Optical Leak Testing of Hermetic Semiconductor, MEMS and Optoelectronic Devices

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Abstract

A production leak test system using digital holography, Optical Leak Testing (OLT), has been developed for simultaneous gross and fine leak testing of hermetic semiconductor, MEMS and Optoelectronic devices. The technique has also shown the unique capability to leak test ceramic SMC's on PCBs, even if conformal coated. Many devices are manufactured using welded, brazed or soldered metal lids with metal or ceramic packages. The most common conventional leak test methods used in the semiconductor industry include gross leak testing by the bubble leak method and fine leak testing with a helium mass spectrometer. The application of these techniques is highly problematic for many OLED display, Optoelectronic and MEMS devices. For maximum sensitivity, bubble leak testing requires the package be immersed in a perfluorocarbon liquid at a temperature of 125°C, exceeding the 90°C limit for most of these devices. In addition, helium absorption by the fiber optic pigtail causes fine leak testing with mass spectroscopy to be highly inaccurate when the helium degasses during testing. Further, neither method can be applied to SMC mounted to PCBs to locate leaking devices cracked during soldering. The Optical Leak Test method overcomes these concerns, and other problems with conventional leak test methods and reports the leak rate for all devices tested at one time. The hermetic devices are placed in the test chamber and exposed to a pressurized low molecular weight gas such as helium. If the package is leaking, the lid responds to changes in pressure differences as the device cavity pressure and test chamber pressure come to equilibrium. Precision chamber pressure measurements combined with lid stiffness and velocity data, obtained with digital holography are used to determine package leak rates in helium cc-atm/sec. Leaks in the range from the "no lid condition" to 5x10E-9 cc-atm/sec. have been measured. The method has demonstrated a very high level of accuracy and repeatability. Throughput is determined by the number of devices that can be placed on the boat for simultaneous testing. Cycle times vary from 2 to 20 minutes depending on package size and internal volume. For hermetic optoelectronic devices the problems of high temperature exposure, contamination and helium absorption/release experienced with conventional leak test methods are overcome. Finally, automated Optical Leak Testers provide near real-time leak test data for process control of metal lid seam sealing operations, minimizing lost production time, rework and scrap. The Optical Leak Test Method has been included in MIL STD 883E since 1995 for conditions C4 and C5.

Key Words: Leak Testing, MIL-STD-883E, Helium Leak Testing, Bubble Leak Testing, Seam Sealing, Metal Lid Packages, Optical Leak Test, Holography Leak Test, Optoelectronic Devices, Fiber Optic Devices, MEMS, Surface Mount Components, Electronic Device Tg

Introduction

Recent extraordinary competitive pressures and the need for automation have created a need for an automated leak testing technology capable of production testing of semiconductor, optoelectronic, microwave, hydrids and MEMS devices throughout the full leak range from the no-lid condition to 5x10E-8 cc-atm./second helium. In addition, recent failures of critical Hi-Rel electronic systems due to cracks in ceramic SMCs highlight the need for a leak testing technology capable of testing completed board level assemblies. An optical leak testing (OLT) technology using digital holography has been developed capable of meeting all of these needs.

Hermetic Packaging

Microcircuits, laser/fiber junctions, inter-connect wires, wire bonds and other components in advanced electronic devices are subject to damage from corrosion or contamination from exposure to water vapor, oxygen and other gases. This damage and the rate of corrosion of these internal components have a direct impact on the reliability and lifetime of hermetic electronic devices. In today's world of telecommunication, and military high reliability electronics, manufacturing devices with less than six sigma reliability is not acceptable. As a result, manufacturing of these devices must include metal or ceramic hermetic packages with soldered, welded or brazed metal lids and extensive leak testing to ensure product reliability and process control. Internal package atmospheres are usually dry nitrogen except MEMS devices, which usually require a hard vacuum for operation. While current lid seam sealers provide highly reliable hermetic joints, leak testing over the full range from gross through fine leak is required to verify hermeticity and achieve the required reliability.

