

Hermetic Packaging for Highly Space-Constrained Applications

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Abstract

Hermetic packaging is required for many electronic components, such as crystals, MEMS inertial sensors and resonators, lithium ion batteries, relays, and various types of chemical sensors. In addition, integrated circuits and multichip modules, which are used in critical military applications, require hermetic packaging to insure stable, reliable operation over many years in a wide range of environmental conditions. Traditionally, devices are hermetically packaged in co-fired ceramic chip carriers with braze attached covers, or machined Kovar boxes with glass sealed feed-throughs. The volume of devices packaged with these technologies typically exceeds that of the functional components, by a factor of three or four.

We have been successful in hermetically packaging small, low I/O components by using an electroformed can that is soldered to a metallized film of liquid crystal polymer. Cans with volumes as small as five cubic millimeters, and with walls 50 micron thick, have been fabricated in pure copper, copper with a finish of gold over nickel, and pure gold metals. The cans are manufactured in an array format, with as many as 36 cans per sheet, to facilitate batch assembly and sealing processes. The liquid crystal polymer covers are also fabricated in an array format, which aligns with that of the cans. The film is metallized on both sides and patterned in such a way as to minimize the area of exposed polymer, while maximizing the distance that gases must diffuse through the polymer to enter the package. Both solder paste and performs have been used to tin the covers before sealing. Reflow is accomplished by aligning the covers and cans, and clamping in place with a glass plate and then rapidly heating the assembly with a flash lamp.

Calculations predict leakage rates in these packages that are comparable to those of conventional hermetic packages. These calculations have been validated using standard gross and fine leak tests as well as aging tests on packages containing lithium metal. We believe that this technology can be adapted to larger devices with higher I/O, such as hybrid circuits and multichip modules.

Key Words: Hermetic Packaging, LCP,

Package Description

The first application of this technology was to repackage a foil pouch, lithium ion battery, into a smaller, more robust form factor. A schematic representation of the battery assembly appears in Figure 1.

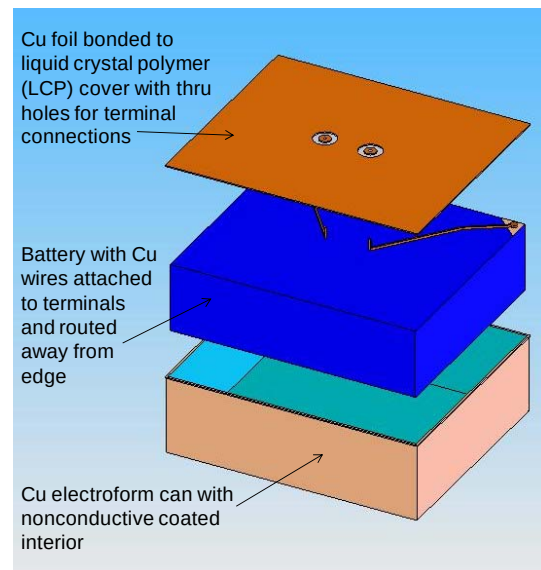


Figure 1. Schematic representation of battery packaged using electroformed can and metallized liquid crystal polymer (LCP) cover.

The five sided, copper can, with 50 micron thick walls was produced by a commercial supplier of electroformed parts. The can has a 50 micron wide flange around its open top to facilitate solder attachment of the cover. The copper can is finished with a gold over nickel flash to minimize any corrosion caused by the battery chemistry. A picture of this can appears in Figure 2.

