Plastic Hermetic Packages for MEMS?

Ken Gilleo, PhD, Cookson Electronics, Foxboro, MA
Gerald Pham-Van-Diep, PhD, Cookson Equipment Group, Franklin, MA

Abstract

The sealed hermetic package is over 100 years old if we include cathode ray and vacuum tubes. While the package has changed, the idea of making a near-perfect gas-tight enclosure has remained constant. The metal and ceramic full hermetic package may be required for applications that cannot use the non-hermetic plastic package, but is there an intermediate package choice? During the last few years, the electronic packaging industry has sought to develop the Near-Hermetic Package (NHP), a design that is "good enough" and "cheap enough" to satisfy some special devices like MEMS.

This paper will describe work with Liquid Crystal Polymer (LCP) injection-molded enclosures that are targeting MEMS and some optical device applications. The work involves sealing lids and chip carriers with laser energy. The package design creates a cavity type enclosure that can provide the "free space" necessary for mechanical motion found in some MEMS devices. We will also briefly describe getters (contaminant scavengers) and fluorinated parylene coatings also useful for MEMS. But the work has had a surprising result. The plastic package has repeatedly passed hermeticity; helium leak test.

Author contact: K Gilleo, e-mail: gilleo@ieee.org.

1.0 Introduction

The full hermetic package for electronics and optoelectronic (OE) devices was first developed in the 1800's and has served these industries well. The earliest optoelectronic devices, cathode ray tubes (CRT) demonstrated in the late 1800's, used a sealed glass vacuum enclosure. The Braun Tube, for example, was a scanning CRT display system that used a glass envelope to seal out the atmosphere and maintain the required vacuum. Later, electronic vacuum tubes were developed, starting with the Fleming diode that also used a glass envelope. A few years later, De Forest introduced the triode (Audion) that was able to amplify, making it the first active electronic device. Many of the early OE and electronic devices required a vacuum to operate because the flow of electrons through free space was part of the mechanism. Today, only a small number of products require an actual vacuum. Yet, the century-old tradition of the full-hermetic sealed enclosure has continued for many products.

2.0 Reactions Inside of Packaging

The device package serves perhaps a dozen functions, but two are critical. The package must provide the interconnection between the device and circuit board, and also protect components from the environment. But protection does not necessarily require that the entire environment be shut out. Device protection is mostly about chemistry and reactions. The package should prevent, or at least retard, chemical reactions inside the package. Chemistry occurring inside an electronic or OE package is generally bad for the device and connections. Ambient atmospheric gasses and contaminants can damage ordinary electronic devices, not just MEMS. Standard electronic components are made less sensitive to the environment by design, materials, and passivation that provide sufficient reliability even with non-hermetic packages. But MEMS devices are difficult to passivate since they can have moving elements. Coating MEMS devices with passivation materials could change the characteristics of sensors or even prevent motion of parts. Optoelectronics devices are also challenging since they are typically constructed from compound semiconductors that are more reactive and sensitive to a broader range of contaminants. OE systems for telecom may have a 20-year life assurance requirement making it difficult to evaluate new packaging concepts. Optical devices could also be degraded or altered by passivation that changes any of the optical properties especially the refractive index. The *de facto* packaging strategy for MEMS, MOEMS and OE products has therefore been the use of full hermetic package designs. But is the traditional hermetic package really essential here, or costly overkill?

3.0 The Traditional Hermetic Package?

One of the most critical issues facing special devices like MEMS is packaging. While conventional electronic packaging and assembly have undergone a steady evolution to deliver low cost and high-level automation, hermetic systems have not really changed that much. Glass has given way to ceramic and metal, but cost has actually increased. Certainly, the full hermetic package provides assured reliability, but it delivers it with hefty penalties. In addition to cost, there is a relatively low degree of standardization and many non-SMT styles preclude automated assembly. While the plastic electronic package accounts for only 4% to 5% of total component cost, the percentage is much higher for hermetic packages and is often the largest single cost element. We need to determine if this package class is the right one for MEMS.

