

ENCAPSULATION MATERIALS AND PROCESSES

Encapsulation is the act of completely embedding electrical components within an inert, solid material to protect them from mechanical and environmental stresses. It differs from protection within metal or ceramic box-like or can-like cavities in that no gas or vacuum space surrounds any of the component parts. The process involves placing a liquid resin around the semiconductor assembly and then solidifying the resin. The assembly contains semiconductor circuits on one or more silicon chips, internal interconnect wiring, and a conductor network leading to the external surface. This encapsulated assembly is called a *package*. The term *bug* came from an early package in which two opposite rows of metallic conductor legs protruded from the black encapsulation resin body, thus creating the image of an insect.

Commercially, the term *encapsulation* is virtually synonymous with transfer molding of epoxy resin compounds. The transfer molding process places the solid, cylindrical epoxy charge into an external chamber, warms it to a liquid state, and then transfers the epoxy into the mold cavities containing the semiconductor assemblies. In 1997 over 100 million kg of transfer-grade epoxy molding compound encapsulated about 50 billion integrated circuit (IC) devices and about 200 billion small discrete devices. All IC cavity packages totaled well under a billion. Liquid epoxy formulations, similar to the solid transfer grade ones, are found in the low-end, toy and watch market, as syringe-dispensed, glob-top, coatings and are not usually considered as “packages.”

The reason for the dominant commercial success of epoxy transfer molding lies in its exceptional productivity coupled with adequate device protection and freedom from damage

during the molding process. Molding, with presses that can contain hundreds of individual devices, takes only 10 s to 180 s. Even though most assemblies contain many gold interconnect wires finer than human hairs, the low viscosity, molten epoxy hardly disturbs them as it fills the mold cavities. Process yields for established packages typically exceed 99%.

Once the devices are removed from the mold cavities, they are virtually indestructible and almost never fail from factors related to the epoxy resin. This is so even though they are not hermetically sealed like ceramic packages. Although moisture can diffuse into and out of the epoxy assembly, it cannot pool and cause significant damage. Indeed, hermetic ceramic packages are much more likely to fail than plastic ones, because they can lose their hermetic seal and allow condensed water to pool atop the silicon circuits.

The functional semiconductor chip is now a small portion of an encapsulated plastic package and even less of an assembled printed-wiring (PC) board. Miniaturization of the package and the assembly has significantly lagged behind chip circuit miniaturization. All future designs aim to minimize the interconnection and protection materials relative to the active chip.

One promising scheme is to flip the chips over and mount them directly to the substrate PC board. As the board wiring density becomes high-density interconnect (HDI), which approaches the chip wiring density, the total chip area can approach the total board area. An underfill dielectric adhesive (between the chip active surface and the substrate) performs the double function of environmentally protecting the chip circuitry and of improving its bond to the substrate. The exposed nonactive back side of the chip usually remains exposed or carries an attached heat sink. However, the application of liquids at the circuit board assembly stage is alien to normal processes and will likely never compete with more efficient alternatives.

An emerging alternative is to protect and interconnect individual chips in miniature packages prior to board assembly. The designs use thin coatings and much more efficient metallic interconnection methods rather than heavy encapsulants. Such designs are referred to as *chip scale packaging* (CSP). Some apply the coating and even the metal interconnections at the silicone wafer level before dicing into individual components. At least 70 different CSP designs competed for dominance in 1998. Until a few become dominant, the designs and material needs will remain ill-defined.

FORMULATION PRINCIPLES

The formulator's task is to minimize viscosity to facilitate molding, while simultaneously optimizing the cured encapsulant properties. When cured, most desirable encapsulation properties come from the filler. It reduces the cost, thermal expansion coefficient (TCE), and moisture absorption while increasing the thermal conductivity, electrical resistance, strength, and impact resistance. Before cure the monomeric epoxy and hardener resins provide the liquidity needed to fill the mold cavities. They cure (polymerize) to become the binder in the cured formulation. This binder also adheres to the other package components and reduces the formulation modulus, thus lowering the stress in the assembly.

Table 1. Influence of Ingredients on Epoxy Mold Compound Properties^a

Ingredient	Filler (>70%)	Epoxy (~10%) and Hardener (~7%)	Elastomer (<5%)	Catalysts	Flame Retardants and Scavengers	Waxes and Oils
Viscosity (rheology)	---	+++		---		
Cure rate (productivity)		+++		+++		
Mold cleanliness			0			00
Mold release		---	--			+++
Stress in device	+		+++			
Tg		0				
Strength	++	0	-			
Moisture absorption	+++	---	-	0		0
Thermal conductivity	+++					
Combustability	+++	-			+++	
Electrical reliability	+	0	-	-	0	0

^a + indicates a positive influence and +++ represents the strongest positive influence, - is unfavorable and 0 can be either favorable or unfavorable. *Note:* This table is a quick overview which shows the composition of typical EMCs by major components and the effect that each of these components has on the key performance properties (molding and cured properties).

Table 1 quantifies the ingredients in typical EMCs and relates them to the basic properties. This table and the discussion that follows also apply to the liquid epoxy-based formulations and non-epoxy-based ones discussed later. Besides the mineral fillers and resins, formulations contain several other key ingredients. An elastomer lowers both the TCE and the elastic modulus. Silicone rubbers and acrylic core-shell rubbers are most common. Catalysts improve the cure rate and the storage stability. Coupling agents chemically bond the filler to the epoxy matrix and also improve adhesion to other surfaces. The silanes dominate; waxes and oils facilitate mold release and aid in processing and molding. Flame retardants limit combustion to meet UL requirements. *Scavengers* or *getters* are insoluble salts that chemically tie up incidental harmful ions. These are usually secret, but antimony pentoxide and bismuth oxide and nitrate mixtures are examples. Colorants give cosmetic features and also prevent light from reaching any sensitive semiconductor surfaces. They also can improve the contrast of laser-drawn identification marks. The most common colorant is carbon black.

Table 2 lists the properties of common fillers. Fused silica dominates EMCs, because it has the lowest TCE with adequate thermal conductivity, low cost, low density, and good electrical properties. It is produced from molten crystalline silica (sand) and comes in a large number of shapes, from crushed angular fragments to spheres and in many different particle size distributions. Larger particles have a lower surface-area-to-weight ratio and allow higher filler loading at the same relative viscosity. However, mixtures of different parti-

cle sizes allow denser packing of the particles without the particle-to-particle contact, which defines the limit of loading. Models guide the formulators toward maximizing the loading while maintaining the minimum viscosity (1,2).

Spherical particles have less surface area and less hydrodynamic drag than angular particles thereby reducing the viscosity. However, they are less effective at reinforcing the cured matrix, especially against crack growth fracture. Fumed silica has an exceptionally small particle size (typically 1 μm would cover several hundred square meters) and can adsorb and immobilize most of the resin even at low loading. It is used to make room-temperature liquid formulations resist flow after deposition and is a common filler in over-the-counter epoxy repair adhesives.

