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Review of test methods used for the measurement of hermeticity in packages containing small cavities

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Abstract— **This paper presents a critical review of the traditional and newly proposed test methods used for the measurement of hermeticity in packages with very small cavity volumes. Closed form expressions of the minimum and maximum true leak rates achievable are derived for the helium fine leak test method. These expressions are shown to provide practical guidelines for the accurate testing of hermeticity for ultra-small packages. A portfolio of hermeticity test methods is also presented outlining the limitations and advantages of each method.**

Index Terms— **Hermeticity, leak detection, packaging, test**

I. INTRODUCTION

HERMETIC packaging is an essential requirement for many microelectronics, optoelectronics devices and Micro-Electro-Mechanical Systems (MEMS) to ensure that a constant environment is kept inside the device package for optimum operational performance and prolonged lifetime. Ingress of foreign gas and moisture can often cause device degradation and eventual failure. When the package of a resonant device sealed in high vacuum is compromised, the Q-factor of the resonator is reduced lowering the sensitivity of the device. To predict device lifetime and performance over time it is therefore important to know how long the package will remain hermetic by measuring its leak rate.

Traditionally, leak rates are determined using the helium fine leak test in conjunction with the gross bubble test. Several standards are in place to ensure the correct use of the test methods. The most referenced standard is MIL-STD-883H TM 1014.13 for which various reject rates are given depending on the cavity volume of the package [1]. The lowest category given in MIL-STD-883H is for packages with volumes below 0.05 cm^3. More stringent reject rates are given in MIL-STD-750E TM 1071.8 for volumes below 0.01 cm^3 [2]. This standard is not often referred to with most researchers quoting MIL-STD-883H.

The helium leak test involves a bombing procedure where the packages are exposed to pressurized helium for a time, t_b, defined as "bombing time" and specified by the standard. Each package is then transferred to a chamber within the leak detector. The chamber is then brought to a high vacuum. The helium leaking out from the package is measured by a mass spectrometer and the first reading from the leak detector is recorded. The standards also specify that the bombed packages must be transferred from the bombing chamber to the leak detector for measurement within a dwell time, t_d, to ensure that enough tracer gas remains within the package for accurate measurement.

In the case of sufficiently small packages, there are two possible true leak rates for each measured leak rate given by the leak detector: a large leak rate would be produced by a large leak channel which allows much of the helium contained in the package after bombing to leak out during the dwell time whilst a small leak rate would be produced by a small leak channel which allows only a small amount of helium to escape before testing. The gross bubble test is used to establish whether or not the device displays this large leak rate which has produced the measured leak rate. The gross bubble test involves the pressurization of the package in an indicator fluid before transfer to a detector fluid which has a higher boiling point than the indicator fluid. The temperature of the detector fluid is between the boiling points of the two fluids. If bubbles escape from the package then a gross leak is present. Leak rate values above 10^{-4} atm.cm^3.s^{-1} can be detected using the gross bubble test. Such test methods work reasonably well for large package volumes. For very small volumes, hasty applications of these tests can however cause erroneous conclusions concerning the hermeticity of packaging. This article aims to provide a clearer understanding of the use of such methods.

An explanation of the types of leaks present in typical small cavity packages is given in section 2. Section 3 provides a theoretical explanation of the limitations of the helium fine leak and gross bubble tests. A review of the other test methods to monitor hermeticity commercially used and proposed by research groups worldwide is presented in section 4. Section 5 summarizes the advantages and drawbacks of each test method detailing the type of packages that can be assessed, any limitations relating to cavity volume and the sensitivity of the method.

II. LEAK TYPES

The key to finding the most effective way to measure gas leak rates of packages with small cavity volumes is to understand the types of leak present in such packages. Traditional leak test methods assume the leak being measured exists due to a capillary or leak channel present in the package wall or seal. Gas flow through capillaries can be molecular, viscous or transitional. Molecular flow occurs when the mean free path of the gas is greater than the characteristic dimension of the leak channel. In such a case, the flow is dominated by the velocity of the gas particles. Viscous flow occurs when the mean fee path of the gas is less than the characteristic dimension of the leak channel. The flow is then dominated by the viscosity of fluid. Transitional flow is a combination of viscous and molecular flows [3].

Near hermetic packaging using polymers has introduced another type of leak for which traditional hermeticity test methods are not designed to quantify. Whereas traditional packages use non porous materials to ensure as hermetic a seal as possible, these new polymer packages are designed to provide a low cost, low stress and low temperature sealing method for less environmentally sensitive devices. These porous materials have an intrinsic leak rate due to the permeation of gases. Permeation occurs in three steps: sorption onto the material surface, diffusion through the bulk materials and desorption into the package cavity. Diffusion is described well by Fick's law, whose mathematical description varies significantly from that of a gas flow through capillaries. [4]

In contrast, some small cavity devices require packaging capable of maintaining an ultra high vacuum environment for over 20 years. This type of package must use the most hermetic materials and sealing techniques. The leak type likely to be of concern in this type of package is outgassing, either during high temperature packaging or throughout the device lifetime. Clearly outgassing cannot be measured by any tracer gas method. Residual gas analysis, RGA, allows the quantification of gasses released from internal materials layers but is destructive and costly [5].