The question takes us back to the chemistry of the MEMS and MOEMS devices. Can any atmospheric gases be tolerated? If the answer is "yes", or "it is not know", then we must look at alternative packaging since this could have as great a positive impact on these specialty devices as its had for standard electronics. We tend to overlook how important the role of packaging has been on affordable electronics. We take molded plastic packages and automated Surface Mount Technology (SMT) for granted, but they are essential to the electronics industry. Let's explore plastic packaging since it is the most efficiently produced making it the most cost-effective.

4.0 Selecting a Packaging Material

Our choice is plastics because simple and highly automated processing provides unbeatable value. Although engineering plastics can cost more per kilogram than metal, the plastic package can be orders of magnitude cheaper. The cost for the process is more critical than cost of materials. Plastic parts can be molded by the dozens or even hundreds during each rapid molding cycle using multi-cavity molds – and all automatically. The next selection choice is the plastic; thermoset or thermoplastic? Although the workhorse plastic for packaging is thermoset epoxy, thermoplastics can be a better choice here. First, a few of the many thousands of thermoplastics have the best barrier properties of any polymers. At least one plastic has about 10 times better barrier properties than epoxy packaging materials. In fact, the best polymers approach the barrier properties of glass. But thermoplastics can be remelting and this provides several key benefits. Thermoplastic resin can be molded into a precise shape including a cap or a cavity that would be needed for the devices that need free-space for movement (MEMS) or a window/port for light transmission for MOEMS and optoelectronics (OE). There is another important attribute that accrues from the remelt property and that is sealability. Thermoplastic packaging can be selectively heated to their melting point to permit a lid, glass window, or fiber to be sealed. Finally, the thermoplastic can be recycled so there is no production waste from runners as is the case with thermoset transfer molding.

What thermoplastic is optimum? The first criterion must be high thermal stability. The melting point should be well above the processing temperature of solder, including lead-free types. We have set the lower limit at about 300^{o}C. The next criterion was high gas barrier, especially moisture. Other desirable properties are low outgassing, low dielectric constant, platability, no halogen, and reasonable economics. Once again, cost per unit weight is less significant if manufacturing is efficient. Plastics have a density of about 1 compared to metals that are about an order of magnitude higher. This means that a kilogram of plastic resin can make about 10 times as many parts as metal. This also means that plastic packaging is lighter. We concluded, as have several others, that the liquid crystal polymer (LCP) class best met all criteria although polyphenyl sulfone is another possibility. The flexible circuit industry has started to adopt LCP laminates for many of the same reasons although low moisture absorption is important rather than moisture barrier, but the two properties tend to go together. Experience in LCP circuitry can be applied to packaging in the future. Table 1 shows properties of LCP films as reported by suppliers while Table 2 gives moisture barrier properties from Auburn University.

PROPERTY	PI 1	PI 2	LCP	Test
Tensile strength (kpsi)	50	42	15	D882, 64T
Elongation %	60	40	15	D882, 64T
Young's Modulus (kpsi)	800	825	700	D882, 64T
Tear strength (gm)	26.2	17.5	15.4	D1922-00A
Heat Shrinkage % @ 200_oC	.08	0.04	0.04	D2732
CTE (ppm/deg.C)	13	14	18	D696, 44
Moisture absorption %	2.4	2.0	0.1	D570, 63
CHE (ppm/%RH)	9	8	2	D570
Moisture Trans. Rate gm/sq/ cm/day	4.2	3.8	0.4	F1249
Dielectric Constant	3.3	3.1	3.0	D150
Dissipation factor	.005	.005	.003	D149

Tested on 2 mil commercial film – data from 3M Co. (typical)

Table 1 – LCP Film Data

Sample ID	WVTR (g/m² -day)	Permeability (g*mil/m²/day)	Diffusivity (cm²/sec)	Solubility (g/cc)
2L (2 mil)	0.1177	0.2354	2.589 x 10e-9	0.000268
2H (2 mil)	0.1373	0.2746	2.838 x 10e-9	0.000284
4L (4mil)	0.0678	0.2712	9.830 x 10e-10	0.000811

Test Conditions

- Conditions: 100% rh @ (55.3 mmHg)
- Carrier Gas: 100% Nitrogen, ambient pressure
- Temperature: 40°C

Auburn University

Table 2 – LCP Moisture Barrier Properties

4.1 Molding LCP Resins

LCP is a popular choice for OE connectors and many precision parts that require high dimensional stability. Resins are commercially available with high melting rangers; 280°C to 330°C. One of the most important attributes for high dimensional stability is low moisture absorption. This is because materials, including plastics, usually expand upon absorbing moisture; coefficient of hygroscopic expansion. Specialty molders therefore use, and have experience with, mold design and processing of LCP. This plastic can be molded into caps suitable for testing and Foster-Miller, Inc. (Waltham, MA), under DARPA contract, has been active here. RJR Polymers (Oakland, CA) also produces plastic cavity type packages. The cap or body can be made into an enclosure that can be hermetically tested by bonding a "lid", a piece of glass in the initial work.

