The Future is Plastics

By Dr. Ken Gilleo and Dennis Jones

Thermoplastics, like LCP, have the right properties for component packaging including high temperature tolerance, low moisture absorption, low flammability, and precision molding.

In the 1967 film, "The Graduate," Dustin Hoffman's character is told: "The future is plastics." Good advice, but what kind of plastics? There are only two main classes of plastics even though thousands of resins are available and millions of tons are used annually. The term "plastics" usually refers to thermoplastics, ever-present in appliances, gadgets, vehicles, offices, and homes. In fact, life without plastics may no longer be possible in much of the world. A day without thermoplastics would be like the alien invasion depicted in "The Day the Earth Stood Still" (1951). Electricity, communications, transportation, and nearly every technical product would stop, disassemble, or disappear. Not only are plastics the most common construction materials, they're also the *universal insulator* for the electrical and electronics industries. How much thermoplastic material is used in electronics for circuit boards and packaging? Close to zero! Did electronics somehow miss the "Plastics Revolution"?

More than a half-century ago, the electronics industry adopted thermoset materials, typified by epoxies, and has yet to embrace the more popular and versatile thermoplastics family. In the early 1900s, Bakelite (phenolic) and other thermosets were adopted for circuit laminates and connector sockets. Thermosets were the only choice back then because they could take the heat of soldering while fledgling thermoplastics had relatively low melting points. Today, modern thermoplastics have softening points above 300°C and lead-free soldering is no problem [1]. Modern thermoplastics now outperform today's epoxies that aren't much different from materials used 50 years ago.

Electronic Packaging

Component packaging is an enabling technology that is evolving at an accelerating pace as the industry races along the performance-density roadmap that is now adopting 3D stacked designs and wafer level packaging (WLP) processes. The package is the vital bridge between devices and printed circuits, but the gap between chips and PCBs grows wider and packaging challenges loom larger. Discovered in 1927, epoxies have been used for a half-century as electronic device encapsulants and are still the "workhorse" polymer for packaging [2]. Thermoset epoxy molding compounds (EMC) have been the standard choice since the invention of plastic non-hermetic packaging.

The deceptively simple electronic package performs a multitude of functions. Some are essential, others are beneficial, and still others are product-specific requirements. The top requirement is providing the electrical interconnect system between the device and PCB. Rerouting is valuable for some applications but not all. Environmental protection is usually a requirement, but it is product-specific ranging from very low protection for passivated chips, to high for many other devices. The package also provides compatibility between PCB and chip pads that are not solderable as fabricated. Other package attributes include, reworkability, testability, standardization, automatic handling, miniaturization, performance enhancement, and heat management. MEM, MOEMS, optoelectronics, very high-frequency RF, and forthcoming Nanoelectronics, are adding unique requirements to the long list [3-5].

Package Types

Electronic device packaging can be divided into two broad classes—hermetic and non-hermetic. The full hermetic package, developed about 150 years ago, has admirably served the electronics and optoelectronics industries. The cathode ray tube (CRT), demonstrated by Braun in the late 1800s, used a glass enclosure to seal out the atmosphere and maintain the necessary vacuum. Later, electronic vacuum tubes were developed as the Fleming diode, followed by the De Forest triode amplifier tube. These early opto- and electronic devices required a vacuum to operate because the flow of electrons through free-space was part of their mechanisms. But today, only a very few systems actually require a vacuum. The early packages evolved from glass to ceramic and metal while the principle of making a near-perfect gas-tight enclosure persisted.

While hermetic packages offer excellent protection, they can be expensive and are "overkill" for most applications. But a cost-cutting breakthrough occurred with the successful launch of the non-hermetic plastic package shortly after the transistor was commercialized more than a half-century ago. Offering low cost, factory automation, and "good enough" reliability, the plastic package became the standard as the dual-in-line (DIP) package gained wide acceptance. The electronic die was attached to a metal leadframe (MLF), then wire bonded, and finally overmolded with epoxy molding compound (EMC). The molding compound is a blend of solid epoxy resins, hardeners, fillers, and additives. The solid preform is temporarily liquefied before being converted to the non-melting package structure. The molding compound makes direct contact with the die, wire bonds and leadframe. Various surface mount packages evolved during the 1980s, but the basic overmolding process continued. The newer BGA (Ball Grid Array) and leadless versions, like QFNs, also use overmolding methods but with the leadframe replaced by an organic chip carrier platform. The 1927 epoxy thermoset technology is the common denominator in all of these new and old packages.