III. LIMITATIONS OF TRADITIONAL HERMETICITY TEST METHODS

The limitations of the helium fine leak test used in conjunction with the gross bubble test can be explained and quantified by examining the Howl-Mann equation, reproduced as equation 1 [6]. This equation yields the measured helium leak rate, R, as a function of the true leak rate, L. P_b is the bomb time, P_0 the atmospheric pressure, M_A the molecular weight of air, M_{He} is the molecular weight of helium, t_b is the bomb time and t_d is the dwell time.

$$R = \frac{LP_b}{P_0}\left(\frac{M_A}{M_{He}}\right)^{1/2}\left(1 - \exp^{\frac{-Lt_b\left(\frac{M_A}{M_{He}}\right)^{1/2}}{VP_0}}\right)\exp^{\frac{-Lt_d\left(\frac{M_A}{M_{He}}\right)^{1/2}}{VP_0}}$$

(1)

A. Influence of the cavity volume

Figure 1 shows variations of the measured leak rate as a function of the true leak rate for cavity volumes ranging from 10 cm^3 to 10^{-5} cm^3. For these plots, P_b=5 atm (5.07 x 10^5 Pa), t_b=6 hours, t_d=10 minutes and P_0=1 atm (1.01 x 10^5 Pa), which are normal conditions of use. For each measured leak rate there are two possible true leak rates, L_{upper} and L_{lower}. The minimum true leak rate detectable in the gross bubble test is around 10^{-4} atm.cm^3.s^{-1}. This limit is indicated by a vertical line in figure 1.
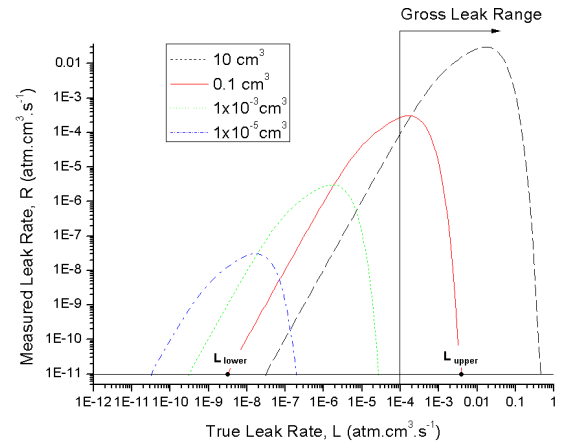

Fig. 1. Measured helium leak rate given as a function of the true helium leak rate for different cavity volumes. The maximum sensitivity of most helium leak detectors, 10^{-11} atm.cm^3.s^{-1} is given as a horizontal line in the figure. As an example, L_{lower} and L_{upper} have been indicated in the case of a cavity of volume of 0.1 cm^3.

The purpose of the gross leak test is to rule-out or confirm the relevance of the upper true leak rate, L_{upper}. For large cavity volumes, the absence or presence of bubbles in the gross test allows to discard the large value of the leak rate, respectively. In the former case, the measured leak rate is related to the lower value of the true leak rate; in the latter case the measured leak rate indicates a large leak rate. As the volume of the cavity is reduced, the upper leak rate drops below the minimum detectable leak rate of the gross test invalidating the traditional test methods. There is no possibility with this method to know whether there is a leak as all the helium present inside the cavity could have escaped during the dwelling time producing therefore a null but false result during the gross bubble test.

In order to determine the limits of validity of the helium leak test method, it would be advantageous to derive analytically the upper limit of the true leak rate at the detection limit of the leak detector which is typically 10^{-11} atm.cm^3.s^{-1} (1.01 x 10^{-12} Pa.m^3.s^{-1}). As L_{upper} decreases with cavity volume,

it would be desirable to attempt to raise this limit by optimizing the test variables using an analytical expression for L_{upper}. If L_{upper} can be increased beyond the minimum detectable leak rate of the gross test, the helium fine leak test method could still be validated for a defined minimum cavity volume. In the region where L_{upper} lies, the true leak rate is large and for small cavity volumes the value within the brackets in (1) tends to unity such that:

$$R = \frac{LP_b}{P_0}\left(\frac{M_A}{M_{He}}\right)^{1/2} \exp^{\frac{-Lt_d\left(\frac{M_A}{M_{He}}\right)^{1/2}}{VP_0}} . \quad (2)$$

