SEMI MS8-0309 (Reapproved 0622)
GUIDE TO EVALUATING HERMETICITY OF MICROELECTROMECHANICAL SYSTEMS (MEMS) PACKAGES

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NOTICE: The section symbol (§) is used to reference a numbered section, paragraph, or header and all subordinate paragraphs, headers, and embedded material (i.e., EXCEPTIONs, lists) therein. The paragraph symbol (¶) is used to reference a particular numbered paragraph and embedded material therein. When duplicated (i.e., §§ and ¶¶) the symbols are used to reference more than one section or paragraph, respectively.

1 Purpose

1.1 Microelectromechanical systems (MEMS) are miniaturized systems requiring packaging for environmental protection and for interconnection. While there are a wide range of MEMS devices, a common need is for packaging that allows movement of the internal device during operation. This is in contrast to the typical integrated circuit that requires only that the device be protected from the environment and that appropriate interconnections are made. In many cases, hermeticity is critical to MEMS device functionality. In other cases, hermeticity is primarily important to reliability of MEMS devices, similarly to integrated circuits. To accelerate improvements of packaged MEMS devices, leading to higher levels of marketplace acceptance, a guide to evaluating hermeticity of MEMS packages is required.

1.2 This Guide is intended to provide an overview of hermetic packaging with emphasis on the evaluation of hermeticity of the smaller internal volumes typical of MEMS.

2 Scope

2.1 This Guide is directed towards evaluating hermeticity of MEMS packages. Areas to be addressed include materials and equipment for producing and evaluating hermetic seals; methods for detection and measurement of leakage; and considerations and recommendation on evaluation of hermeticity.

2.2 This Guide is applicable for use in connection with establishment of evaluation methods and procurement of materials, equipment and facilities relating to manufacturing, quality and reliability assurance for all phases of research, development, and production.

2.3 Devices for which this Guide is expected to be relevant include, but are not limited to; gyroscopes and accelerometers, RF MEMS switches, optical mirrors and switches, pressure sensors, resonators, filters, and microfluidics devices including valves and pumps.

NOTICE: SEMI Standards and Safety Guidelines do not purport to address all safety issues associated with their use. It is the responsibility of the users of the Documents to establish appropriate safety and health practices, and determine the applicability of regulatory or other limitations prior to use.

3 Limitations

3.1 Users of packaged MEMS devices require assurance that hermeticity is adequate both initially and over operating life. In turn, designers and manufacturers of MEMS packages must be able to demonstrate that internal ambient conditions of packaged devices meet design requirements:

- manufactured seals have sufficient integrity;
- material permeability to gases and liquids present in the operating environment is compatible with maintenance of internal ambient conditions over operating life and;
- outgassing is managed to ensure maintenance of internal ambient conditions over operating life.

However, the current Standard is primarily focused on evaluation of hermeticity at or near the time of initial manufacture. A future Standard will address reliability of hermeticity over operating life.

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3.2 The maximum permissible leak rate of a hermetic package is unavoidably related to the degree of outgassing and permeation, since these mechanisms lead to buildup of moisture levels internal to the package. For purposes of the current Standard it is assumed that the packaging materials and processes are sufficiently well controlled that outgassing and permeation effects are negligible. This simplifies determination of the maximum permissible leak rate.

4 Referenced Standards and Documents

4.1 *SEMI Standards and Safety Guidelines*

SEMI MS3 — Terminology for MEMS Technology

4.2 *ASTM Standards*[1]

ASTM F97-72 (2002)e1 — Standard Practices for Determining Hermeticity of Electron Devices by Dye Penetration (Withdrawn 2008)

ASTM F98-72(1997) — Recommended Practices for Determining Hermeticity of Electron Devices by Bubble Test (Withdrawn 1990)

ASTM F134-85(1990) — Test Methods for Determining Hermeticity of Electron Devices with a Helium Mass Spectrometer Leak Detector (Withdrawn 1996)

4.3 *JEDEC Standards*[2]

JEDEC JEP144 — Guideline for Residual Gas Analysis (RGA) for Microelectronic Packages

4.4 *United States Military Standards*[3]

MIL-STD 883 — Department of Defense Test Method Standard: Microcircuits, Test Method 1014.12 and Test Method 1018

NOTICE: Unless otherwise indicated, all documents cited shall be the latest published versions.