New Age of Materials

Polymers are long-chain molecules that occur naturally, but are synthesized for industrial use. Plastics are arguably the most important materials today. Materials have been so important to civilization that entire eras have been named for them; the Stone Age, Bronze Age, etc. We are in the Plastics Age of materials and plastic (organic) electronic devices may eventually displace inorganic silicon. This is already happening in displays; e.g.; OLEDs. Fundamentally new polymers continue to be invented and innovative processes are being developed such as nano-imprinting. Consider that much of emerging Nanoelectronics is based on organic, polymer-like structures that could someday replace wires and silicon transistors. DNA is the most complex polymer, and while invisibly small, a single DNA stand is about 6-feet long when unfolded, unwound and straightened out; coded information amounts to 100-million written pages of data.

Plastic packaging accounts for about 95% of the market because of low cost, versatility, and automation simplicity. We can view flip chips as a special form of plastic packaging where underfill is the encapsulant and performance-enhancing polymer. Epoxy was the first successful organic packaging material type and still dominates today. Since epoxies are thermosets, they are permanently "set" by polymerization. Thermoset ingredients are mixed prior to use and usually refrigerated to prevent premature polymerization. Once polymerized, they can't remelt, even at high temperatures. But inability to remelt prevents reuse and waste is generally handled as hazardous material making disposal increasingly difficult. This will become a hurdle to recycling in the future. Most EMCs still contain bromine flame retardant that will be outlawed just like lead in solders. Epoxies are also relatively poor gas and moisture barrier materials, but chip passivation has allowed most devices to work well enough to bring success to the plastic package. Relatively high moisture absorption is an increasing concern as soldering temperatures rise. Many believe that thermoset epoxies have reached a final plateau and will continue to fall short as packaging and PCB requirements increase. Let's look at how thermosets are processed into packages.

The Transfer Molding Process

The transfer molding process has been used for about 50 years to encapsulate chips. The steps are straightforward: a die is attached to a leadframe that can be in a strip or an array. Die attach adhesive affixes the chip to the leadframe that is then wire bonded. The "loaded" leadframe is now placed into a mold cavity. The molding press consists of a resin-heating chamber connected to an array of mold cavities by a system of runners and gates. The loaded mold closes and the EMC preform is melted and forced through into the cavities and over the chips. Post heating may be required to fully-polymerize the epoxy. Figure 1A shows a leadframe, 1B shows EMC preforms, and 1C depicts the transfer molding process.

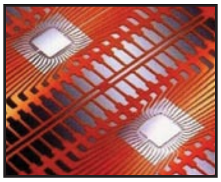

Figure 1A. Metal Leaf frame.

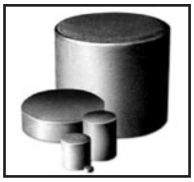

Figure 1B. EMC Preforms.

Thermoplastics

Thermoplastics have long polymer chains, just like thermosets, but chains are independent (not cross-linked). This seemingly small difference permits thermoplastics to melt

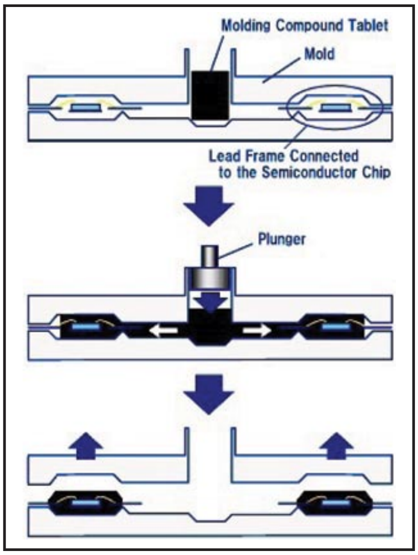

Figure 1C. Transfer Molding.

because chains can move past one another with sufficient heating. Cooling returns the plastic to a solid without altering properties. Thermoplastics can be easily shaped and reshaped and this is the basis for injection molding and other thermoforming processes. Millions of pounds of thermoplastics are formed into objects ranging from thin films to complex microstructures. Today's thermoplastics are superior to EMCs in critical categories and can easily take the abuse of lead-free soldering. Plastics, like LCP (Liquid Crystal Polymer; a class of polymers), have 10-times better moisture resistance, are rapidly shaped into precision 3D structures, and pass flammability tests without adding flame retardants. Since LCPs only contain the elements carbon, oxygen, and hydrogen, it doesn't get much "greener." Table 1 shows selected properties for LCP and other high-temperature thermoplastics. Next, we'll look at shaping methods.