Equation 2 can be re-arranged to be of the form $z = f(y) = ye^y$ as shown in (3).

$$z = \frac{Rt_d}{VP_b} = \frac{Lt_d}{VP_0}\left(\frac{M_A}{M_{He}}\right)^{1/2} \exp^{\frac{-Lt_d\left(\frac{MA}{M_{He}}\right)^{1/2}}{VP_0}} \quad (3)$$

With,

$$y = \frac{Lt_d}{VP_0}\sqrt{\frac{M_A}{M_{He}}} . \quad (4)$$

The inverse function of z, allow the determination of y or L as a function of R. This can be achieved using the Lambert W-function [7]. Using this function,

$$L_{upper} = \frac{-W\left(\frac{R\dot{t}_d}{VP_b}\right)VP_0}{t_c\left(\frac{M_A}{M_{He}}\right)^{1/2}} . \quad (5)$$

For sufficiently small z, the following asymptotic formula can be used to obtain an approximation for w(z) [7].

$$w(z) = \ln z - \ln\ln z + \sum_{k=0}^{\infty}\sum_{m=0}^{\infty} c_{km}\left(\ln\ln z\right)^{m+1}\left(\ln z\right)^{-k-m-1} \quad (6)$$

For all practical purposes and under normal test conditions, the first two terms of this approximation are sufficient and provides a goodness of fit of above 0.99 between the closed form expression of L_{upper} given by Equation 7, and its numerical derivation using Equation 1. As P_0 is atmospheric pressure and R, the minimum detectable leak rate of a standard leak detector, is about 1×10^{-11} atm.cm^3.s^{-1}, this approximation shows that L_{upper} can be strongly influenced by the volume of the cavity and the dwell time.

$$L_{upper} = \frac{-\left[\ln z - \ln\ln z\right]VP_0}{t_d\left(\frac{M_A}{M_{He}}\right)^{1/2}} \quad (7)$$

From Equation 5, for any cavity volume, the highest value of L_{upper} is given for the lowest practical value of the dwell time. Although the argument of the Lambert function contains the dwell time and bomb pressure, this function depends only weakly on these variables and is dominated by the limit of the measured leak rate, R, and volume. It can therefore be surmised, as shown in Figure 2, that the upper limit is inversely proportional to the dwell time. Practically, the dwell time cannot be reduced indefinitely. A minimum dwell time of around 3 minutes is recommended for practical purposes [8].
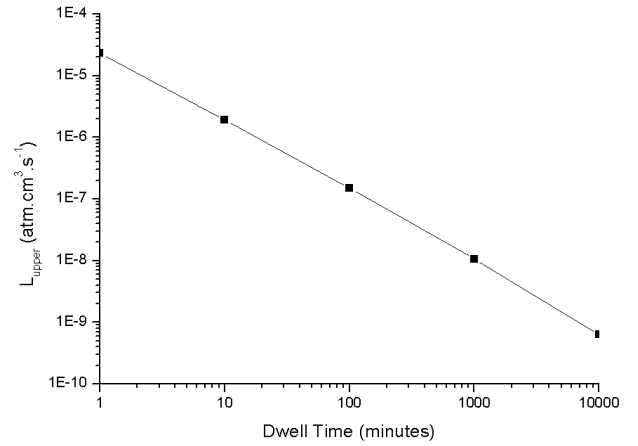

Fig. 2. L_{upper} as a function of the dwell time for R=1×10^{-11} atm.cm^3.s^{-1}, P_b=5 atm, t_b= 6 hours, V = 1×10^{-4} cm^3.

Figure 3 shows the relationship between the volume and upper true leak rate measurable using the helium leak test for a dwell time of 3 minutes, the practical limit, and 1 hour, as specified by the standards when all other variables are kept constant. From this figure, the helium leak test can be used accurately in conjunction with a gross leak test that can measure leak rates above 1×10^{-4} atm.cm^3.s^{-1} for packages with internal cavity volumes of 3×10^{-3} cm^3 or greater when the dwell time is kept to the practical minimum of three minutes.