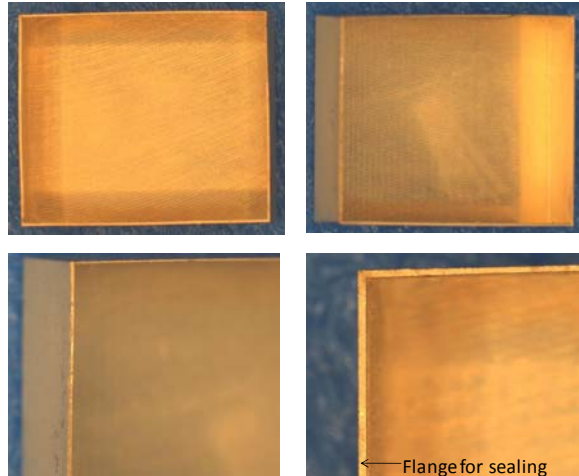


Figure 2. Electroformed copper can with gold over nickel finish

The cover is a sheet of liquid crystal polymer (LCP) that is metallized on both sides with copper that has a gold over nickel flash finish. The contact pads of the two electrodes are each patterned as two different size disks on the top and bottom sides of the LCP film so as to maximize the diffusion path for moisture ingress. A picture of the cover appears in Figure 3.

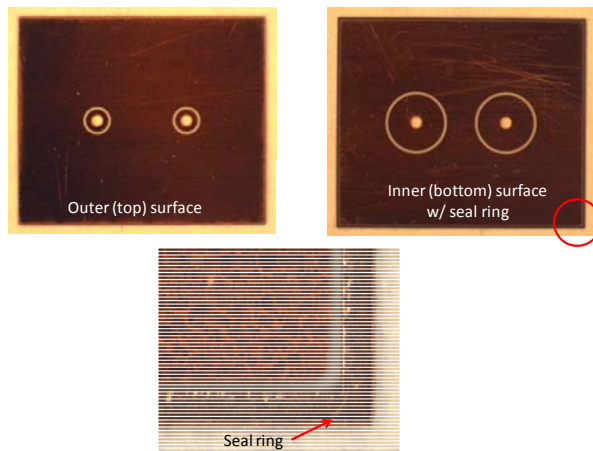


Figure 3. Copper metallized liquid crystal polymer (LCP) cover.

The cover was reflow soldered to the box by coating the seal ring of the cover with solder paste, reflowing it and cleaning. The pre-soldered cover and can were

placed in an alignment fixture and the cover pressed against the can by a glass plate. The solder seal was made by exposing the assembly beneath a high intensity lamp, which heated the cover and reflowed the solder to the can flange. Optical and x-ray images of the sealed can appear in Figure 4.

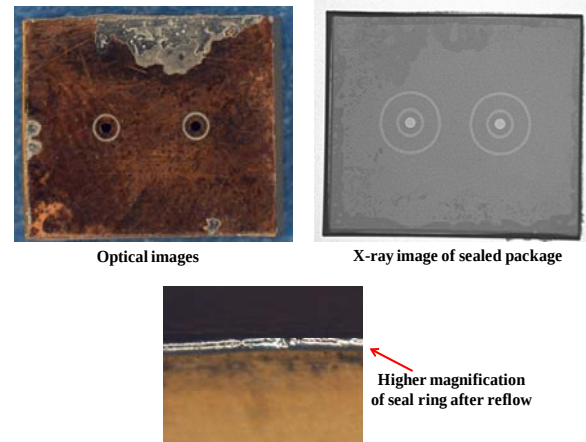


Figure 4. Optical and X-Ray images of a sealed cover and can assembly

We have successfully demonstrated this simple type of hermetic package for a two terminal device. In the remainder of this paper, we demonstrate how this concept can be extended to higher I/O devices.

Description of High I/O Device Structure

The metallization pattern for the outside layer of the ball grid array, BGA, package is shown in Figure 5. It consists of large squares, with truncated corners, that are arranged along the square grid of the I/O pattern. The other I/O, at the corners of the large squares, are covered by smaller squares. The metallization pattern on the first inside layer is identical to that of the outside layer, but it is shifted by one I/O pitch length, P . The next metal layer pattern is identical to and aligned with the outside layer. The outside layer of metallization is covered by a mask layer, which defines the location of the solder balls, as shown in Figure 6. A cross section view of these three metallization layers is presented in Figure 7. As shown in this figure, the metallization layers are separated by a dielectric layer of thickness, t . All three metal layers are connected by an array of solid vias, which are centered on the square I/O grid.