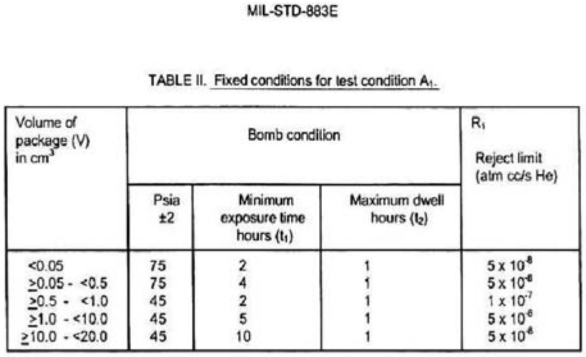
Conventional Leak Test Methods

The most frequently used leak test methods in the semiconductor industry are bubble leak testing and helium mass spectroscopy. For gross leaks, the bubble method is performed by immersion of the device into a bath of perfluorocarbon liquid. Bubbles emanating from the package indicate a leak. For fine leaks, a mass spectrometer is often used to detect helium leaking from packages. Bubble leak testing is applicable for gross leaks only. Helium mass spectroscopy is valid only for fine leaks, smaller than about 1x10E-6 cc-atm/sec. While these methods have been used for years for many semiconductor and hybrid packages, bubble and helium mass spectroscopy leak testing suffer from a number of intrinsic problems especially when applied to optoelectronic and MEMS devices.

Bubble leak testing requires immersing the packages in perfluorocarbon liquid heated to 125°C, necessary since the internal gas pressure inside the device must be raised high enough to generate a gas flow through the leak. The gas bubble escaping from the package is observed by the operator viewing through a window in the side of the illuminated tank. Testing at lower than optimal temperatures may not increase the gas pressure inside the package sufficiently resulting in a significant loss of sensitivity. Gross leaks can be missed. Unfortunately, for most of the adhesives and epoxies used for bonding laser devices, fiber optic cable terminations and other components inside the device, the required 125°C temperature approaches or exceeds the glass transition temperature. Exposures to the required 125°C temperature will severely damage most fiber optic devices. In addition, for many fiber optic devices, the intrusion of perfluorocarbon liquid into the cavity causes severe contamination. In many instances, devices failing gross leak bubble testing are considered as scrap since cleaning the laser/fiber junction is impossible. Bubble leak testing can also contaminate polished fiber optic cable ends on packages with pigtails. Finally, for many packages without fiber pigtails, with lenses or optical windows in the side of the package, contamination can easily occur during bubble leak testing again causing expensive rework or scrap.

Helium mass spectroscopy detects helium emanating from inside the package. The test can be set up two ways. First, a specified amount of helium, usually a 10% concentration with dry nitrogen, can be sealed into the package by having a controlled concentration of helium in the seam sealer dry box. This may not be desirable for optoelectronic devices since the helium will separate from the nitrogen and migrate to the top of the package cavity affecting both thermal conductivity of components in the device as well as the index of refraction at the laser/fiber junction. Both of these effects can severely degrade the laser signal entering or leaving the fiber, especially for externally mounted fibers. Sealing the lid in a 90% dry nitrogen and 10% helium atmosphere has additional problems in that the helium concentration may change over time at the package sealing location within the dry box. This can substantially influence any subsequent leak test data by changing the concentration of helium inside the package at the time of sealing.

Second, the packages can be bombed, by placing the devices in a chamber with helium at 45 or -75 psi for a period of time up to ten hours based on package volume. Table 1, below, shows the helium bomb time-pressure required by Mil Std. 883E. Helium will diffuse into leaking packages and be detected later when it diffuses out of the package in the vacuum test cell of the mass spectrometer. Testing must be performed immediately after bombing or sealing in the helium during the lid attach.



MIL-STD-883E

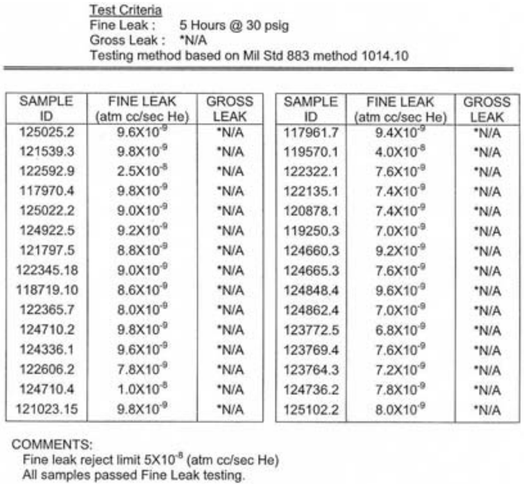
TABLE II. Fixed conditions for test condition A_1.