The other fillers are used principally to increase the thermal conductivity of the EMC. Crystalline silica is economical but its abrasiveness leads to mold wear. Alumina has an even higher thermal conductivity and greater abrasiveness but is commercial in a spherical form, which reduces wear and viscosity. The nitrides have the highest thermal conductivity values but at a premium price. Aluminum nitride is not hydrolytically stable, and one commercial grade uses a thin silica shell to protect the aluminum nitride core from hydrolysis (3). This also reduces the abrasiveness. Boron nitride has a similar effect on thermal conductivity but it is hydrolytically stable (4). It has a platelike structure, which is believed to be contributory to high thermal conductivity and unfortunately also reduces the strength of the cured formulation. Aluminum nitride is only angular. Silicon carbide and silicon itself are

Table 2. Properties of the Major Fillers Used in Epoxy Molding Compounds

Filler Type	TCE (ppm/K)	TC (W/mK)	Density (kg/L)	Size Ranges ($\times 10^{-6}$ m)	Shape	Cost (\$/kg)	Vicker's Hardness (GPa)
Fused silica	2-4	1.3	2.2	0.1-100	all	1-15	6
Crystalline silica	15	10-14	2.6	2-35	ang	1-3	10
Alumina	6-7	20-35	3.9	0.4-40	ang	1-3	20
				12-18	sph	5-10	20
Boron nitride (hex.)	1-2	55	1.9	7-50	plate	70-80	<3
Silica coated AlN	4-5	130-260	3.3	30-60	ang	30-50	6

(Dow Chemical's "SCAN")

patented high-thermal-conductivity fillers, but their high abrasiveness limits use (5). None of these fillers begins to match the commercial size, shape, and distribution ranges of the fused silicas. Most would be used along with fused silicas.

Fillers like Wollastinite and Cordierite have attractive properties like low TCE, low abrasion, and good reinforcement (6). Their naturally high level of ionic contamination prevents use with most semiconductor encapsulation.

Natural minerals often contain radioactive impurities. Alpha radiation can generate a temporary soft error in operating dynamic random access, high-density memory (DRAM) devices. Low-alpha encapsulants must have alpha radiation levels less than 0.001 alpha particles/cm²·h⁻¹. The filler is the most dominant source of alpha particle contamination. Most low-alpha silica comes from mines with naturally low levels of alpha contaminants. A few are synthetic. Other formulation ingredients can also contain such contamination and purer versions find use in memory device applications.

Epoxy and Hardener Resins

Epoxy resins dominate the encapsulant chemistry because of a combination of features. They have low viscosity, fast cure, low shrinkage during cure, and excellent adhesion to the other device components. They do not release by-products, and they are made with low levels of ionic contaminants. These cured thermoset resins resist hydrolysis and thermal degradation and out-gassing. Their dielectric and electrical resistance values are good (7–11).

Resin synthetic chemists seek new molecules with the lowest possible cost, viscosity, impurity levels, and inherent moisture absorption while maintaining low viscosity, fast cure, and high polymeric glass transition temperature (T_g). Novalac resins dominate as the hardener components, and some resins are reacted with epichlorohydrin to produce the epoxy components. The novalac hardener and the epoxy resins formulation ratios usually are near stoichiometric. The preferred resins have the lowest possible molecular weight and narrowest molecular weight distributions while still having at least two reactive groups per molecule.

The favorite novalac hardener is simple phenol novalac made by condensing phenol and formaldehyde. This hardener reacts quickly and is inexpensive but it is quite hydrophilic. The dominant epoxy resin is based on the novalac from epoxy—O—cresol novalac (ECN) (see Fig. 1). The pendent hydrophobic methyl (cresol) groups reduce moisture absorption and do not inhibit cure because of their distance from the epoxy rings.

Biphenyl epoxy is a single molecule made from 3,5-3',5'tetra methyl-biphenyl, rather than a mixture of molecules typical of the resinous novalacs. It melts sharply around 105°C to a much lower viscosity than the resinous epoxies. It

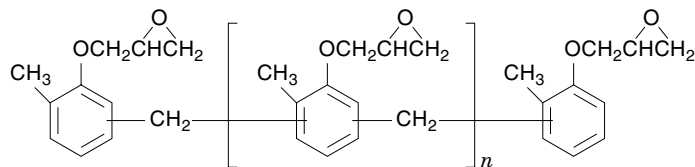


Figure 1. O-cresol novalac epoxy resin structure.

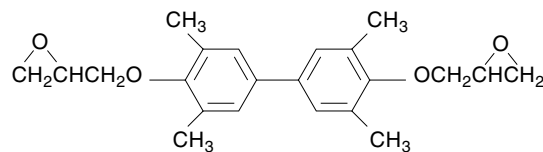


Figure 2. Biphenyl epoxy structure.

allows the highest filler loading and has low moisture absorption. However, it also has a polymeric T_g value at least 30°C below that of the cresol novalac epoxies, which hurts storage stability and device reliability. Its high cost effectively doubles the EMC cost. Also, its sharp melting point creates challenges for both the EMC formulator and the molding packaging house. It enjoys considerable use in packages demanding resistance to moisture damage during printed circuit board assembly (the so-called popcorn effect). The biphenyl precursor is not reactive enough to use as a hardener (see Fig. 2).

Low-molecular-weight bisphenol-A-based, liquid epoxy resins are common in liquid epoxy encapsulants. They are inexpensive, readily available, and reasonably pure. They lead to a much lower T_g than the novalac-based epoxies.

Anhydrides are another class of hardener coreactants used with epoxy resins, especially with liquid formulations. The anhydrides deliver excellent high-temperature electrical properties, but their willingness to hydrolyze reduces the formulation's storage stability.

The epoxy-hardener reaction yields a pendant betahydroxy group for each opened epoxy ring. This hydroxy group is responsible for most of the moisture absorption in the cured matrix. Newer epoxy and hardener resins seek to reduce the hydroxy concentration by adding pendant hydrophobic groups or hydrophobic bridging groups into the precursor resins. The biphenyl epoxy resins are a good example since they contain four pendant methyl groups. Dicyclopentadiene (DCPD) is an inexpensive bridging resin building block (see Fig. 3). Added along the novalac resin's backbone, it reduces moisture resistance with little effect on reactivity, viscosity, or cost. The properties of DCPD-extended epoxy formulations generally fall between the ECNs and the biphenyls with projected costs nearer the inexpensive ECNs (see Table 3).

Release Agents

All EMC formulators add waxes and oils in trace amounts to aid in mixing, to improve mold release, and to improve molding in general (12). The formulators seek release agents that will not significantly harm adhesion to the silicon die surface or the leadframe or the solder mask on the array board. They also seek ones that will not build up in the mold causing staining and requiring frequent mold cleaning. This is more an art than a science and is secretive.

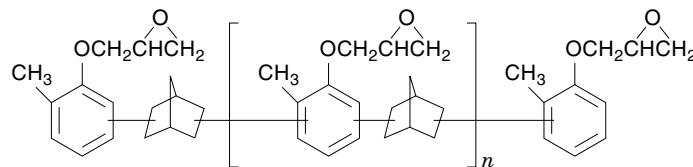


Figure 3. Dicyclopentadiene epoxy resin structure.

Table 3. Typical Properties of Common Epoxy Resins

	T_g (°C)	EMC Moisture (%, relative)	Cost (\$/kg)
Epoxy cresol novalac	155–165	0.4–0.5	8–9
Biphenyl epoxy	120–135	0.2–0.3	25–30
Dicyclopentadiene epoxy	140–150	0.3–0.4	10–14
Multifunctional ECNs	>200	0.4–0.6	25–30

Carnuba wax is historical and often named as a standard in patents. It is very effective but leads to staining. Modern formulations use polyethylene waxes, montanic acid esters, silicone oils, and fatty acid esters or their metal sterates.

Flame Retardants

At filler levels below approximately 88% by weight, the cured epoxy formulations will support combustion as defined by the UL VO standards (13). Brominated resins reduce combustion by chemically terminating the active free radical combustion products to a more stable bromine free radical.

Antimony oxides are synergists, that promote the bromine radical effectiveness thereby reducing the bromine level (14). Antimony trioxide is most common but antimony pentoxide better protects the package reliability at temperatures well below combustion (15). This is discussed further in the section on Reliability.

Recycling laws in Europe promote the replacement of halogen and antimony species. Phosphate esters offer promise (16). Other flame retardation systems such as hydrates see little use because of ionic purity issues or inefficiency. Another approach is to use filler loading above 88% to avoid flame retardants altogether.

