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Measurement of Leak Rate for MEMS Vacuum Packaging

Many Micro-Electro-Mechanical Systems (MEMS) devices such as accelerators, gyroscopes, uncooled infrared sensors, etc., require vacuum packaging. The vacuum maintaining lifetime directly determines the vacuum packaging reliability. This research presented a quantitative analysis of the relationship between the leak rate and the vacuum maintaining lifetime, and demonstrated that the leak rate measurement plays an important role. This paper also explored the application limitations in vacuum packaging using a helium spectrometer leak tester to measure the leak rate because the measured leak rate was nonlinear with respect to the actual leak size. According to the fact that the damping coefficient changes with the pressure, a tuning fork crystal chip as a pressure sensor was used to monitor the pressure changes in the package cavity. The leak conductance was also calculated from the pressure tracking data to analyze the leak modes; the molecular flow model and gas desorption model were found to fit the measurement results of leak conductance.
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Keywords: vacuum packaging, molecular flow, leak rate, MEMS packaging

1 Introduction

Much research on vacuum packaging was focused on the electronic vacuum tube packaging before MEMS emergence [1–4]. Novel MEMS technologies have given birth of many new products into applications. Some of the promising devices such as gyroscopes, accelerators, and uncooled infrared sensors based on MEMS technology need to work in vacuum environment to enhance their performance [5–9]; therefore vacuum packaging is essentially needed. MEMS chip size is normally as small as about 1 mm^2, and required small and compact packages. Vacuum packaging processes developed for MEMS devices are typically metal or ceramic packages. These processes are quite different from those in electronic vacuum tubes, which are normally glass or quartz packages. The volume of the packages for electronic vacuum tubes is much larger than that of MEMS packages. Many mature processes for vacuum tubes such as pressure monitoring, sealing process, etc., cannot be directly applied to MEMS vacuum packaging. Leak rate measurement always uses tracer gas detection method. Helium and radioactive ^{85}Kr are often used as a tracer gas [10], but the standard measurement is mainly developed for hermetic packages, not for vacuum packages, especially MEMS vacuum packages. MEMS vacuum packaging technology faces great challenges and need more fundamental investigation

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before being qualified for real world applications [11–13]. First of all, this study theoretically analyzed the vacuum packaging requirements for leak rate. A tuning fork crystal was then installed as a monitor chip in the package to monitor the pressure evolution of the package cavity as a function of time. The leak conductance was calculated from the changes in pressures via time in package cavity. The working principle of the helium spectrometer leak tester was explored in detail to show the difference between the measured leak and the actual leak in the considered vacuum packages, and the limitations for applications in vacuum packaging. Two models were established to explain the leak mode, with the first one based on the molecular flow, and the second one based on the gas desorption theory. The model simulation results were in agreement with the leak conductance measurement.

2 The Relationship Between Vacuum Maintaining Time and Leak Rate

The devices that need to work in vacuum environment not only require a specific vacuum level, but also a long vacuum level maintaining time to ensure its working lifetime. Generally changes in the vacuum pressure come from two factors. One is that the gases absorbed on the surface and dissolved in the package materials are released into package cavity. The other is that the gases outside the package permeate into package cavity, especially through the welding seam. We assume the package cavity vacuum level is about 0.1 Pa, and the changes in the vacuum pressure come mainly from leaks. Leak rate (Pa g m^3/s) or leak conductance (m^3/s) is usually used to describe welding seam leak quantitatively. The following equation can be used to formulate the changes in the vacuum pressure:

$$V\frac{dP}{dt} = Cg(P_0 - P) \tag{1}$$

where C is the leak conductance [13], P_0, normally 1 atm, is the pressure outside the device package, and P is the pressure in the package with the volume V. The leak rate is adopted to evaluate the welding quality. Leak rate is not only dependent on the bonding or welding quality, but also proportional to the pressure difference. Therefore, a concept named as effective leak size, symbolized as L, is defined to compare the welding quality, which is the leak rate formulated as Eq. (2) while the pressure outside the package is 1 atm, and the pressure in the package is taken as vacuum.

$$L = CgP_0 \tag{2}$$

Assuming that failure criterion is taken as the vacuum changes in package cavity by 50%, the relationship between the leak size and vacuum maintaining time can be plotted in Fig. 1 by using MATLAB program, where the package volume is about 2 cm^3.