Volume of package (V) in cm^3	Bomb condition			R_1 Reject limit (atm cc/s He)
	Psia ±2	Minimum exposure time hours (t_1)	Maximum dwell hours (t_2)	
<0.05	75	2	1	5×10^{-8}
≥0.05 - <0.5	75	4	1	5×10^{-8}
≥0.5 - <1.0	45	2	1	1×10^{-7}
≥1.0 - <10.0	45	5	1	5×10^{-6}
≥10.0 - <20.0	45	10	1	5×10^{-8}

Table 1. Helium Bomb time-pressure requirements as a function of cavity volume, per Mil Std. 883E.

Due to the very fast helium migration rate through gross leaks, the amount of helium detected may be extremely small or non-existent by the time the device is tested in a mass spectrometer. Whatever helium may have been present might be gone, allowing gross leaking devices to be passed. In order to ensure packages are not leaking over the full range from the "no lid condition", gross leak through fine leak using conventional leak test methods, multiple techniques must be used. Helium mass spectroscopy alone cannot verify hermeticity.

Table 2. shows helium mass spectrometer test results for 30 fiber optic modulators with 1.2 cc cavity volumes. All devices have passed gross leak testing with helium but could not be gross leak tested with the fluorocarbon bubble leak method due to the high temperature requirement. Optical leak testing demonstrated every device was in fact a gross leaker.



Test Criteria
Fine Leak : 5 Hours @ 30 psig
Gross Leak : *N/A
Testing method based on Mil Std 883 method 1014.10

SAMPLE ID	FINE LEAK (atm cc/sec He)	GROSS LEAK	SAMPLE ID	FINE LEAK (atm cc/sec He)	GROSS LEAK
125025.2	$9.6X10^{-9}$	*N/A	117961.7	$9.4X10^{-9}$	*N/A
121539.3	$9.8X10^{-9}$	*N/A	119570.1	$4.0X10^{-8}$	*N/A
122592.9	$2.5X10^{-8}$	*N/A	122322.1	$7.6X10^{-9}$	*N/A
117970.4	$9.8X10^{-9}$	*N/A	122135.1	$7.4X10^{-9}$	*N/A
125022.2	$9.0X10^{-9}$	*N/A	120878.1	$7.4X10^{-9}$	*N/A
124922.5	$9.2X10^{-9}$	*N/A	119250.3	$7.0X10^{-9}$	*N/A
121797.5	$8.8X10^{-9}$	*N/A	124660.3	$9.2X10^{-9}$	*N/A
122345.18	$9.0X10^{-9}$	*N/A	124665.3	$7.6X10^{-9}$	*N/A
118719.10	$8.6X10^{-9}$	*N/A	124848.4	$9.6X10^{-9}$	*N/A
122365.7	$8.0X10^{-9}$	*N/A	124862.4	$7.0X10^{-9}$	*N/A
124710.2	$9.8X10^{-9}$	*N/A	123772.5	$6.8X10^{-9}$	*N/A
124336.1	$9.6X10^{-9}$	*N/A	123769.4	$7.6X10^{-9}$	*N/A
122606.2	$7.8X10^{-9}$	*N/A	123764.3	$7.2X10^{-9}$	*N/A
124710.4	$1.0X10^{-8}$	*N/A	124736.2	$7.8X10^{-9}$	*N/A
121023.15	$9.8X10^{-9}$	*N/A	125102.2	$8.0X10^{-9}$	*N/A

COMMENTS:
Fine leak reject limit $5X10^{-8}$ (atm cc/sec He)
All samples passed Fine Leak testing.

Table 2. Leak rates for 30 modulators tested with helium mass spectroscopy to Mil Std. 883E. All devices have measured leak rates small than 5x10E-8 cc-atm/sec. helium, the reject limit. Optical leak testing showed all 30 devices are gross leakers.

Another problem for many fiber optic devices is caused by helium absorption by fiber armor cladding and boots (see Photo 1.) and subsequent de-gassing during the helium leak testing process when the package is subjected to a vacuum. The resulting false calls can lead to scrapping parts or needless and very expensive rework. Highly skilled operators and stringent adherence to procedures is critical. Even then, mass spectrometer leak test results are not highly repeatable. Recent tests of a population of 50 devices at 5 different test facilities showed a two order of magnitude variation on 4% of the parts and 0.5 an order variation on more than 25% of the devices. Further, when helium is detected during batch leak testing of multiple devices at one time, the operator can not determine from one test if all of the devices are leaking or just one device is the leaker. The population must be divided in half and retested until the individual leaking package(s) are located, a costly, labor intensive and time-consuming process.