4.2 Sealing Processes

A variety of energy sources can be used to bring an LCP package, or sealing ring, to the melting point of around 300^{o}C. These can be convection, direct, and radiant heating, as well as mechanical methods that generate heat at the bond site, like ultrasonic bonding. We ruled out mass heating methods, like convection, since the molded part would soften and deform if everything were to be heated. Localized heating was the right choice and it will also prevent damage to MEMS or OE chips that can be thermally sensitive. The alternate process has been to use thermoset glue for lid bonding, but this is slower, requires adhesive application, and probably results in a poorer gas barrier.

Under a DARPA contract, Foster Miller, Inc. directed us to investigate laser heating while they explored ultrasonic methods. Initial testing showed that Near-Infrared (NIR) was a suitable energy source for sealing LCP to glass. Both IR and NIR readily travel through glass without appreciable loss. However, LCP does not absorb and convert IR/NIR to heat. We needed an energy absorber. LCP becomes a strong IR/NIR absorber when a small amount (>1% by weight) of carbon black is added. Carbon black is commonly used as an LCP filler and resin is commercially available that is compounded with carbon. IR/NIR dyes are available, but offer no obvious advantage over low-cost and very inert carbon.

4.3 Equipment

We used a prototype diode laser-soldering machine from Electrovert (Cookson) designated as the DLS (Diode Laser Soldering). Although the 30-watt laser with output at 802 nm wavelength was designed for selective soldering, it worked well for plastic sealing. Figure 1 shows the machine system and the laser head. The laser energy is produced by a diode bar containing multiple laser sources in a strip. Optics consolidates the “line of light” into a spot that is transmitted along a glass fiber to the head above. The head has optics that allows the circular beam to be focused and also to be observed with a camera. Motion is provided using a programmable X-Y table.