If the minimum vacuum maintaining time required for applications is more than 3 years, the effective leak sizes required for some typical package vacuum level are summarized in Table 1. The typical leak sizes needed for vacuum packaging are much lower than that for hermetic packaging of typical leak size lower than 10^{-8} Pa g m^3/s [14,15].

3 Application Limitations of Helium Leak Tester for Vacuum Packaging

In our laboratory, helium spectrometer leak tester is available for our tests. Furthermore, helium leak tester is widely used for hermetic testing in packaging laboratories. Its working principle is based on molecular flow mode and viscous flow mode. Using the back pressuring technique [14], the packages are placed in a chamber filled with 3–5 bar helium gas for about 2–5 h dependent on the different volume of the packages. Then the packages are transferred to the chamber of the helium leak tester to measure the leak rate. The dwell time from the helium pressurized chamber to the leak test chamber is recommended to be lower than 1–2 h.

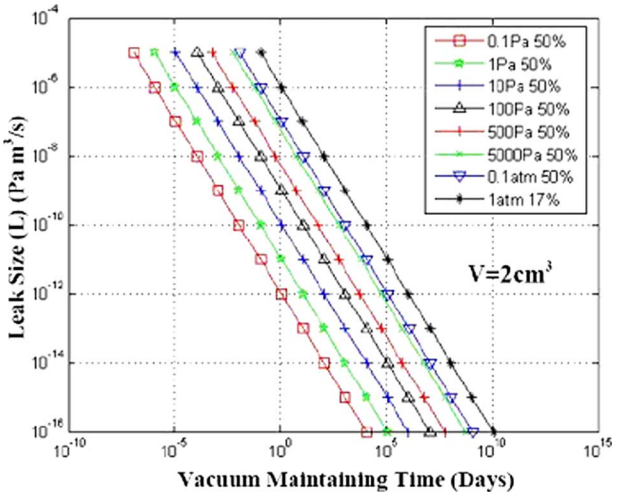

Fig. 1 The theoretical relationship between the leak size and vacuum maintaining time

3.1 Hermetic Packaging. For hermetic packaging, the measured leak rate by a helium leak tester was formulated by Eq. (3) for molecular flow mode, and Eq. (4) for viscous flow mode [16]. Taking leaking mode as either molecular flow or viscous flow was the assumption only for both of the formula, actual leak mode may be very complicated with combination of molecular and viscous leak modes.

$$\begin{aligned} R_{\text{molecular}} &= L\frac{P_2}{P_0}\sqrt{\frac{M_{\text{air}}}{M_{\text{He}}}} \\ &= L\frac{P_{\text{He}}}{P_0}\sqrt{\frac{M_{\text{air}}}{M_{\text{He}}}}\left\{1 - \exp\left[-\frac{LT}{VP_0}\sqrt{\frac{M_{\text{air}}}{M_{\text{He}}}}\right]\right\} \\ &\quad \times \exp\left[-\frac{LT}{VP_0}\sqrt{\frac{M_{\text{air}}}{M_{\text{He}}}}\right] \end{aligned} \tag{3}$$

$$R_{\text{viscous}} = \frac{P_{\text{He}} - P_0}{P_{\text{He}}}L\left\{\frac{1 + S\exp(-2LT/(P_0V))}{1 - S\exp(-2LT/(P_0V))}\right\} \tag{4}$$

where L is the leak size, P_{He} is the helium pumping pressure, P_0 is the air pressure, T is the dwell time, M_{air} is the average molecular weight of air, M_{He} is the helium molecular weight, and $S = (P_{\text{He}} - P_0)/(P_{\text{He}} - P_0)$.

3.2 Vacuum Packaging. Hermetic packages are normally filled with about 1 atm N_2, and the pressure in the vacuum packages is roughly lower than 10 Pa. Molecular flow is the same as the diffusion processes. The leak rate depends on the partial pressure difference for the specific gas, which determines that the molecular leak rate for vacuum packages is the same as that for hermetic packages. However, in terms of viscous flow, this may make a big difference because viscous leak rate is proportional to the total differential pressure across the leak paths.

