scale factor of 0.67 mV/deg/s, bandwidth of 50 Hz (at −90 phase delay) and angular velocity range of +300° s [6].

2.2. Theory of measurement

The general principle of the MEMS gyroscope is that comb structure mass is electrically vibrated one direction (drive axis). When the gyroscope sensor rotates around and axis is orthogonal to the die plane, the sensing mass experiences the Coriolis force. Since drive, sense and rotational axes are orthogonal, the Coriolis acceleration acts along sense axis. The degree of angular velocity is measured by the capacitive changes of the vibrating mass and electrode. When the gyro structure is vibrated in air, its flow and viscosity produces resistance against the vibration of the structure. Consequently, Q-factor and sensitivity are decreased, and these weak signals are difficult to detect. For this reason, it has to be packaged in vacuum condition to maximize the sensitivity of the gyroscope [8].

Q-factor is the index of energy loss of a moving mechanical structure by the damping effect. From 'free decay curve', resonance frequency is 'ω_n', −3 dB below the max amplitudes, which are 'ω_1' and 'ω_2', and damping ratio is 'ζ', mass of moving mechanical structure is 'm', stiffness is 'k', damping coefficient is 'c', and then, Q-factor is defined in the equation below

$$\frac{\omega_2 - \omega_1}{\omega_n} = 2\zeta = \frac{1}{Q} \tag{1}$$

$$\therefore Q = \frac{\sqrt{mk}}{c} \quad \left(\zeta = \frac{c}{2\sqrt{mk}}, \omega_n = \sqrt{\frac{k}{m}}\right) \tag{2}$$

Both the damping coefficient and Q-factor are closely related with the vacuum condition of the device [9]. Normally, the mass and spring constant of a vibrating structure are fixed and calculated from design and material parameters. Damping coefficient varies with the circumstantial vacuum condition. So, we can calculate the Q-factor of a vibrating structure by measuring the damping coefficient of a structure.

2.3. Experimental design

This proposed test system is composed of the interconnection jig, signal process circuit; vacuum chamber, signal analyzer, and DC power supply. The interconnection jig connects the structure and circuit electronically. The signal process circuit drives the comb structure stably and amplifies the detected signals. The vacuum level in the vacuum chamber can be controlled using throttle valve. The signal analyzer measures the damping coefficient and resonance frequency of the comb structure. In order to measure the Q-factor as the vacuum level, the gyro structure placed on the proposed interconnection jig must be prepared by another fabrication method.

SOI wafer is used to fabricate gyro structure, which is consisting of three layers. Silicon as a top layer, oxide as a middle layer and silicon as a substrate layer. Top silicon structural layer, is p-type, (1 0 0) with a resistivity of 0.01–0.02 Ω cm and the thickness is 40 μm. The oxide layer thickness is 3 μm and this layer is used as a sacrificial layer. This wafer is very useful to fabricate micro floating structure like a membrane or cantilever. Gyroscope structures are patterned with a GXR 601 PR (Photo-Resist) and top silicon layer 40 μm is vertically etched with the ICP-RIE (inductively coupled plasma reactive ion etcher). After silicon etching process, PR is coated on the gyro structure wafer again to protect the comb structure from Si particles. The gyro chip structure wafer is diced into

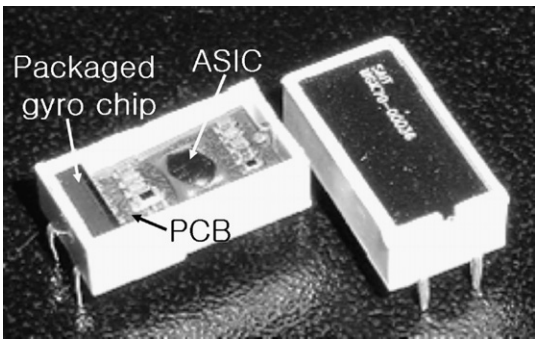

Fig. 3. Assembled gyro sensor.

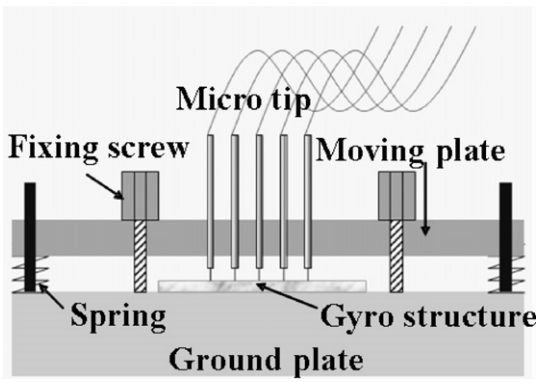

Fig. 4. Cross-sectional view of interconnection test jig.

