Background Statement for SEMI Draft Document 5266
NEW STANDARD: TEST METHOD TO MEASURE FLUID PERMEATION THROUGH MEMS PACKAGING MATERIALS

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Background

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 prediction and measurement of permeation of MEMS hermetic packages is required. This document is intended to provide an overview of design considerations and hermetic packaging with emphasis on the evaluation of permeation of MEMS hermetic packages having internal cavity volumes that are very small compared to conventional packages. Additional examples and flow chart shall be considered for future work.

Responses received will be reviewed by the MEMS Packaging Task Force. If you have any questions or concerns, please contact Paul Trio at SEMI (ptrio@semi.org).
SEMI Draft Document 5266
NEW STANDARD: TEST METHOD TO MEASURE FLUID PERMEATION THROUGH MEMS PACKAGING MATERIALS

1 Purpose
1.1 Microelectromechanical systems (MEMS) are miniaturized systems requiring packaging for environmental protection and for interaction with the external environment. While there is a wide range of MEMS devices, a fairly common need is for packaging that allows movement of some of the internal sub-components of the device during operation. This is in contrast to the typical integrated circuit that requires only that the device be protected chemically and mechanically from the environment and that appropriate electrical interconnections are made. In many cases, hermeticity is critical to MEMS device functionality. In other cases, hermeticity is primarily important to the 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 prediction and measurement of permeation of MEMS hermetic packages is required.

1.2 This document is intended to provide an overview of design considerations and hermetic packaging with particular emphasis on the evaluation of permeation of MEMS hermetic packages having internal cavity volumes that are very small compared to conventional packages.

2 Scope
2.1 This standard is directed towards defining a common method of measurement of permeation through technical films that are used in sealing hermetic 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 recommendations on the evaluation of hermeticity.

2.2 This standard additionally provides methods for quickly evaluating compliance of a specific hermetic cavity package to application requirements. The standard may be useful for establishing protocols 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 microfluidic 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 hermetic cavity packages for 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 fluids (gases or 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.

3.1.1 The current document is primarily focused on the evaluation of material permeability coefficients at or near the time of initial manufacture, and in the prediction of the impact of permeation on reliability of hermeticity over operating life.

3.2 The permeation of a hermetic package is related to capillary leaks or permeability properties of the material making the package or the seal. Indeed these characteristics lead to the buildup of air species (including moisture) levels within the package. For purposes of the current document, it is assumed that the packaging materials and processes have been controlled to a level where outgassing and capillary leaks are considered negligible. This
This simplifies the calculation of the maximum permeation that can be tolerated according to users’ or manufacturers’ requirements.

4 Referenced Standards and Documents

4.1 SEMI Standards and Safety Guidelines
SEMI MS3-0307 — Terminology for MEMS technology

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

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

5 Related Documents

5.1 ANSI/ASQC Standards
ANSI/ASQC Z1.4-1993 — Sampling procedures and tables for Inspection by Attributes
ANSI/ASQC Z1.9-1993 — Sampling procedures and tables for Inspection by Variables for percent nonconforming

5.2 ASTM Standards
ASTM D3985-95 — Standard Test Method for Oxygen Gas Transmission Rate through Plastic Film and Sheeting Using a Coulometric Sensor
ASTM F97-72 (2002)e1 Standard practices for determining hermeticity of electron devices by dye penetration
ASTM F979-86 (2003) Std. test method for hermeticity of hybrid microcircuit packages prior to lidding

5.3 ISO Standards
ISO 2556(1974) Plastics — Determination of the gas transmission rate of films and thin sheets under atmospheric pressure (Manometric method)
ISO-Std-2859 Sampling procedures for Inspection by Attributes

5.4 JEDEC Standards
JEDEC JESD22-A102 — Moisture resistance 96 Hr; 100%RH; 121 C
JEDEC JESD22-A104 — Temperature cycling 600 cycle; -65 to +150 C

5.5 JIS Standards
JIS K 7126(1987) — Testing Method for Gas Transmission Rate through Plastic Film and Sheeting

5.6 Military Standards and Documents

2 American National Standards Institute, 25 West 43rd Street, New York, NY 10036, USA; Telephone: 212.642.4900, Fax: 212.398.0023, http://www.ansi.org
3 American Society for Quality, 600 North Plankinton Avenue, Milwaukee, WI 53203, USA; Telephone: 414.272.8575, Fax: 414.272.1734, http://www.asq.org
4 American Society for Testing and Materials, 100 Barr Harbor Drive, West Conshohocken, PA 19428-2959, USA; Telephone: 610.832.9585, Fax: 610.832.9555, http://www.astm.org
5 International Organization for Standardization, ISO Central Secretariat, 1 rue de Varembé, Case postale 56, CH-1211 Geneva 20, Switzerland; Telephone: 41.22.749.01.11, Fax: 41.22.733.34.30, http://www.iso.ch
7 Japanese Standards Association, 4-1-24 Akasaka, Minato-ku, Tokyo 107-8440, Japan; Phone: 81.3.3583.8005, Fax: 81.3.3586.2014, http://www.jsa.or.jp
Mil-HDBK-108 — Quality control and reliability - Sampling procedures and tables for Life and reliability testing (based on exponential distribution)
Mil-Std 690 — Failure rate sampling plans and procedures
Mil-Std 750 — Test Method Standard Test Methods for Semiconductor Devices

5.7 Other Related Documents


C. Pernicka, “The Value of RGA in Semiconductor Manufacturing” (paper presented at the RGA Task Group, JEDEC/G-12 Meeting, Columbus, OH, Sept. 8, 2003

Moisture Ingress into Nonhermetic Enclosures and Packages - a Quasi-Steady State Model for Diffusion and Attenuation of Ambient Humidity Variations, M. Tencer, Electronic Components and Technology Conference, 1994


Helium, deuterium and neon migration in a common borosilicate glass, J. E. Shelby, Journal of applied physics, vol 45, no 5, May 1974

Diffusive gas losses from silica glass ampoules at elevated temperature, W. Palosz, Journal of Crystal Growth 191 (1998) 897-903