Table 1 Effective leak size required for typical package vacuum level

Package vacuum level (Pa)	The effective leak size required (Pa g m^3/s)
0.1	10^{-15}
1	10^{-14}
10	10^{-13}

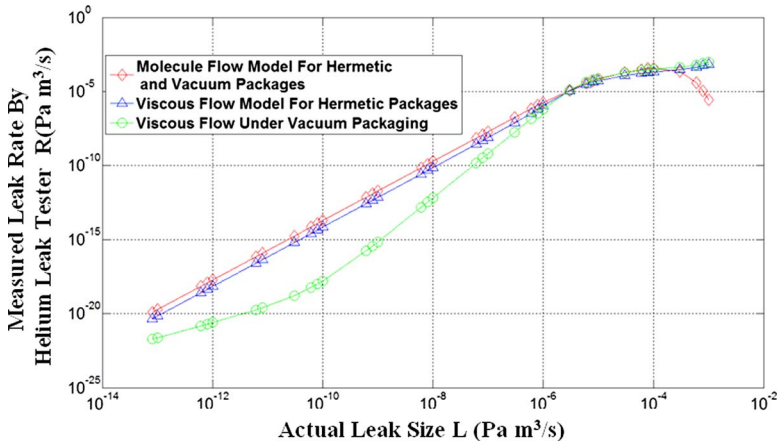

Fig. 2 The relationship between the measured leak rate and actual leak size

As for helium leak testing processes, the packages were first placed in a jar filled with helium gas of 3–5 bars; the equation for laminar flow of gas through a leak into a volume V is

$$V\frac{dP}{dt} = \frac{C'}{2\eta}(P_{\mathrm{He}}{}^2 - P^2) \tag{5}$$

where C' is a constant dependent on the geometry of the leak, and η is the viscosity of the gas. Most of the common gases have viscosities with little difference from the viscosity of air at room temperature.

After helium pumping process, the pressure P_1 in the packages will be given by

$$\frac{P_{\mathrm{He}} - P_1}{P_{\mathrm{He}} + P_1} = \exp\left(-\frac{C'TP_{\mathrm{He}}}{\eta V}\right) \tag{6}$$

The tested packages are then held for a time T in the atmosphere and the pressure P_1 in the packages will be changed to P_2. Then the governing equation will be as follows:

$$V\frac{dP}{dt} = \frac{C'}{2\eta}(P_0^2 - P^2) \tag{7}$$

and P_2 is given by

$$\frac{P_0 + P_1}{P_0 - P_1}g\frac{P_0 - P_2}{P_0 + P_2} = \exp\left(-\frac{C'P_0T}{\eta V}\right) \tag{8}$$

The air outside the packages permeates through the package cavities, and the gas in the cavities of the packages is a mixture of air and tracer gas helium. The measured leak rate will be

$$R = -V\frac{dP}{dt_{P=P_2}} = \frac{P_1}{P_2}g\frac{C'}{2\eta}P_2^2 = \frac{P_1}{P_2}g\frac{L}{P_0^2}P_2^2 = \frac{P_1P_2L}{P_0^2} \tag{9}$$

4 Discussions

In order to compare the results for different applications of the helium leak tester, the relationship between leak size and measured leak rate will be plotted for Eqs. (3), (4), and (9). Figure 2 shows that the measured leak rate for hermetic applications is proportioned to the leak size lower than 10^{-6} Pa m^3/s, and the curves for molecular and viscous flows are nearly parallel; even if the leak flow is a combination of molecular and viscous flows, the measured leak rate is still proportioned to the actual leak size, which is favorable for measurement. As for vacuum packages, however, the curve for viscous flow mode is nonlinear, which makes the calibration a difficult task. When the actual leak flows are very complicated, typically with a mixture of molecular and viscous flows, the calibration becomes more difficult.