Injection Molding

Thermoplastics can be overmolded but this has not been a widely accepted method because hot molten plastic can damage components. A more suitable process, injection molding (IM), begins by liquefying the plastic resin, injecting it into a mold where it cools to a solid, and ejecting the solidified part. IM is one of the most ubiquitous manufacturing processes in the world and used to produce large and small parts for every industry, including photonics and electronics. A complete molding cycle takes only about 10 seconds. Although a part can be produced cheaply, it is a pre-molded package without any electronic device. The

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Table 1 – Thermoplastics for Packaging

Plastic	water abs. %	MP	UL94	CTE/30% glass
LCP	0.02 - 0.10 %	280 - 352°C	V-0	0 - 12 ppm
PEEK	0.15%	340°C	V-0	16 ppm
PPA	0.15 - 0.29 %	310 - 332 °C	H-B V-0	22- 40 ppm
PPS	0.01 - 0.04 %	280°C	V-0	19 – 27 ppm

LCP = Liquid Crystal Polymer; PEEK = Polyetheretherketone
PPA = Polyphthalamide; PPS = Polyphenylene Sulfide

electronics must be added after the package is formed, not before, as with transfer molding. This means that the package style must allow the device to be added after formation and a cavity design is the most common approach. Plastic injection molding is well suited for making precise and intricate 3D shapes at low cost, but it has not yet been widely accepted for electronic packaging. Although a plastic cavity package can be produced at a fraction of the cost of a ceramic or metal type, it is not fully hermetic. A few companies now offer molded cavity style packages made with high-temperature plastics such as LCP or PPS (Polyphenylene Sulfide).

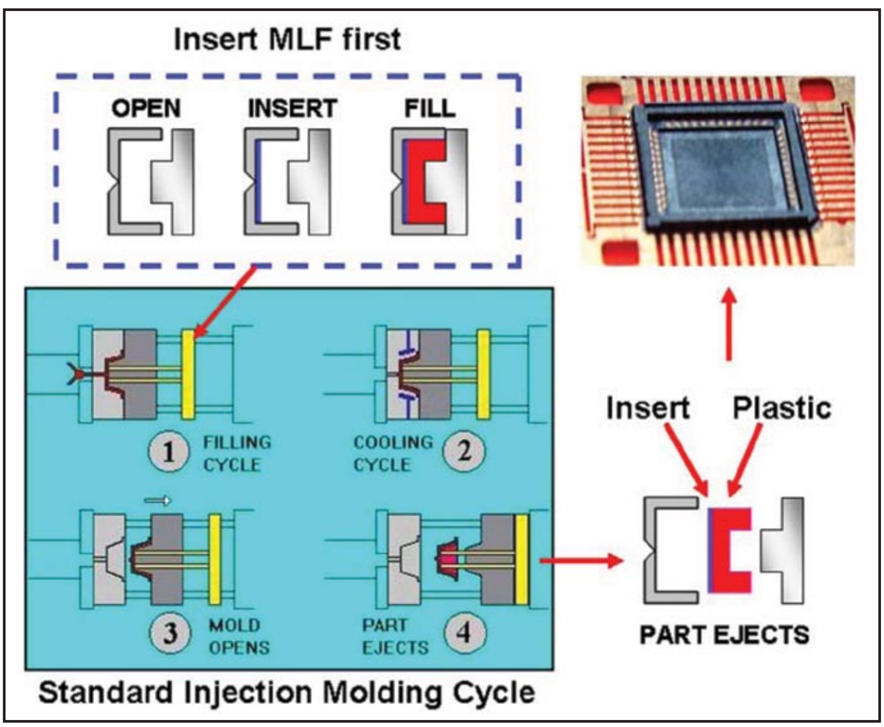

Figure 2. Insert Molding Process.