Hermeticity Evaluation of Polymer-Sealed MEMS Packages by Gas Diffusion Analysis

On the applicability of MIL-Spec-based helium fine leak test to packages with sub-micro liter cavity volumes, A. Goswami and B. Han, Microelectronics Reliability, Vol 48 (2008) 1815-1821


6 Terminology

6.1 Abbreviations and Acronyms

6.1.1 DUT — device under test

6.1.2 MEMS — micro electro-mechanical systems

6.1.3 SOI — silicon-on-insulator

6.1.4 LPCVD — low pressure chemical vapor deposition

6.1.5 PECVD — plasma enhanced chemical vapor deposition

6.1.6 TEOS — tetraethyl orthosilicate

8 United States Military Standards, Available through the Naval Publications and Forms Center, 5801 Tabor Avenue, Philadelphia, PA 19120-5099, USA; Telephone: 215.697.3321.
6.1.7 STP — standard temperature and pressure

6.2 Definitions

6.2.1 device under test (DUT) — the device undergoing evaluation

6.2.2 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.

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

6.2.4 hermetic vacuum package — hermetic package sealed with vacuum in the interior of the package.

6.2.5 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.

6.2.6 micro electro-mechanical system (MEMS) — see 4.1.1 (“integration of microelectronics devices or fabrication technology with micrometer-scale mechanical devices to form a system”).

6.2.7 near hermetic package — at least a portion of the package materials is formed of materials having permeability as high as $10^{-8}$ –$10^{-10}$ atm·cc/sec. An example of such a material is liquid crystal polymer (LCP).

6.2.8 outgassing — release of gases absorbed on interior package surfaces and devices 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 millitorrs, much of the load in a vacuum hermetic package may be from outgassing. In addition, outgassing may be due to virtual leaks, or the slow release of gases that have been inadvertently trapped within the enclosure.

6.2.9 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.

6.2.10 seal integrity — a measure of the quality of the package seal. 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 is necessary to determine the seal integrity. The width or thickness of the seal material may also be important to the integrity, based on the permeability of the material and/or the structural strength required for the application.

6.2.11 time zero — the beginning point of the operating life of a packaged device, 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.)

6.2.12 atmosphere — throughout this document one atmosphere is defined as being equal to 1000 millibars (= 100 kPa), often referred to as a technical atmosphere.

6.2.13 permeation — the penetration of a permeate (fluid = gas or liquid) through a solid.

6.2.14 fluid transmission rate — the quantity of fluid passing through a unit area of the specimen per unit time under the test conditions. The fluid transmission rate depends on the barrier properties of the material and the partial pressure difference between the two sides of the specimen. Expressed in units of cm$^2$ (at STP)/ cm$^2$-sec., or moles/ cm$^2$-sec. Acronym FTR may be used.

6.2.15 permeance — a measure of the ability of a solid specimen material to conduct fluid. Also defined as the volume of fluid which, under steady conditions, crosses unit area of the sample in unit time under unit pressure difference and at constant temperature. Permeance depends only on the specimen itself. Symbol Q is used.

6.2.16 material permeability — the tendency of fluids to directly migrate through the walls of the package. Bulk permeability depends on chemical composition and diffusion, as well as solubility and desorbability. For example, diffusion of fluids may be accelerated along grain boundaries. Stainless steel in half-hard condition will have small grain sizes relative to package wall thickness, while in fully annealed condition the grain size may be comparable to package wall thickness. In the latter case material permeability is increased although the chemical composition is unchanged.
6.2.17 *permeability coefficient* — a measure of the capability of a specimen to permit the flow of fluids through its surrounding walls. The product of permeance and the wall thickness. Defined as the volume of fluid passing through a material of unit thickness, per unit area and unit time, under unit partial-pressure difference between the two sides of the specimen. Determined by both the geometrical and material properties of the specimen. Symbol P is used, or P'O; to express the permeability coefficient specifically of oxygen gas, for example.

6.2.18 *partition coefficient or equilibrium constant* — the ratio of gas concentration at the solid-gas interface at the package exterior to the partial pressure of the gas in the surrounding medium. Symbol K is used.

6.2.19 *diffusivity* — the rate at which a dissolved fluid will be transmitted through the specimen material. Strictly defined by Fick’s first and second laws. Symbol D is used.

6.2.20 *solubility* — the relative capability of a fluid being dissolved into a material.

6.2.21 *desorbability* — the relative capability of a fluid to escape from a solid surface and enter the gas or liquid phase.

6.2.22 *relative humidity* — the ratio of the actual vapor pressure to the vapor pressure in the state of equilibrium with the liquid.

6.2.23 *dew point* — the saturation point of water, or the temperature to which a given volume of air must be cooled, at constant barometric pressure, for water vapor to condense into liquid water. When the temperature is equal to the dew point the relative humidity is 100%.

6.2.24 *frost point* — the temperature to which a given volume of air must be cooled, at constant barometric pressure, for water vapor to condense into ice. Since ice has a stronger bonding between neighboring molecules, it is more difficult for water molecules to escape a frozen surface.

7 Permeation

7.1 Permeation of fluids through package materials causes a change in the internal package pressure. As such, package materials must be chosen carefully.

7.2 MEMS building block materials must be qualified for permeability. Materials of commercial interest having specifically defined deposition conditions are addressed: See Appendix C.

7.3 Depending upon the material and deposition method, the film structure may be porous and/or metastable even at room temperature. Sputtered films may contain enough (several atomic %) of the sputtering gas species (usually Argon) to cause significant outgassing later. Plating solutions may include organics or other chemicals that will be included in the plated layers and later evolve into outgassing species. Air species (including moisture) absorbed during fabrication may be desorbed later.

