Vacuum measurement on vacuum packaged MEMS devices

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Abstract. This paper investigates the relationship between the resonance impedance of a tuning fork quartz oscillator and the small size cavity vacuum pressure and develops an on-line vacuum measurement system to track real-time vacuum pressure in MEMS devices. Furthermore, authors completely analyze all facts that affect the resonance impedance. A set of metal vacuum packaged devices have been monitored for more than 10 months using this on-line vacuum measurement system. The results indicate that it is very critical to investigate vacuum packaging processes, reliability and durability of the vacuum devices by using this on-line vacuum measurement system.

Keywords: vacuum measurement, vacuum monitor, vacuum packaging, MEMS devices.

1. Introduction

Concept of Micro-electro-mechanical system (MEMS) was proposed decades ago and its development has been slow and MEMS products in the market are still few. One of the key reasons is that the packaging technology has not been very mature. MEMS packaging, especially vacuum packaging, is one of the key barriers of the development of those MEMS devices such as high-performance inertial, mechanical resonance and RF devices which require high vacuum packaging.

Nearly all the vacuum gauges available from market today are not suitable for small MEMS devices of vacuum measurement. It is impossible to track the pressure in the cavity of MEMS devices after vacuum packaging because of the lack of appropriate means for small-scale measurement, as one can only estimate vacuum pressure, and consider pressure in the cavity to be the same as the initial pressure in the vessels of packaging equipment when MEMS devices are packaged. It has been demonstrated by the authors in our experiments that the pressure in the cavity of MEMS devices can be affected by dynamic vacuum distribution, welding processes, bonding quality, and device materials, etc. The pressure in the cavity is not equivalent to the pressure in the packaging vessels, sometimes with several magnitudes greater than the pressure of the vessel. Therefore, it is significant to come up with an on-line vacuum measurement system for vacuum packaging research and qualification control.

The objective of this paper is to propose a measurement of vacuum pressure in the cavity of vacuum packaging devices by using a traditional tuning fork oscillator. While the gas pressure...
surrounding tuning fork changes, the resonance impedance will change. Based on this theory, Japanese scientists, K Kokubun, M Hirata, Y and M T. Toda[1][2][3][4][5][6], have used tuning fork oscillators as measurement sensors for vacuum measurement. The above research and their products are used for vacuum gauges, and these are not suitable for vacuum pressure measurement of vacuum packaged MEMS devices that are so small in size. This paper uses tuning fork quartz oscillators directly placed in MEMS devices as a monitor chip, which can be wired out for signals by device pin-outs, thus achieving vacuum measurement for MEMS devices.

2. Theory of vacuum measurement

When X-cut or Y-cut crystal is working on the bending mode in vibration, the change of resonance impedance of tuning fork with gas pressure is very big. According to small ball models, tuning fork quartz oscillators vibrating in the air can be understood as a damping factor caused by gas friction force [1]. The resonance impedance of tuning fork oscillators is \( Z = Z_0 + \Delta Z \), and \( \Delta Z \) is caused by the gas friction force. The resonance impedance can be calculated by the following formula [3].

\[
Z = \frac{2\eta_0 V^2 \cos \theta}{A^2} \cdot f
\]  

where \( Z \) is the impedance of the oscillator due to an ambient gas; \( V \) is the driving voltage of the oscillator; \( \eta_0 \) is the conversion efficiency of the electric energy to the mechanical energy; \( \theta \) is the phase difference between the voltage and the current; \( A \) is the amplitude of the forced vibration; and \( f \) is the coefficient of friction drag force.

For a specific tuning fork oscillator, coefficient \( (2\eta_0 V^2 \cos \theta)A^{-2} \) is determined. \( \Delta Z \) changes with the change of \( f \). The formula are different for different gas flow models [3].

At the molecular flow region:

\[
f = R^2 \sqrt{\frac{8\pi M}{R_0 T}} \cdot P
\]  

At the viscous flow region:

\[
f = 6\eta R + 3\pi R^2 \sqrt{2\eta \rho \omega}
\]

where \( R \) is the radius of the sphere, which is nearly equal to the thickness of the tuning fork; \( M \) is the molecular weight of the ambient gas; \( R_0 \) is the gas constant; \( T \) is the temperature; \( \eta \) is the coefficient of viscosity; \( \rho \) is the density of the gas, which is proportional to the molecular weight and pressure \( P \); and \( \omega \) is the resonance frequency, which is proportional to \( T^{1/2}/L \), where \( L \) is the length of the fork. From the above formula, when gas flow is the molecular flow, \( \Delta Z \) is proportional to \( P \) and \( M^{-1/2} \). In two different models of the gas flow, \( \Delta Z \) will change with temperature, therefore it is better to measure vacuum pressure under constant temperature.
3. On-line vacuum measurement system

Tuning fork crystals are used in actual measurements, and the fundamental resonance frequency is 32.768KHz. These types of crystal oscillators are very mature products and easy to obtain from the market. Other resonance frequency crystals can also be used and have shown interoperability for vacuum measurement.

