Advanced Packaging Using Liquid Crystalline Polymer (LCP) Substrates

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Abstract

Liquid crystalline polymer (LCP) substrates offer a number of advantages for high-density packaging. These properties include high temperature capability (>250^{o}C), low coefficient of thermal expansion (8ppm/^{o}C), low moisture permeability (comparable to glass), smooth surface, and good high frequency characteristics. LCP substrates can be fabricated as flexible films (2mil thick) or as rigid multilayer substrates.

In this paper the processing of rigid and flexible LCP substrates are first discussed including etching, drilling, and plating. Next, the compatibility of LCP substrates with wire bond and flip chip assembly processes and materials are examined. Specific tests include solderability with eutectic Sn/Pb and lead-free alloys, surface insulation resistance with no-clean fluxes, gold wire bondability and flow/wetting of underfills for flip chip assembly. The high temperature capability of the LCP is compatible with the higher reflow temperatures associated with lead–free solders and also allows thermosonic gold wire bonding at a substrate temperature of 200^{o}C. Solder dips in lead free alloys at 274^{o}C have shown no delamination of the copper foil. Gold ball shear test results demonstrate average shear strength of 62.4 grams with a standard deviation of 4.3 grams when bonded at 200^{o}C.

Optical fibers can be molded into the LCP substrate for optical connections and optical fibers can also be molded into the package sidewall for optical connections. Finally, hermetic packages have been fabricated and shown to pass fine and gross leak tests.

Key Words: Liquid Crystalline Polymer, Printed Wiring Boards, Packages

LCP Properties and Applications

LCPs are so called because their molecules can be mutually aligned and organized (crystal), yet the bulk LCP can flow (liquid) in the molten state. This behavior is unlike ordinary polymers, which are randomly configured in the melt or in solution. The liquid crystal state results from the rigid nature of segments of the LCP molecules (Figure 1). When LCP flows in the liquid crystal state, the rigid segments of the molecules align next to one another in the shear flow direction, creating locally oriented domains. The domains, in turn, create macroscopic-oriented regions. Once the oriented regions are formed, their direction and structure persist, even when the LCP approaches the melt temperature because of the long relaxation time of the stiff chain LCP molecules.

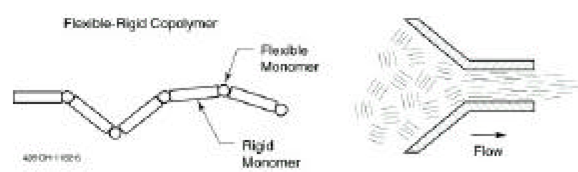


Figure 1 - Liquid Crystal Polymers have Rigid Segments, which tend to Align in Shear Flow

Although thermotropic LCPs possess a variety of properties that make them attractive candidates for electronic substrates, standard LCP processing techniques result in films with anisotropic in-plane properties. For example, extruded uniaxial LCP film has machine direction mechanical properties that are about one order of magnitude higher than those in the transverse direction. By having highly anisotropic tear and impact behavior, traditional processing of LCPs has not resulted in a product suitable for electronic packaging applications.

Foster-Miller developed a proprietary processing technology that permits control of the fibrillar LCP orientation to any desired value, including quasi-isotropic, simply by varying the processing parameters (1). By utilizing a novel annular die, sheet and films can be produced with controlled directions of orientation. A combination of rotational shear and elongational flow during the extrusion process orients the LCP molecules. This controlled biaxial orientation, which is compared with uniaxially oriented films in Figure 2, is accomplished with an innovative counter-rotating die that aligns the LCP molecules along two distinct axes within a single ply.

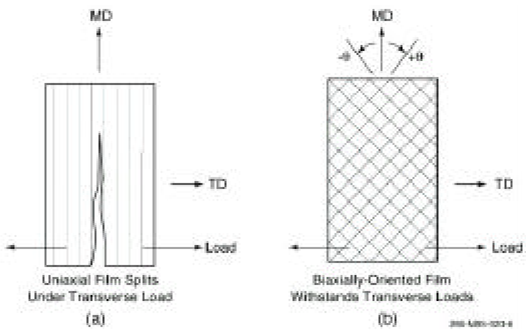


Figure 2 – Comparison of Uniaxially abnd Biaxally Oriented LCP Film

Figure 3 shows how biaxial orientation is achieved with a counter-rotating circular die, which takes advantage of LCP's propensity to self-align in shear flow by using transverse shear to produce transverse orientation. A combination of processing parameters, including rotation rate, blow-up ratio and draw rate, can be used to control the film orientation rate and, subsequently, critical film properties such as CTE, tensile strength and tensile modulus.

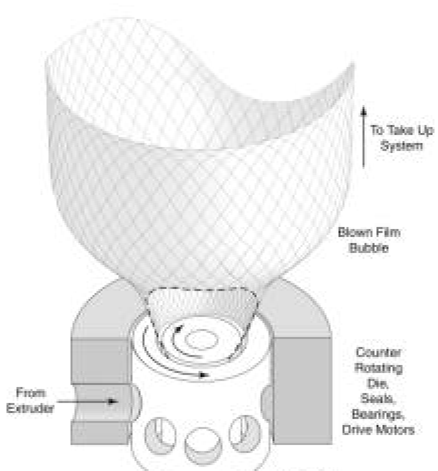


Figure 3 - Biaxial Orientation is Achieved Using the Counter Rotating Circular Die

LCPs have a unique combination of properties that make them ideally suited for high density electronic substrate and packaging applications, including [2-6]:

- Excellent electrical properties even up to millimeter wave frequencies (dielectric constant, 2.9; loss tangent, 0.002 at 20 GHz).
- Extraordinary barrier properties, comparable to that of glass; LCPs are virtually impermeable to moisture, oxygen and other gases and liquids.
- Low coefficient of thermal expansion (CTE) 8 or 17 ppm/°C.
- Very low moisture absorption, <0.04% by weight.
- Excellent dimensional stability (< 0.1%).