EPOXY CURING CHEMISTRY

The copolymerization of the epoxy and hardener resins converts the liquid mix, which fills the mold into the hard, thermoset structure protecting the package. Catalysts are always used. The phosphine type (e.g., Toshiba) promote nearly exclusive addition of phenoxide hardener moieties to the epoxy rings. Tertiary amine catalysts also promote this addition, but they allow for a small level of epoxy-to-epoxy addition called homopolymerization (see Fig. 4).

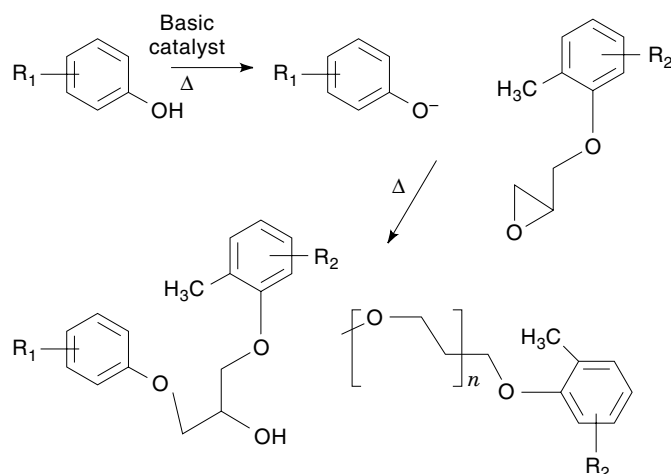


Figure 4. The typical curing reactions of novalac epoxies with novolac resin hardeners using basic catalysts.

It is generally felt that homopolymerization leads to poorer electrical properties. Other catalyst classes are used less frequently. Lewis bases, like diazabicycloundecene (DBU), behave similarly to amines and lead to good electrical properties, low moisture absorption, and good storage stability. Imidazoles, like 2-methyl imidazole, have high reactivity and good high-temperature resistance but moisture and electrical properties are lower. Lewis acids initiate cycloaliphatic epoxies cationically.

Catalyst selection is another highly secret formulator art. The desire is for a truly latent catalyst that will accelerate the cure suddenly upon mold cavity fill temperatures around 130°C but keep the EMC stable indefinitely at storage conditions, typically -5°C . Chemically blocked catalysts are revealed (17) but no one manufacturer seems to have a significant advantage. Toxicity, safety, cost, and convenience (usually solid forms are preferred) contribute to catalyst choices.

RELIABILITY

A reliable semiconductor package performs its electronic function properly throughout its expected lifetime in its normal working environment. It does this by providing a tough, solid encasement that is low in corrosive ions and retards migration of harmful chemical species within or outside the package.

However, it also contributes new potential reliability issues. The plastic package is not hermetic like ceramic box packaging. It reduces moisture penetration rates and it can prevent water from pooling at the semiconductor surface, but moisture is always absorbed within the plastic. This moisture can transport ions to the semiconductor surface. It can also vaporize during board assembly, thereby exploding or damaging the package. The term *popcorn* refers to such explosive damage. Some plastic formulation ingredients themselves can supply harmful chemical species. The plastics cure shrinkage and thermal expansion mismatch with the die, substrate, or leadframe create stresses.

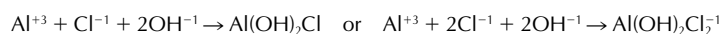
Reliability engineers expose packages to accelerated testing, generally at temperature extremes, to generate statistical data of failure rates and to study failure mechanisms. Models then predict expected real-world performance lifetimes from this data (18).

Stress

The greatest source of stress at the semiconductor and printed circuit board surfaces is the result of a thermal expansion mismatch between the components. The silicon die has a TCE of only approximately 2.3 ppm/K. The encapsulants typically have values of 10 ppm/K to 25 ppm/K, the leadframe metals have values of 4 ppm/K to 20 ppm/K and printed circuit boards have values near 15 ppm/K. A simple model for such stresses is one part of the popcorn model described later.

The design engineer must account for all interfaces and structures within the semiconductor package and the assembled PC board. Finite element calculations find extensive use. Moire fringe analysis and stress sensors provide direct stress data. Semiconductor manufacturers test real package electrical performance after extensive cold-to-hot temperature cy-

The adsorption of the aggressive halide ion (Cl^- or Br^-) on the aluminum oxide film:



The thinning of the oxide film and direct attack of the exposed metal with the formation of transient complexes:



The transient complexes hydrolyze producing the aggressive Cl^- anion:



And, this anodic reaction recycles.

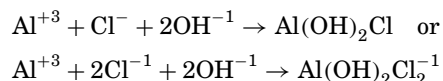
Figure 5. The halide catalyzed aluminum corrosion cycle (9,20).

cles. Generally, the plastic encapsulant transitions the stresses from the low-expansion silicon chip to the high-expansion PC board.

Corrosion

Corrosion refers to the semiconductor metal traces on or within the die surface. This corrosion involves water and usually an ionic species, which catalyzes the metal oxidization to a nonconductor. For epoxy molding compounds the most known ionic species is the chloride ion, always present as an epoxy resin contaminant. Figure 5 is the classical corrosion mechanism.

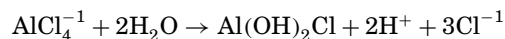
The adsorption of the aggressive halide ion (Cl^- or Br^-) on the aluminum oxide film can be expressed as follows:



The thinning of the oxide film and the direct attack of the exposed metal with the formation of transient complexes, that is,



The transient complexes hydrolyze producing the aggressive Cl^- anion:



and, this anodic reaction recycles (19,20).

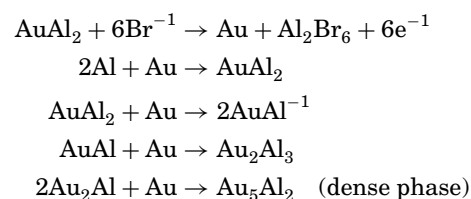
Commercial encapsulants have tolerably low chloride levels, but other ions can come from the environment, typically from solder fluxes and other processing chemicals. These ions can quickly enter the package along any delamination pathways between the encapsulant and the assembly. Scavenger ions or getters help immobilize these corrosive species (20–22).

Semiconductor producers use accelerated testing to validate corrosion resistance. All tests use heat and moisture usually applied to devices operating at excessive dc voltages to encourage ion migration. The most severe is the highly accelerated stress testing (HAST) which usually operates at a couple of atmospheres of unsaturated steam pressure at the corresponding temperature (typically 145°C). Devices that

survive over a couple of hundred hours under such corrosion stress generally provide excellent real-world corrosion resistance performance. C-mode scanning acoustic microscopy (SAM) is widely used by plastic engineers to detect the delamination of the transfer molded packages. It has proved to be very useful.

Intermetallic Bond Failure

Most semiconductor devices use aluminum (and, more recently, copper) metal conductor traces and gold wires to connect these conductors to the metal leadframe or solder ball interconnects. A classical failure mechanism involves the gold–aluminum interface. It results from a dense gold–aluminum phase that forms at the interface. The dense phase robs the surrounding region of metal, thus creating voids leading to bond weakening. This occurs even with bare-wired devices, but is accelerated in the presence of the molding compound. The brominated resins used to flame retard slowly liberate bromine ions and these accelerate the dense intermetallic phase formation (see Fig. 6):



Encapsulant formulators mitigate these effects by minimizing the bromine resin levels, adding insoluble salts called scavengers or getters to chemically or physically intercept the bromine radicals and by using polymeric systems with high glass transition temperatures to retard molecular diffusion. Anti-

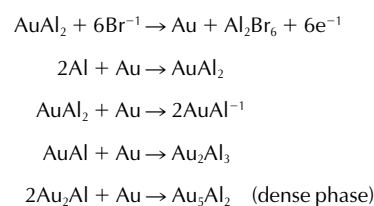


Figure 6. The chemistry of ball bond weakening from intermetallic alloying catalyzed by bromine ions.

mony pentoxide is preferred because it requires higher temperatures to catalyze the bromine radical release. Biphenyl resin chemistry is particularly prone to problems because of its low T_g .