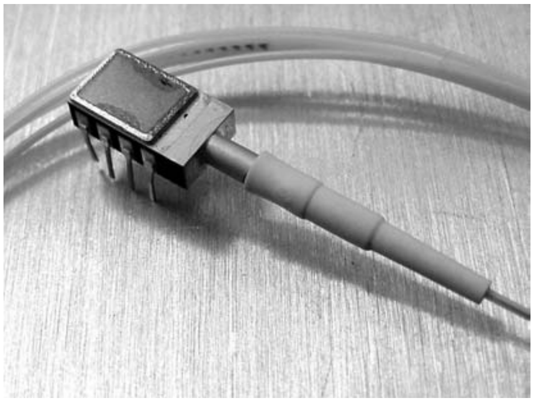


Photo 1. Above is an 8 Pin fiber optic device with a 4x7 mm. lid. The plastic boot and fiber optic pigtail are excellent helium absorbers. Helium absorbed during bombing or seam sealing in a 10% helium atmosphere and subsequent de-gassing, causes mass spectrometer leak test results to vary widely.

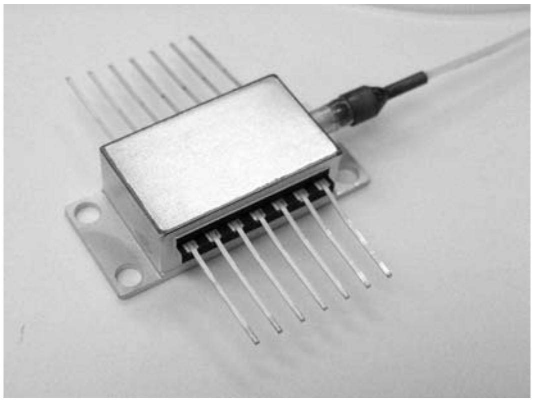


Fig. 2. Shown is a typical 14 pin butterfly package with a 12 x 20 mm lid, used widely for fiber optic device packaging. The fiber optic cable exits the package on the right side. Optical leak testing is sensitive to all leak paths allowing gas exchange between the package cavity and the atmosphere, including leaking lead and fiber penetrations and faulty lid seals.

Finally, conventional leak test methods are difficult to automate, the key to lowering manufacturing costs for fiber optic devices. And while leak testing measures the quality of the lid seam sealing operation, conventional methods can not provide a means of process control due to the time delay between lid welding and reporting leak test results.

SMC Board Level Leak Testing

Recent failures of critical flight systems caused by leaking ceramic surface mount components are a cause for considerable concern. While these SMC devices passed all bubble and helium mass spectrometer leak tests per Mil Std. 883E at the component level, thermal shock during soldering the SMCs to the board caused the ceramic packages to crack. The compete boards were tested using optical leak testing and more than 25% of the ceramic SMCs were found to be gross leakers. The boards had been conformal coated.

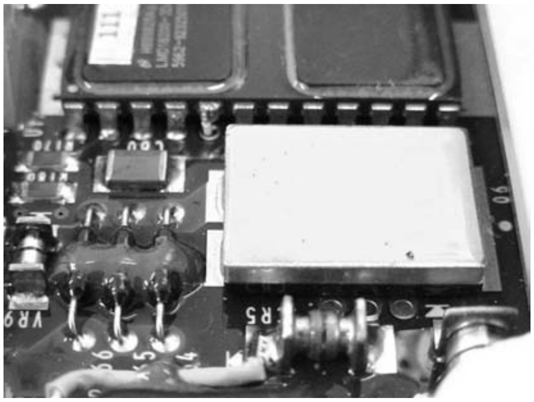


Photo 3. Conformal coated, SMC devices mounted on a circuit board, cracked due to thermal shock during soldering. This type of gross leak failure can only be detected with optical leak test methods.

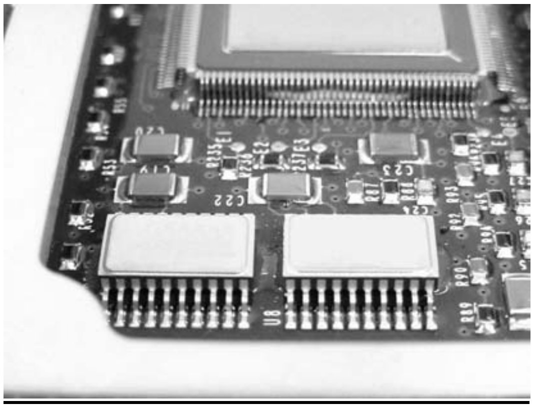


Photo 4. Cracked SMC devices tested with optical leak testing at the board level.