Designing Thermoplastic Packages

Thermoplastics can be molded into 3-dimensional structures and several cavity package designs have been introduced. The most common thermoplastic package uses a metal leadframe that is insert-molded (See Figures 2 and 3). The leadframe can be a strip or an array for increased productivity. The MLF strip is placed into the mold cavity, but contains no chips. The mold closes under high clamping pressure and the injector ram forces melted plastic into the mold cavities. The injected plastic quickly hardens, the mold opens, and the finished part is ejected. The steps are continually repeated and the press is typically run fully automated.

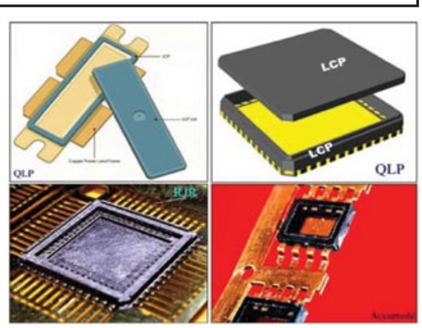

Figure 3. Thermoplastic Packages.

The Low Ball Package

Several injection-molded package designs have been developed, but most use insert-molded leadframes as shown in Figure 3. But there are other approaches to adding conductors, including metallization after molding, and insert-molding flexible circuits.

We decided to test out an even simpler concept—inserting discrete connectors instead of using a leadframe. We selected the metal sphere as the optimum discrete connector. The sphere is the most natural and pervasive shape in the universe making it an easy and economical geometry to manufacture. Spheres are easy to handle since they are totally symmetrical. Industry produces thousands of spherical products including BGA solder balls and billions of metal spheres are used in ballpoint pens and ball bearing assemblies. Since solder would melt during molding at more than 300°C, the sphere choice was narrowed to copper or nickel, but copper provided more advantages. We tested two different finishes on the copper spheres, gold (Au) and palladium (Pd), both with plated nickel (Ni) barriers. Pd over Ni has been used on leadframes for decades by Motorola and others, and is now used as a lead-free finish. Palladium is suitable for wire bonding and removes concerns about solder embrittlement that can be an issue with gold. We selected a size of 30 mils for the spheres and a package thickness of 10 mils to allow each sphere to protrude through the package bottom and into the cavity floor.

The metal sphere can be thought of as equivalent to the pin in a Pin Grid Array (PGA), but with a simple spherical shape for easy manufacturability and cost minimization. The sphere "footprint" is determined by the mold tool that has an array of concave depressions, or dimples, to hold the metal spheres. The mold "programs" the "leadframe" so that the inventory is a bottle of metal spheres. Spheres can be automatically placed into the mold tool using a vacuum pick-up similar in concept to the BGA solder ball placers. The entire package can be manufactured in a standard injection-molding machine, but a robotic "sphere placer" is needed for full automation. Arrays, or strips, of packages can be produced by adding small temporary links to hold individual packages together for chip assembly and testing. The packages can then be singulated by punching, cutting, lasing, or snapping the tabs. Testing can be carried out while packages are still in an array since the metal spheres are isolated, while conventional leadframes must be singulated. We added one more step, although it could be eliminated by modifying the mold. The spheres protruding inside the package were coined flat to aid wire bonding and to insure a tight seal, using a micro-press. The copper is easily shaped without damage to the finish. Figure 4 shows the package interior with coined gold-plated copper spheres and package cross-section.