5 Terminology

5.1 *Abbreviations and Acronyms*

5.1.1 *DUT* — device under test

5.1.2 *MEMS* — microelectromechanical systems

5.1.3 *SOI* — silicon-on-insulator

5.2 *Definitions*

5.2.1 *device under test (DUT)* — the device undergoing evaluation.

5.2.2 *equivalent standard leak rate* — the leak rate when the pressure one side of the package is at standard temperature and pressure (~760 mm Hg absolute) while the other side of the package is at vacuum (less than 1 mm Hg absolute), often referred to as the true leak rate, or the leak rate normalized for a unit pressure differential.

5.2.3 *hermetic package* — completely sealed with minimal communication of either gases or liquids between the interior and the exterior of the package over operating life.

5.2.4 *hermetic vacuum package* — hermetic package sealed with vacuum in the interior of the package.

5.2.5 *material permeability* — the tendency of gases to directly migrate through the walls of the package. Bulk permeability depends on both chemical composition and diffusion. For example, diffusion of gases may be accelerated along grain boundaries. Stainless steel in half-hard condition will have small grain sizes relative to package wall

[1] ASTM International, 100 Barr Harbor Drive, West Conshohocken, PA 19428-2959, USA; Telephone: +1.610.832.9585, Fax: +1.610.832.9555, http://www.astm.org

[2] Joint Electron Device Engineering Council, 3103 North 10th Street, Suite 240-S, Arlington, VA 22201, USA; Telephone: +1.703.907.7560, Fax: +1.703.907.7583, http://www.jedec.org

[3] United States Military Standards, Available through the Naval Publications and Forms Center, 5801 Tabor Avenue, Philadelphia, PA 19120-5099, USA; Telephone: +1.215.697.3321. Download latest revision at www.dscc.dla.mil/

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thickness, while in fully annealed condition the grain size may be comparable to package wall thickness. In the latter case permeability is increased although the chemical composition is unchanged.

5.2.6 *measured leak rate* — the leak rate of a given package as measured using a specific set of operationally defined conditions and test media, often referred to as the apparent leak rate.

5.2.7 *microelectromechanical system (MEMS)* — refer to SEMI MS3 ("integration of microelectronics devices or fabrication technology with micrometer-scale mechanical devices to form a system").

5.2.8 *near hermetic package* — at least a portion of the package materials are formed of materials having permeability as high as 10^{-8} to 10^{-10} atm-cc/sec. One such material is liquid crystal polymer (LCP).

5.2.9 *outgassing* — release of gases absorbed on interior package surfaces or evolution of gases due to chemical change of enclosed materials. For example, epoxies, silicones, and Teflon all tend to outgas water vapor. As the pressure is reduced below about 100 millitorr, much of the load in a vacuum hermetic package may be from outgassing. In addition, outgassing may be due to virtual leaks, or slow release of gases that have been inadvertently trapped within the enclosure.

5.2.10 *quasi-hermetic package* — hermetic over a limited amount of time. Conventional package materials such as metal, glass or ceramic are used but an organic adhesive material forms the seal.

5.2.11 *seal integrity* — evaluation of the seal material for any paths that could allow environmental conditions to ingress the cavity or egress from the cavity and the bond quality between the package and seal material or the seal material and the lid. The width or thickness of the seal material may also be important to the integrity, based on the permeability of the material and/or structural strength required for the application.

5.2.12 *time zero* — the beginning point of the operating life of a packaged devices, generally the time at which the hermetic seal is actually formed. (Note that when surface mount reflow follows formation of the hermetic seal, this definition holds only assuming that the high reflow temperatures do not irreversibly alter the hermetic seal. Otherwise, time zero would begin at completion of surface mount reflow.)