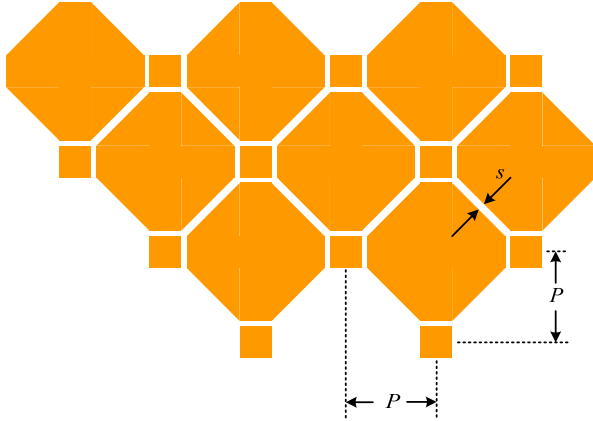


Figure 5. Bottom metallization pattern of a BGA which has I/O on a square grid, of pitch P . The spacing between metal pads is s .

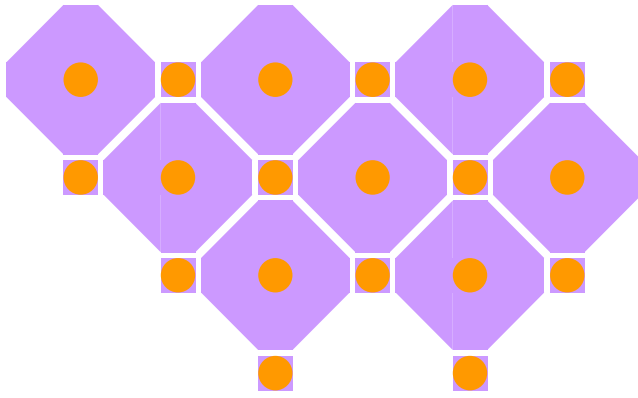


Figure 6. Bottom metallization with solder mask to define solder ball attachment areas.

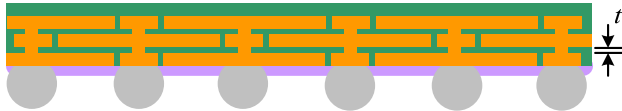


Figure 7. Cross section view of the BGA assembly.

Diffusion Model

To facilitate an analytical calculation of the flux of gas and moisture through this structure, a cylindrical coordinate system is used, with circular metal pads centered on the z axis. A conservative estimate is obtained by inscribing a circle within the large pad and circumscribing a circle around the small pad, as illustrated in Figure 8. The orientation of the cylindrical coordinate system is shown in Figure 8. Its origin is located at the interface between the bottom metal and dielectric layers. The path of the

diffusion flux through the structure is also depicted in Figure 8. This flux moves down the concentration gradient, which is governed by the differential equation

$$\frac{\partial^2 C}{\partial R^2} + \frac{1}{r} \frac{\partial C}{\partial r} + \frac{\partial^2 C}{\partial z^2} = 0. \quad [1]$$

Some further simplifying assumptions for boundary conditions are needed to make the calculation of the diffusion flux amenable to analytical solution.

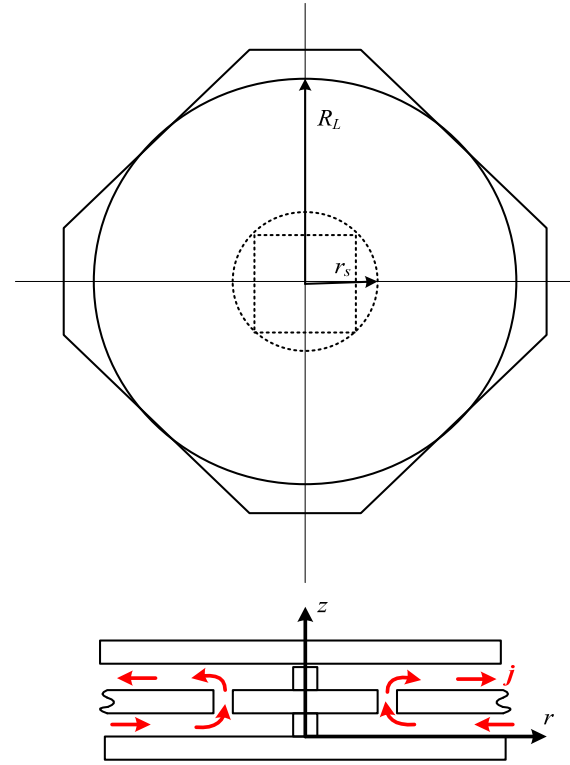


Figure 8. Construction used in the calculation of diffusion flux into package.