Moisture-Induced Assembly Failure

This is the so-called popcorn phenomenon. Moisture within the package vaporizes during high temperature assembly operation like reflow soldering. The steam pressurizes pockets within the package, particularly at interfaces. The package bulges and cracks (with a popping sound) creating damage to the package and sometimes the semiconductor assembly (23–25). Formulators seek to minimize this failure mode by maximizing the adhesion to the assembly surfaces and maximizing the strength and fracture toughness at the solder reflow temperatures while minimizing the moisture absorption and the stress from thermal expansion mismatches.

One model assumes that failure originates in a region of adhesive delamination caused by the thermal expansion mismatch of the plastic and lead metal at reflow temperatures. It then compares the ability of the plastic to resist being ruptured by the steam generated within the delamination region (26).

$$\tau_{\text{FEM}} = 0.293 \times \{(4.731 - 4.024 \times t_{\text{chip}}) + (2.514 + 1.176 \times t_{\text{chip}}) \times \ln(t_{\text{pkg}})\} \times E_R \times \Delta T \times \Delta\alpha$$

where

$$\begin{aligned} \tau_{\text{FEM}} &= \text{stress calculated from the finite element model} \\ t_{\text{chip}} &= \text{chip thickness} \\ t_{\text{pkg}} &= \text{package thickness} \\ E_R &= \text{Young's modulus of EMC at reflow temperature} \\ \Delta T &= (T_{\text{reflow}} - T_{\text{mold}}) \\ \Delta\alpha &= (\alpha_{\text{EMC}} - \alpha_{\text{chip}}) \end{aligned}$$

To avoid delamination, the measured adhesive shear strength under hot, wet reflow conditions must be greater than this stress from thermal expansion mismatches ($\tau_{\text{FEM}} < \tau_{\text{meas}}$).

The package will crack if the force from the internal steam pressure is great enough:

$$K_j = 0.1943 \times 224.5 \times (Ns) \times [(P_w)^{1.946}]/[(t_b)^{1.294}]$$

where

$$\begin{aligned} K_j &= \text{calculated cracking potential ratio} \\ Ns &= \text{moisture absorbed after Level 1* conditioning in grams per cubic millimeter} \\ P_w &= \text{die pad width (shorter dimension) in millimeters} \\ t_b &= \text{thickness of the plastic between bottom of the package and bottom of die pad in millimeters} \\ * \text{Level 1: Test condition } &-85^\circ\text{C}/85\% \text{ RH for 168 h by JEDEC} \end{aligned}$$

To avoid cracking the K_j value should be less than the measured fracture toughness, K_{1C} , of moisture conditioned plastic, again at the reflow temperature.

Even this model is too simple to accurately predict the popcorn performance over a broad number of package design dimensions and plastic properties. However, by studying a re-

sponse surface plot of the delamination potential ratio ($\tau_{\text{meas}}/\tau_{\text{FEM}}$) values versus the resistance to steam-induced cracking ratio (K_{1C}/K_j), good design rules emerge. For thinner packages (1.0 mm or less), improving the adhesion will be more effective than improving the EMC toughness in reducing cracking. However, for the thicker packages (3.6 mm and above) improving the EMC toughness will be the more effective strategy to control cracking. It should also be obvious that package cracking is less likely if the silicon die is smaller and if the ratio of plastic to die is large.

A more recent model uses fracture mechanics analysis of an inherent edge crack along the die pad–plastic interface toward the center of the pad, leading to total delamination and then popcorn failure (27). This study shows that the delamination is more likely as the package cools after the reflow soldering and is then more susceptible to failure. Another study considers the stresses caused by both the thermal and moisture expansion of the polymer. It recognizes that the moisture absorption is time dependent and that it varies within the plastic cross section (28).

NON-EPOXY-BASED PACKAGING POLYMERS

Polyimides

The superior thermal stability (up to 500°C), mechanical properties, and electrical properties of polyimide provides high performance. In addition, polyimides show very low electrical leakage in surface or bulk. They form excellent inter-layer dielectric insulators and also provide excellent step coverage, important in fabrication of the multilayer IC structures. They require wet processes like spraying or spinning and can be imaged by a conventional photolithography and etch processes.

Most polyimides are aromatic diamine and dianhydride compositions (see Fig. 7). Changes in the diamine and dianhydride allows broad tailoring of the basic tensile properties. Polyamic acids are precursors of the polyimides. Thermal cy-

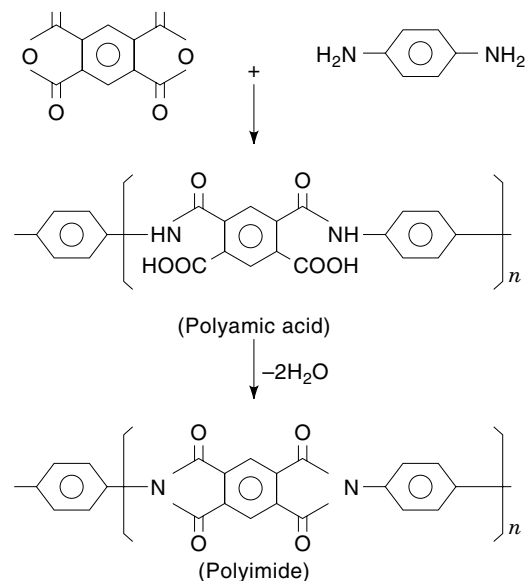
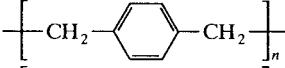
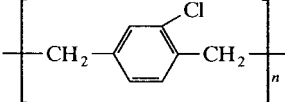
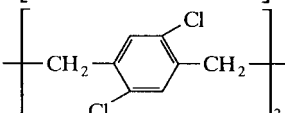


Figure 7. Typical polyimide synthesis and cure mechanism.

Table 4. Typical Properties of Parylenes

Type of Parylenes	Deposition Rate ($\mu\text{m}/\text{h}$)	Properties		
		Dissipation Factor	Dielectric Constant	Water Absorption (%)
N type: 	1	0.0002	2.6	0.02
C type: 	3–5	0.02	3.1	0.06
D type: 	10–15	0.01	3.6	0.07

clization of polyamic acid is a simple curing mechanism for this material. However, the affinity for moisture absorption due to the carbonyl polar groups of the polyimide, a high-temperature cure, and high cost of the polyimide are the only drawbacks that prevent its use in low-cost consumer electronic application. Preimidized polyimides that cure by solvent evaporation reduce the drawback of a high temperature cure of the material but does not reduce the high-moisture absorption. Photo-definable polyimides, particularly the positive acting ones, are becoming commercially attractive.

Parylenes

Parylene, a poly-(para-xylylene), was first developed by Union Carbide Corporation (29). The process uses a thermal reactor to first vaporize (at 150°C , 133 Pa pressure) and pyrolyze (at 680°C , 67 Pa) the di-para-xylylene, then polymerize the dimer into polymer at room temperature. This room temperature deposition is a very attractive encapsulation process, especially for temperature-sensitive, low T_g substrate materials. There are no solvents, catalysts, or other impurities in the formed film. Parylene deposition provides an excellent conformal step-coverage and conformal film with thickness ranging from $2\ \mu\text{m}$ to $50\ \mu\text{m}$. Because it is a room-temperature, spontaneous, and a gas-to-solid deposition process, encapsulated electronic parts experience minimal stress.