PCB Processing

Image and Etch

In a subtractive circuit patterning process, the key requirements of the base laminate are to enable adequate adhesion of the photoresist and not absorb process chemicals. Once the circuit pattern has been defined via the resist, the actual circuit is defined by etching the exposed copper away, using chemistries like Cupric Chloride. The key requirements of the base laminate are to have good adhesion between the copper and polymer, good resistance to etching chemistry, and a copper foil compatible with etching. When using industry standard practices, such as a 1.5mil aqueous dry film photoresist and a Cupric Chloride etchant at 125°C, lines as small as 1.5mils with copper foil as thick as 18μm have been demonstrated. Mound Flextek Inc. was able to demonstrate this in a continuous, roll-to-roll process. The key to LCP's success is its inherent chemical/moisture resistance, preventing any undercutting at the polymer/copper interface (see Figures 4 and 5) as well as the specific copper foil selected.

Figure 4 – Cross-Section LCP Circuit Traces (Courtesy of Mound Flextek)

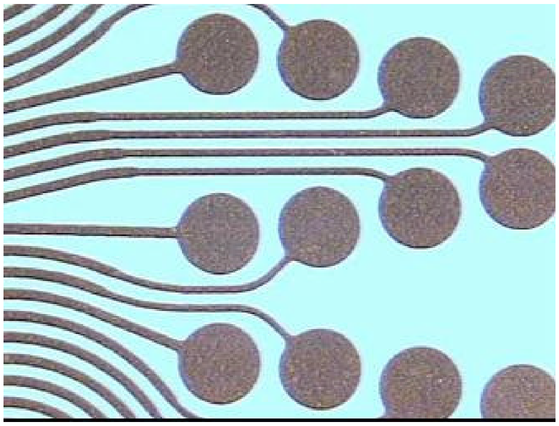


Figure 5 – LCP Circuitry – Traces and Pads (Courtesy of Mound Flextek)

Mechanical Drilling

For hole sizes 8 mils or greater, the standard industry practice is to use mechanical drilling techniques. It is important that a set of optimal drill conditions must be determined for any new material system. A study was performed, varying rotational speed (200-500 SFM), infeed rate (2-8 mils/in), and retraction rate (300-700 IPM) using a single drill size (20mils). Figures 6 – 8 show that infeed rate is the most critical factor for hole wall quality with retract rate second, and drill rotational speed having almost no effect.

It is clear that lower infeed rate (sometimes referred to as chip load) combined with high retract rates, produced the best hole quality.

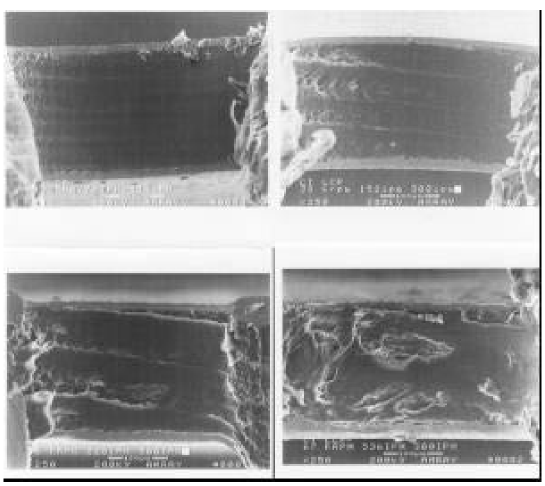


Figure 6 – Drilled Hole Wall vs. Infeed Rate (slowest is shown in upper left)

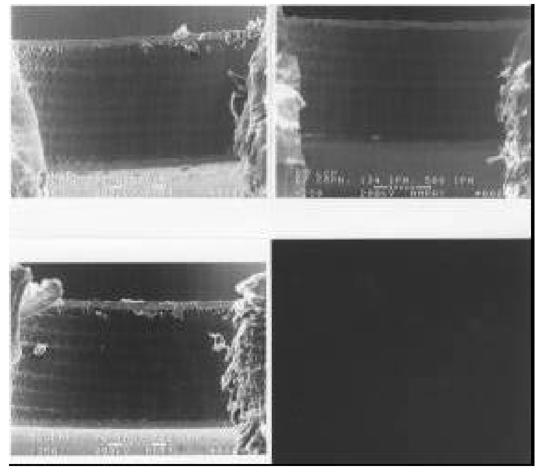


Figure 7 – Drilled Hole Wall vs. Retraction Rate (slowest in shown in upper left)

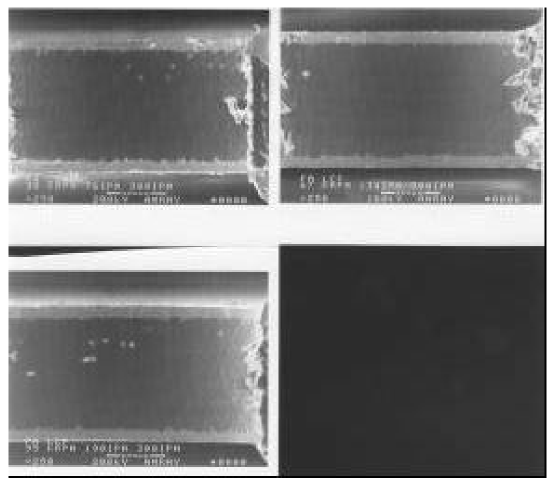


Figure 8 – Drilled Hole Wall vs. Rotational Speed (slowest is shown in upper left)