Another problem for the helium leak tester to measure vacuum packages is the measurement sensitivity limitation. Figure 2 shows that the measured leak rate for vacuum packages is one to four orders lower than that for hermetic packages. Vacuum packages require the bonding quality with the leak rate lower than at least 10^{-12} Pa g m^3/s (10 Pa vacuum level and maintaining for about 100 days), which makes helium leak tester beyond its measurement sensitivity for vacuum packaging.

5 The Vacuum Pressure Monitoring for MEMS Device Level Vacuum Packaging

Since MEMS devices are usually miniaturized, any vacuum gauges cannot be fitted into the package cavity to measure the vacuum pressure, which is a big obstacle for MEMS vacuum packaging research. This paper proposed a way of real-time monitoring of vacuum level by using a 32.768 kHz tuning fork crystal. The crystal was used as a chip and installed in the packages, with crystal leads soldered to the package leads. Because of gas damping, the resonant resistance of the crystal will be changed with the pressure in the package. Figure 3 is the measurement diagram.

The calibration was carried out and the results were shown in Fig. 4, which demonstrated that the measurement range is from 0.1 Pa to 1 atm. Because of the specific difference of every crystal, each crystal needs to be calibrated before being used as a monitoring chip. The measurement activity should be taken under the same temperature environment, because of the sensitive characteristics of the crystal to temperature.

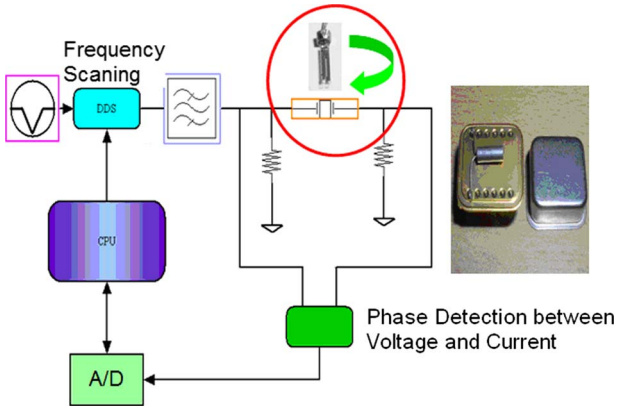

Fig. 3 Vacuum level testing diagram by tuning fork crystal

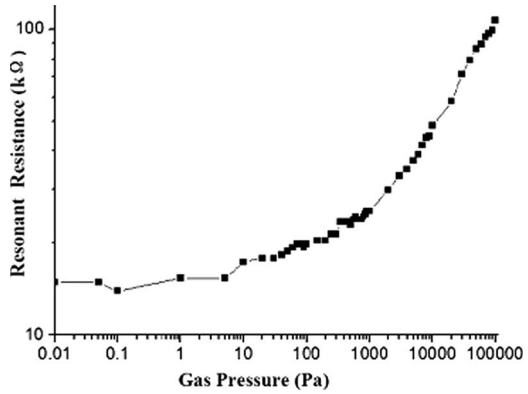

Fig. 4 Crystal calibration curve of resonant resistance versus gas pressure

The vacuum packaging experiments were carried out by using the resistance welding method. The metal package samples shown in Fig. 5 were welded in a chamber with a 10^{-3} Pa vacuum. Each sample was monitored for the internal vacuum level by a tuning fork crystal. The initial vacuum pressures were about 1–10 Pa, and the vacuum pressures in the packages were tracked for about 250 days. Some of the typical pressures' tracking curves were shown in Fig. 6. The vertical axis in Fig. 6 used the voltage across crystal resonant resistance to denote the pressure changes, since crystal resonant resistance would directly change with vacuum pressure inside the package. Then the voltage on the resonant resistance would monotonically change with the vacuum pressure inside. Figure 6 shows that the internal vacuum pressure increases slightly. From the pressure changes in the packages and the relationship between the vacuum maintaining time and the leak size shown in Fig. 1, the actual leak size can be deduced to be about 10^{-12} Pa m^3/s–10^{-13} Pa m^3/s, which is out of the range of helium leak tester measurement.