8 Detection and measurement of hermetic package permeability

8.1 Permeation involves three steps. First, a fluid surrounding the material being permeated absorbs into the solid at the solubility limit. Second, the fluid diffuses away from the surface, driven by the concentration gradient towards the interior of the package. Third, the fluid that has diffused to the package interior desorbs. The first two steps are generally rate controlling, with desorption occurring very rapidly by comparison. In equation form:

\[ P = K \times D \]

where

- \( D \) is the diffusivity in \( \text{cm}^2/\text{s} \)
- \( K \) is the solubility in \( \text{cm}^3 \text{ (at STP)} / \text{cm}^3/\text{Pa} \)
- \( P \) is the permeability coefficient in units of \( \text{cm}^3\text{(at STP)}/\text{cm}^2/\text{s}/\text{Pa} \)

The above equation implicitly assumes that 100% of the fluid diffusing through the package walls desorbs. For MEMS packages where the interior surface to volume ratio is very high, it might become important to separately consider desorption. Data is not currently available to support such consideration.
8.2 Diffusivity (D) is defined by Fick’s first and second laws:

\[ J = -D \frac{\partial \phi}{\partial x} ; \quad \frac{\partial \phi}{\partial t} = -D \frac{\partial^2 \phi}{\partial x^2} \]

where \( \phi \) is the concentration in g/cm\(^3\)

8.3 The partition coefficient K, also called equilibrium coefficient, is the ratio of fluid concentration at the solid-fluid interface to the partial pressure of the fluid in the surrounding medium, K = \( \frac{c}{p} \). Solubility follows Henry’s or Sievert’s Law, depending on the fluid species.

8.3.1 Henry’s Law states that the amount of a given fluid dissolved in a given type and volume of solid (liquid) is directly proportional to the partial pressure of that fluid in equilibrium with that solid (liquid):

\[ p = k_H \cdot c = K \cdot c \]

where \( p \) is the fluid partial pressure in Pa
\( k_H \) is the Henry’s constant of the material in Pa/mol
\( c \) is the concentration of the dissolved fluid at the interface in cm\(^3\)/m\(^3\), or in mol/m\(^3\)

8.4 Diffusivity, solubility and desorbability follow Arrhenius relationship with temperature:

\[ D = D_0 e^{\frac{-E_D}{kT}} \]

where \( D_0 \) is a constant in cm\(^2\)/sec
\( E_D \) is an activation energy in eV
\( k \) is Boltzmann’s constant = 8.62 X 10\(^{-5}\) eV/Kelvin
\( T \) is the temperature in Kelvin

Note that \( E_D \) is always a positive value in that equation, i.e. D always increases with T. A phase transition of the permeated material (such as a glass transition temperature \( T_g \)) or the permeating species (such as a fluid critical point) may affect the values of \( D_0 \) and/or \( E_D \).

8.5 The temperature dependence of the solubility coefficient is determined as:

\[ K = K_0 e^{\frac{-E_S}{kT}} \]

where \( K_0 \) is a constant in cm\(^3\) at STP/cm\(^3\) Pa
\( E_S \) is an activation energy in eV

Note that \( E_S \) is usually a negative value in that equation, i.e. K usually decreases with T. A phase transition of the permeated material (such as a glass transition temperature \( T_g \)) or the permeating species (such as a gas critical point) may affect the values of \( K_0 \) and/or \( E_S \).
8.6 Clearly, since $P = K \cdot D$, the temperature dependence of the permeability coefficient can be expressed as:

$$P = P_0 e^{-\frac{E_p}{kT}}$$

where $P_0$ is a constant in cm$^3$ at STP/cm$^2$/sec*Pa

$E_p = E_D + E_S$ is an activation energy in eV

Note that $E_p$ may be a positive or negative value in that equation, i.e. $P$ may increase or decrease with $T$, depending upon the signs and magnitudes of $E_D$, $E_S$, and $E_p$; however, in practice $E_p$ is usually a positive value, i.e. $P$ usually increases with $T$. A phase transition of the permeated material (such as a glass transition temperature $T_g$) or the permeating species (such as a gas critical point) may affect the values of $P_0$ and/or $E_p$. Clearly, these phase transitions should be taken into account when performing hermeticity accelerated stresses.

8.7 Solubility can also be expressed in terms of molecules/cm$^3$ by applying the ideal gas law:

$$K = \frac{c}{p} = \frac{\rho}{nR_0T/V} = \frac{M}{R_0T}$$

where $p$ is the pressure differential in Pa

$\rho$ is the fluid density in g/cm$^3$

$V$ is the volume in cm$^3$

$N$ is the number of moles

$R_0$ is the gas constant, equal to $8.314 \times 10^{15}$ m$^3$ Pa/K@mol

$T$ is the temperature in Kelvin

$M$ is the fluid molar mass in kg/mole

8.8 Permeation of a package can be considered as a mass flow from exterior to interior. This can be considered as analogous to electric current, or charge flow, according to Ohms law:

$$I \left( \frac{\text{coulombs}}{\text{sec}} \right) = \frac{V(\text{volts})}{R(\text{ohms})}$$

8.9 The electrical resistance of a conductor and current can be further defined by the material and geometry properties:

$$R = \rho \left( \frac{L}{A} \right) = \frac{1}{\sigma} \left( \frac{L}{A} \right) \quad I = \sigma V \left( \frac{A}{L} \right)$$

where $\rho$ is the resistivity, a material property with units of ohm-cm

$L$ is the length of the conductor in cm

$A$ is the cross-sectional area in cm$^2$

$\sigma$ is the conductivity, the inverse of resistivity

8.10 Now consider a package having a seal of thickness, $t$, width, $W$, and perimeter length, $l$, (see Figure 1). The cross-sectional area $A_c = t \cdot l$. The mass flow can be defined simply as:

$$I_{\text{gas}} = P_0 \left( \frac{A_c}{W} \right)$$
8.11 Clearly the permeability coefficient \( P \) is analogous to electrical conductivity, and partial pressure \( p \), the driving force for permeation, is analogous to voltage in an electrical circuit.

8.12 Further, the permeation of a package can be easily estimated by considering the various elements of the package as resistive components. Similarly to adding electrical resistors in parallel, the total resistance is determined by adding reciprocals, then taking the inverse.