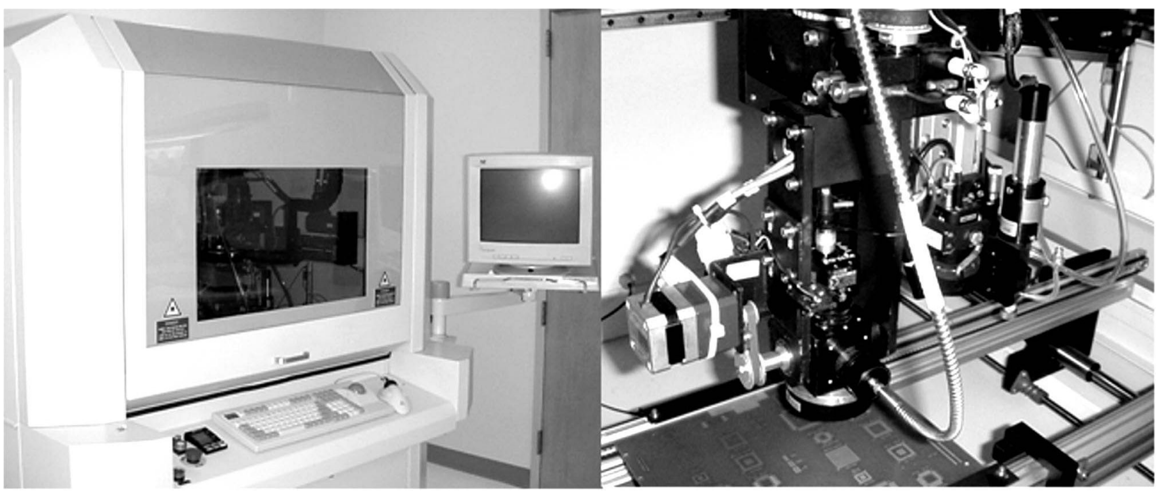

Figure 1 - Laser Equipment

5.0 Experiments

Experiments done with Foster Miller, Inc., under their DARPA contract, began with LCP film but the company did not supply material with carbon. Later, molded caps with carbon black were provided to us for laser testing. No significant heating occurred unless carbon filler was used in the LCP. However, dark ceramic substrate could be bonded to unfilled LCP by sending the laser beam through the film and heating the ceramic. Carbon can be added directly by dissolving, or swelling, the surface of the LCP film with hexafluorobenzene, but this not considered more than a laboratory process at best. The laser beam was directed through glass placed on top of the molded LCP cap, and onto the plastic surface. LCP surface melting occurred at 5 watts although 15 to 30 watts gave the most satisfactory results. The X-Y table was programmed so that the laser spot traveled along the perimeter of the cap so that a sealed enclosure was produced. The process appears to be robust giving a good seal unless energy is too low to melt the LCP, or so high that decomposition occurs (>450^{o}C). Excessive heating was quickly noted since the plastic darkened and produced gas bubbles. The resulting bubbles generated voids that were detected as leaks. Force must be applied to the lid for good sealing. The DSL does not have the ability to apply force and glass weights were used initially. Later, a laser optical bench with force application was set up at Cookson Electronics Equipment Group R&D in Franklin, MA. The equipment can rapid scan the beam in a pre-programmed pattern.

Bond strength tests gave values of about 100 PSI. Glass breakage and fracturing, leaving particles attached to the plastic, were the most common failure modes. The bond to glass was excellent and this may be due to a low polymer melt viscosity at the processing temperature of 400^{o}C to 425^{o}C as indicated by thermocouples. Samples of LCP caps with sealed glass lids were tested for hermeticity using the well-accepted helium leak method. Helium gas was introduced into a hole created in the plastic cap and the He detector measured leaking gas. The standard for hermeticity is a value $< 1 \times 10^{-8}$ cc/@ 1 atm. He. The team had hoped to achieve a value that approached these criteria but expected it to be much poorer. In fact, the project was first named NHP (Near-Hermetic Package). We were surprised when the independent test lab reported that the package simulator passed full hermeticity. Values for "good" samples were in the 10^{-9} range, the limit of the equipment. The "known bad" samples gave the expected poor results and served as a control. Those run at low power showed opens, but those sealed with excessive power, and visible degradation, ranged around 10^{-5}.

5.1 Moisture Barrier

We recognize that the leak test is intended to measure seals rather than material properties and that it can only be a first approximation with plastics. The next phase of testing will measure moisture barrier that is expected to be good based on the intrinsic properties of LCP shown in the tables. The first stage involves placing activated desiccant inside the package, exposure to high humidity, and then measuring weight change. We hope to also place a humidity-detecting die inside the package.

6.0 Design Concepts

The test vehicle was only designed to measure intrinsic characteristics of LCP and seals. There were no I/O paths. The laser-sealing concept can be applied to bonding glass lids to LCP housings for MOEMS, and perhaps certain OE products. An all-plastic BGA can also be envisioned where the laser is used to seal an LCP chip carrier platform to an LCP molded cap. The laser beam could pass through the unfilled platform but generate sealing heat upon striking the carbon-filled cap. Wafer-level processes are also possible although chip I/Os would need to be routed to the back to produce a CSP or Flip Chip. However, several vertical rerouting processes have appeared in the literature. A wafer-level packaging (WLP) process is certainly feasible. We are now working with a partner who has produced plastic "butterfly packages with up to 52 I/Os so the potential exists for "live" chip tests in the near future.

6.1 Plated LCP

We considered that a metal coating over the LCP caps might be necessary in the future and provided samples to Enthone (Cookson) for testing. First, a metal coating adds an additional barrier if we needed a higher barrier than the LCP could offer. But the metal coating can also be used as an RF shield that could be required for RF-MEMS packaging. Enthone developed an electroless/electrolytic nickel-plating process as well as copper plating. The Ni coated had strong adhesion and could even be soldered without loss of adhesion. Enthone provided us with LCP caps with nickel and gold-over nickel and Figure 2 shows plated parts. No attempt was made to selectively plate the caps, but methods exist if this becomes desirable to provide a bare plastic edge for laser sealing. Alternately, a fully metallized cap could be sealed to a lid with solder to provide a high-level full hermetic package.