Laser Drilling

Lasers are typically used for holes and vias less than 8 mils in diameter. The most common lasers used for PCB hole making are CO_2 or YAG. A study was performed comparing LCP to an all-polyimide, FR-4, and epoxy resin-coated-copper (RCC) product. For the YAG (355nm) experimentation, a single set of laser conditions was used – 1W of power and a 1 mil beam size Results are shown in Figure 9.

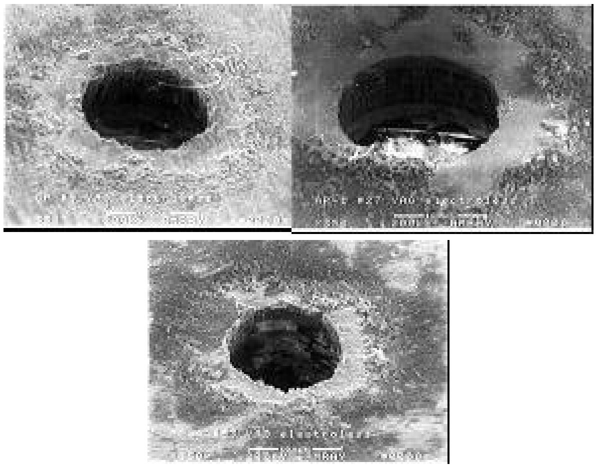


Figure 9 – YAG Drilld Vias in LCP, All-Polyimide, and Epoxy RCC (clockwise starting in upper left corner)

For the CO_2 drilling work (Table 1), some optimization of conditions was performed. Holding power constant, the pulse length, rate, and total number of pulses were varied to make the best vias in the materials. For the LCP material, the best vias were made with shorter, more frequent pulses – and higher number of pulses than some of the other materials.

Table 1 – Via Drilling Conditions for Various Materials 0 CO_2 Laser

Parameters	LCP	API	FR-4	RCC
Power	40W	40W	40W	40W
# of pulse	13	3	15	4
Pulse width	25	35	25	35
Pulse period	50	70	50	70

Desmear

After drilling, the vias or holes typically require a cleaning step prior to metallization. This step removes debris while preparing the polymer surface for metal deposition. The most common desmear method is a wet chemical, permanganate exposure. As shown in Figure 10, this method is not effective with the LCP material due to LCP's extreme chemical resistance.

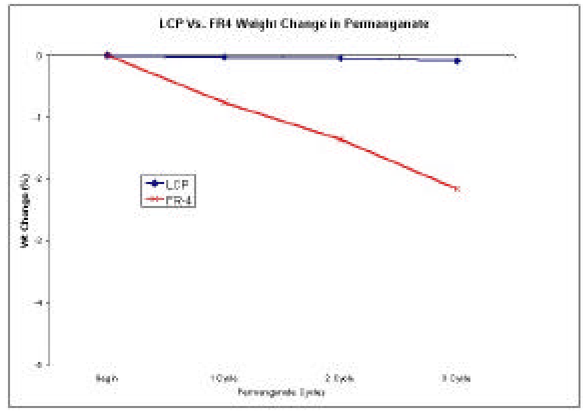


Figure 10 – Weight Loss through Permanganate Exposure

In contrast, plasma treatment is very effective at cleaning holes and preparing the LCP metallization. The SEM photographs in Figure 11 show a drilled via before and after plasma. The conditions used are presented in Table 2.

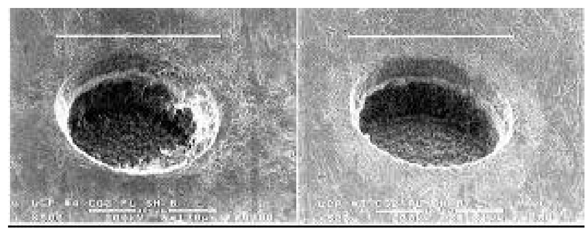


Figure 11 – LCP as Drilled (left) – After Plasma Desmear (right)

Table 2 – Typical Plasma Desmear Cycle

Power	6000W
Pressure	350mtorr
Gas	80% N_2/20% O_2
Time	15 minutes

Metallization

Two seed layer metallization approaches were evaluated: electroless copper plating and the Shadow® direct metallization process from Electrochemicals, Inc. The seed layer's role is to provide a well-adhered, conductive layer for copper to be electrolytically plated onto. Electroless copper plating results showed good coverage and adhesion when combined with a plasma desmear. Figure 12 below shows a 5 mil blind via fully plated.