8.13 Permeation is one component considered in modeling the lifetime of a hermetic package. As the cavity pressure of a hermetic package changes over lifetime, the difference in the partial pressure between the exterior and interior of the package decreases. This can be addressed mathematically. However, for significant reductions in the pressure differential, the package is already compromised. Therefore, for all practical purposes the simpler equations are useful and provide sufficient accuracy in predicting the package lifetime.

8.14 There is a lag time between initial application of differential pressure across the package walls and the time that the diffusing fluid appears in the interior. It is useful (see reference 4.2.4) to define a time constant \( \tau \) such that

\[
\tau = \frac{VL}{AP} + \frac{L^2}{2D} + \tau_G - \tau_O
\]

where

- \( V \) = cavity internal volume
- \( L \) = cavity wall thickness
- \( A \) = cavity wall area (perpendicular to the concentration gradient)
- \( P \) = permeability coefficient for the cavity wall material
- \( D \) = diffusion rate through the cavity wall
- \( \tau_G \) = time constant associated with internal gettering (Note: Considered negligible for this method)
- \( \tau_O \) = time constant associated with internal outgassing (Note: Considered negligible for this method)

For thin or non-absorbing walls the first term dominates. In the case of thick or absorbing walls, the second term of the equation dominates. For typical MEMS packages where the volume, \( V \), is small, the second term will generally dominate. In that case, the time constant is proportional to the square of the wall thickness. It is therefore very advantageous to have thick and/or absorbing walls for a MEMS cavity, since in that case the internal volume or wall area has little effect. See reference 4.2.2 regarding the proper measurement of moisture in small packages.

The effect of gettering (outgassing) is to decrease (increase) the rise of the partial pressure of the relevant fluid in the package interior. Gettering and outgassing are very important considerations in designing hermetic packaging; however, both are beyond the scope of the present document and are not considered for this method.

9 Examples

9.1 Two examples of geometry and material choices are included below. The procedure for calculating whether a package will meet requirements is to:

9.1.1 Determine the materials and geometries to be evaluated.
9.1.2 Calculate the flux of each specific gas of interest at STP conditions.
9.1.3 Calculate the dew point of water at the lowest operating temperature.
9.1.4 Estimate the flux of each specific gas at worst case temperature.
9.1.5 Compare flux and dew points to requirements.
9.1.6 Adjust materials or geometries if requirements are not met and repeat the analysis.

9.2 Example 1: Consider a specific package with a lifetime requirement of 5 years. Assume permeation of oxygen at 25°C through a square polymer seal material. For convenience, assume an oxygen partial pressure differential of \( 2 \times 10^4 \text{ Pa} \) (~0.2 atm).
9.2.1 Procedure: Determine the materials and geometries to be evaluated.

Seal thickness, \( t = 2 \mu m = 2 \times 10^{-4} cm \)
Seal width, \( W = 1 mm = 1 \times 10^{-3} cm \)
Side length, \( S = 4 mm = 4 \times 10^{-1} cm \)
Cavity depth, \( D = 20 \mu m = 2 \times 10^{-3} cm \)
Polymer permeation coefficient, \( P = 2 \times 10^{-10} \text{ cm}^3/(\text{cm}^2\text{s}\text{Pa}) \)

9.2.2 Procedure: Calculate the flux of each specific gas of interest at STP conditions.

Enclosed Volume:

\[
V = S^2D = (4 \times 10^{-1})^2 \times 2 \times 10^{-3}
\]
\[
V = 3.2 \times 10^{-4} \text{ cm}^3
\]

Active Surface Area:

\[
A_c = 4S^t = 4 \times 4 \times 10^{-1} \times 2 \times 10^{-4}
\]
\[
A_c = 3.2 \times 10^{-4} \text{ cm}^2
\]

Fluid Flow:
\[ I_{\text{fluid}} = P \cdot p (A_c / W) = 2 \times 10^{10} \cdot 2 \times 10^4 / (3.2 \times 10^4 / 1 \times 10^4) \]
\[ I_{\text{fluid}} = 1.28 \times 10^8 \text{ cm}^3 \text{ s}^{-1} \]

Fluid Flux (fluid flow per unit area):
\[ J_{\text{fluid}} = I_{\text{fluid}} / A_c = 1.28 \times 10^8 / 3.2 \times 10^4 \]
\[ J_{\text{fluid}} = 4 \times 10^{-5} \text{ cm}^3 / (\text{cm}^2 \text{ s}^{-1}) = 4 \times 10^{-5} \text{ cm} \text{ s}^{-1} \]

By multiplying by the conversion factor given in Appendix A (1 / 22.4L), flux can be expressed in moles / (cm\(^2\) s\(^{-1}\)):
\[ J_{\text{fluid}} = 1.786 \times 10^{-9} \text{ mol} / (\text{cm}^2 \text{ s}^{-1}) \]

By definition 1 mole of oxygen fluid has a mass of 32g, or 3.2 \times 10^{-2} kg. Therefore:
\[ J_{\text{fluid}} = 5.714 \times 10^{-11} \text{ kg} / (\text{cm}^2 \text{ s}^{-1}) \]

9.2.3 Procedure: Estimate the flux of each specific gas at worst case temperature.

Clearly this package design is unable to sufficiently prevent the ingress of oxygen at room temperature over the desired 5 year lifetime. Further assume that the activation energy for permeation is 0.5 eV. Then at 100 °C, the lifetime is reduced by factor 50 relative to room temperature:
\[ e^{0.5/kT_1} / e^{0.5/kT_2} = e^{0.5 \left( \frac{T_1}{T_2} \right)} \approx 50 \]

In practice, the temperature dependence is due to the sum of three activation energies, and permeation might actually decrease with increasing temperature. The designer should rely on published data on specific materials being used.