Optical Leak Testing

Optical Leak Testing was first developed by the author and associates in 1984 to leak test computer modules for a military application. Ceramic packages with ceramic lids and glass frit seals had cracked due to thermal shock during wave soldering. Our first holographic leak test system consisted of a chamber fabricated from a six-inch thick aluminum plate, machined to create a recessed cavity to accept the modules. An O-Ring groove and two inch thick glass lid allowed the devices on the module to be imaged using a film based holography camera. With this setup the cavity could be evacuated or pressurized with helium. The use of a low atomic weight gas increases diffusion rates for leaks smaller than 1x10E-6 cc-atm/sec., increasing sensitivity. Leaking devices were detected by the change in contour of the ceramic lid as the internal pressure in the cavity came into equilibrium with the high-pressure atmosphere in the chamber. Some 700 printed circuit board assemblies were inspected with a total of 21,000 ceramic devices mounted on the circuit board. 600 devices failed our holography leak test procedure and were replaced by hand soldering. At the time, the limited leak sensitivity of 5x10E-7 cc-atm/sec. for these devices was the best attainable with film holography. But for this particular application, these results were sufficient and no other known leak test technology was able to provide leak test capability for hermetic packages soldered devices soldered to PC boards.

The rapid advances in 1990's of computers, digital CCD video cameras and the solid state, single frequency laser emitting visible light, led to the development of the current automated optical leak test systems based on digital electronic holography interferometry. These production systems are not only easy to use but also have demonstrated greatly increased leak sensitivity to 2x10E-9 cc-atm/sec., at least a two order of magnitude increase. Optical Leak Test technology marries electronic digital holography, a test chamber with computer controlled precision helium pressurization system and software to determine leak rates from the analysis of package lid deformation measurements, instantaneous lid velocity and changes in lid velocity over time. The phase stepping, digital holography camera developed for our leak test systems is capable of measuring changes in package lid out-of-plane contour as small as 2 nanometers during the 1 to 3 minute test period. The result is a high throughput, automated system for the detection and measurement of leaks in hermetic packages in the range from the "no lid condition" to fine leaks as small as 2x10E-9 cc-atm/sec. helium. The ultimate sensitivity for a given package is dependent on package stiffness, lid thickness, lid type (stepped or plane), lid dimensions, cavity volume, lid modulus of elasticity and test hold time; the time allowed for the lid deformation data to taken. Leak rates well down to 5x10E-8 cc-atm/sec are detected for devices with 3x5 mm. lids. For fiber optic devices in larger packages, in the size range of 14 pin butterfly packages (12x20 mm) and larger, sensitivity to 5x10E-9 has been demonstrated in production.

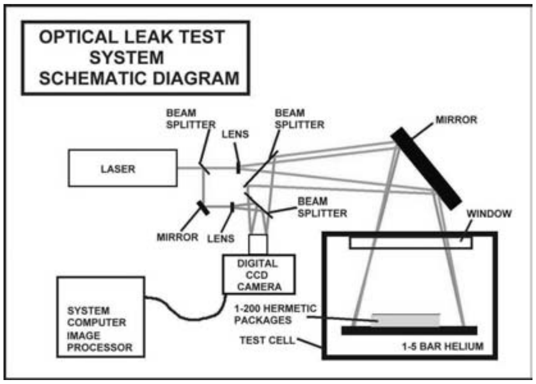


Fig. 3. Schematic Diagram of Optic Leak Test System showing the digital holographic camera imaging hermetic packages in the helium test cell.