Fig. 5 Vacuum packaged samples by resistance welding

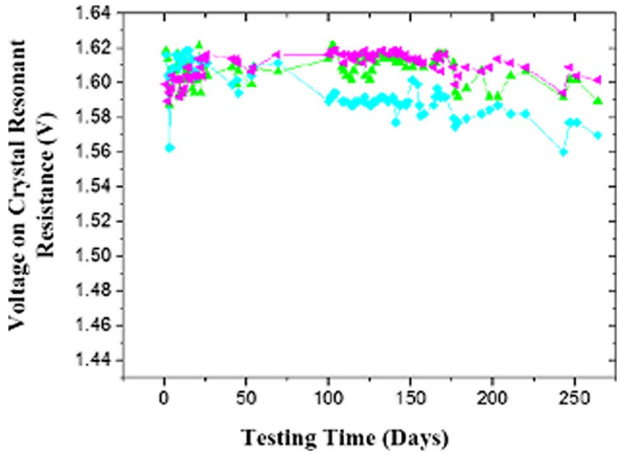

Fig. 6 The pressure tracking of the internal package

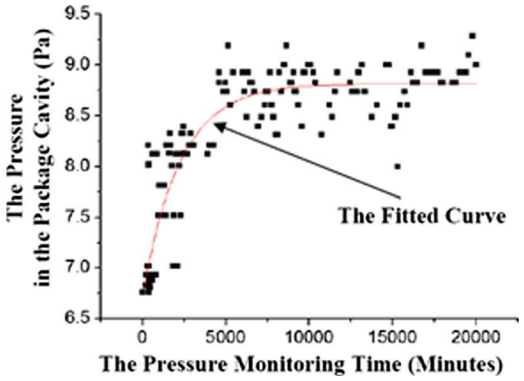

Fig. 7 The pressure tracking in the package cavity by time

6 Measurement of Leak Conductance

In order to explore the method to improve the welding quality, the leak flow modes were experimentally investigated. The leak conductance C in Eq. (1) depends on the geometry and the pressure of the leak path. In a short period, however, pressure across the leak path changes so little that the leak conductance can be considered as a constant. By this assumption, the leak conductance can be deduced from the curve in Fig. 7, where the scattering points can be fitted into a curve. The fluctuation error mainly comes from measurement circuit analog/digital (A/D) conversion error. The calibration showed that the measurement was reliable and the estimate of standard deviation is about 0.33 Pa. Namely, pressure tracking curve by time can be converted into a curve that leak conductance changes by time or the internal pressure as in Fig. 8.

Some of vacuum packaged samples with different welding qualities were monitored to track the changes in the internal pressures of the packages. All the calculated curves of leak conductance by pressure based on the tracking data were drawn in Fig. 9.

The experimental data showed two key points.

(1) The leak conductance of some packages is nearly constant, not changing with the internal pressures in the packages, and the flow characteristic is more like the molecular flow mode. The leak conductance lower than 10^{-14} m^3/s of some packages decreases sharply while the internal pressure increases; consequently the internal pressure will tend to be at a stable pressure level.
(2) The welding quality seems to have a threshold point with the leak conductance of about 10^{-14} m^3/s (the leak rate is 10^{-9} Pa g m^3/s–10^{-10} Pa m^3/s) for the metal packages used in the experiments. The leak conductance lower than the threshold has better welding quality and the changes in

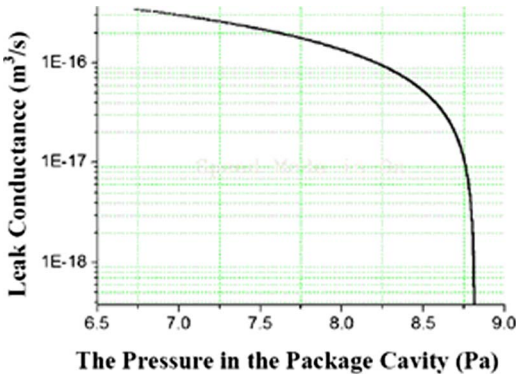

Fig. 8 The calculated leak conductance with internal pressure from the pressure monitoring data