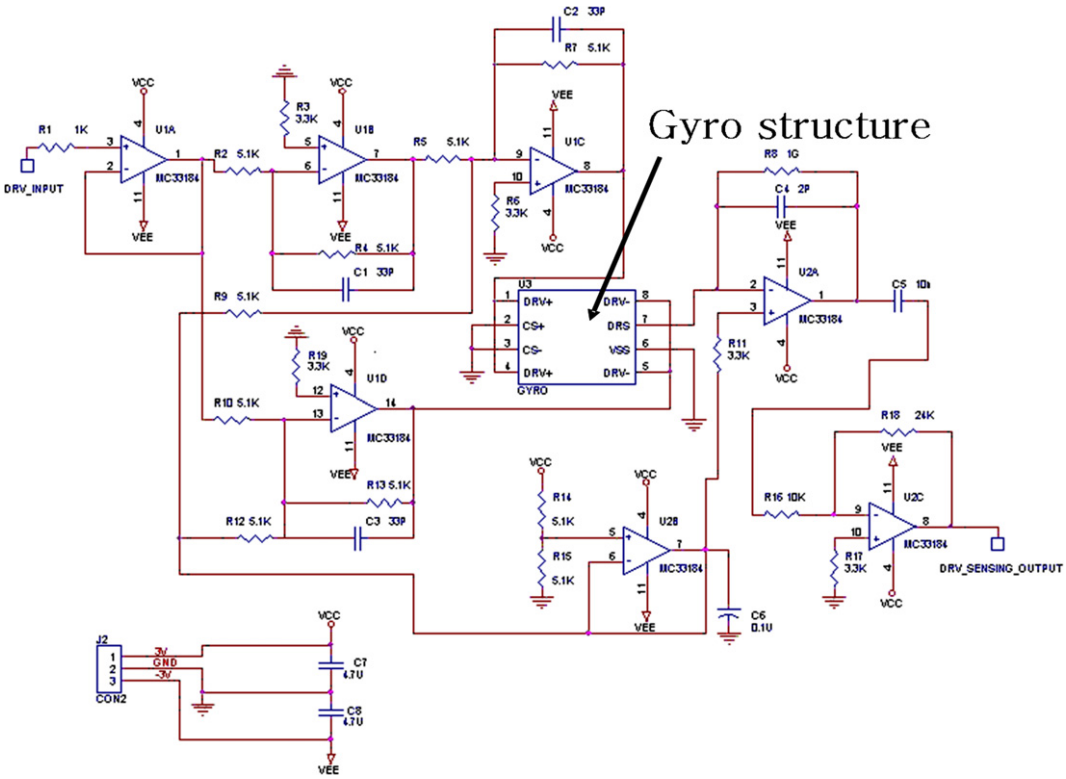

Fig. 5. Circuit diagram for microstructure driving and signal detection.

3 cm × 8 cm size because it is easy to handle and can be properly placed on the interconnection jig. In this diced wafer, about 60 gyro structures are contained. Si particles are washed out using the ultrasonic cleaning method, and PR is removed using a wet remover. The gyro structure is released by the oxide layer etching in BOE (buffered oxide etcher) and rinsed. After the cleaning step, it is soaked in boiling IPA (isopropyl alcohol) for about 3 min and pick out slowly to prevent sticking of the structure.

The interconnection jig consists of the ground plate and transparent moving plate. A gyro structure is placed on the ground plate and micro tip to interconnect the structure, and a circuit is fixed in the moving plate. Ground plate with the gyro structure is placed on a low magnified microscope to align with the micro tip of the moving plate, which is fixed on the transparent acrylic plate. The electrode pad of the gyro structure and micro tips are seen through the microscope at the same time. By moving the gyro structure, micro tip and electrode pad are aligned. After alignment, the electrode pad of the gyro structure on the ground plate and micro tips are

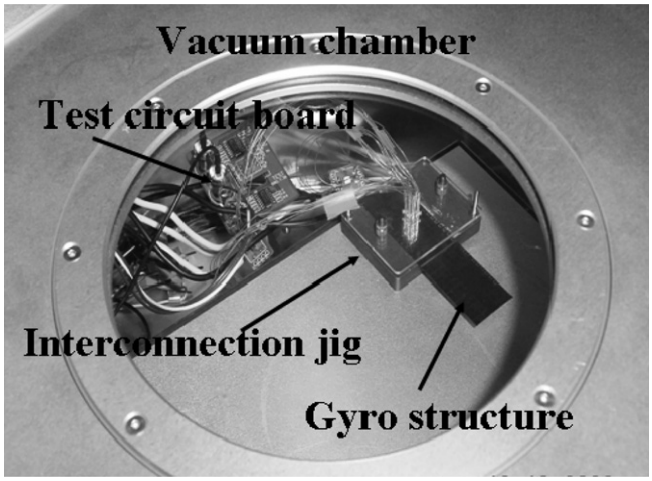

Fig. 6. Interconnection jig with gyro structure placed in the vacuum chamber.