The deposition rate of parylene depends on the types of parylenes. The dichloro- and monochloro-substituted on the benzene ring of the Parylene D and C, respectively, and tetrafluoro-methylene substituted Parylene F, have a faster deposition rate than the normal unsubstituted Parylene N. The deposited Parylene film has excellent electrical properties, low-water absorption, and excellent chemical resistance (see Table 4).

This process is widely used in conformal coatings on military circuit boards to resist severe abrasion. Recently, parylene coatings are being used as the sole package protection for flip-chip multichip module assemblies. They also form the underfill adhesive. However, the high cost of the starting dimer and the deposition equipment prohibits its wide use in consumer electronic applications.

Benzocyclobutenes

The high-performance benzocyclobutene (BCB) polymers were developed by Dow Chemical Company from the structure

shown in Fig. 8. The cross-linking process is carried out by the thermal rearrangement of the dicyclobutene monomer to form the reactive intermediate orthoquinodimethane, which can polymerize with the unsaturated functional group. Because it is based on the thermal rearrangement process, BCB requires no catalyst and there are no by-products during the curing process. The properties of BCB can be modified by the substituted group X in structure 1 of Fig. 8. Dimethylsiloxane groups as the substituted X groups, enhance BCB's adhesion and reduce its modulus. BCB monomers are normally *B-staged* (partially thermally cross-linked) to enhance their vis-

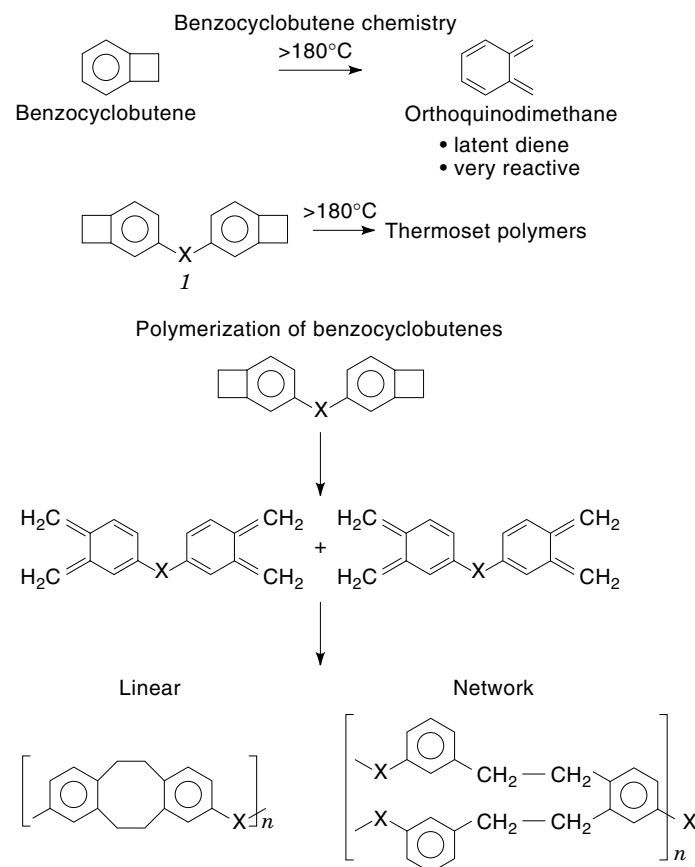
**Figure 8.** Synthesis and polymerization of benzocyclobutene.

Table 5. Typical Properties of Benzocyclobutene

Flexural modulus, psi	498,000
Dielectric constant, 10^4 – 10^7 Hz	2.68
Dielectric strength	10,000 V/mil
Dissipation factor, 10^4 – 10^7 Hz	$<10^{-3}$
Coefficient of thermal expansion (25–3000°C), ppm	34
Safe use temperature (in nitrogen)	348°
0% weight loss temperature, °C	450
T_g , °C	350
Resistivity	10^{19} Ω/cm
Water absorption	0.2 (24-h water boil)
Flexural strength	10,300 psi
Elongation	$<1\%$
Hardness	3H (pencil lead test)

cosity stability. The commercially available BCB is usually in a B-stage diluted with xylene for spin-coating application. BCB has excellent physical, chemical, and electrical properties similar to polyimides. With its low dielectric constant (2.7), low moisture absorption ($<1\%$), and good adhesion properties, BCB is a candidate for thin coating type applications (refer to Table 5).

Polyurethanes

These are tough, elastomeric polymers made by reacting isocyanate pendent molecules with polyols. The reaction is rapid, even at room temperature, but gaseous by-products, like carbon dioxide, can lead to voids. Indeed, synthetic rubber foams are almost always based on this chemistry. The wear-resistant, no-wax layers on vinyl flooring provide testament to the durability of polyurethanes. The difficult control of the curing reaction limits urethanes to coatings such as conformal coatings applied over a populated circuit board. Alternatively, a prereacted urethane oligomer can be capped with epoxy or acrylate end groups and cured by more appropriate reactions (including ultraviolet radiation). Like the polysiloxanes, the low T_g values allow rapid migration of water, gases, and ionic contaminants. Unlike the polysiloxanes (see below), the urethane chemistry does little to protect the semiconductor surfaces from the corrosive influence of these migrating species.

Silicones (Polyorganosiloxanes)

Silicone polymers have a backbone repeat of alternating silicon and oxygen atoms (the siloxane group). They were one of the first polymeric encapsulants and still find some use,

especially where their low modulus minimizes strain. Room temperature vulcanizing (RTV) silicones cure by a condensation reaction. The moisture-initiated, catalyst (such as tin dibutyl dilaurate) assisted cure chemistry generates water or alcohol by-products which can cause outgassing and voids. This severely restricts their use to either thin coatings or applications tolerant of slow curing and baking stages. Their low surface tension helps them to creep and run over the encapsulated IC circuits. Solvents like xylenes and Freons reduce the encapsulant viscosity and are baked out during the condensation cure.

Table 6 shows a typical RTV silicone formulation used by AT&T (now, Lucent Technologies) in electronic encapsulation. This RTV silicone has been used to protect the bipolar, metal oxide semiconductor (MOS), hybrid IC for over 20 years. The ability of the RTV silicone to form chemical bonds with the coated substrate is one of the key reasons the material achieves excellent electrical performance. The reactive alkoxy functional groups of the silicone react with the surface hydroxyl groups to form a stable inert silicon–oxygen–substrate bond. In addition, this chemical reaction consumes the substrate surface hydrophilic hydroxyl groups that hydrogen bond with diffused moisture. Even though the silicones have low T_g values and high moisture diffusion coefficients, this surface bond occupation mechanism protects the semiconductor devices from corrosion, providing reliability without hermeticity.

Heat curable silicones (either elastomer or gel) cure much faster than the RTV-type silicone, do not liberate volatile by-products, and have slightly better high-temperature stability. The cure chemistry is the addition of a hydrosilyl (Si–H) group to a vinyl group, catalyzed with platinum compounds such as chloroplatinic acid (see Fig. 9 for the cure mechanism). A low viscosity formulation contains a vinyl-terminated polydimethylsiloxane with a moderate low-viscosity range from 200 to a few thousand centipoise (cps), and a low viscosity (range from a few cps to ~ 100 cps) di- or multifunctional hydride-terminated polydimethylsiloxane.