9.2.4 Procedure: Compare flux and dew points to requirements.

With the package cavity enclosed volume a quick estimate can be made of the time, \( t_{\text{increase}} \), for the partial pressure of oxygen in the cavity to rise to 1% of the ambient partial pressure, assuming density, \( \rho \), of 1.4 kg/m\(^3\) at 25 °C:
\[ t_{\text{increase}} = \frac{\Delta p \cdot V \cdot \rho}{J_{\text{fluid}} \cdot A_c} = 0.01 \cdot 3.2 \times 10^{-4} \cdot 1.4 \times 10^{-6} / 5.714 \times 10^{-11} \cdot 3.2 \times 10^{-4} \]
\[ t_{\text{increase}} = 245 \text{ s} \]

9.3 Example 2: Next consider a conventional, hermetically sealed package having 1 cm\(^3\) volume. The seal thickness is 20 µm, the width is 200 µm. Assume permeation of water at 25 °C through a metal seal material and a 20 year required package lifetime. For convenience, assume a water partial pressure differential of 3.65 \times 10^4 Pa.

9.3.1 Procedure: Determine the materials and geometries to be evaluated.

Seal thickness, \( t = 20 \mu m = 2 \times 10^{-2} \text{ cm} \)
Seal width, \( W = 200 \mu m = 2 \times 10^{-2} \text{ cm} \)
Side length, \( S = 1 \text{ cm} \)
Cavity depth, \( D = 1 \text{ cm} \)
Metal permeation coefficient, \( P = 1 \times 10^{-16} \text{ cm}^3 / \text{cm}^2 \text{ s} \text{ Pa} \)
Relative Humidity, \( \text{RH} = 50\% \)
Temperature, \( T, = 25\degree C \)

9.3.2 Procedure: Calculate the flux of each specific gas of interest at STP conditions.

Active Surface Area:
\[ A_c = 4*S*t = 4*1*2 \times 10^{-3} \]
\[ A_c = 8 \times 10^{-3} \text{ cm}^2 \]

Fluid Flow:
\[ I_{\text{fluid}} = P*p(A_c / W) = 2 \times 10^{-16} \times 3.65 \times 10^{4} (8 \times 10^{-3} / 2 \times 10^{-1}) \]
\[ I_{\text{fluid}} = 1.46 \times 10^{-12} \text{ cm}^3 \text{.s}^{-1} \]

Fluid Flux (fluid flow per unit area):
\[ J_{\text{fluid}} = I_{\text{fluid}} / A_c = 1.46 \times 10^{-12} / 8 \times 10^{-3} \]
\[ J_{\text{fluid}} = 1.825 \times 10^{-10} \text{ cm}^3 / (\text{cm}^2 \cdot \text{s}) \]

By multiplying by the conversion factor given in Appendix A (1 / 22.4L), flux can be expressed in moles / (cm$^2$·s$^{-1}$):
\[ J_{\text{fluid}} = 8.14 \times 10^{15} \text{ mol / (cm}^2 \cdot \text{s}) \]

By definition 1 mole of water fluid has a mass of 18 g, or 1.8×$10^2$ kg. Therefore:
\[ J_{\text{fluid}} = 1.47 \times 10^{-16} \text{ kg / (cm}^2 \cdot \text{s}) \]

9.3.3 Procedure: Calculate the dew point of water at the lowest operating temperature.

An approximation of the dew point can be made using the Magnus-Tetens Equation for partial pressure of water vapor [ref: Bahernbrug]:
\[ T_{dp} = \frac{b \ln(RH) + \gamma(T, a, b)}{a - \ln(RH) - \gamma(T, a, b)} \]
Where $T_{dp}$ is the dew point temperature, RH is relative humidity, a is equal to 17.27, b is equal to 237.7 and $\gamma(T, a, b)$ is given by:
\[ \gamma(T, a, b) = \frac{aT}{b + T} \]
This approximation is valid when $5 \leq T \leq 40^\circ C$ and $10\% \leq RH \leq 80\%$.

\[ a = 17.27 \, , \, b = 237.7 \]
\[ \gamma(T, a, b) = 1.64 \]
\[ T_{dp} = 237.7 * (\ln(0.5) +1.64) / (17.27 - \ln(0.5) - 1.64) \]
\[ T_{dp} = 13.8^\circ C \]

9.3.4 Procedure: Compare flux and dew points to requirements.

With the package cavity enclosed volume a quick estimate can be made of the time, $t_{\text{increase}}$, for the partial pressure of water in the cavity to rise to 5000ppmv of the ambient partial pressure, assuming density, $\rho$, of 1 kg/m$^3$ at 25 °C:
\[ t_{\text{increase}} = \frac{\Delta p * V * \rho}{J_{\text{fluid}} * A_c} = 5 \times 10^{-3} \times 1 \times 10^6 / 1.47 \times 10^{-16} \times 8 \times 10^{-3} \]
\[ t_{\text{increase}} = 4.25 \times 10^9 \text{ s} \approx 135 \text{ years} \]

Evidence supports the conclusion that electrochemical corrosion can initiate once three (3) to eight (8) monolayers of water having accumulated on interior surfaces. A quick estimate can also be made for the time taken for 3 monolayers of water to be present on the surface area of the cavity at 25°C:

Not including the base, the surface area, $A_s$, of the package:
\[ A_s = S^2 + 4*S*D = 1^2 + 4*1*1 \]
\[ A_s = 5 \text{ cm}^2 \]

The diameter of a water molecule is $4.47 \times 10^{-8}$ cm, so 3 monolayers are $1.34 \times 10^{-7}$ cm thick.

Assuming the density of water, $\rho_{\text{H}_2\text{O}}$, to be $3.35 \times 10^{22}$ molecules / cm$^3$, the number of molecules, N, present when 3 monolayers of water is present on the surface of the cavity is:
\[ N = A_s \times \text{thickness} \times \rho_{\text{H}_2\text{O}} = 5 \times 1.34 \times 10^{-7} \times 3.35 \times 10^{22} \]
By definition 1 mole = 6.02214×10^{23} molecules. Therefore:

\[ J_{\text{fluid}} = 4.9 \times 10^9 \text{ molecules} / (\text{cm}^2 \cdot \text{s}) \]

\[ t_{\text{increase}} = \Delta \text{molecules} / J_{\text{fluid}} \cdot A_c = \frac{2.24 \times 10^{16}}{4.9 \times 10^9 \cdot 8 \times 10^{-3}} \text{s} = 5.71 \times 10^8 \text{ s} \approx 18 \text{ years} \]

The vast difference in the calculated lifetime when the limits of 5000 ppmv and 3 monolayers of water present in the cavity are applied show the importance of recognizing the true moisture ingress limit of the package concerned.