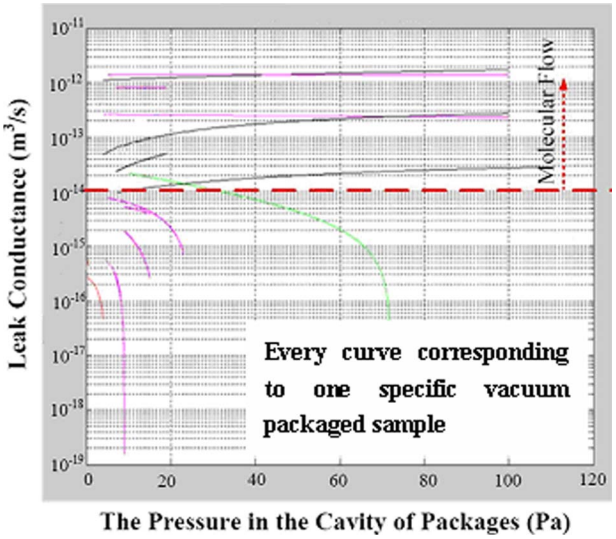

Fig. 9 Conductance changes with internal pressure

pressure are beyond the understanding of molecular flow. The leak conductance higher than the threshold can be understood to be within the molecular flow tube leak mode.

7 Theoretical Analysis of the Leak Mode

In order to explain the flow modes of the measurement, two models were established to explain the measured results shown in Fig. 9.

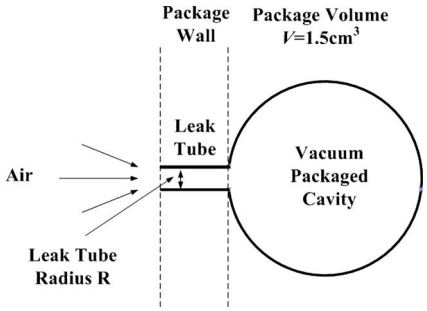

Fig. 10 The model of molecular tube flow leak mode

7.1 Molecular Leak Mode Over the Threshold Point. It is assumed that the whole leak of the package be a tube leak. The radius of the leak tube is R, and the volume of the vacuum package is V. The model is simplified to be as that schematically shown in Fig. 10.

It is assumed that the leak conductance per unit length be κ, and κ would be $\frac{2}{3}\pi R^3 \bar{v}$ for molecular tube flow leak. Molecular tube flow leak can be expressed as a form of diffusion equation

$$\kappa \frac{\partial^2 P}{\partial x^2} = \pi R^2 \frac{\partial P}{\partial t} \tag{10}$$

Because the leak tube radius is small, the gas absorption and desorption should be considered. Assuming the average dwell time for the gases absorbed on the leak tube wall is τ, the gas absorption σ per unit area can be given as [17]

$$\sigma = \frac{1}{4} n \bar{v} \beta s \tau \tag{11}$$

where n is the density of air, $\bar{v}$ is the average molecular speed of air, s is sticking coefficient, and β is the roughness value. Considering the contribution of Eq. (10), the equation for molecular tube leak flow can be changed into

$$\kappa \frac{\partial^2 P}{\partial x^2} = \pi R^2 \frac{\partial P}{\partial t} + \frac{\pi}{2} R \bar{v} s \beta \frac{\partial P}{\partial t} \tag{12}$$

Using MATLAB programming, the relationship between the internal pressure and the leak rate was plotted in Fig. 11; any molecular leak would enhance the internal pressure gradually up to balance air pressure. That the leak conductance showed a constant for a wide range of the pressure changes meets the experimental results in Fig. 9.

7.2 Gas Absorption and Desorption Below the Threshold Point. When leak conductance is lower than 10^{-14} m^3/s, the leak conductance measurement in Fig. 9 showed that the internal pressure would tend to balance at a stable pressure point, which was very different from the situation for molecular flow mode. That phenomenon can be understood that the tube leak was small such that the gas absorption and desorption became a dominant factor to influence the pressure of the package. In fact, the stable pressure point was not a balanced point, and any leak would increase the pressure in the package. It looked like a balanced point because the pressure change was too small to be beyond the sensitivity of the crystal pressure measurement system.