Silicone–Polyimides (New Modified Polyimides)

Combining the low modulus of the siloxane, and the high thermal stability of polyimide, the siloxane–polyimide (SPI) copolymers are fully imidized copolymers and are soluble in low boiling solvents such as diglyme which reduces the high processing temperature and eliminates the outgassing of water during the normal polyimide imidization (cure) process. The SPI has good adhesion to many materials, and eliminates

Table 6. Typical RTV Silicon Formulation

Ingredients	Concentration (phr)	Impact on Properties
Base polymer (OH-terminated polydimethylsiloxane)	100	Physical and mechanical
Crosslinker: (OMe) ₃ SiMe	8	Physical and mechanical
Catalyst (titanate)	0.5	Cure rate
Inhibitor (isopropanol)	0.25	Longer shelf-life and pot-life
Filler(s): SiO ₂	10	Physical and mechanical
TiO ₂	2–3	Opacifer
C-black	0.05	Pigment
Solvent (xylenes)	0–50	Rheological control diluent

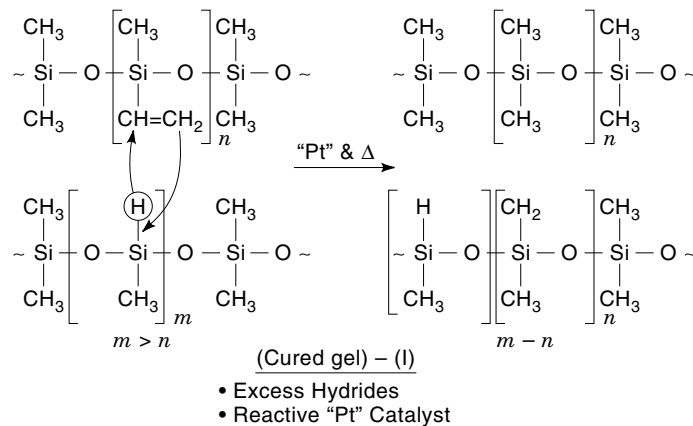


Figure 9. The chemical reaction mechanisms of silicone gel (hydrosilylation).

the need for an adhesion promoter. Polycondensation and poly addition reactions synthesize these materials as both thermoplastics and thermosets. In addition, photo- and thermocurable SPIs are also obtainable by incorporating a photo-reactive functional group into the polymer chains. These materials find use in device encapsulants, interlayer dielectrics, and coatings that demand high performance and can tolerate high costs and solvent-based processing.

Thermoplastics

Several thermoplastics, particularly poly(phenylene sulfide) and liquid crystal polyesters have attractive properties for packaging. Being thermoplastic, all molding scrap from runners and culls is recyclable and they would be used without refrigeration for storage. However their relatively high molecular weight, compared with uncured epoxy resins, and the higher temperatures and pressures associated with injection molding has always lead to excessive wire sweep. Newer, low-molecular-weight liquid crystal polyesters may allow injection molding of some packages, particularly passive devices with sturdy wiring (30).

PROCESSING

Transfer Molding

A transfer mold (17,31) contains a series of in-line cavities, one for each eventual semiconductor package. Each cavity has very small exhaust channels, called vents, that allow air to exit the cavity as the molding compound enters. A runner lays parallel to the strip cavity set, and it feeds the molding compound to each cavity through small entrance ports called gates. Usually, the runners are cut into only one-half of the mold. Large molds also contain primary runners, which connect these strip runners to the main transfer pot. The transfer pot is a cylinder cut through one of the mold halves, and it receives the molding compound initially. It is often near the center of the mold. Knockout pins lay flush with the runner and cavity surfaces during the molding cycle and then extend into those regions to push the molded devices and runners out when the mold opens. The mold may contain heater elements within its body or it may depend on heat transfer from the press structure.

The operational process is simple and usually automated (refer to Fig. 10). The mold opens and new strips of several in-line, preassembled devices load into the inline cavities. The actual active silicon devices are somewhere near the middle of the cavities. The mold closes and the molding compound, almost always a solid tablet, is placed into the transfer pot. This tablet may be prewarmed or it may rely on heat transfer from the mold. Then, the transfer ram compresses the tablet into the runner system. By the time material starts to enter the cavities, it is fully molten and usually at its viscosity minimum. This transfer continues at near-atmospheric pressures until all cavities fill. The pressure then increases to approximately 6.4 MPa to pack-out the molding compound. This increase in pressure effectively reduces the diameters of any voids to a fourth their original values and it ensures that the sharp cavity corners fill out completely. This pressure holds until the molding compound cures and becomes rigid enough to support the devices and the strips. The mold opens, the knockout pins automatically extend and all molded packages and runners eject into collection systems. Brushes then clean away any residue or flash molding compound and the cycle begins again.

Conventional molds dominated in the 1970s through the 1980s. These were huge, complex molds with a single, large pot often holding up to a half-kilogram EMC tablet. There were several dozen to a thousand individual package cavities. The strip loading, tablet loading, parts removal, and cleaning operations were usually manual because of the complexity of the molds. While these molds were extremely economical, they were also unbalanced, meaning that some cavities were filled sooner than others. This design allowed variations in gold or aluminum interconnect wire movement (called *wire*

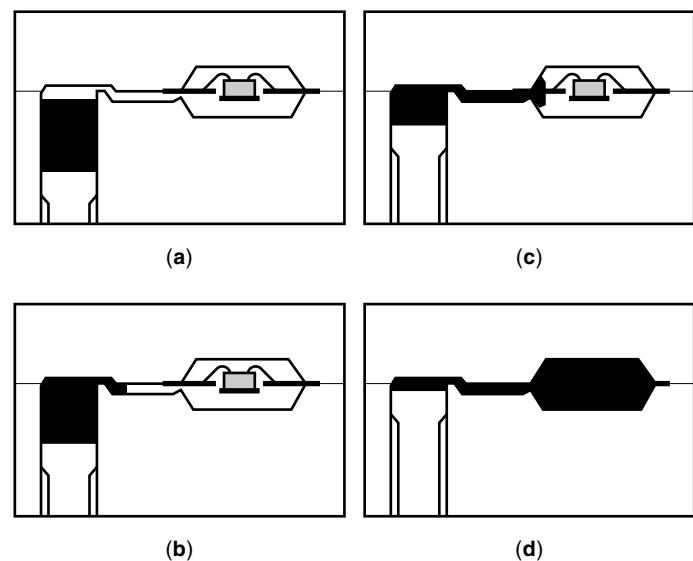


Figure 10. Schematic of the transfer molding process (cross section of the closed mold). (a) The mold is closed and the preform of EMC is in the transfer pot (the illustration shows only one cavity with a lead-frame and wired die). (b) The transfer ram begins to transfer the warm molding compound into the molding runners. (c) The molding compound has now entered the cavity through the gate. (d) The cavity is completely filled and the pressure increases to compress any remaining air pockets.

sweep), and variations in void levels and sizes. Cycle times ran from 90 s to 240 s.

Newer molds now use several smaller pots and rams, and the cavities are symmetrically located. These are balanced, and all cavities experience the same flow profiles and pressure profiles during fill. These are called *gang-pot molds* because of the chain-gang alignment of the plungers and pots.

The presses, which hold and operate the mold, have three main functions: They clamp the molds closed, they move the transfer ram, and they control the mold temperature. Automated presses, typical for gang-pot molds, manage all other functions like device loading, device/runner ejection, and cleaning robotically with almost no operator input. Hydraulic clamping and transfer control is trending toward stepping motor control. Stepping motors do not vent airborne oil, they generally require less maintenance, and they are readily controlled with digital electronic processing. Cycle times under a minute are typical and some operate as low as 15 s. A state-of-art, fully automated, gang-pot press costs over a million dollars.

Liquid Dispensing Processes

Room-temperature liquid formulations and their simpler processes are more convenient than high-temperature tablet transfer molding for some applications. A glob-top encapsulate is dispensed atop the semiconductor assembly and solidified by heat or radiation. The capital equipment investment can be negligible. Applications that have lower appearance and reliability demands and more available labor than capital often use glob-top processes. The primary examples are for protection of electronics in quartz watches and in toys and novelties.