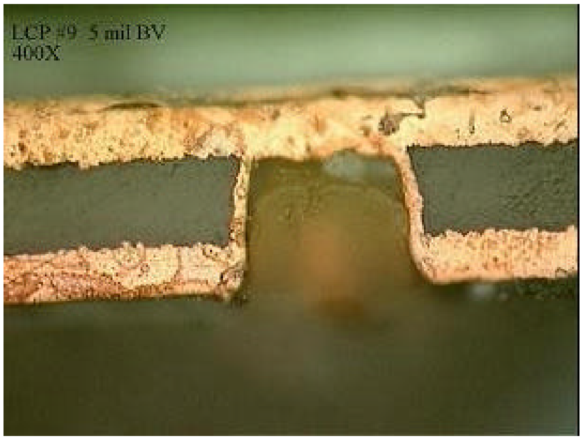


Figure 12 – Metallized Via with Electroless followed by Electrolytic Copper Plating

The Shadow® direct metallization process showed excellent coverage and adhesion, as illustrated in Figure 13. With the LCP material, Shadow® appeared to be much less sensitive to drilling and desmear conditions than the electroless approach.

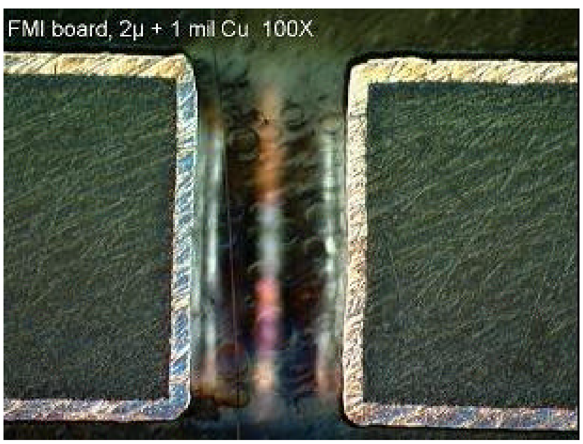


Figure 13 – Metallized Via with ShadowÒ followed by Electrolytic Copper Plating

Finish Metallization

Typical printed circuits require that some of the circuitry remain uncovered without solder mask and remain exposed for access to connections. Typically these exposed areas have a metallic finish applied to protect the copper from corrosion. Common finishes are various tin/lead solders, immersion tin, or electroless nickel/immersion gold. The solder is often applied using the hot air solder leveling (HASL) process which exposes the PCB material to very high temperatures. The other two finishes are applied using processes which expose the PCB material to very corrosive chemistries. The LCP circuit material was compatible with all three finishes.

Assembly Processing

For surface mount assembly, solderability and surface insulation resistance (SIR) are important considerations, particularly with no clean flux.

Solderability

Solderability test coupons were fabricated according to IPC J-STD-003 with an electroless nickel/immersion gold finish. The solderability was measured using a 6-Sigma Wetting Balance Tester. Aim 266-3 no clean flux was used with 63Sn/37Pb and 96.5Sn/2.25Ag/0.75Cu/0.5Sb solder alloys. A characteristic wetting curve is shown in Figure 14. The key wetting balance parameters measured were T_a and F_{max}. T_a is the time to the buoyancy corrected force line. At this time the solder contact angle to the test coupon is 90^o and the wetting forces pulling the coupon into the molten solder equals the buoyancy force pushing the less dense coupon out of the molten solder. The smaller the T_a, the quicker the solder wets to the coupon. F_{max} is the maximum wetting force exerted by the solder on the coupon and is directly proportional to the height the solder climbs up the coupon. F_{max} is the sum of the buoyancy force and the maximum force, F_{inst}, recorded by the wetting balance during a particular test as illustrated in Figure 14.

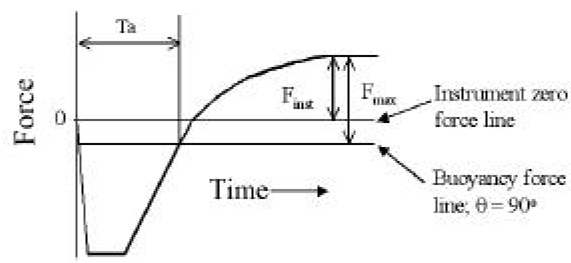


Figure 14 - Characteristic Wetting Force vs. Time Graph

The solder pot temperature was varied and the variables T_a and F_{max} as a function of solder temperature are plotted in Figures 15 and 16, respectively. The dip depth was 5mm and the dip time was 5 seconds.

As expected, T_a decreases and F_{max} increases with temperature. The lead-free alloy requires higher soldering temperatures due to its higher melting point, but exhibits excellent solder wetting. There was no evidence of damage to the LCP test coupon at the maximum solder temperature, indicating the compatibility of LCP with higher temperature lead-free soldering.

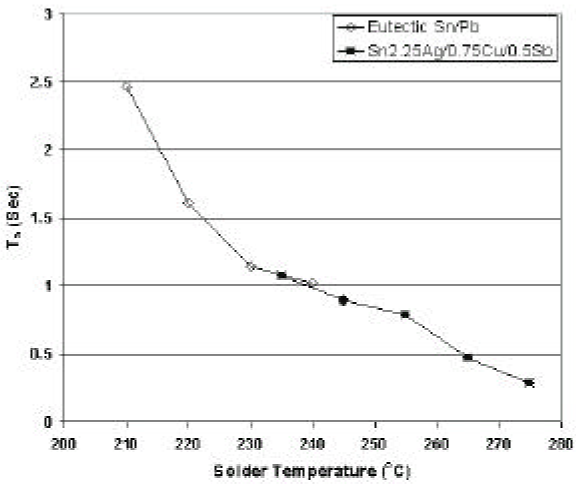


Figure 15 - T_a as a Function of Temperature for the Two Solder Alloys

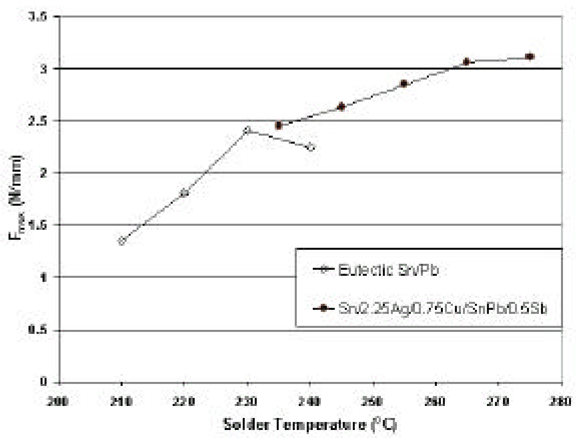


Figure 16 - F_{max} as a Function of Temperature for the Two Solder Alloys

Surface Insulation Resistance (SIR)