In thermal equilibrium condition, gas absorption and desorption are in a balanced state; the desorption rate can be expressed as follows by gas absorption theory [18]:

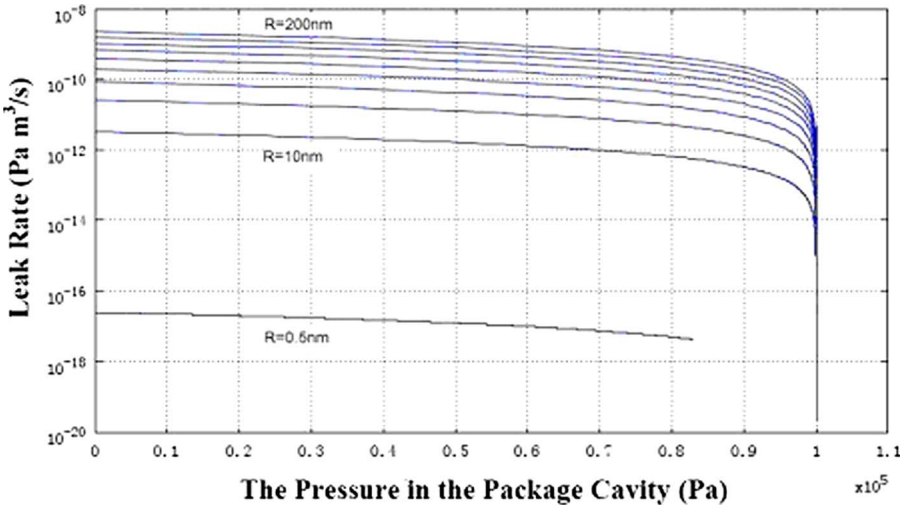

Fig. 11 Molecular flow leak mode

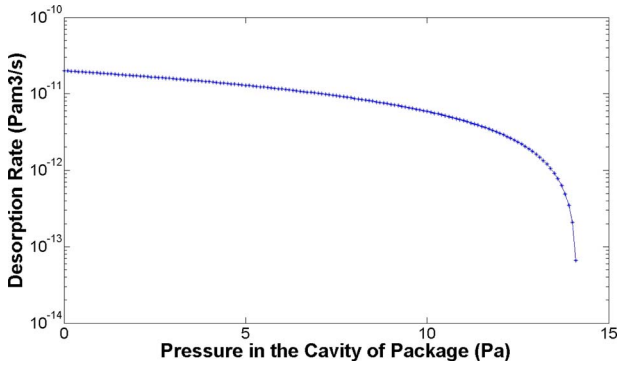

Fig. 12 The desorption rate by the internal pressure

$$-\frac{d\sigma}{dt}_{\text{desorption}} = \frac{\sigma_0}{\tau} e^{(-t/\tau)} \tag{13}$$

If σ_0 is replaced with Q_0 using a leak rate unit, and the internal pressure is only influenced by gas desorption, the internal pressure in the package can be formulated by the following:

$$V\frac{dP}{dt} = Q = \frac{Q_0}{\tau} e^{(-t/\tau)} \tag{14}$$

Assuming the initial pressure in the package is zero, the equivalent leak rate Q change can be expressed as follows:

$$P = \frac{Q_0}{V} - \frac{\tau}{V} Q \tag{15}$$

Using appropriate data of Q_0 and τ, the relationship between the internal pressure and leak rate can be plotted in Fig. 12, which showed good agreement with the trend of the measurement results in Fig. 9.

8 Conclusions

This investigation showed that vacuum packaging required the welding or bonding quality so high that the leak rate would be lower than 10^{-12} Pa g $m^3/s - 10^{-13}$ Pa g m^3/s, which is beyond the sensitivity of the helium spectrometer leak tester. The theoretical study on the helium leak tester illustrated that the measured leak rate is nonlinear with the actual leak size while being used to measure the leak rate for vacuum packages, which made the measured results not reliable. Using the crystal vacuum measurement system to monitor the pressure changes in vacuum packages, the experiments showed that the leak flow was molecular flow while the leak conductance of the welding quality is about 10^{-14} m^3/s, and molecular flow would decrease sharply with the leak conductance of the welding quality less than 10^{-14} m^3/s, and the gas desorption would be a dominant factor to influence the vacuum packaging at the beginning.

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