Liquid dispensing is appropriate in some high-end applications. Some ball grid array package designs mount the device into a cavity, which could not be filled readily by transfer molding but which nicely contains a dispensed liquid. Some applications cannot tolerate the higher temperatures associated with transfer molding. Liquid assembly adhesives, underfills, and coatings often are part of the PC board assembly operation. Automated equipment controls the dispensing processes using syringes as the formulation reservoir and hypodermic needles to deliver it to the proper position. This equipment must visually identify the application locations and paths, precisely position the dispensing syringe needle (in three dimensions), deliver a precisely measured amount of liquid (often along a path), and prevent drips into unwanted areas. Furthermore, the equipment often must carefully preheat the compound in the syringe and preheat the assembly region (often in all three dimensions). This involves rastering the syringe and/or PC assembly in a thermally controlled oven while microdispensing the liquid, all under sophisticated computer controls. In applications where a single, low-viscosity liquid would migrate away from the intended area of deposit, a dam of high-viscosity immobile compound first surrounds the region to contain the low-viscosity encapsulant within the dam. These glob-top, adhesive and underfill compounds are much more expensive than transfer grade encapsulants. Therefore, these liquid processes are expensive and used only when transfer molding is not a good option. Furthermore, dispensing is virtually a one-package-at-a-time, slow process. This liquid processing is a good option for prototype parts, because machined molds are unnecessary.

Potting is a term associated with the simplest possible liquid encapsulation process. It involves placing the electronic component within a container, filling the container with a liquid resin, and then curing the material as an integral part of the component. Polymeric resins (such as epoxies, silicones, and polyurethanes) are typical potting materials. The potting containers, like metal or plastic cans or boxes are integral to the final package and enhance the effectiveness and appearance of the encapsulated package. Like the low-end glob-top process, potting is favored where labor is more available than capital and for processing small numbers of large parts.

Other Processes

Passivation. Application of a *passivation layer* usually completes the wafer IC fabrication process ahead of encapsulation. This coating mechanically protects the IC devices during dicing of the wafer (singulation process). It also greatly reduces mobile ion migration into the semiconductor layers. Accordingly, it is sometimes considered the first layer of packaging protection. Inorganic polymers such as silicon dioxide, silicon nitride, and silicon oxynitride dominate. Although, silicon dioxide and silicon nitride are both excellent moisture barriers, silicon dioxide is still permeable to mobile ions such as sodium, particularly, under bias conditions. The use of a getter such as phosphorus pentoxide (P_2O_5)-doped silicon dioxide or P glass mitigates this. However, silicon nitride eliminates these mobile ion diffusion problems. Sometimes, organic polymers such as polyimides, benzocyclobutenes, and silicone-polyimides, in particular, the photodefinable derivatives serve as passivating materials. The material usually deposits with a thickness of $0.25\ \mu\text{m}$ to $2\ \mu\text{m}$, with multilevel coating for better reliability protection of the ICs. Photolithography removes the coatings from the bond pad areas of the IC. Several of the ingredients in the epoxy molding compound, later encapsulating the device, help to restore flaws in the passivation layer. In particular, silane coupling agents and hydrophobic release agents help isolate damaged regions.

Assembly Cleaning. The assembly of the semiconductor chip to its lead metal or organic substrate can create surface contamination, which would interfere with proper encapsulant adhesion. Precleaning the assembly is sometimes essential and almost always desirable, but production economics minimize its general use. The cleaning processes can also activate the surfaces to better react with the encapsulant-forming chemical bonds to enhance adhesion. In particular, the solder mask surface of the organic substrate used with ball grid array packages is formulated to repel solder, and it also repels the encapsulant. Plasma cleaning prepares the solder mask for good adhesion and also improves adhesion to the silicon chip, the gold wires, and the aluminum pads.

Chemical cleaning processes use organic solvents and detergents to remove organic contaminants. Inorganic contaminants use aqueous or polar solvents like alcohols. Restrictions on the use of chlorinated solvents and health, safety, and disposal issues have limited the chemical cleaning process to high-value and low-volume packaging operations. The dry process is preferred.

Reactive oxygen cleaning is one such dry process effective in removing low-level organic contaminants. These use ultraviolet light, oxygen plasma, and ozone (alone or in pairs) to

remove a few monolayers organics from the substrate surface. Ultraviolet chambers generate ozone from air and are inexpensive. Plasma oxygen operates at 13.6 MHz radio frequency (RF), is fast and effective in cleaning an MOS device, and preserves the aluminum metallization of the devices. However, the thermal stress associated with the plasma process may damage some device structures. Microwave discharge oxygen cleaning at 2.5 GHz RF is a similar technique. Reactive dc-hydrogen plasma processes are common. The plasma process use an argon-hydrogen discharge generated between the heated filament (cathode) and the reactor wall (anode) at a current density from 10 A to 100 A and low voltage of 20 V to 30 V. The process is simple, environmentally friendly, and does not oxidize metal surfaces.

HERMETIC PACKAGES

No material is truly hermetic to moisture. The permeability to moisture of glasses, ceramics, and metal, however, is orders of magnitude lower than for any plastic material. Although polymeric-sealed devices can be designed to pass even fine leak tests, moisture will move through the seal in hours. Hence, the only true hermetic packages are those made of metals, ceramics, and glasses. There are two basic types of hermetic packages in wide use today: (a) metal packages and (b) ceramic packages.

The common feature of these packages is the use of a lid or a cap to seal in the semiconductor device mounted on the bottom of a boxlike or canlike hollow substrate. The leads entering the package also need to be hermetically sealed. In ceramic packages, the leads are formed by thick-film screen and fire techniques and are commonly embedded in the ceramic itself. Cerdip packages are unique in that the same sealing member seals in both the cap and the leads. To satisfy the requirement of hermeticity, cap seals in all these packages are formed by fusing a suitable glass or metal. In brazing and soldering, a low-melting braze or solder alloy forms the seal. In welding, the cap itself is partially melted to effect the seal. These different types of seals are described in greater detail later.

Metal hermetic packages are used extensively in military applications because of their enviable record of reliability under the harshest use conditions. There are four types of metal packages: round header [Fig. 11(a)], platform [Fig. 11(b)], flat pack [Fig. 11(c)], and monolithic [Fig. 11(d)]. The round header or the TO packages have been in use since the earliest days of the transistor and are still employed to package discrete devices and smaller hybrid circuits. The platform packages provide up to 16 leads (inputs and outputs), whereas the more versatile flat pack is a low-profile package used for LSI and VLSI with up to 200 leads. The monolithic package is a rugged package constructed of a single-piece platform providing up to 88 leads. Nearly 80% of all metal packages are welded, with the remaining 20% being soldered.

Ceramics and glasses, defined as inorganic and nonmetallic materials, have been an integral part of the semiconductor industry. Glasses and ceramics possess a combination of electrical, thermal, and dimensional stability properties unmatched by any group of materials. For example, ceramics have dielectric constants from 4 to 20,000, thermal-expansion coefficients matching silicon (3×10^{-6} ppm/K), and thermal

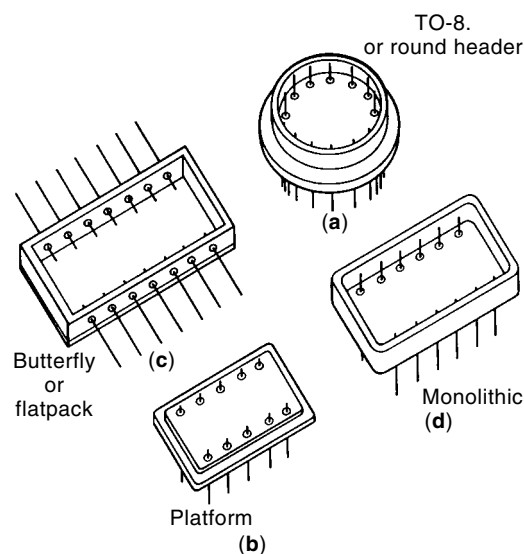


Figure 11. Common types of metal packages.

conductivity from that of insulated brick ($0.2 \text{ W/m} \cdot \text{K}^{-1}$) to better than aluminum metal ($220 \text{ W/m} \cdot \text{K}^{-1}$), which is one of the best metallic thermal conductors known.