Figure 2 – Plated LCP Caps – Enthone (Polyclad)

6.2 Getters

We considered options for boosting plastic package performance if it became necessary. Since we did not expect to achieve such high He leak rate values, we worked on parallel approaches to improving the package interior. Getters were an obvious consideration. They are chemical scavengers that extract contaminants from the inside atmosphere of the package. In the case of MEMS with moving parts that can wear, particulate can be generated that will interfere with movement. Particle getters, sticky polymers with low outgassing, can be used and are available. Moisture getters, such as Staydry, are also commercially available that could be useful. The high moisture barrier of LCP suggests that a moisture getter may not be required for typical applications. However, an OE requirement of 5 to 20 years could benefit from a moisture getter. We will use moisture getters to measure barrier properties by noting weight gain as discussed in section 5.1.

6.3 Parylene, friction and stiction

Friction is something that all mechanical products must deal with and MEMS is no exception. But traditional lubricants are not a practical solution. But there is another surface effect problem that is somewhat unique to micromechanical devices called *stiction*. The tiny MEMS elements, once they make contact with one another, are held together by surface tension and atomic-level forces. Flat, smooth surfaces that come in contact become stuck together. This becomes a terminal problem when there is no mechanism to break the attraction. A commercial accelerometer can be tested, calibrated and shipped. During transportation and installation, the device can experience enough G-force to make the combs or beams stick together. The stuck sensors are now immobilized and the product is useless. The most obvious solution is to apply a low surface energy coating.

Parylene conformal coating technology, originally developed by Union Carbide, has been in commercial use for more than 25 years. Parylene (poly-para-xylylene) is a high temperature polymer film applied to substrates in a vacuum chamber by means of a gas phase polymerization that provides unusual electrical and environmental performance. This class of polymer has been used for decades on a variety of applications especially those involving the protection of electronic devices and circuitry. CVD is used to form an insulating thermoplastic coating with a high degree of chemical inertness, absence of pinholes and perfect conformity to the topography of the surface applied. Coefficients of friction range from 0.25 to 0.33 so that the lubricity is close to that of Teflon.

A new fluorinated parylene, Nova HT, shares the unique properties of the other parylenes but offers properties that should be ideal for anti-stiction. The film is deposited in a molecule-by-molecule polymer process, with no cure-related stress that can occur with liquid polymers. There is no liquid phase, no hydraulic forces, and the coating conforms to substrate features rather than pooling or bridging in the manner of conventional liquid coatings. Free molecular dispersion of the monomer results in the development of an overlying film on all exposed surfaces, with equal thickness on inside and outside corners, flat surfaces, and in crevices. Parylene can effectively penetrate inside surfaces through small openings.

The new **Nova HT** has a crystalline melting point above 500°C, which is at least 250°C higher than the recommended continuous exposure level for the conventional parylenes. Nova HT could be used for applications that require exposure to lasers and high intensity lamps such as MOEMS with its improved UV resistance. It is particularly resistant to yellowing and physical degradation under such conditions. Two MEMS manufacturers are testing Nova HT.

7.0 Conclusion

Preliminary testing on simulators and actual packages indicates that plastic may provide a good level of hermeticity. If this is borne out in more extensive testing, then plastic packaging could be suitable for MEMS and MOEMS devices. The very long-term lifetime requirements for telecom optoelectronics do not allow us to extrapolate our conclusion to this class. The helium leak test, while generally accepted for metal and ceramic packages, may not be suitable for plastic. Plastic packaging of real devices, followed by extensive testing appears warranted on the basis of the preliminary data.

Acknowledgements

Foster-Miller, Inc. (Waltham, MA) provided LCP samples for laser testing.

P. Chouta (Cookson Electronics) ran laser sealing and mechanical tests.

G. Pham-Van-Diep (Cookson Electronics Equipment Group) ran design of experiment tests and had the He leak tests run.

Brian Griffith, Enthone/Polyclad/Cookson Electronics (West Haven, CT) plated LCP caps.

Marc Apel, of Electrovert (Cookson Electronics Equipment Group), provided the DLS equipment.

Matrix Corp. (E. Providence, RI) produced the LCP caps.