The SIR coupons were designed per IPC-B-24 and the test method was per IPC-TM-650, Number 2.6.3.3. Coupons were cleaned in a 50:50 deionized water/alcohol bath prior to testing to remove any contamination from the coupon fabrication process or handling. A low residue, low viscosity, no-clean flux was sprayed on one set of samples that were then passed through a standard eutectic Sn/Pb reflow cycle. The second set of coupons was tested 'as-cleaned'. The coupons were stored for 168 hours with a 45 Vdc bias at 85%Rh/85^{o}C. Periodic insulation measurements were made by applying a 100Vdc reversed bias and measuring the resulting current flow. The minimum surface insulation (12 samples per condition) is plotted in Figure 17. In both cases the coupons exceed the 10^9 Ohm specification. There is no indication of chemical interaction between the flux and the LCP.

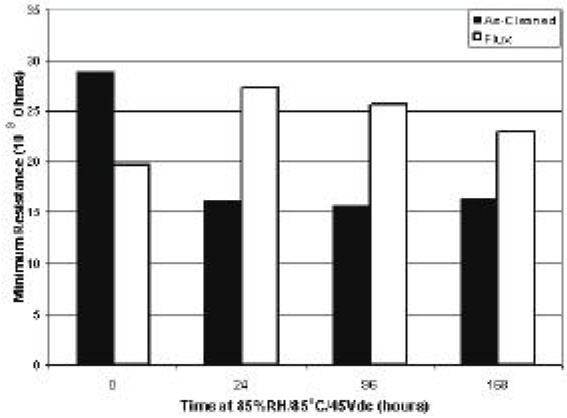


Figure 17 - Minimum SIR Test Results

Assembly

For advanced packaging applications, compatibility with flip chip and wire bond assembly is required. A flip chip test vehicle was fabricated using the PB-8 flip chip test die (0.200" x 0.200" with 0.008" bump pitch). The LCP board had an electroless nickel/immersion gold surface finish. A die site is shown in Figure 18. There is no solder mask beneath the area on which the die will be placed. The flip chip die were assembled with a Siemens F5 pick and place machine using Kester 6502 dip flux. The boards were reflowed in a nitrogen atmosphere with a Heller 1800 reflow oven. The peak temperature for the eutectic Sn/Pb was 220^{o}C and for the eutectic SnAgCu was 245^{o}C. After reflow, the die were x-rayed with a Phoenix micro-focus x-ray and good alignment and wetting were observed (Figure 19). Next the die were underfilled with Loctite 3563 (a fast flow, snap cure underfill) using a Camalot 3700 dispense system. After underfill cure (165^{o}C for 5 minutes), a Sonix scanning acoustic microscope was used to examine the underfill. As seen in Figure 20, no voids were observed, indicating good flow of the underfill over the LCP substrate.

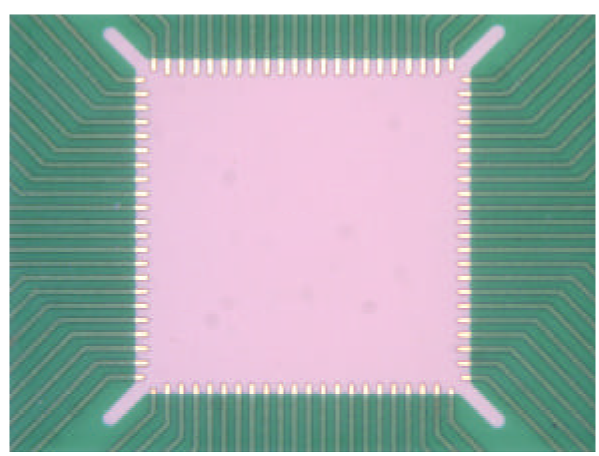
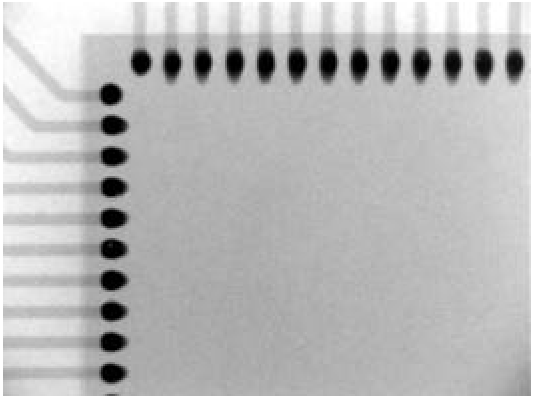
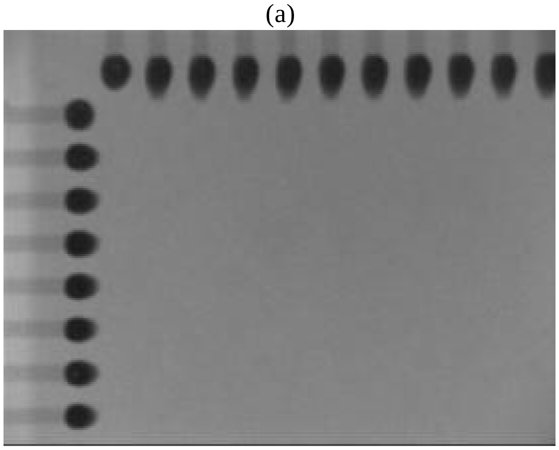