On the circumferences of the large and small pads, the concentration has uniform constant values, which are distinct at each of the three pads. In the dielectric between pads, the flux only has a radial component, so equation [1] simplifies to

$$\frac{\partial^2 C}{\partial R^2} + \frac{1}{r} \frac{\partial C}{\partial r} = 0, \quad [2]$$

The boundary conditions on the concentration in the dielectric between the lower and middle pads are

$$\text{at } r = R_L; \quad C = C_0, \quad [3]$$

$$\text{at } r = r_s; \quad C = C_1. \quad [4]$$

The solution to equation [2], which also satisfies boundary conditions [3] and [4] is

$$C = C_0 + (C_1 - C_0) \frac{\ln(r/R_L)}{\ln(r_s/R_L)}. \quad [5]$$

By Fick's first law, the corresponding flux in this dielectric layer is

$$j_1 = -D \frac{\partial C}{\partial r} = D \frac{(C_0 - C_1)}{\ln(r_s/R_L)} \frac{1}{r}, \quad [6]$$

where D is the diffusivity of moisture and gas through the dielectric material. The boundary conditions on the dielectric between the upper and middle metal layers are

$$\text{at } r = R_L; \quad C = C_2, \quad [7]$$

$$\text{at } r = r_s; \quad C = C_1. \quad [8]$$

The solution to equation [2] which also satisfies boundary conditions [7] and [8] is

$$C = C_2 + (C_1 - C_2) \frac{\ln(r/R_L)}{\ln(r_s/R_L)}. \quad [9]$$

The corresponding flux driven by this concentration gradient is

$$j_2 = -D \frac{\partial C}{\partial r} = D \frac{(C_2 - C_1)}{\ln(r_s/R_L)} \frac{1}{r}. \quad [10]$$

Under steady state conditions, $j_1 = -j_2$, so combining equations [6] and [10] yields

$$C_1 = \frac{C_0 + C_2}{2}. \quad [11]$$

Substitution of this result into equation [6] evaluated at $r = R_L$, and multiplied by the cross sectional area of dielectric surrounding the large pad, Area = $2\pi R_L t$, yields an expression for the leakage, Q_1 , through one I/O connection

$$Q_1 = 2\pi R_L t j_1 = \pi t D \frac{(C_0 - C_2)}{\ln(r_s/R_L)}. \quad [12]$$

Referring to Figure (1), the radius of the large pad can be written in terms of the I/O pitch, P , and spacing, s , between metal pads,

$$R_L = \frac{1}{2}(\sqrt{2}P - s). \quad [13]$$

Substitution of this result into equation [12] allows the leakage rate to be expressed in terms of the I/O pitch

$$Q_1 = \pi t D \frac{(C_0 - C_2)}{\ln[2r_s/(\sqrt{2}P - s)]}. \quad [14]$$

The concentration, C_0 , of moisture at the surface of the dielectric is the product of the relative humidity, the equilibrium vapor pressure of water at the ambient temperature, and the solubility of moisture in the dielectric

$$C_0 = \frac{\%RH}{100} \times p(T) \times \text{Solubility}. \quad [15]$$

The saturation vapor pressure $p(T)$ is computed using the set of empirical equations given in the IAPWS Industrial Formulation for the Thermodynamic Properties of Water and Steam [1]. These formulae are reproduced in Appendix A.