For industrial applications, batches of packages are usually checked for hermeticity. In such cases, it may be necessary to allow a dwell time longer than 3 minutes in order to bomb and test as many packages as possible in a single test run to ensure some helium is still present inside the cavity to achieve an accurate measurement. For a dwell time of one hour, packages with internal cavity volumes of 0.06 cm^3 or greater can still be tested accurately.
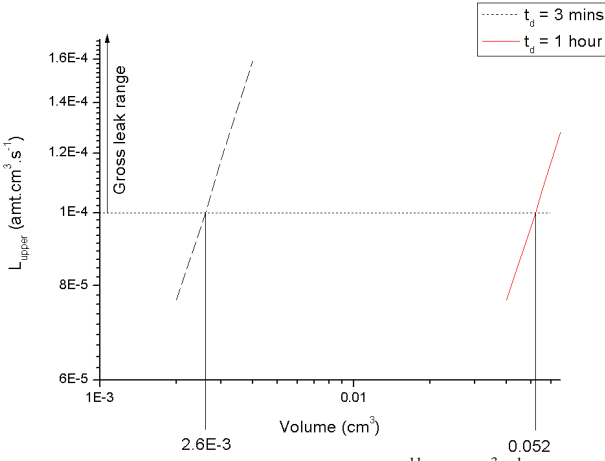
Fig. 3: L_{upper} as a function of volume for R=1x10^{-11} atm.cm^3.s^{-1}, P_b=5 atm, t_b= 6 hours.

B. Minimum true leak rate

The lowest measurable leak rate of most helium leak detectors is dictated by the sensitivity of the mass spectrometer used. The lowest true leak rate, L_{lower}, however depends on the bomb pressure, bomb time and sample cavity volume. The analytical dependence of these variables on L_{lower} can be obtained by reducing the Howl-Mann equation such that:.

$$R = \frac{LP_b}{P_0}\left(\frac{M_A}{M_{He}}\right)^{1/2}\left(1 - \exp^{\frac{-Lt_b\left(\frac{M_A}{M_{He}}\right)^{1/2}}{VP_0}}\right) \quad (8)$$

In the region of interest, the exponential term in the brackets can be approximated using a MacLaurin expansion and the equation re-arranged to give L_{lower} in terms of the measured leak rate, (9).

$$L_{lower} = P_0\sqrt{\frac{RV}{P_bt_b}\left(\frac{M_{He}}{M_A}\right)^{1/2}} \quad (9)$$

A reduction in the volume of the cavity decreases the true minimum leak rate. The same trend is observed if the bomb time or the bomb pressure is increased. Practically, the bomb pressure and time cannot be increased indefinitely. As the bomb pressure is increased, the likelihood of the sample package experiencing a 'one-way leak' is increased. A 'one-way leak' occurs when the bomb pressure induces a leak channel that under normal operating conditions would not be present. The helium would then enter the package during the bombing process and upon release the induced leak channel will close, trapping the helium inside the package. Since the helium test relies on measuring the helium leaking out of the cavity after bombing, it is impossible to determine when a one-way leak has occurred using this method. It has become common practise to keep the bomb pressure between 3 and 10 atm although 5.103 atm (75 psi) is recommended in the military standards.

The bomb time can be increased depending on the time available for test. Figure 4 shows the dependence of L_{lower} on bomb time for a measurable minimum leak rate of 10^{-11} atm.cm^3.s^{-1}, a minimum cavity volume of 2.6 x 10^{-3} cm^3 and bombing pressure of 5.103 atm. Increasing bomb time above 12 hours has a minimal effect in reducing the minimum true leak rate. Using these test parameters with the minimum cavity volume defined in the previous section as 2.6 x 10^{-3} atm.cm^3.s^{-1}, the minimum detectable leak rate of the helium leak test method is 1.28 x 10^{-10} atm.cm^3.s^{-1}. This minimum leak rate would guarantee that the ambient environment of a 0.1mm^3 cavity package sealed in 9.87 x 10^{-5} atm (0.1 mbar) be kept with 10% of its initial pressure for less than 4 minutes. Leak rates of the order 10^{-16} atm.cm^3.s^{-1} are required for low volume, vacuum packaging of typical MEMS. The fine leak test is therefore clearly inadequate for the measurement of the hermeticity of devices with very small cavity volumes.
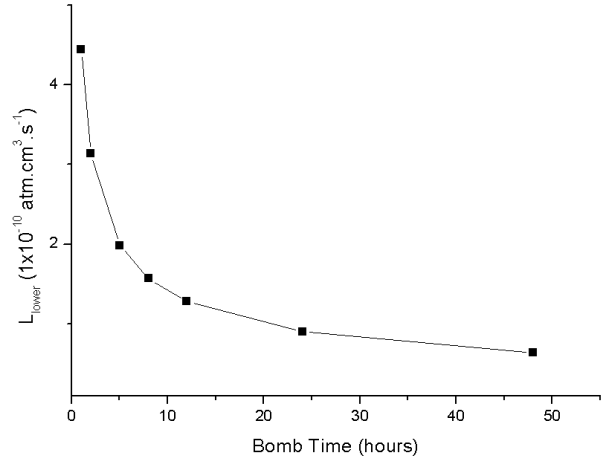

Fig. 4. L_{lower} as a function of the bomb time for R=1x10^{-11} atm.cm^3.s^{-1}, P_b=5.103 atm and V=2.6x10^{-3} cm^3.