Figure 18 - Flip Chip Assembly Site



(a)



(b)

Figure 19 - X-ray Images after Reflow (a) Eutectic Sn/Pb and, (b) Eutectic SnAgCu

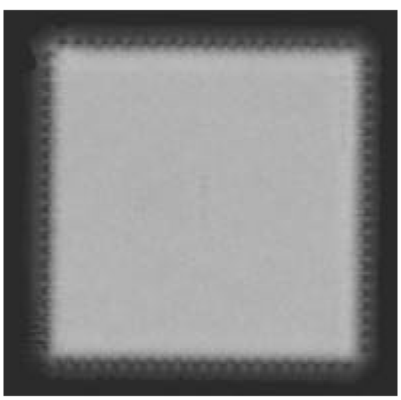
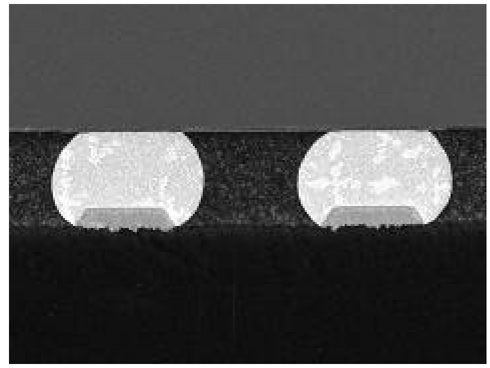
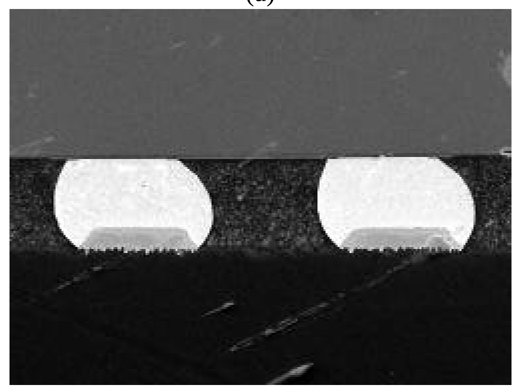


Figure 20 - Typical C-SAM Image After Underfill and Cure

Figure 21 shows cross sections with the eutectic Sn/Pb and eutectic SnAgCu solder bumps. Good solder wetting and no underfill settling or de-wetting were observed.



(a)



(b)

Figure 21 - Cross-section Images (a) Eutectic Sn/Pb and, (b) Eutectic SnAgCu.

A Palomar Product 2460 Model V automatic thermosonic wire bonder was used to evaluate the wire bondability of an LCP test board with an electroless nickel/electroless gold finish. The wire diameter was 0.001” and the stage temperature was 200^{o}C. The high temperature capability of the LCP allowed a higher stage temperature than is typical with laminate substrates. With metal leadframes, 200^{o}C is commonly used. Shear tests were performed. The results are summarized in Table 3.

Table 3 – Wire Bond Shear Test Results

	Shear Strength (g-f)
Average	62.4
Standard Deviation	4.3

Packaging Developments

In addition to its excellent properties as a PCB substrate material, LCP offers the systems designer a complete packaging solution wherin the material can be used both as the interconnect substrate and the lid assembly. An all-LCP package assembly offers several key performance advantages, including:

- Excellent Barrier Properties: LCPs have excellent barrier properties, comparable to glass (Figure 22), that offer the_potential of near-hermeticity of the sealed package. The low moisture permeability of LCP makes it an ideal candidate for fabrication of low cost, near-hermetic cavity packages for electronics and MEMS devices.

- CTE Matching: The use of an all-LCP construction eliminates stresses induced by different packaging materials. In addition, the LCP can provide a close CTE match to either silicon or copper.
- Dimensional Stability: LCP's excellent dimensional stability makes it a viable solution for passive alignment packaging systems for optical microsystems.
- Localized Thermoplastic Sealing: Thermoplastic sealing, such as ultrasonic welding or laser welding, have shown great promise with LCPs.
- Low-Cost Optical Feedthroughs: Optical feedthroughs can be integrated into LCP packages by reflowing the LCP around the glass-clad fibers.

The following paragraphs highlight some more in-depth background and details on some of our recent LCP-based packaging activities:

LCPs Barrier Properties: Thermoplastic LCP films offer the potential of near hermetic packaging due to their low moisture and oxygen permeability, especially with films extruded with Foster-Miller's unique biaxial orienting dies. LCP film samples were submitted to MOCON/Modern Controls, Inc., for permeability testing. The permeant was water (100% RH at 40oC) and the carrier gas was nitrogen at ambient pressure. The results are given in Table 4. The moisture permeability value corresponds to common glass and is substantially lower than typical polymers. Figure 22 highlights the moisture permeability of oriented LCP film in comparison to hermetic materials (metals, ceramics and glasses) and non-hermetic polymers. The data shows that LCP offers the potential of a hermetic plastc package, a hitherto unimaginable concept.