Package Leak Rate

For a square package of edge length, L , with n_{row} , I/O per row, the pitch, P , is given by

$$P = L/n_{row} \quad [16]$$

which allows a space of $P/2$ between the corner I/O and the edge of the package, as shown in Figure 9. The corresponding leakage rate of the package, Q_{pack} , is

$$Q_{pack} = n_{row}^2 \times Q_1 = n_{row}^2 \pi t D \frac{(C_0 - C_2)}{\ln[2r_s/(\sqrt{2}(L/n_{row}) - s)]}. \quad [17]$$

The physical properties of a candidate dielectric material, liquid crystal polymer manufactured by Quantum Leap, are listed in Table 1¹. This is comparable to properties listed for Vectran™ LCP².

Table 1. Quantum Leap LCP Test Data

Quantity	Value	Units
Test Humidity	100	% RH
Test Temperature	37	°C
Sample Thickness	0.0508	mm
WVTR	0.095	gm m ⁻² day ⁻¹
Permeability	1.03 × 10⁻⁵	gm cm m ⁻² day ⁻¹ mmHg ⁻¹
Diffusivity	4.97 × 10⁻¹⁰	cm ² sec ⁻¹
Solubility	2.39 × 10⁻⁵	gm cm ⁻³ mmHg ⁻¹

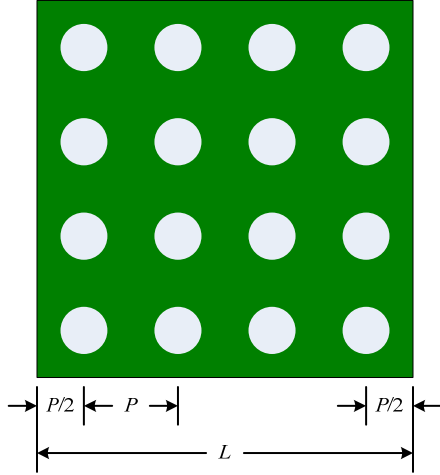


Figure 9. I/O pattern on a square circuit board of edge length L .

The property values listed in Table 1 were used to evaluate equations [14], [15] and [17] at a temperature of 37°C, 98% relative humidity to obtain plots of Q_{pack} versus number of I/O, for a package size of $L = 1$ centimeter, and a metal spacing of $s = 0.025$ millimeters. Curves for two different dielectric thicknesses, $t = 10$ and $t = 25$ microns, are shown in Figure (6).

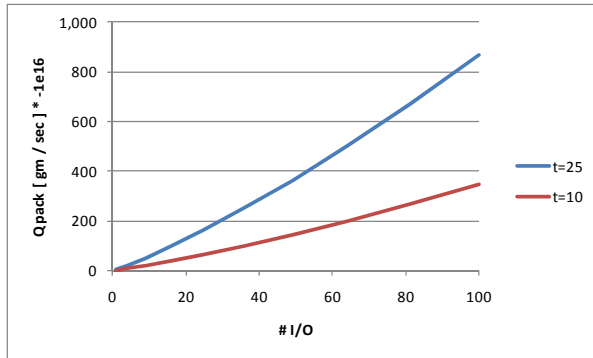


Figure 10. Moisture ingress rates calculated for dielectric thicknesses of 10 and 25 microns.

Package Life

A standard applied to hermetically packaged microelectronic devices is that water vapor within the package cannot exceed 5000 ppm³. Using the moisture ingress rate given by equation [17], the time required to attain this threshold is computed as follows. With reference to Figure 11, the internal free volume, V_F , of the package is given by

$$V_F = hL^2 - ed^2. \quad [18]$$

Substitution of this volume into the perfect gas law equation yields the number of gas molecules, N_F , in the package

$$N_F = \mathcal{A} \frac{PV_F}{RT}, \quad [19]$$

Where $\mathcal{A}$ is Avogadro's number, R is the gas constant, and P and T are the absolute pressure and temperature, respectively.

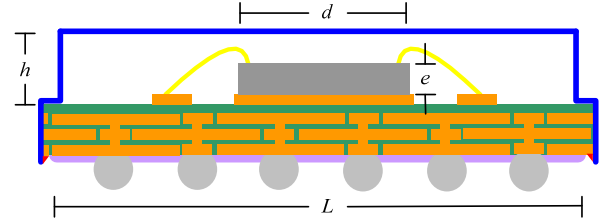


Figure 11. Cross section of a package showing feature lengths used in free volume calculation.