10 Measurement of permeability of MEMS technical materials

10.1 Measurement of the permeability coefficient requires that a significant area of thin film be exposed to a pressure differential of the test fluid for a set time period, with the thin film held at a well controlled temperature. All fluid that permeates that thin film must be collected and its volume and composition measured, for example, by a mass spectrometer to determine the mass flow rate in kg/sec.

10.2 One recommended test structure is a silicon chip. The material to be studied may be deposited on top of the silicon chip as a thin film. Using photolithography masking, a cavity can then be etched by either wet or dry anisotropic etching to create a stand-alone membrane consisting of the material to be studied. This silicon chip may then be packaged such that a test gas sensor can be applied to one side of the membrane. The other side of the membrane can be connected to a mass spectrometer, for example, to quantify the amount of gas passing through the membrane as a function of time.

11 Comments on quality and reliability assurance

11.1 Design verification may involve extensive testing on a few units with the goal of measuring key parameters and validating key design assumptions. Both permeation and outgassing in hermetic packages occur continuously over operating life and may not be testable at time zero. Therefore, performance for these attributes is typically guaranteed by design. (Note: For this test method we are considering outgassing (gettering) to be negligible in order to calculate the permeability of a package or seal material.) For example, the permeation of a package is governed by the material type and thickness of the package walls. Typically, permeability coefficients are assumed during the design phase and the design is completed. Verification of overall package permeation is required on initial production units and may not be required for future production. Design verification often involves a series of non-destructive followed by destructive tests.

11.2 Design surveillance may be required depending on the characteristics of the specific package materials. For example, polysilicon is the material comprising the sidewalls of many MEMS hermetic packages. The permeability coefficient of polysilicon may vary depending on the deposition conditions and the thermal history of the films, which may also vary between production lots. Therefore, some form of ongoing surveillance may be required to monitor possible changes in the permeability coefficient of the polysilicon films. Design surveillance may also involve a series of non-destructive followed by destructive tests.

11.3 Batch qualification is a useful method for screening a batch of production devices. The intention of batch qualification is to avoid incurring significant costs in further assembly and testing of units that are members of a batch of material having a common flaw. Batch qualification testing is typically not visible to the user and is seldom standardized. However, batch qualification may become more important for reliability of devices for industrial, commercial and consumer applications, or when applying new technology such as wafer-scale polysilicon sealing of MEMS devices.

11.4 Individual unit testing is often unavoidable and may be required at each of the first and second package levels. The industry norm for hermetic packages is to perform Gross and Fine leak testing on 100% of individual units. Statistically based sampling plans may be applied for devices with less critical reliability requirements in order to reduce manufacturing costs. It is typically assumed that permeation and outgassing over life are guaranteed by design and cannot be verified by individual unit testing.

11.5 Integrated sensors are useful for individual unit testing. In some cases data may be extracted immediately following wafer fabrication and/or at final test. In any case such data may be collected following surface mount.
12 Design considerations relating to materials permeability

12.1 Specifically for MEMS packages having very small enclosed volumes, a reasonable practice is to assume that zero permeation is allowable. Efforts must be concentrated on reducing effects from leaks and outgassing, and materials and geometry selections should be made to absolutely minimize permeation.

12.2 Permeability is a temperature dependent material property. The rate of permeation of a hermetic package depends on the temperature, geometries, the material properties, and the partial pressure difference between the outside and the inside of the package. In addition, it should be kept in mind that for many applications the permeation of water is of primary concern, and the permeation rate is often concentration dependent. For all-metal enclosures the effect of permeation is generally much less than the effect of leaks. There is less cumulative experience with non-metal enclosures and some caution should be exercised in considering permeation.

12.3 Individual unit testing can be applied to measure hermeticity at or near time zero. Individual unit testing of hermeticity over operating life is not practical (except perhaps when integrated sensors are applied). A combination of design verification, design surveillance and batch testing can be applied to make statistically based predictions on hermeticity over operating life.

12.4 The maximum permissible permeation is determined by the package internal volume, the required operating life of the package, and the maximum permissible moisture level inside the package. According to military standards (supported by literature), the maximum permissible moisture level is taken as a partial pressure of 5000 ppmv at 100°C (See 4.1.2, 4.2.9, 4.2.10, 4.2.11, 4.2.12). It has been shown that this level is a good approximation of the point at which an adsorbed surface layer of water is capable of sustaining current flow for dendritic growth or corrosion. Specifically for a cubic package with internal volume of 1.0 cc, this corresponds to a total of three monolayers of surface moisture. The small enclosed volumes of MEMS packaging further increases the already large ratio of internal surface area-to-volume typical of microelectronics packages. And, in the case of a micromotor, where surfaces are in rubbing contact during operating life, it has been demonstrated that the moisture level must be kept above a minimum to avoid premature wearout (See 4.2.13). In addition, the maximum permissible leak rate depends on the average ambient moisture level in the operating environment. For this reason the maximum permissible leak rate to be tested is often determined experimentally for a given product or by negotiation between the user and the manufacturer.

12.5 Many MEMS technologies rely on geometries and materials that are ideally suited for hermeticity. At the same time, enclosed volumes are so small as to challenge existing hermeticity test methods (See 4.2.13, 4.2.14, 4.2.16). As new sensor and actuator device types are developed, new packaging materials and techniques are essential to allow interaction with the external environment while protecting the device circuitry from contaminants. For these reasons, individual unit testing of hermeticity is likely to be more problematic for MEMS as opposed to conventional microelectronics packages. For example, an enclosed volume created by direct silicon fusion bonding is ideal in the sense that:

- Silicon, a very low permeability coefficient, ultra-high purity material, is the only “package” material involved.
- Fusion bond annealing involves temperatures of 1000°C or higher, sufficient to cause reaction to completion of water, oxygen or organic materials remaining in the enclosed volume. In addition, any free hydrogen generated by chemical reactions will rapidly diffuse from the package at high temperatures.