Figure 2 shows the principle of measurement circuits. Direct digital frequency synthesizers (DDS) modular unit exports simulation scanning frequency of sinusoid signals with preset phase and magnitude, then passes through low-filter (LPF) module and exports high Signal-to-Noise waveform to inspire the tuning fork oscillator. The tuning fork oscillator with a small laser-drilled hole on the package is connected into the resistance network. When the tuning fork oscillator achieves resonance the crystal can be taken as pure resistor in the circuit with zero phase difference between the voltage and the current. The crystal resonance impedance can be measured as a voltage values shown on the display.

4. Experiment of vacuum measurement

4.1. Calibration of different crystal oscillators

Due to the difference of individual crystals, the resonance impedances of specific crystal oscillators under the same vacuum pressure are different, and the output voltage values of online measurement systems are also different, therefore each tuning fork crystal oscillator used should be calibrated before
vacuum measurements. It can be observed from figure 3 that, although output voltages of each tuning fork oscillator at the same vacuum pressure are different, the trends of all the curves are the same: the voltage values increase while vacuum pressures increase. As shown in figure 4, the sensitivity will decrease in the lower vacuum pressure, especially when the pressure is below 2Pa, where the voltage values will fluctuate when vacuum pressures are below 0.1Pa. The measurement shows great accuracy with the pressures greater than 2Pa.

4.2. Repeatability of calibration experiments

Using tuning fork oscillators for vacuum measurements, repeatability is a very important issue. As shown in figure 5, calibration of a tuning fork oscillator has been done several times under the same temperature to test its repeatability. Calibration results show that overall repeatability is suitable for applications, especially repeatability below 20Pa is better than between 20-100Pa as shown in figure 6, 10Pa is the key parameter for vacuum packaging research, and repetitive accuracy near 10Pa is acceptable.

4.3. Influence of temperature on calibration and measurement

Placing a device packaged under vacuum pressure 10Pa at 25°C in a temperature chamber, the device internal pressure was measured at different temperature points as in figure 7. The experiments showed that the internal pressure changes when the temperature changes, but the curve does not obey the formula that the pressure is proportional to temperature. It shows that temperature not only influences the internal pressures, but also affect the crystal resonance impedance. The above equations (2) and (3) indicate that the resonance impedance changes with temperature fluctuations, but it is difficult to coordinate the equations to the curve in figure 7, the further study is required to make clear the exact model to describe the crystal resonance impedance dependence on temperature. In practical
vacuum measurements of MEMS devices, temperature impaction can not be ignored, a stable temperature environment is strongly recommended while conducting measurement.

4.4. Aging experiments before using

As vacuum packaged MEMS devices always need to pass temperature cycling tests from -40°C to 125°C, the influence on the calibration should be explored in details. Tuning fork crystal oscillators are placed in temperature cycle chamber from -40°C ~+125°C, figure 8 indicates that the calibration curve changes after temperature cycling, the calibration curve will remain stable after 48 more cycles, which demonstrates that crystal oscillators have better repeatability after aging, especially the repeatability at the pressure greater than 60Pa will become even better.

4.5. Tracking of long time vacuum maintenance after vacuum packaging

In those experiments above, the vacuum vessel is utilized in which the pressure is at the level of 10⁻³Pa, the MEMS devices are placed in that vessel, and traditional resistance welding method is used for vacuum packaging. Through the on-line vacuum measurement system, it has been found that the pressure in the device cavity is not equivalent to the pressure in the vessel, which may have several magnitudes difference.

A set of vacuum packaged devices have been tracked for longer than ten months as in figure 9. Five of these seven devices are still maintaining high vacuum degree. Output voltage of device A has dropped greatly because of leakage by accident; Output voltage of device G also dropped shortly after packaging as a result of crystal weak contact, but rose again after a period of time. At the end of the curve, temperatures changed a little bit because the air conditioner ran into problem, which affected the output voltage values with large fluctuations.

5. Conclusion

Based on the principle that the resonance impedance of tuning fork crystal oscillators significantly changes with the air pressure surrounding, the paper presents a method to measure the vacuum degree of MEMS devices, an on-line vacuum measurement system has been developed, and many experiments have been conducted to explore the performance of the measurements. All kinds of possible factors that may affect the changing of resonance impedance are analyzed in this paper. It has been found that different tuning fork oscillators have different calibration curve with the same trend. It has also been found that aging of tuning fork crystal will help to increase the calibration repeatability. Another conclusion is that the calibration will be slightly different at different temperatures and temperature contributes the nonlinearity of measurement. Also a collection of vacuum packaged MEMS devices are tracked for a long time, and the results show that on-line vacuum measurement is very critical for vacuum packaging research and qualifications.
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