C. Diffusion through packaging materials

As most packages operate in an ambient air environment, air leak rates are normally used to compare the hermeticity properties of packaging materials and bonding techniques. A true helium leak rate is converted to a true air leak rate using the molecular weights of air, M_A, and helium, M_{He}, as shown in Equation 10. This expression is incorporated into the Howl-Mann equation to give a helium reject leak rate, R, for the test parameters used and the true air leak rate, L, which the package under test must not exceed according to the military standards.

$$L_{Air} = L_{He}\sqrt{\frac{M_{He}}{M_{Air}}} \quad (10)$$

To achieve a value for the air leak rate from a helium leak rate, an average value of the atomic weight of air, 28.7g, is used. This gives an accurate value when the leak rate is caused by a leak channel present in the package wall or seal.

In the MEMS manufacturing industry, glass is often used as a package material to allow optical access to the device. Other packaging materials, in particular polymer seals, are

increasingly being used to replace traditional metallic packages. These materials offer advantages such as lower bonding temperatures and pressures which allow sensitive structures to be submitted to less thermo-mechanical stress during packaging. As some of these materials are porous and therefore not hermetic, the package has an intrinsic leak rate caused by diffusion through the package walls even in the absence of leak channels. For some MEMS applications hermeticity is not essential and the benefits these materials bring to the manufacturing process outweigh the problems associated with contamination. However, it is still necessary to know the leak rate of the packages to assist in the lifetime predictions of the device.

During the bombing process of the helium leak test, helium will permeate slowly through the package material into the cavity by sorption onto the surface, then diffusion through the bulk material followed by desorption into the cavity [9]. When the package is transferred to the mass spectrometer and the chamber is evacuated, the reverse process will occur. Over time the helium that permeated into the cavity during bombing will permeate out and be detected by the mass spectrometer. It is not possible for the traditional helium leak test to differentiate between helium coming through a leak channel and desorbed helium from a package material surface. The Howl-Mann equation is applicable only to molecular leaks [6]. Therefore, should the measured leak rate be caused by permeation, the conversion from a measured leak rate to a true leak rate using the Howl-Mann equation is incorrect.

When conducting the helium leak test, the first reading given by the leak detector is taken as the measured leak rate. For package materials such as glass and polymers, the tracer gas may not have permeated through the bulk materials into the package cavity at all, yet a leak rate is measured due only to helium which has sorbed into the surface of the materials. Figure 5 shows a graph of measured leak rate over time. The zero signal defined by Goswami et al. shows the amount of time required to evacuate the test chamber and achieve a steady minimum leak rate when the test chamber is empty [10]. A 10.1x10.1x1.2 mm borosilicate glass chip, and a 6.2 mm diameter, 15 μm thick BCB ring on silicon were bombed separately in helium at 4 atm for 4 hours and transferred to the helium leak detector. Figure 5 shows that the helium leaking out of the glass chip and BCB ring are orders of magnitude higher than the minimum leak rate of the set-up after 28 seconds when the zero signal has stabilized. The measured leak rate of the glass chip and BCB ring are therefore, $8x10^{-8}$ atm.cm^3.s^{-1} and $9x10^{-6}$ atm.cm^3.s^{-1}, respectively, although neither sample contains a cavity into which helium could have leaked. It has been shown that any helium sorption into silicon is insignificant when the zero signal method is applied, therefore the measured helium leak rate of the second sample but be due to sorption of helium into the BCB ring and not the silicon substrate [10].

This shows that helium is leaking out of the glass and polymer material. Erroneous leak rates will therefore be measured and it is possible that suitably hermetic packages are rejected.
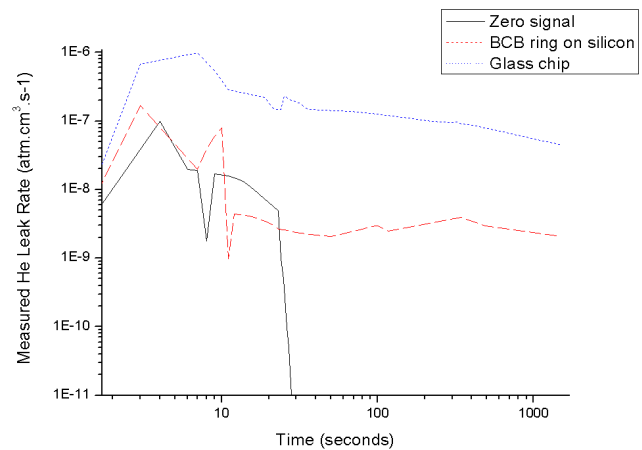

Fig. 5. Leak rate over time showing zero signal and significant helium leaking from glass chip and BCB ring.