6 Reliability Categories by Application Requirements

6.1 The reliability categories are defined as:

Table 1

Category (refer to ¶ 6.2)	*Lifetime in Years*	*Temperature Range °C*	*Application*
R1A or R1B or R1C	>10	−55 to +150	Military, space, aviation
R2A or R2B or R2C	>10	−20 to +65	Telecommunications
R3A or R3B or R3C	5–10	−40 to +125	Automotive
R4A or R4B or R4C	2–5	−20 to +65	Industrial
R5A or R5B or R5C	0–2	0 to +50	Commercial, consumer

#1 There is some arbitrariness in defining categories as above. The intention is to provide some structure to guide discussion. The specified lifetime and temperature ranges are intended to approximate requirements for the listed applications.

6.2 The reliability category is further defined by the letter 'A' to indicate that the performance of the enclosed device is directly related to the package hermeticity; the letter 'B' to indicate that the package hermeticity is required only for general reliability; or the letter 'C' to indicate that hermeticity is only required to protect the MEMS during the assembly and surface mount processes. For example, reliability category R3B may refer to an automotive application where the required operating life is 5–10 years, the operating temperature range is −40 to +125°C, and the hermeticity is required only for general reliability.

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7 Hermetic Sealing

7.1 *Sealing Materials*

7.1.1 The choice of hermetic sealing materials is intimately related to the sealing methods and equipment to be used. Generally, sealing materials comprise metals, inorganic glasses, or polymers. Metal, glass and polymer sealing materials are capable of supporting seals at the leak rate levels of about 10^{-16} (calculated, not measurable), 10^{-10}, and 10^{-6} atm-cc/s, respectively. Metal sealing materials are recommended for categories R1, R2 and R3, while glasses can be used for category R4 and perhaps for R3.

7.1.2 In the past polymer materials have not been capable of qualifying for hermetic seals. Newer materials such as liquid crystal polymer (LCP) are capable of quasi-hermetic or near hermetic seals. Such near hermetic polymer sealing materials may be considered for category R5 applications.

7.1.3 In direct bonding, the seal is composed of the interface between the two substrates being bonded. The interface layer is usually very thin, on the order of a few nanometers, and comprised of an oxide layer. For example, for direct bonding of silicon to silicon, the interface seal is comprised of only silicon and silicon dioxide.

7.2 *Sealing Methods and Materials*

7.2.1 *Intermediate Layer Bonding*

7.2.1.1 Eutectic/solder bonding employs a wide range of low-melting point eutectic alloys, often applied as intermediate layer bonding material. Generally it is desirable to apply alloys having a low melting point. In addition, corrosion resistance or compatibility with harsh environments is often a selection criteria. The eutectic alloy of gold and tin (AuSn) has a eutectic point of 280°C and is often chosen for critical applications. For lower cost applications, both solder materials and the eutectic alloy of aluminum and germanium (AlGe) having a eutectic point of 424°C are attractive alternatives. Solder bonding is a type of eutectic bonding involving materials containing tin (Sn) alloyed with other elements. Solder material placement in the bond zone is by evaporation, screen printing, or performs. In the past, lead-tin (PbSn) solders have been widely used. Recent trends are towards lead-free solders, such as tin-silver-copper (SnAgCu). Eutectic alloy is placed on a piece part having a metal film able to wet the alloy (e.g., gold (Au) with an underlayer is often used). Following placement the piece part is brought into close proximity with the part to which it is to be joined, and the assembly is heated above the eutectic temperature.

7.2.1.2 Welding is accomplished by application of energy directly to the mating joint. Both laser and electron beam welding develop localized power density of about 100 watts/cm^2 in the weld joint, with minimal heating of adjacent components. While both methods produce high quality joints, electron beam welding is higher cost since it must be completed under vacuum. Arc welding, having advantages of much lower capital and maintenance costs, can also be used but is considered to be less clean due to use of fillers and fluxes. The associated materials may introduce contaminants that result in outgassing during operating life. In addition, heat is not as localized as with laser or electron beam welding.