The leak rate given by equation [17] is in units of grams per second. This rate is converted to molecules per second by dividing Q_{pack} by the molecular weight of water and multiplying by Avogadro's number to yield

$$\dot{N} = \frac{Q_{pack} \mathcal{A}}{18} = n_{row}^2 \pi t D \frac{\mathcal{A}(C_0 - C_2)}{18 \ln[2r_s/(\sqrt{2}(L/n_{row}) - s)]}. \quad [20]$$

The time, τ_{Fail} for the moisture level to attain the 5000 ppm limit is given by

$$\tau_{Fail} = \frac{N}{\dot{N} \times 5000 \times 10^{-6}}. \quad [21]$$

The time predicted by equation [21] for moisture ingress to attain a 5000 ppm level within a package is plotted in Figures 12 and 13, as a function of the number of I/O on a 20 millimeter square package. In each figure, three curves are plotted that represent dielectric thicknesses of 5, 10, and 20 microns, as labeled in the figure legends. The plots in Figures 12 and 13 correspond to packages with internal cavity heights of two and four millimeters, respectively.

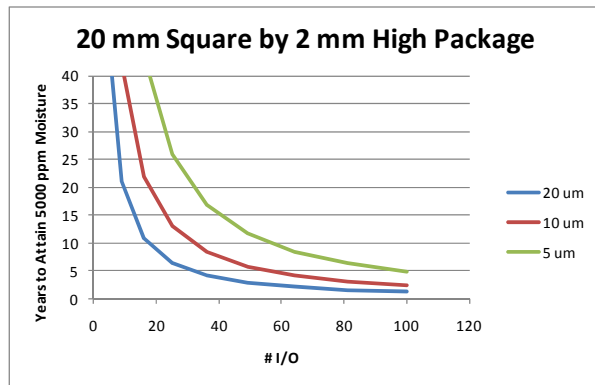


Figure 12. Predicted hermetic lifetime as a function of number of I/O and dielectric thickness, for a 20 millimeter square package with an internal volume of 800 cubic millimeters

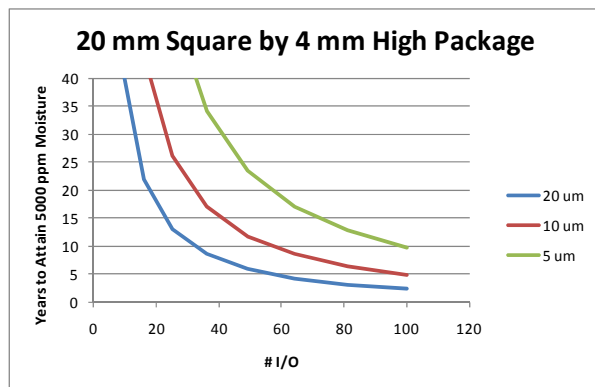


Figure 13. Predicted hermetic lifetime as a function of number of I/O and dielectric thickness, for a 20 millimeter square package with an internal volume of 1600 cubic millimeters.

An important point to be made regarding these results is that they are based on package substrates with just two dielectric layers. The predicted lifetimes could easily be doubled or tripled by increasing the number of dielectric layers to four or six, respectively.

Discussion

This Metal Can On Laminate (MCOL) packaging technology offers a number of advantages over conventional hermetic packages. Figure 14 presents cross section sketches of an MCOL package along with those of a metal can on a low temperature cofired ceramic substrate, ceramic chip carrier, and all metal can packages. The MCOL package is smaller and lighter than these other packages.

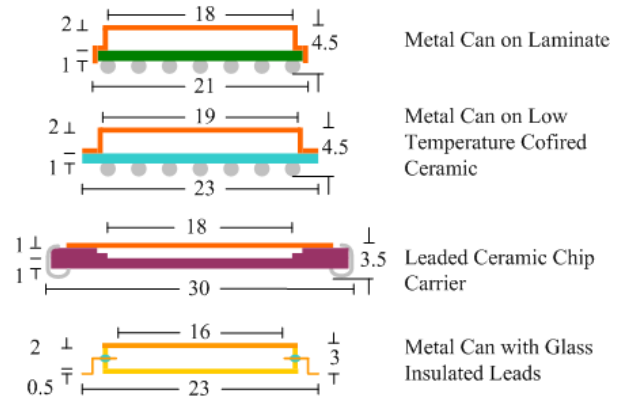


Figure 14. Comparison of MCOL package with comparable size metal and ceramic hermetic packages.