For these reasons, it is not possible to achieve accurate leak rates of permeable packages using the traditional helium leak test. To measure leak rates caused by leak channels in permeable packaging materials, tracer gases which do not permeate through the material must be used. In the case of glass, nitrogen can be used as a replacement for helium. For polymer materials, another type of test must be found as most gases will permeate through polymers at different rates depending on the porosity of the permeated material, the size of the gas molecules, the weight and mean free path of the gas, and the chemical affinity of the permeating gas with the permeated material. In situ test structures could provide a solution to the testing issues associated with permeable packaging. However, if the package concerned is not hermetic and permeation rates are dominant, the determination of the permeation constants for typical gases through packaging materials could allow package leak rates to be modeled successfully.

IV. REVIEW OF OTHER TEST METHODS

MIL-STD-883H gives the descriptions of two other fine leak test methods, the radio-isotope fine leak test and the optical fine/gross leak test. The cumulative helium leak test is also included in MIL-STD- 750E. The advantages and limitations of these methods when applied to MEMS packaging are explained in this section along with further hermeticity test methods proposed by other research groups worldwide.

A. Radioisotope fine leak test

A documented drawback of the radioisotope fine leak test is associated with the use of a radioactive tracer [8]. However, Krypton-85 decays by low energy beta and gamma ray emission, both of which are comparatively safe forms of emission. The quantities of Krypton-85 required for the test are also so low that the operator is exposed to only a fraction of the US government maximum exposure limits. Another possible limitation is the potential for failures caused by tracer gas interference with small device geometries [8].

This method has been used successfully in industry for high volume applications as detection is easier over a longer period of time than with helium. However, the gas used in the radio-isotope fine leak test escapes from a gross leak before it can be measured as in the helium test. For this reason a gross leak test must also be conducted. A radio-isotope gross leak test using pressurised liquid instead of gas is also described in the military standards [1]. As with the helium leak test there will be a volume limitation associated with this method. One possible option for low cavity volume packages is to use coconut shell charcoal inside the package to act as a getter material for the hermeticity test tracer gas [11]. The tracer gas is thus held within the package allowing a gross leak to be measured. The minimum detectable leak rate of the radioisotope leak test is 10^{-12} atm.cm^3.s^{-1} [12]. The sensitivity of this method is therefore not sufficient for packages with low cavity volumes.

B. Optical fine/gross leak test

The optical fine/gross leak test relies on the package lid being flexible enough to deflect according to pressure difference between the inside and the outside of the package. The device under test is placed in a chamber where the pressure can be varied according to the maximum permissible pressure of the package or the limit of the chamber. An optical interferometer monitors the deflection of the lid. If there is no deflection as the chamber pressure is changed, the package has a gross leak. If the deflection is not proportional to the pressure variation then there is a fine leak. The package also fails the test if the lid deforms while the chamber pressure is kept constant [1].

The sensitivity of this test depends not only on the lid stiffness, thickness and test duration but also on the sensitivity of the optical interferometer used. Generally, the method is able to detect leak rates down to 10^{-10} atm.cm^3.s^{-1} [12]. Sensitivity is therefore an issue with this technique and such a method should not be regarded as a viable replacement for the helium fine leak test for packages with small cavity volume held at high vacuum. However, wafer level testing can be conducted with such a technique as several devices can be tested at once. The method is also capable of distinguishing between a leak rate caused by flow through a leak channel and a permeation leak and could therefore be used to measure permeation leaks into polymer sealed packages.

C. Cumulative helium leak detection technique

Another variation of the helium leak test, the cumulative helium leak detector (CHLD), is described in the MIL-STD-50 standard. Such a technique requires the device to be either packaged in the presence of helium or bombed with the tracer gas. The presence of a cryo-pump in the CHLD test permits the measurement of the helium leaking out during the initialization step, when the package is placed in the detector chamber which is being pumped down to around 1×10^{-5} atm. It is therefore reportedly possible to measure gross leaks using the CHLD method. Unlike the traditional method, the leak rate is determined from the slope of the helium count as a function of time. For this reason it is actually possible to measure the leak rate of the package even if the tracer gas has leaked out and the internal pressure of the package is in equilibrium with the ambient environment [13]. The 5 ppm of helium present in ambient air is apparently enough to allow detection of a gross leak. The minimum volume of package that can be accurately assessed is determined by the ability of the set-up to measure a gross leak one hour after removal from the pressurisation chamber. The maximum detectable leak rate is reported to be up to 1 atm.cm^3.s^{-1} [13]. This method can detect leak rates as low as 3×10^{-13} atm.cm^3.s^{-1} according to MIL-STD-750 [2]. Although the sensitivity of this method is up to three orders of magnitude greater than the traditional helium leak method, it is still not stringent enough for many low volume vacuum package applications. The way in which this minimum leak rate has been measured is also unclear as such low calibrated leaks are not commercially available. Some further independent testing and qualification of this method would be beneficial to understand more fully the advantages and limitations of this test method.