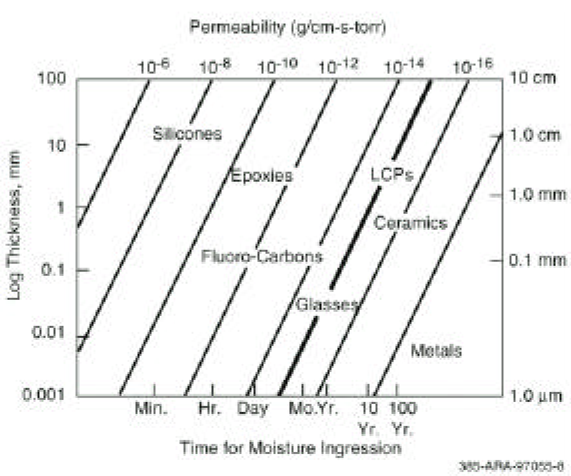


Figure 22 - Permeability of LCP and General Packaging Related Materials

Table 4 – Moisture Properties of LCP Films

Thickness (mil)	WVTR (g/m^2-day)	Permeability (g-mil/m^2-day)	Diffusivity (cm^2/sec)	Solubility (g/cc)
2	0.1177	0.2354	2.589 x 10^{-9}	0.000268
4	0.0678	0.2712	9.830 x 10^{-10}	0.000811

Package Sealing:: Three approaches for sealing LCP packages are under investigation namely solder, ultrasonic, and laser sealing:

Solder Sealing is readily achievable using a metalized lid, a solder preform and a seal frame on the interconenct substrate. Molded LCP lids have been metallized via plating and deposition processes and, subsequently, soldered sealed to a seal frame on the interconnect substrate.

To prove the reliability of solder-sealed LCP packages, a solder-sealed cavity package was designed using an LCP substrate for a MEMS humidity sensor. The package design concept utilized a double-sided LCP printed circuit board that had patterned copper on both sides. Press fit nickel/gold plated kovar pins were inserted into drilled through-holes and soldered to copper landings on both sides of the LCP board. The top side of the board had traces that ran from the copper landings to bond pads for the MEMS humidity sensor. Also, on the top side of the board was a copper ring that encircled the pins and components. The package lid was a machined copper lid, nickel and gold plated. The lid was vacuum solder sealed to the copper ring using Sn/Pb solder. The package is shown in Figure 23.

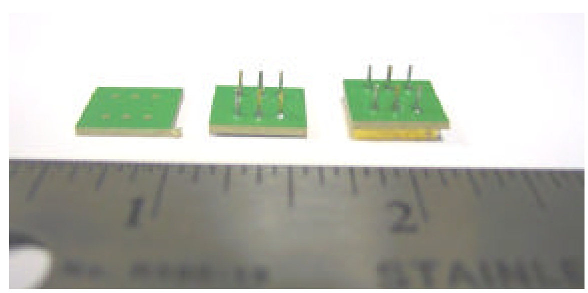


Figure 23 - LCP MEMS Package.

Five sealed packages were submitted to the Reliability Analysis Laboratory at Raytheon (Lexington, MA) for fine and gross leak testing. The packages were helium pressure bombed at 3 atmospheres for 90 hours for fine leak testing. Three packages started at $4x10^{-8}$ Atm cc/sec, decayed to $1.3x10^{-8}$ Atm cc/sec over 6 hours and to 3.5 $x10^{-9}$ Atm cc/sec over 22 hours. The fourth package started at $4x10^{-8}$ Atm cc/sec, decayed to $2x10^{-8}$ Atm cc/sec over 6 hours and to $1.8x10^{-8}$ Atm cc/sec over 22 hours. These four packages passed fine and gross leak testing. The He decay rates for the four packages were consistent with He being absorbed by LCP during pressure bombing and desorbed during the leak test. The fifth package showed a steady leak rate of $2.5x10^7$ for 4 hours, consistent with a fine leak in the solder seal.

Ultrasonic sealing is accomplished by applying ultrasonic heating to the sealing edge of the lid while the lid is in place on the substrate. An ultrasonic horn was designed to be used in a standard "plunge welding" ultrasonic welding system. Ultrasonic welding has shown some promising results for rugged LCP package designs, but, due to the intensity of the process, may not be the optimum welding technique for sensitive component applications. Delicate wirebonds and surface mount components have been damaged or broken by the ultrasonic process.

The final package sealing approach, and likely the most attractive and promising is laser welding. Laser welding is a high-speed and efficient method for the joining of thermoplastics. However, with common, high power laser systems, the laser energy tends to decompose the thermoplastic. The key is to use lower power laser systems combined with a suitable absorbing material at the bondline. The presence of an absorbing material at the bondline will provide enough absorption of the laser energy to form a robust weld. Nearly all polymers are transparent to infrared energy in the near infrared optical spectrum. Even polymers that are opaque to visible light, such as LCP, are highly transparent and can be welded using appropriate absorbing layers. The welding process works when laser radiation is passed through a transparent polymer to an absorbing interface that is in contact with the transparent polymer, as shown in Figure 24[10] Heat generation at the interface melts the transparent polymer. The heat source is outside the weld zone. The work part can be moved, on an x-y table, under the laser beam to generate the desired weld pattern.