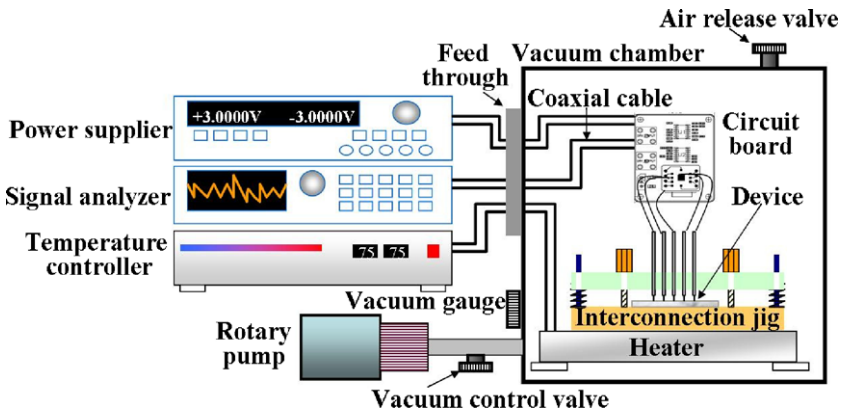

Fig. 7. Block diagram of measurement system.

fixed by using a plate screw. Fig. 4 shows the fabricated interconnection test jig and Fig. 5 shows the circuit diagram that drives the gyro structure and detected signals. This signal needs to be amplified because it is too weak to detect without an amplifier. This gyro structure drives in the 7 kHz range. Fig. 6 shows that interconnection jig with the gyro structure is placed in the vacuum chamber.

The circuit board is connected to the signal analyzer (HP35670A) and the power supply by using the feed-through of the chamber. The chamber is evacuated to the specific vacuum level, which can be controlled particularly by using the air release valve. When the vacuum is set to a specific range, the frequency and damping coefficient are read from signal analyzer and translated to the Q-factor. In this way, Q-factors as vacuum level of gyro structures are measured. Fig. 7 shows the block diagram of the measurement system, and Fig. 8 shows the organized measurement system.

3. Results and discussion

Fig. 9 shows the Q-factor as vacuum level of 15 gyro structures. Average and standard deviation of measured samples is shown in Fig. 10. Fig. 11 shows the average and regression of these data from 3000 to 6000 of the Q-factor.

By using this graph, we set the vacuum level of chamber to 740 mTorr and package the gyro structure with glass cap wafer by anodic bonding method. Outgasing from glass is prevented by coating the noble metal on the surface of glass cavity. After wafer level package process with glass, we measured quality factor of whole samples. Among 804 samples, 502 packaged gyro chips are worked. Fig. 12 showed the distribution of quality factor of

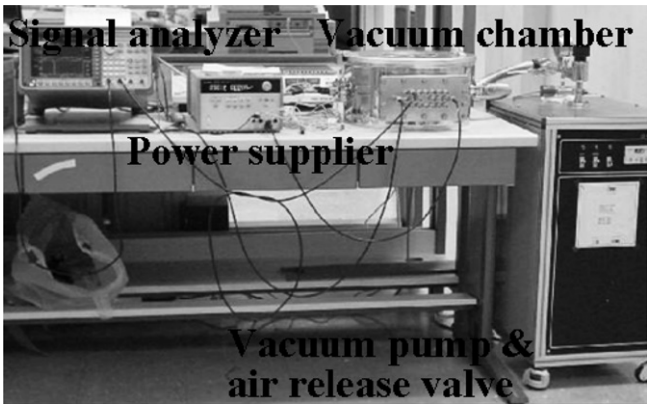

Fig. 8. Organized systems for measuring Q-factor as vacuum level of MEMS gyro structure.