The Leak Testing process starts with loading the devices, usually in the same tray, boat or carrier used for the lid sealing operation, into the open chamber door. The door is closed and the test initiated. The test chamber is purged of air and flushed with helium, then pressurized to the test pressure, determined by package volume, being careful not exceed the maximum allowable pressure for the device. Gross leaking devices are detected through measurement of lid

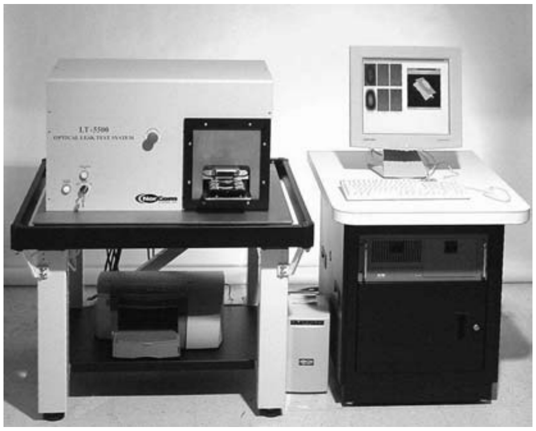


Fig. 4. The LT-5500 Optical Leak Test system showing the test chamber with the access door open, control console, printer and UPS. The digital holography camera is located above the test chamber. This system is designed specifically for leak testing optoelectronic devices in carrier trays up to 288mm in length. Gross and fine leak testing is automatic.

Fig. 5 Tray of devices loaded into LT-5500. Other system models are configured for semiconductor, MEMS and board level leak testing.

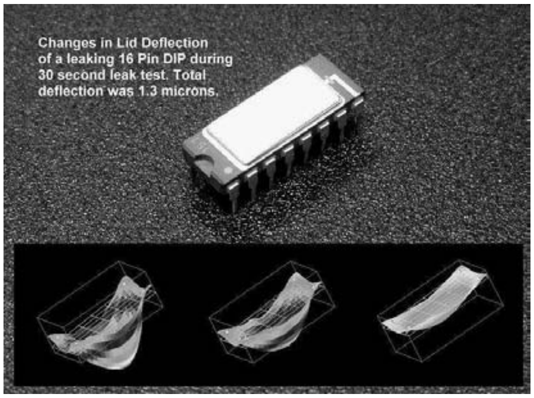


Fig.6 The deformation of a metal lid 16 pin package with a brazed metal lid is shown in this 3D plot made with holographic data captured while the devices was subjected to 45 psi helium pressure. The deformation of the lid at left is due to helium pressure. The leak allowed helium to enter the package and increase the cavity pressure causing the lid to deform back toward the original shape. The resulting lid deformation totaled 1.3 microns during this 30-second test.

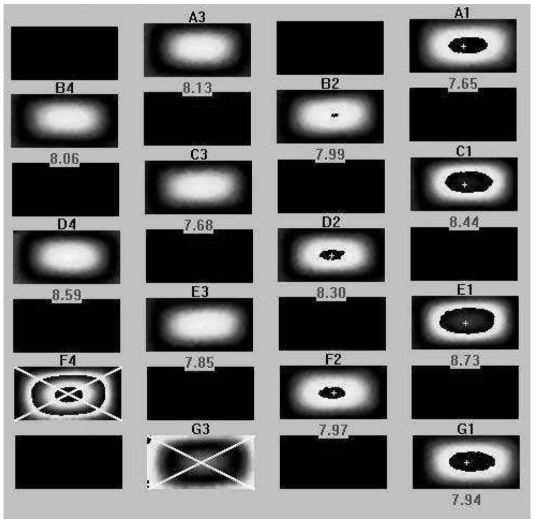


Fig. 7 A digital holography phase map shows lid deformation on fourteen devices mounted in a staggered pattern in the tray. Placed inside the test chamber, the devices have been subjected to 45-psi. helium pressure. An initial holographic image was captured at T=0. Here, after 20 seconds, packages in the F4 and G3 position have already been identified as Gross Leaks.

movement during a change in chamber pressure. A negative response indicates rapid equalization of the gas pressure between the cavity of the device and the test chamber pressure. Fine leak devices are detected by a change in lid contour during a period of stable elevated chamber pressure. Leaking devices will be detected by a gradual change in the out-of-plane contour of the lid.

In practice, up to 200 devices may be tested at once with leak rates reported on each individual package. Large devices, and especially fiber optic packages, require considerable space to manage the fiber optic pigtails and ensure that bends smaller than the minimum bend radius are not experienced. Fig. 5 shows 14 fiber optic devices being tested at one time, mounted in a staggered pattern on the tray. The phase map provides data showing the change in lid contour to 2 nanometers. Interpretation of the data is automatic and output for each package tested is selectable: Deformation (microns), Helium Leak Rate (cc-atm/sec. Helium) or threshold designations of Gross Leak, Fine Leak, and Pass.