However, typical MEMS cavity volumes are so low that conventional leak detection techniques are not capable of measuring the ultra low leak rates, which can adversely affect some MEMS device types.

12.6 Another concrete example is a volume encapsulated by a polysilicon shell. Again, the processes and materials are ideally suited for hermeticity, yet the enclosed volumes are very small.

12.7 For type A MEMS, devices requiring a high level of vacuum for operation, it is important to recognize that helium readily permeates silicon dioxide (SiO₂). For this reason, when a SiO₂ interface vacuum seal is used in conjunction with lateral electrical feed-throughs, the package interior pressure cannot be less than about 5.0 X 10⁻³ mBar (natural abundance of helium in air). In addition, usage of helium for leak testing is problematic when a SiO₂ vacuum seal exists. In such case, neon gas can be considered as an alternative, as the permeation rate of neon through SiO₂ is small in comparison to helium.
12.7.1 Note that for small pressure rise, the internal pressure is almost linear with time. For small leaks, the value of 
\( (1 - \exp(x)) \) is well approximated as \( x \) when \( x \) is small. Although the leak rate depends exponentially on the pressure 
differential, for the range used in the example a linear assumption is valid.

13 Vacuum lifetime modeling

13.1 Given the complexity and number of control parameters to ensure high levels of hermeticity over operating life, 
use of predictive models is essential to achieving consistent results.

13.2 Input parameters for a vacuum lifetime model may include:
- Cavity internal volume
- Cavity internal surface
- Permeated walls thickness
- Phase transitions for the permeated materials and permeating species
- Pressure sensitivity
- Getter capacity and pre-saturation
- Partial gas pressures in air
- Backfill pressure and gas type
- Molecular fluid flow
- Working and storage temperature and pressure
- Time

13.3 A vacuum lifetime model can be applied to determine bombing pressure and times, gettering requirements, and 
effectiveness of various methods of evaluating hermeticity. For example, see 4.2.15, Chapter 42 by W. Reinert and 
D. Kahler.

13.4 Calculation of the dew point for water can be made with inputs of ambient temperature and either the partial 
pressure of water in ppmv or the relative humidity. The Arden-Buck equation, valid over the range of -80 to +50 °C, 
is:

\[
13.5 \quad p_w = 6.1121 \exp \left[ \frac{18.678 - T / 243.5}{257.14 + T} \right] 
\]

where \( p_w \) = the saturation vapor pressure of water in millibar

\( T \) = the ambient temperature in degrees C

\( \exp \) = the exponential function

The saturation vapor pressure \( p_w \) and relative humidity are interrelated:

\[
RH = \frac{p_{H_2O}}{p_w} \cdot 100; \quad p_w = \frac{p_{H_2O}}{RH} \cdot 100
\]

where \( RH \) is the relative humidity, expressed as a percent

\( p_{H_2O} \) = the partial pressure of water in the ambient in millibar
APPENDIX 1
UNITS CONVERSION

NOTICE: The material in this Appendix is an official part of SEMI [designation number] and was approved by full letter ballot procedures on [A&R approval date].

A1-1 Units Conversion

A1-1.1 Coefficient P is defined in units of volume of fluid permeating a film of a given thickness per given area in a given period of time, with a specific pressure differential (amount of fluid)/(film thickness) per (film area)/(time)/(partial pressure gradient).

<table>
<thead>
<tr>
<th>Convert from</th>
<th>Convert to</th>
<th>Multiply by</th>
</tr>
</thead>
<tbody>
<tr>
<td>cm$^3$ (at STP)/cm$^2$/s/Pa</td>
<td>cm$^3$ (at STP)/cm$^2$/s-atm</td>
<td>1.01325E+5</td>
</tr>
<tr>
<td>cm$^3$ (at STP)/cm$^2$/s/Pa</td>
<td>cm$^3$ (at STP)/cm$^2$/s-torr</td>
<td>1.33323E+2</td>
</tr>
<tr>
<td>cm$^3$ (at STP)/cm$^2$/s/Pa</td>
<td>cm$^3$ (at STP)/cm$^2$/s-mm Hg</td>
<td>1.33323E+2</td>
</tr>
<tr>
<td>cm$^3$ (at STP)/cm$^2$/s/Pa</td>
<td>in$^3$ (at STP)/in$^2$/s-psi</td>
<td>1.0687E+3</td>
</tr>
<tr>
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<td>in$^3$ (at STP)/in$^2$/s-atm</td>
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<tr>
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<td>in$^3$ (at STP)/in$^2$/s-torr</td>
<td>2.06649E+1</td>
</tr>
<tr>
<td>cm$^3$ (at STP)/cm$^2$/s/Pa</td>
<td>in$^3$ (at STP)/in$^2$/s-mm Hg</td>
<td>2.06649E+1</td>
</tr>
<tr>
<td>in$^3$ (at STP)/in$^2$/s-psi</td>
<td>in$^3$ (at STP)/in$^2$/s-atm</td>
<td>1.46959E+1</td>
</tr>
<tr>
<td>in$^3$ (at STP)/in$^2$/s-psi</td>
<td>in$^3$ (at STP)/in$^2$/s-torr</td>
<td>1.93367E+2</td>
</tr>
<tr>
<td>in$^3$ (at STP)/in$^2$/s-psi</td>
<td>in$^3$ (at STP)/in$^2$/s-mm Hg</td>
<td>1.93367E+2</td>
</tr>
</tbody>
</table>

e.g. 1 cm$^3$*cm$^2$/s*Pa = 1.01325E+5 cm$^3$*cm$^2$/s*atm

A1-1.2 However, for purpose of predicting lifetime of a hermetic package it may be useful to work with units of mass flow. This enables ready combination of the three sources of degradation of the integrity of a hermetically sealed package, namely leaks, outgassing, and permeation. For this purpose, units of the gas permeability coefficient may be converted by the user from volume to moles.