The only packages that achieved the highest reliability have been ceramic packages, and, as a consequence, the packages that are used today where there are stringent reliability requirements are ceramic packages. These uses include most of the defense and aerospace applications and the leading-edge microprocessors (Pentium and Power PC) for commercial application. However, Intel is beginning to use plastic packages for its Pentium II microprocessor. They do not absorb and retain moisture, nor do they allow permeation of gases. Second, their dimensional stability during and after high-temperature processing is exceptional. Some of the advantages of this stability come from the intrinsic low thermal expansion, similar to that of silicon IC devices. Third, the chemical inertness of most of the ceramics to water, acids, solvents, and other chemicals is outstanding.

Ceramics are brittle, making them prone to catastrophic failure and sensitive to stress corrosion. They do not support the interconnection wires and therefore cannot stand acceleration forces as well as plastic packages. Furthermore, lead seals are much more easily damaged by testing or assembly than plastic packages. This leads to higher failure rates soon after assembly. Although the fired ceramic package components have exceptional dimensional stability they cannot be made with as precise dimensional specifications as plastic packages. This is because of the loss of dimensional control during the firing process itself.

BIBLIOGRAPHY

1. D. R. Hudson, Density and packing in an aggregate of mixed spheres, *J. Appl. Phys.*, **20**: 154–162, 1949.
2. H. S. Katz and J. V. Milewski (ed.), *Handbook of Fillers for Plastics*, New York: Van Nostrand-Reinhold, 1987.
3. Dow Chemical Company, 1-800-477-4369, *Introducing SCAN*, Form No. 618-00132-1096 SMG, 1996.

4. I. Birkby, Boron nitride—a review, *Ceramic Technol. Int.*, 57–61, 1994.
5. H.-J. Lindner, Germany Patent No. 3862057, 1975; also P. J. Proctor, U.S. Patent No. 4,826,896, 1989.
6. M. Shinohara, U.S. Patent 4358552, 1982.
7. E. W. Flick, *Epoxy Resins, Curing Agents, Compounds and Modifiers*, Park Ridge, NJ: Noyes, 1987.
8. C. A. May, *Epoxy Resins Chemistry and Technology*, New York: Marcel Dekker, 1988.
9. B. Ellis, *Chemistry and Technology of Epoxy Resins*, Glasgow: Blackie, 1993.
10. J. I. DiStasio (ed.), *Epoxy Resin Technology Developments Since 1979*, Park Ridge, NJ: Noyes, 1982.
11. H. Lee and K. Neville, *Handbook of Epoxy Resins*, New York: McGraw-Hill, 1982.
12. E. W. Flick, *Plastic Additives; An Industrial Guide (Supplier Sources)*, Park Ridge, NJ: Noyes, 1986.
13. M. Shinohara, Popcorn resistant mold compound with improved HTOL performance. Plastic Packaging Manufacturing Conference, Semicon West 1997, H1, 1997.
14. I. Touval, Antimony flame retardants, *Plastics Compounding*, 106–117, 1985.
15. E. R. Hunt, R. K. Rosler, and J. O. Peterson, U.S. Patent 4282136, 1981.
16. K. Shimizu, M. Tanaka, and A. Todunaga, World Patent application WO 9724402 A, 1997.
17. N. Kinjo et al., Epoxy molding compounds as encapsulation materials for microelectronic devices, *Adv. Polymer Sci.*, **88**: 24–48, 1989.
18. D. A. Jeannotte, L. S. Goldmann, and R. T. Howard, Package reliability, in R. R. Tummala, E. J. Rymaszewski, and A. G. Klopfenstein (eds.), *Microelectronics Packaging Handbook*, New York: Chapman and Hall, 1997, chap. 5.
19. X. Shan, M. Pecht, and A. Christou, Corrosion modeling in microelectronic devices, *Int. Soc. Hybrid Microelectron.*, **15** (1): 1–10, 1992.
20. M. M. Khan and H. Fatemi, Gold aluminum bond failure induced by halogenated additives in epoxy molding compounds, *Proc. Int. Symp. Microelectron.*, 1986, pp. 420–429.
21. S. Mizugashira, H. Higuchi, and T. Ajiki, Improvement of moisture resistance by ion-exchange process, *Proc. IEEE Int. Rel. Phys. Symp.*, 1987, pp. 212–215.
22. C. P. Wong, U.S. Patent 4,278,784, 1981.
23. N. Mogi and H. Yasuda, Development of high-reliability epoxy molding compounds for surface mount devices, *Proc. 42nd Electron. Components Technol. Conf. IEEE, New York*, 1992, pp. 1023–1029.
24. S. Altimari et al., Role of design factors for improving moisture performance for plastic packages, *Proc. 42nd Electron. Components Technol. Conf. IEEE, New York*, 1992, pp. 71–77.
25. H. Harada et al., X-ray analysis of the package cracking during reflow soldering, *30th Annu. Proc. Reliab. Phys. IEEE, New York*, 1992, pp. 182–189.
26. Y. Inoue et al., A synthetic criterion for level-1 crack-free package—proposal of a superior package structure, *46th Electron. Components Technol. Conf. IEEE, New York*, 1996, pp. 71–77.
27. Y. B. Park and Jin Yu, A fracture mechanics analysis of the popcorn cracking in the plastic IC package, *Proc. IEEE CPMT Int. Electron. Manuf. Technol. Symp.*, 1997, pp. 12–19.
28. S. Yi, J. S. Goh, and J. C. Yang, Residual stresses in plastic IC packages during surface mounting process preceded by moisture soaking test, *IEEE Trans. Comp. Packag. Manufact. Technol. B., CPMTB-20*: 247–255, 1997.
29. W. F. Gorham, A new general synthetic method in the preparation of linear poly-p-xylylenes, *J. Polymer Sci.*, **4**: 3027–3035, 1996.
30. P. Koning, A thermoplastic encapsulant for electronic packaging. *Semicond. Packag. Symp., Semicon West 1998*, 1998, p. G4.
31. L. T. Manzoni, *Plastic Packaging of Microelectronic Devices*, New York: Van Nostrand-Reinhold, 1990.

Reading List

- M. T. Goosey, *Plastics for Electronics*, Essex, England: Elsevier, 1985.
- J. Lau, C. P. Wong, and W. Nakayama, *Electronic Packaging, Design, Materials, Process, and Reliability*, New York: McGraw-Hill, 1998.
- M. G. Pecht, L. T. Nguyen, and E. B. Hakim (ed.), *Plastic-Encapsulated Microelectronics*. New York: John Wiley, 1995.
- C. P. Wong et al., Sealing and encapsulation, in R. R. Tummala, E. Rymaszewski, and A. Klopfenstein (eds.), *Handbook of Electronic Packaging*, New York: Chapman and Hall, 1997, chap. 10.
- C. P. Wong (ed.), *Polymers for Electronics and Photonics Applications*, New York: Academic Press, 1993.

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ENCRYPTION. See CRYPTOGRAPHY.

ENERGY. See HYDROGEN ENERGY SYSTEMS.

ENERGY CONVERSION. See THERMIONIC CONVERSION.

ENERGY CONVERSION, OCEAN THERMAL. See OCEAN THERMAL ENERGY CONVERSION.

ENERGY FROM WASTES. See WASTE-TO-ENERGY POWER PLANTS.

ENERGY MANAGEMENT. See LOAD MANAGEMENT.