Optical Leak Testing as Process Control for Optoelectronic Device Packaging

With capability for simultaneous and automatic testing for gross and fine leaks, individual reporting of leak rates for each device and high speed-high throughput, the Optical Leak Test System can provide process control data over a local area network (LAN) for lid sealing equipment on the production line. Lid sealing problems can be detected and corrected with the fewest number of rejected devices possible, lowering production costs.

Optical Leak Testing Data Analysis

Optical leak testing systems can provide test results in several ways. First, they can provide a go - no go indication of a leak by viewing the formation of fringes in the output image. This is a simple but labor-intensive method used during the early development of the technology but now obsolete. Second, lid deformation may be measured by digital holography and compared to a measured deformation of similar packages with known leak rates. Calibration is by way of a look up table that compares lid deflection over time at the test pressure to the deformation of a package leaking at the threshold level for acceptance. While this provides automated leak testing, calibration requires a substantial population of devices with known leak rates determined with helium mass spectroscopy, already shown to yield widely varying leak rates for repeated tests on the same package. Multiple mass spec tests must be run to obtain statistically good leak rate data. This is time consuming and costly except for high volume production runs of identical devices.

A third method, Pressure Modulated Optical Leak Testing, yields very accurate, repeatable leak rates in cc.-atm/sec. helium (fine leak) for any package for which the internal volume is known. This method is very simple to calibrate requiring a similar package known to be hermetic. Further, this method provides truly automated leak testing for:

1. very high volume production of identical devices
2. Short runs with widely varying package designs and volumes
3. board level leak testing with a wide variety of package designs and volumes

Pressure modulated optical leak testing combined with other algorithms described herein provides a direct measurement of electronic package leak rates over the full range of leaks from the no-lid condition to well beyond the 1x 10E-8 cc.-atm/sec. for most package configurations.

Determination of Helium Leak Rates with the Pressure Modulated Optical Leak Testing Method

The leak test system is loaded with parts of known internal volume. During the course of the test, the chamber pressure is slowly modulated about the working pressure. The basic equation governing package lid deflection may be expressed as:

$$d(t) = c_0\left(p_c(t) - p_p(t)\right) \tag{1}$$

Where:

$d(t)$ = observed lid deflection.

c_0 = package lid stiffness (um/psi).
p_c = observed change in chamber pressure.
p_p = change in internal package pressure.

The change in internal package pressure during the course of the test can be approximated by a 2nd order polynomial of the form:

$$p_p(t) = c_1 t^2 + c_2 t \qquad (2)$$

It is important to note that in order to differentiate lid deflection due to chamber pressure fluctuations $p_c(t)$ from lid deflection due to changes in internal package pressure $p_p(t)$, the two components must be linearly independent. For this reason a sinusoidal pressure modulation function is used for $p_c(t)$. By substituting equation (2) into equation (1) we get:

$$d(t) = c_0\left(p_c(t) - c_1 t^2 - c_2 t\right) \qquad (3)$$

At this point, the three unknown parameters in equation (3) can be determined using standard linear estimation techniques.

Figure 1 presents a typical example of the leak deflection model. The data shown in Figure 1 were generated by a package that tested at $5.6\text{x}10^{-7}$ atm-cc/sec using traditional helium mass spectrometry leak testing. As can be seen in the figure, the modeled total deflection closely fits the observed total deflection. In addition to the total modeled lid deflection, the plot shows the component of total modeled deflection due to chamber pressure modulation and the component due to internal pressure change.

Once the leak deflection model has been solved, the actual change in internal package pressure is found by evaluating (3) using the total test time t. With the change in internal package pressure known, the measured helium leak rate can be calculated using equation (4)[1]. Note that the Δp terms in equation (4) represent the difference between the chamber pressure and the internal package pressure.

$$\Delta p_t = \Delta p_i e^{-Lt/V} \qquad (4)$$

Where:

Δp_i = initial pressure difference (atm).
Δp_t = final pressure difference (atm).
R = measured leak rate (atm-cc/sec).
V = internal package volume (cc).
t = length of test (sec).

For the current example, the computed change in internal package pressure was $3.76\text{x}10^{-2}$ atm, the chamber working pressure was 3.68 atm, and the test time was 556 sec. The internal package volume was estimated at 0.1 cc.

Using the previously listed test parameters and the computed internal pressure change of $3.76\text{x}10^{-2}$ atm, equation (4) yields a measured leak rate of $2.53\text{x}10^{-6}$ atm-cc/sec. Finally, the measured leak rate is converted to the true leak rate using equation (5)[2]

$$L = R / p_w \qquad (5)$$

Where:

L = true leak rate (atm-cc/sec).
R = measured leak rate (atm-cc/sec).
p_w = chamber working pressure (atm).