<table>
<thead>
<tr>
<th>Convert from</th>
<th>Convert to</th>
<th>Multiply by</th>
</tr>
</thead>
<tbody>
<tr>
<td>cm$^3$ (at STP)/cm$^2$/s/Pa</td>
<td>mole/cm$^2$/s/Pa</td>
<td>4.46148E-5</td>
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<tr>
<td>cm$^3$ (at STP)/cm$^2$/s/Pa</td>
<td>mole/cm$^2$/s-torr</td>
<td>5.94817E-3</td>
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<td>mole/cm$^2$/s-atm</td>
<td>4.52061</td>
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<td>mole/in$^2$/s-psi</td>
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<td>mole/in$^2$/s-atm</td>
<td>1.14824E+1</td>
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<td>cm$^3$ (at STP)/cm$^2$/s/Pa</td>
<td>mole/in$^2$/s-torr</td>
<td>1.51083E+2</td>
</tr>
<tr>
<td>in$^3$ (at STP)/in$^2$/s-psi</td>
<td>mole/in$^2$/s-psi</td>
<td>7.31110E-4</td>
</tr>
</tbody>
</table>
According to Graham’s law, the square root of the ratio of gas molecular weights will give a good approximation of the permeation rate of one gas, knowing the permeation rate of the other through the same material. Graham’s law is applicable when Knudsen’s flow is the dominant gas transport mechanism. Knudsen flow, in turn, applies when the mean free path of the molecule being transported is large in comparison to the pore along which the fluid is flowing.

Graham’s law is not applicable when any other gas transport mechanism is dominant such as surface diffusion, bulk diffusion or molecular sieving. In such cases, the rate of permeation of gases through packaging materials depends 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.

For reference, the molecular weights of several common gases are included below. To convert to gram mass of a particular gas type, find the desired unit in moles from the table above and multiply by the molecular weight.

<table>
<thead>
<tr>
<th>Gas type</th>
<th>Molecular weight (g/mol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water vapor</td>
<td>18.0</td>
</tr>
<tr>
<td>Air</td>
<td>29.0</td>
</tr>
<tr>
<td>Oxygen</td>
<td>32.0</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>28.0</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>2.0</td>
</tr>
<tr>
<td>Helium</td>
<td>4.0</td>
</tr>
</tbody>
</table>

e.g. 1 mole/cm²*s*Pa (water vapor) = 18 g*cm / cm²*s*Pa (water vapor)

The table presented here is therefore solely intended for unit conversion. This table should not to be used to infer a permeation rate of a gas based on the measurement made using another gas.

Special caution is advised in converting from inert gas such as Helium to permeation by water or other polar molecules. Approximating permeability of water, for example, using data on permeability of helium, may give completely erroneous results. The solubility of helium is complicated. While the small atom may easily penetrate to the package interior, a good deal of helium may remain trapped on the interior walls.

i.e. 1 mole/cm²*s*Pa (helium) ≠ 18 g*cm / cm²*s*Pa (water vapor)
APPENDIX 2
WATER CONTENT OF AIR

Water content vs. dewpoint temperature for 1 atm and 0.5 atm

Notes:
1) The saturated water vapor pressure $p_w$ is the volume of water per $10^6$ volumes of dry air. Calculation is based on Buck Research Manual (1996) as:

$$p_w = 6.1121 \exp \left[ \frac{(18.678 - T / 243.5) * T}{257.14 + T} \right]$$

2) Relative humidity RH is defined as:

$$RH = \frac{P_{H_2O}}{P_w} * 100$$

where $P_{H_2O}$ is the vapor pressure of water in the ambient.
### APPENDIX 3

#### TABLE OF MATERIAL PROPERTIES

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>TYPE</th>
<th>GROWTH METHODS</th>
<th>MAIN APPLICATIONS</th>
<th>CONCERNS</th>
</tr>
</thead>
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<td><strong>Metals / Metalloids</strong></td>
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<td></td>
<td></td>
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</tr>
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<td>1. Si</td>
<td>Silicon</td>
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<td>X</td>
<td>X</td>
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<td>2. Al</td>
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</tr>
<tr>
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<td>X</td>
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<tr>
<td>5. Cr</td>
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<td>7. Ni</td>
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</tr>
<tr>
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<tr>
<td>9. Cu</td>
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<tr>
<td>14. Au</td>
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</tr>
<tr>
<td>15. Sn</td>
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<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>28. Sb</td>
<td>Antimony</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

### Notes

1. **PERMEABILITY INDEX**
   - 1: Very Low
   - 2: Low
   - 3: Medium
   - 4: High
   - 5: Very High
   - Note: These indices are for perfect non-porous materials; actual values are usually higher.

2. **OUTGASSING INDEX**
   - 1: Very Low
   - 2: Low
   - 3: Medium
   - 4: High
   - 5: Very High
   - Note: These indices are for perfect non-porous materials; actual values are usually higher.

3. **CVD / LPCVD vs. PECVD**
   - RECOVA films tend to include more gases and have lower purity than their LPCVD counterparts.
   - However, they can be deposited at lower temperature.

4. **PVD / SPUTTER vs. EVAPORATION**
   - Sputtered films tend to include gas sputtering species - usually Argon - associated with evaporated films.
   - Alloys and compounds are easier to deposit with good stoichiometric control by sputtering than by evaporative deposition.
   - Good film adhesion is more difficult to achieve by sputtering than by evaporation.

5. **PLATING**
   - Electroplated films tend to include impurities from the plating solution.
   - Stress, grain size, porosity, roughness, etc. are process dependent and may change over time even at room temperature.

6. **SPIN CASTING**
   - Spin-coated films tend to include residual solvents and be porous when insufficiently cured and dried.

7. **GENERALITIES**
   - Permeability & outgassing are mitigated by optimizing design, material properties and fabrication process.
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