D. Fourier Transmission Infrared Spectrometry (FTIR)

This technique involves the pressurisation of the package in a suitable tracer gas, usually nitrous oxide, for silicon packages. The package is then analysed using FTIR to determine the concentration of the tracer gas inside the package [14]. This is a quantitative measurement that can be monitored over time to determine the leak rate of the package. Unlike in the helium method, this technique measures the tracer gas inside the package and not the gas leaking back out of the cavity. 'One-way leakers' can therefore be identified using FTIR testing. The minimum detectable leak rate is of the order 10^{-12} atm.cm^3.s^{-1} [12]. As this technique uses infrared light, the package must have an IR transparent cap. Calibration is required to remove any interference from the internal reflections of the package.

This method uses a tracer gas to bomb the package therefore the same volume limitations that were apparent with the helium leak test will still apply. The only difference will be with the molecular weight of the tracer gas and the detection limit of the method. As nitrous oxide will not permeate through glass unlike helium, the FTIR method can be used to determine the leak rate due to flow of gas through a leak channel in glass packaged devices.

The FTIR method has been used to assess the hermeticity of BCB sealed packages with cavity volumes down to 5 mm^3 [15]. In this study, the results of the FTIR analysis proved that thicker organic seals created a more hermetic package. The FTIR method is therefore able to be used to assess permeation of a tracer gas through a package material assuming that the seal and package have no leak channels other than those related to the intrinsic permeability of the material. It may also be possible to test other package materials by using a tracer gas with high absorption within the range of the material optical transmission [14].

E. Raman spectroscopy test

Raman spectroscopy can be used to identify foreign gas inside packages [16]. Some MEMS devices require packaging in inert gas and, in such packages, small leaks can be present yet undetected as the electrical and mechanical responses of structures within the package are initially unchanged.

Degradation occurs slowly in the presence of a foreign gas such as oxygen and reliability of the device is then compromised. Raman spectroscopy has been used to identify leaks in packages with transparent lids or windows. The presence of a foreign gas such as oxygen in the inert gas filled cavity is identified by its Raman signature indicating that a leak is present. The test is slow however due to the long integration time needed to allow adequate signal to noise ratios [16]. The test methods could be accelerated by bombing the DUT in tracer gas to give a leak rate. This would inevitably introduce a limit to the sample volume as with the traditional helium leak test and the FTIR method. The potential problem of creating a leak channel through environmentally induced stress during bombing would also apply. Better confocal rejection using a high powered laser could allow this time to be reduced although it may be better applied as a failure analysis technique than an end-of-line testing method.

F. Q-factor method

Many in-situ test structures have been designed for use as pressure sensors to monitor the leak rates in small packages. Q-factor testing is commonly used within the MEMS industry. When the device contains a free standing structure the Q-factor of the unpackaged device can be measured as a function of pressure [17]. Determining the Q-factor after packaging will therefore indicate the internal pressure. This test can be conducted at any stage throughout the device lifetime for long-term monitoring of leak channels, permeation and outgassing.

G. Copper test patterns

Another in-situ test method uses copper test patterns within the package to monitor the internal pressure. In this method the optical transmission of copper over time is measured as the material oxidises [18]. This technique relies on the package material being transparent to IR wavelengths. The technique is suitable for on-wafer testing but is a one test technique. Once the copper test pattern is oxidised the test cannot be repeated. This is a sensitive technique that is capable of measuring leak rates down to 5×10^{-16} atm.cm^{3}s^{-1} [18]. It can however be time consuming with test duration of 4800 hours necessary to allow enough oxygen into the package to show a low leak rate. This time can be reduced, often down to several days, by increasing the oxygen pressure and maintaining the temperature for oxidation at 125-150°C [18].

H. In-situ pressure sensor

Several other test structures that exploit the relationship between thermal conductance and pressure have been designed to monitor hermeticity [19]. Electrical resistance is increased when a metal structure is heated. Depending on the amount of gas surrounding the structure, this heat will be conducted away from the structure such that the temperature, hence resistance, will decrease. The structure can be calibrated to indicate the internal cavity pressure through the measurement of electrical resistance. In-situ testing has proved to be the most sensitive way to monitor internal pressure of small cavities and is effective in monitoring long-term stability. They are particularly useful as they can be used to detect gas entering the package through leak channels, permeation or present through outgassing. Accelerated testing can be applied although care should be taken to avoid creating a leak under conditions of elevated pressure out with those of normal operation.

V. SUMMARY

To determine hermeticity of MEMS and other small cavity volume packages a portfolio of test techniques is needed. Table 1 presents a summary of the hermeticity test methods available today.

Table 1: Summary of hermeticity test techniques.