7.2.1.3 Glass frit is generally accomplished by screen printing of appropriate material. Following a drying cycle, a glazing step done at 400°C or greater results in volatilization of most of the binders. Then the parts to be joined are mated and the temperature is raised above the melting point of the glass frit, typically 25°C or more above the temperature of the glazing step. Glass frits specifically designed for compatibility with MEMS devices are available for joining silicon (Si) to alumina, borosilicate glass or Kovar.

7.2.1.4 Adhesive bonding is supported by a wide variety of materials such as epoxy and cyanoacrylate support adhesive bonding. Generally, adhesive bonding materials are incompatible with hermetic seal formation due to high permeability.

7.2.1.5 Other polymer bonding makes use of several materials available for spin coating or lamination. For example, benzocyclobutene (BCB), SU8 and polyimide materials can be spin-coated onto substrates and are capable of providing a seal. Unfortunately, the seal is inadequate for many hermetic applications due to high permeability. When the polymer bond layer is thin and the joint is wide, the bond joint may qualify as being near-hermetic or quasi-hermetic. Liquid crystal polymer (LCP), available in both laminate and spin-coat formats, is capable of providing near-hermetic performance and may be considered for R5 applications.

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7.2.2 *Direct Bonding*

7.2.2.1 *Fusion Bonding* — Provides nearly perfect hermetic seals. The method requires that mating surfaces be polished to Ra (average of a set of individual measurements of a surfaces peaks and valleys) of less than 2 nanometers. In addition, final bond formation requires exposure to temperatures in the range of 800°C to 1100°C for several minutes. Fusion bonding is flexible for a wide range of materials, but most typically involves silicon.

7.2.2.2 Anodic bonding also provides an excellent hermetic seal. The method is applicable to a few ion exchange materials. For example, 7740 Pyrex glass is often used to join with silicon (Si). Importantly, this particular glass contains about four percent sodium oxide (Na_2O_3), which provides ions for exchange. The mating surfaces must be polished to Ra of less than 20 nanometers, less stringent than that required for fusion bonding. The method involves simultaneous exposure to temperature in excess of 350°C and voltage in excess of 1,000 volts.

7.2.2.3 Metal-to-metal bonding forms a hermetic metal-to-metal seal via diffusion, friction-stir or ultrasonic bonding.

7.2.2.3.1 Diffusion bonding is a direct bonding process resulting in hermetic bonds with no adhesive. Sometimes interfacial materials are used to enhance the bonding process although these materials are not adhesives. Diffusion bonding can be used for a variety of solid materials and is not limited to metals. Diffusion bonding permits formation of complex shapes with minimal machining. The method requires that the mating surfaces be in intimate contact during the bonding process. Bonding is accomplished by controlled application of physical pressure and temperature over a specific time period. A partial list of test techniques relevant for determining bond integrity are peel strength testing, lap shear testing and burst testing.

7.2.2.3.2 Friction stir bonding is another technique that has been applied for joining metals. Generally, friction stir bonding is used with aluminum (Al) and aluminum alloys.

7.2.2.3.3 Ultrasonic welding has been widely used for joining of thermoplastics, but can also be used with metals. Ultrasonic welding of metals is generally limited to thin sections and small welds of materials such as aluminum, copper and nickel.

7.2.3 *Wafer Level Sealing by Encapsulation*

7.2.3.1 Sealing by encapsulation provides an alternative method of hermetic sealing wherein a polysilicon shell is formed over a cavity integral to wafer fabrication. According to this method, a sacrificial thin film is deposited over the device requiring hermetic seal. The sacrificial thin film is patterned and etched to remove the material in a region surrounding the cavity being formed. Next a polysilicon thin film having thickness of perhaps 2.0 micrometers is deposited and forms a seal to the surface. An access hole is opened in the polysilicon thin film to allow for penetration of an etchant. An etch procedure is applied to dissolve the sacrificial thin film from beneath the polysilicon shell, forming a cavity surrounding the device. Finally, depositing additional thin film material under vacuum seals the access hole. For example, the access hole may be sealed by sputtering silicon nitride (Si_3N_4) at a pressure of about 10 millitorr. This sealing method has gained favor where smallest size and low cost are required. The method requires that the device being sealed is unaffected by the etchants being used.