The substrate that comprises the bottom of an MCOL package is fabricated using the same materials and processes that are used to produce chip on flex carriers for plastic over molded packages. Consequently, different package configurations can be produced more quickly and with smaller investments in tooling than required by other hermetic packaging technologies. Copper or nickel metal cans are easily fabricated in small quantities by electroforming. Alternatively, metal stamping could be used to produce cans at much lower cost when the investment in tooling is justified by the production volume.

Finally, the thermal expansion coefficient of an MCOL package matches that of the printed circuit board on which it is mounted. This allows an MCOL package to be configured as a ball grid array package, while ceramic packages require leads or solder posts to accommodate thermal induced strains.

Summary

1. Metal Can on Laminate, MCOL, technology has been used to hermetically package low I/O devices.
2. This technology offers size, weight and cost advantages compared to more conventional hermetic packages.
3. Straightforward calculations indicate that MCOL technology can be extended to larger devices such as hybrid circuits and multichip modules, which require higher a number of I/O.
4. Unlike leadless ceramic packages, MCOL packages can be directly attached to printed circuit boards using ball grid array formats.

Acknowledgement

The genesis of the idea for using a polymer sandwiched between two metal films to hermetically seal a metal can is in our collaboration with Professor Yet-Ming Chiang at Massachusetts Institute of Technology. Funding for that effort was provided by DARPA under the Micropower Sources Program.

References

- (1) www.QLPkg.com, Data obtained during private conversation with Quantum Leap Representative.
- (2) www.Ticona.com/products/Vectra , Physical properties of Vectran™ LCP.
- (3) MIL-STD-883, Method 1018
- (4) International Association for the Properties of Water and Steam, p32, Equations for Region 4.

Appendix A⁴

Saturation Pressure Equation

The saturation pressure, p_s , normalized by a standard pressure of 1 mega-Pascal, p^* , is given by

$$\frac{p_s}{p^*} = \left[\frac{2C}{-B + (B^2 - 4AC)^{\frac{1}{2}}} \right]^4 \quad [A1]$$

$$A = \varphi^2 + n_1\varphi + n_2 \quad [A2]$$

$$B = n_3\varphi^2 + n_4\varphi + n_5 \quad [A3]$$

$$C = n_6\varphi^2 + n_7\varphi + n_8 \quad [A4]$$

$$\varphi = \frac{T_s}{T^*} + \frac{n_9}{(T_s/T^*) - n_{10}} \quad [A5]$$

Where T_s and T^* are the saturation temperature and a reference temperature of 1°K. The constants n_1 through n_{10} have the following values

$$n_1 = 0.116\,705\,214\,527\,67 \times 10^4$$

$$n_2 = -0.724\,213\,167\,032\,06 \times 10^6$$

$$n_3 = -0.170\,738\,469\,400\,92 \times 10^2$$

$$n_4 = 0.120\,208\,247\,024\,70 \times 10^5$$

$$n_5 = -0.323\,255\,503\,223\,33 \times 10^7$$

$$n_6 = 0.149\,151\,086\,135\,30 \times 10^2$$

$$n_7 = -0.482\,326\,573\,615\,91 \times 10^4$$

$$n_8 = 0.405\,113\,405\,420\,57 \times 10^6$$

$$n_9 = -0.238\,555\,575\,678\,49$$

$$n_{10} = 0.650\,175\,348\,447\,98 \times 10^3.$$

The saturation pressure, in units of millimeters of mercury, is obtained by multiplying p^* by 7500.615. Thus, equation [A1] becomes

$$p_s = 7500.615 \times \left[\frac{2C}{-B + (B^2 - 4AC)^{\frac{1}{2}}} \right]^4 \quad [A6]$$