Method	Gross leak test required	Min. Leak Rate measurable (atm.cm^3.s^{-1})	Advantages	Limitations	Leak types
Helium fine Leak	Yes	1×10^{-10} (Volume dependent)	• Standards apply. • Non-destructive.	• Not applicable for glass and polymers as helium diffuses through such materials. • Surface sorption problems with glass/polymers. • Bomb required so potential for one-way leak. • Gap occurs in detectable leak range for small cavity volumes. • Sensitivity issues for small volumes and vacuum applications. • No measurement of outgassing.	Leak channels

Method	Gross leak test required	Min. Leak Rate measurable (atm.cm^3.s^{-1})	Advantages	Limitations	Leak types
Radio-isotope fine leak	Yes	1x10^{-12}	• Standards apply. • Longer time to detect so more suitable to industry.	• Can be destructive for small structures. • Sensitivity issues for small volumes and vacuum applications. • No measurement of outgassing.	Leak channel Permeation
Optical leak	No	1x10^{-10}	• Standards apply. • No bombing required. • Non-destructive.	• Lid materials must be flexible. • Sensitivity issues for most applications. • No measurement of outgassing.	Leak channel Permeation
CHLD	No	3x10^{-13}	• Standards apply. • Non-destructive • Full leak range measurable. • Virtual leaks caused by surface sorption can be identified.	• Bomb required so potential for undetectable one-way leak. • Sensitivity issues for small volumes and vacuum applications. • No measurement of outgassing.	Leak channel Permeation
FTIR	Yes	1x10^{-12}	• Non-destructive • No surface sorption issues.	• Not standardized. • IR transparent cap required. • Gap occurs in detectable leak range for small cavity volumes. • No measurement of outgassing.	Leak channel
Raman spectroscopy	No	Under study	• Non-destructive • No surface sorption issues. • Full leak range measurable. • No bombing required.	• Not standardized. • Transparent cap and reflective surface. • End-of-line leak rate measurement only possible through test acceleration.	Leak channel Permeation Outgassing? (dependant on minimum detection)
Q-factor	Yes	~10^{-14} (Depends on device geometry)	• Non-destructive. • No surface sorption issues. • Monitoring of long-term pressure stability. (No bombing required) • No volume dependency.	• Calibration required for each device type. • Free standing internal structure required. • Long test duration for larger cavity volumes or acceleration process required.	Leak channel Permeation Outgassing
Copper test pattern	Yes	5x10^{-16}	• Non-destructive. • No surface sorption issues. • No volume dependency.	• Transparent cap required. • One-time test only. • End-of-line leak rate measurement only possible through test acceleration. • Long test duration. • Measurement by oxidation – no other foreign gases will be measured.	Leak channel Permeation Outgassing – O$_2$ only
In situ pressure sensor	Yes	Depends on structure. Typically 10^{-15} is achievable.	• Non-destructive. • No surface sorption issues. • Monitoring of long-term pressure stability. (No bombing required) • No volume dependency. • Electrical measurement.	• Requires additional structure to be fabricated inside the cavity. • Long test duration for larger cavity volumes or an acceleration process required.	Leak channel Permeation Outgassing
RGA	No	Measurement of gas type and pressure in package (limit 9.87x10^{-15} atm)	• No surface sorption issues • No accelerated testing conversion required – pressure in package measured.	• Expensive • Destructive • Time consuming • Requires expert analysis or results • Volume limitation due to ability to break package in vacuum chamber.	Outgassing

VI. CONCLUSIONS AND FUTURE WORK

The limitations of the military standard methods for hermeticity testing have been well documented and are compiled in this paper. The helium test method is applicable to packages with cavity volumes above 2.6 x 10^{-3} cm^3 for dwell times of 3 minutes. The helium leak test is also limited to testing samples that do not contain materials that allow permeation of helium. The helium leak test is therefore not applicable to glass capped or polymer sealed packages. The minimum leak rate detectable using the helium leak test is of the order 10^{-10} atm.cm^3.s^{-1}. This test is not sensitive enough to measure the ultra-low leak rates which can adversely affect MEMS structures. A standard that reflects typical MEMS cavity volumes and the ultra-low leak rates necessary for vacuum packaging is required by the MEMS industry.

A portfolio of test techniques is necessary to measure hermeticity of MEMS, small volume microelectronics and optoelectronic devices. Some test methods have shown

promise for particular applications but require further development. A portfolio of suitable test methods is presented. The detection limits are given and the advantages and limitations of the tests are listed. This portfolio of test methods should be regarded as a living document and will require amendment as new research is undertaken. Further work into the area of mean time to failure (MTTF) to discover the maximum permissible leak rate for typical MEMS is also needed. This would allow a suitable reject value to be obtained for small cavity volumes allowing researchers to focus on suitable test solutions.

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