With a chamber working pressure of 3.68 atm, the true leak rate for the example package works out to $6.88\text{x}10^{-7}$ atm-cc/sec. This result agrees reasonably well with the previously stated helium leak test result $5.6\text{x}10^{-7}$ atm-cc/sec.

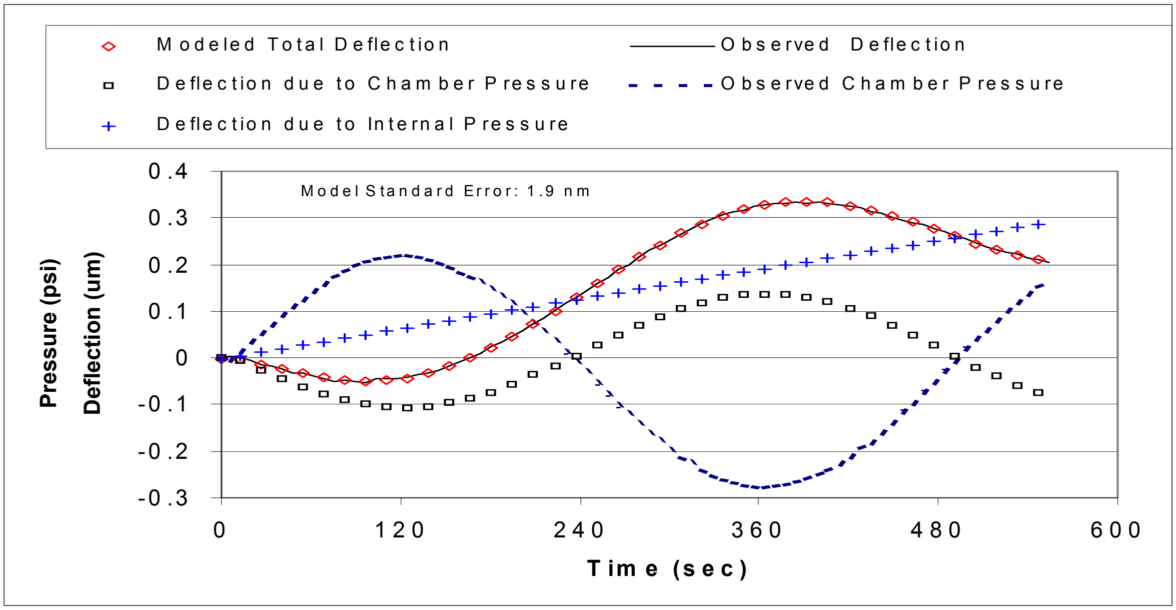


Figure 1 Leak test and modulated pressure data for a package tested at 5.6x10E-7 cc-atm./sec. using Helium Mass Spectroscopy. Optical Leak Testing determined a leak rate of 6.8 x10E-7cc-atm/sec.

Conclusion

Optical leak testing has been developed and implemented in production lines for optoelectronic, MEMS, and semiconductor devices. Important technical and cost benefit features of this new technology have been identified leading to substantial improvements in product reliability and lower costs. This important technology substantially overcomes many of the problems experienced with conventional bubble leak testing and helium mass spectroscopy when applied short runs of widely varying configurations as well as to high volume production. Optical leak testing with pressure modulation offers the most direct, accurate and repeatable leak testing capability available today. Additional benefits include:

- Simultaneous, automated Gross and Fine leak testing.
- Leak test from no-lid to 1x10E-8 based of package configuration.
- Unaffected by helium absorption by fiber cladding and boot.
- Avoids subjecting devices to high, damaging temperatures during Bubble Gross Leak testing.
- Provides near real time data on LAN for process control of metal lid seam welders.
- Higher production rates, lower production costs and better reliability for the optoelectronic device manufacturer.
- Board Level leak testing of ceramic SMC devices.
- Optical Leak Testing is included in MIL STD. 883E for Conditions C4 and C5.
- Directly measures leak rate in cc-atm./sec. in helium.

References:

[1] Greenhouse, Hal, *Hermeticity of Electronic Packages* William Andrew, pp 302 (2000)

[2] Greenhouse, Hal, *Hermeticity of Electronic Packages*, William Andrew, pp 51 (2000)