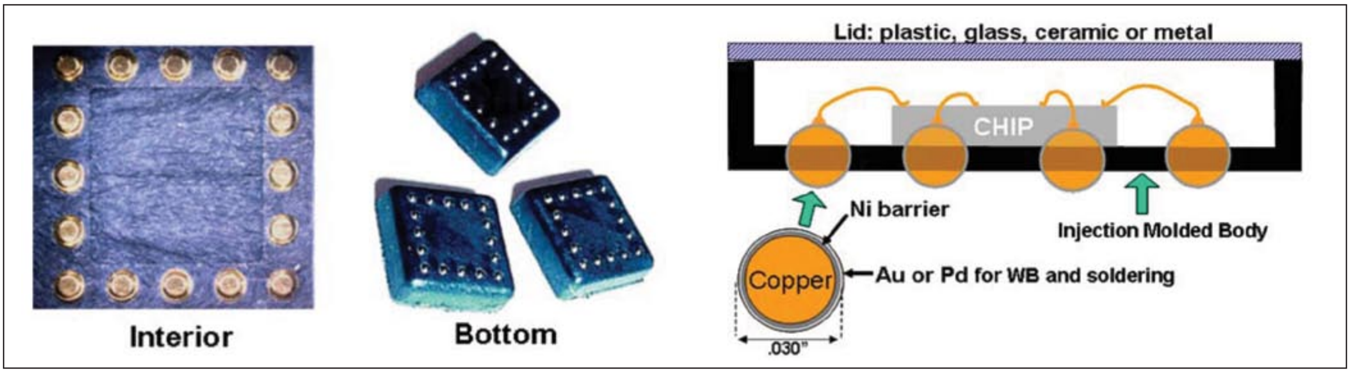

Figure 4. Diagram: Low Ball Simplest Cavity Package.

Lids and Sealing

Once a die is attached and wire bonded, the package is ready to be sealed. The lid can be made from almost any conductive or non-conductive material depending on the application; metal, ceramic, glass, or plastic. Transparent lids of plastic or glass can be heat-sealed using IR or NIR lasers and this has been reported [6]. The idea of using lasers for sealing plastic-to-plastic goes back to the 1960s. Lids can also be sealed with a variety of adhesives and this provides more versatility and availability.

Applications for Thermoplastics

Although pre-molded cavity packages can be used for any type of device, maximum benefits accrue for chips that require a cavity or some other feature readily obtained by injection molding. While most electronic chips can be overmolded, many new devices, especially mechanical, must remain free from contact on the active face of the chip. MEMS devices, for example, have moving parts or transport materials. They obviously need "free-space," or "head room." One option is to cap the devices and then overmold, but this is limited to inertial sensors that don't need access to the environment. Not all capped chips can be overmolded since the stress produced by the hardened epoxy encapsulant can degrade chip performance. So if free space is required, epoxy overmolding is a poor option. However, plastic injection molding is an ideal method for producing cavities, ports, and various 3-dimensional precision structures. Optical-MEMS, or MOEMS, lighting, and imaging chips can take advantage of thermoplastic cavity packages and the ease of adding a transparent lid. The optical device area appears to be a good fit for thermoplastic packages, including more complex structures for cameras. Figure 5 shows how the same insert-molded ball package could be used for a cell phone camera by designing the lens housing as a sealable lid. The lid could be designed for laser sealing to avoid adhesives that could outgas. And since package-on-package (PoP) is a hot item, consider how easy this would be with insert-molded infusible metal spheres as shown in Figure 6; A is unmodified wire bonded/compression bonded, but B and C require routing for flip chip.

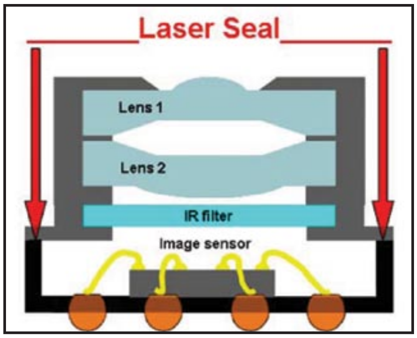

Figure 5. Camera Module.

Conclusion

Thermoplastics, like LCP, have the right properties for component packaging including high temperature tolerance, low moisture absorption, low flammability, and precision molding. But thermoplastics are less suitable for overmolding. However, cavity packages can be readily molded from thermoplastics using metal leadframe insert molding. We tested a simpler and potentially lower cost concept where metal balls were insert-molded into the package to protrude into the base and exterior bottom. The low-cost concept package accommodates wire bonding and SMT assembly, meets present and predicted regulations, and can be recycled. Injection molding is a highly versatile plastic shaping process that could also be used to make more complex packages including, optical, multi-chip and stackable types. Although injection molding is not widely available within the packaging industry, there are tens of thousands of contract molders throughout the world.

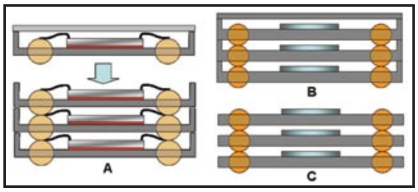

Figure 6. Thermoplastic PoP.

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