Figure 25 shows a specially designed LCP package that was designed for laser welding. The package design for laser welding incorporates an extended lip on the sealing edge of the package lid. The LCP material is transparent to the IR radiation and therefore requires the introduction of an IR susceptor. This IR susceptor absorbs the IR energy and produces localized heating to melt and seal the LCP at that specific point. This IR susceptor may come in a variety of materials including, but not limited to iyanocyanine green and ClearWeld ™.[9] The IR susceptor is applied to the welding seam by printing, screening, or painting the material to the substrate at the mating point to the package lid.

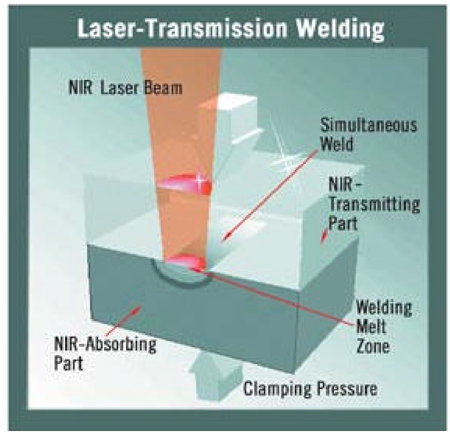


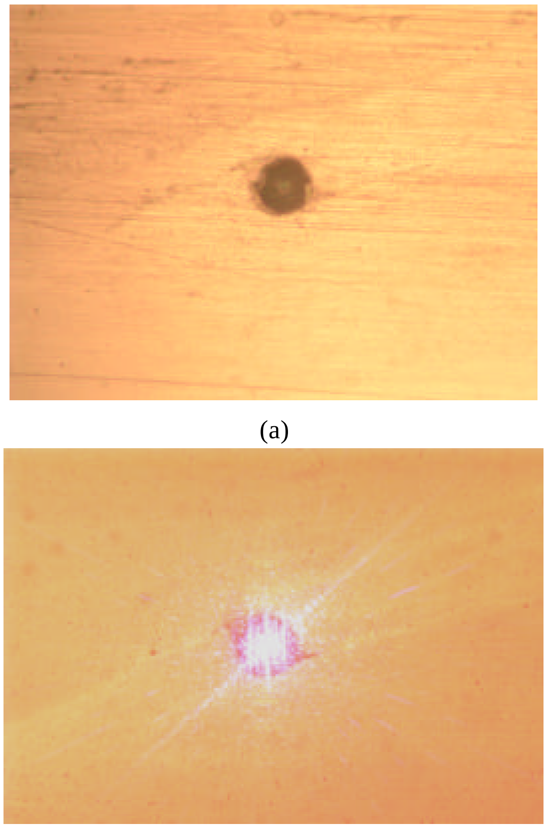
Figure 24 - Laser Welding of Thermoplastics[9]

Figure 25 - LCP Lid Designed for Laser Sealing

Laser sealing of LCP packages offer many advantages in emerging markets such as temperature sensitive MEMS and optical components. Laser welding creates only localized heat and therefore does not harm the components being packaged, whereas, current solder reflow processes create potentially harmful heat through the entire package assembly. Also, laser sealing is environmentally friendly.. Market and environmental pressures are pushing for the lead-free initiative adoptation. Laser sealing of LCP is a clean, safe, and environmentally friendly solution for near hermetic packaging needs.

Optical Packaging

Perhaps the most immediate market to benefit from this developing LCP packaging technology lies in the area of optoelectronic subsystems. The dramatic expense associated with optoelectronic subsystem packaging can, potentially, be greatly reduced using lower cost LCP materials and packaging methodologies. Initial experiments have yielded some interesting results and processes that should open up new and interesting design options for optoelectronic packaging. We have demonstrated some initial optical packaging processes. Optical fibers can be laminated between layers of LCP to form optical interconnects that can be embedded in the substrate or can be embedded into package sidewalls to provide optical I/O. Figure 26(a) is a cross section of an optical fiber laminated inside an LCP substrate, while Figure 26(b) shows light transmitted to the exposed end of the fiber. Figure 27 shows a final image of a fiber embedded into the sidewall of a package. Given the near-hermeticity of LCP packages and the ease with which opical fibers can be laminated into the LCP, LCP is being investigated for packaging of optical components including MOEMS.



(a)

(b)

Figure 26 - Cross Section of Optical Fiber Laminated within an LCP Substrate (a) and Light Emission from Fiber (b).

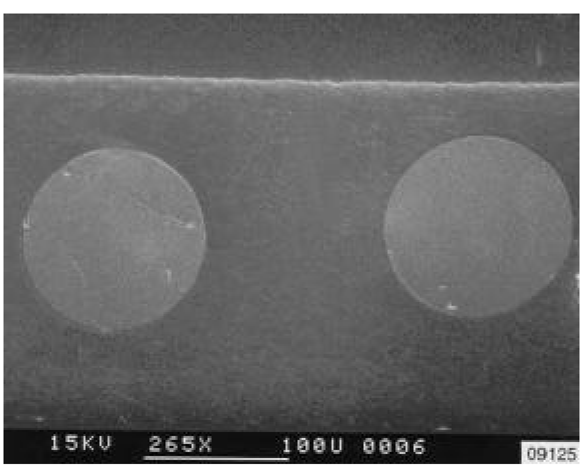


Figure 27. Scanning Electron Micrograph of Optical Fibers Through LCP Package Wall

Summary

After many years of development, Liquid Crystalline Polymer circuit materials are now commercially viable. Combining attractive electrical and physical properties with commercially viable PCB and package fabrication processes should enable LCP materials to be used for the next generation of high performance electronics.

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