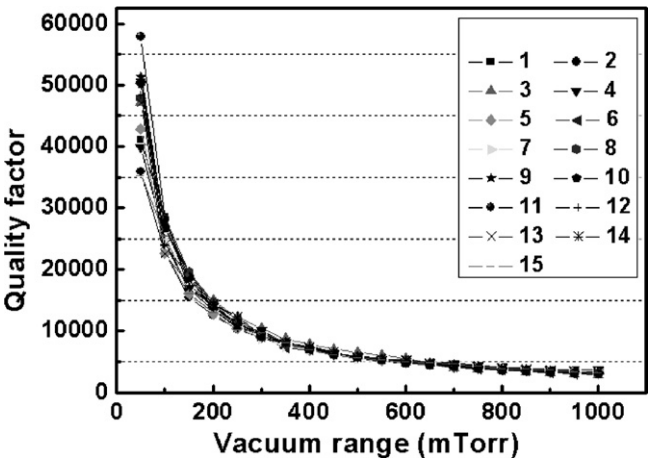

Fig. 9. Q-factor as vacuum level of 15 gyro structures.

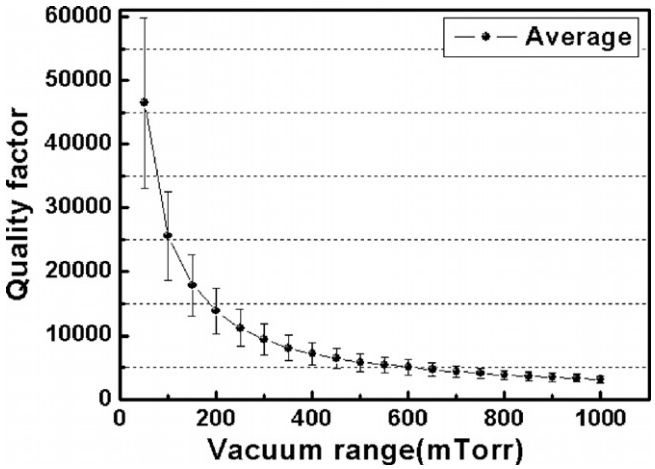

Fig. 10. Average and standard deviation of measured samples.

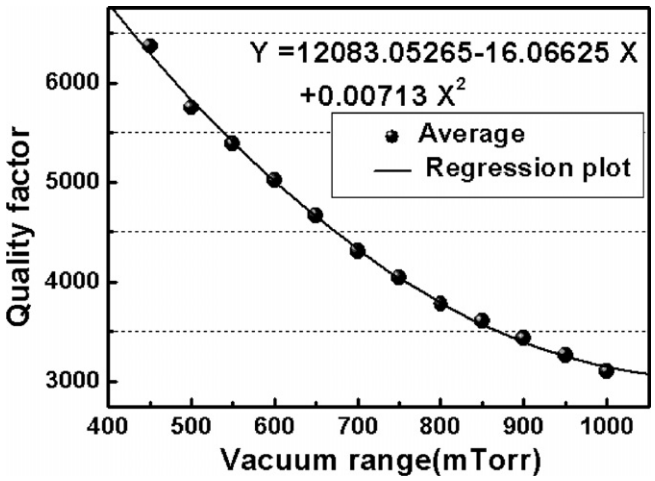

Fig. 11. The median and regression of Q-factor as vacuum level.

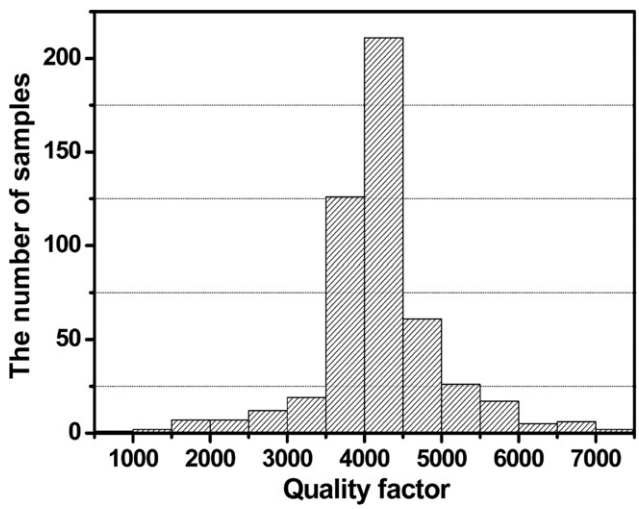

Fig. 12. The distribution of quality factor of measured gyro chips.

measured chips. The quality factor of 67% samples is between 3500 and 4500 range.

4. Conclusion

In this paper, Q-factors as vacuum level of the gyro structure are measured. Interconnection jig, gyro structure driving and signal detection circuit, and vacuum level controllable chamber are organized to measure them. Fifteen gyro structures are measured to acquire reliable data and the variation of each sample, and we found that the vacuum level of the desired Q-factor 4000 is in the range of 740 mTorr. From the measured graph, we can fabricate the wafer level package gyro-chip of the desired Q-factor by controlled the basic pressure of package bonding chamber just prior to the bonding process.

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