7.2.3.2 This method results in ultra-small hermetically sealed volumes, posing special challenges for evaluating hermeticity.

8 Seal Integrity Evaluation

8.1 Adequate seal integrity is one requirement for package hermeticity. Current methods for evaluation of seal integrity include acoustic (ultrasonic) and X-ray inspection. Acoustic inspection typically involves imaging based on reflection from interfaces and is highly sensitive in detecting unintended gaps between package members. X-ray inspection typically involves imaging based on transmission and is highly sensitive in detecting variations in density. Ultrasonic imaging may or may not be destructive, depending on details of implementation. X-ray inspection may be considered to be non-destructive, assuming that the packaged device is not sensitive to the radiative energy. Acoustic Microscope (AM) inspection can also be performed at wafer level, immediately after wafer bonding. (For this reason AM is often used for inspection of SOI wafer bonds.) The technique is useful during process development. However, at present it is not possible to use AM inspection when an edge is adjacent to the region to be imaged, as occurs when forming cuts in the lid of a package to access interconnect points. In addition, insight on seal integrity can be gained by integration of microsensors in the package.

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8.2 *AM Inspection Method for Inspecting Package Seal Integrity*

8.2.1 The spot size of the transducer and pixel spacing chosen for the AM imaging is selected to adequately view the details of interest.

8.2.2 The part to be examined is placed within the scan stage of the AM system.

8.2.3 The selected transducer is centered over the part to be examined.

8.2.4 Scan size and resolution (pixel spacing) are chosen to be adequate for imaging the whole wafer or the individual part being examined.

8.2.5 A time base scale adequate to view the A-Scan is selected.

8.2.6 After finding the edges of the part, the transducer is re-centered based on the edges of the part.

8.2.7 The front interface echo, which is associated with the surface of the part, is found by examining the acoustic scan.

8.2.8 The gate position (echo time slice) and width are adjusted to completely enclose the front interface echo.

8.2.9 The transducer is lowered until the acoustic scan echo from the surface is at its maximum height, indicating it is at the optimum focus level.

8.2.10 The part is scanned to produce a surface image.

8.2.11 The acoustic surface image of the seal integrity is further optimized by adjusting the transducer height and signal gain and by setting the gate so that it completely encloses the cover to cavity echo. Typically the signal gain is adjusted so that the maximum A-scan height within the gate is between 90% and 100% of maximum.

8.2.12 The scan command is executed to acquire an AM image of the seal level.

8.2.13 Images are saved as appropriate.

8.2.14 Seal integrity is evaluated by analyzing the AM image manually or with image analysis software. The actual width of the window seal bond surrounding the cavity is measured to determine if it is within an acceptable range for the application and whether any channels or paths that could allow contamination of the cavity are present.

8.3 *X-Ray Inspection*

8.3.1 Methods for determination of seal integrity by X-ray inspection are very similar to that for ultrasonic inspection except that it is a through transmission rather than a reflection technique.

8.3.2 Rather than adjusting for variation in pulse echoes as with ultrasonic inspection, X-ray inspection imaging requires adjustment of energy level and contrast to compensate for variations in density to obtain an image of the seal being inspected.

8.4 *Integrated Sensors*

8.4.1 Sensors may be integrated into the package for the sole purpose of providing information on the level of hermeticity.

8.4.2 Examples of micro sensors available for integration to package cavities to detect the presence of air instead of the normal packaging atmosphere include:

- Pirani gauge for measurement of thermal conductivity
- Resonator for measurement of absolute pressure
- Spark gap for measurement of dielectric strength
- Inter-digitated combs for measurement of surface moisture conductivity

8.5 *Fourier Transform Infrared (FTIR) Inspection*

8.5.1 When the bonding atmosphere is a gas whose main infrared (IR) absorption peak lies within the lid IR transmission window (e.g., sulfur hexafluoride with a silicon lid), reflective FTIR spectroscopy may be used to detect the presence of gas in the cavity.

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