PACKAGING, ELECTRONIC MATERIALS

1. Introduction

Materials play an important role in the electronics industry. The effectiveness of the electrical performance of the system, its reliability, and its cost all depend on the packaging materials used, which are chosen for their properties and applications. As a result, the practicing engineer must have ready access to current information on the materials that can be used in product development. This article gives an overview of the various material choices for the elements of an electronic product.

Electronic packaging refers to the placement and connection of many, sometimes thousands, electronic and electromechanical components in an enclosure that protects the system from the environment and provides easy access for routine maintenance (1). The packaging process starts with a chip, which is fabricated from a wafer. A chip is electrically connected to a chip carrier or substrate. This is the first level of interconnection, for which various interconnection methods are available, including wire-bonding, tape automated bonding (TAB), and flip-chip (2). The substrate-chip assembly is packaged in a case; the chip carriers are then mounted to a common base, normally a printed circuit board. Various chip carriers are electrically connected by metallized conductor paths, forming the second level of interconnection. Next, the various printed circuit boards are mounted on a backplane, forming the third level of interconnection. Several racks may be interconnected to form a cabinet. The fourth level of interconnection involves the interconnection between various cabinets. Figure 1 illustrates the various levels of packaging, Figure 2 shows a ceramic package, and Figure 3 shows a plastic package.

2. Semiconductor Materials

Semiconductors (qv) are materials with resistivities between those of conductors and those of insulators (between 10^6 and 10^{-3} $\Omega{\cdot}\text{cm}$). The electrical properties of a semiconductor determine the functional performance of the device. Important electrical properties of semiconductors are resistivity and dielectric constant. The resistivity of a semiconductor can be varied by introducing small amounts of material impurities or dopants. Through proper material doping, electron movement can be precisely controlled, producing functions such as rectification, switching, detection, and modulation.

Silicon [7440-21-3] is by far the most commonly used die material in electronic packaging, employed by over 90% of the electronic industry. Among the other semiconductors popularly used are gallium arsenide [1303-00-0], indium phosphide [22398-80-7], germanium [7440-56-4], and silicon carbide [409-21-2]. A list of the materials used as semiconductors, along with their various properties, is given in Table 1. Silicon is similar to diamond and germanium, and is characterized by a negative temperature coefficient of resistance. Silicon, which has a gray metallic luster, is normally considered a brittle material, with a hardness intermediate between those of germanium and quartz. Silicon is most widely used in electronic applications as a material for dies, and also in the production of integrated circuits, rectifiers, diodes, transistors, and triacs.

Gallium arsenide is a dark gray material that is becoming increasingly popular as a semiconductor material. It is a compound semiconductor; the crystalline structure consists of gallium atoms alternating with arsenic atoms. Gallium arsenide is used in microwave devices, varactor diodes, schotty barrier diodes, light-emitting diodes, injection lasers, as well as Gunn-mode oscillators.

3. Substrate Materials

A substrate is a robust element that provides mechanical support for the die. It can be mounted with more than one die; such packages are called multichip modules. Because parasitic capacitance effects are directly proportional to the dielectric constant, substrate material should have a low dielectric constant. To minimize electrical losses, especially at high frequencies, a low dissipation factor is required. High volume resistance provides good insulation to prevent electrical current leakage between the conductor tracks. Since the substrate provides mechanical support to the die, its material should have good mechanical strength; it should also be thermally conductive to dissipate heat produced by the active devices. The coefficient of thermal expansion (CTE) of the substrate should match closely to that of the die to avoid thermomechanical stresses due to a CTE mismatch. The CTE of silicon is 2.3–4.7 ppm/°C and for GaAs, 5.4–5.72 (2,4).

Materials used for substrates can be broadly classified into ceramics and metals. Commonly used ceramics, ie, alumina, aluminum nitride, and beryllia, can be easily incorporated into a hermetic package, ie, a package permanently sealed by fusion or soldering to prevent the transmission of moisture, air, and other gases.

Alumina, or aluminum oxide [1344-28-1], has a thermal conductivity 20 times higher than that of most oxides (5). The flexural strength of commercial high alumina ceramics is two to four times greater than those of most oxide ceramics. The drawbacks of alumina ceramics are their relatively high thermal expansion compared to the chip material (silicon) and their moderately high dielectric constant.

Although beryllium oxide [1304-56-9] is in many ways superior to most commonly used alumina-based ceramics, the principal drawback of beryllia-based ceramics is their toxicity; thus they should be handled with care. The thermal conductivity of beryllia is roughly about 10 times that of commonly used alumina-based materials (5). Beryllia [1304-56-9] has a lower dielectric constant, a lower coefficient of thermal expansion, and slightly less strength than alumina. Aluminum nitride materials have begun to appear as alternatives to beryllia. Aluminum nitride [24304-00-5] has a thermal conductivity comparable to that of beryllia, but deteriorates less with temperature; the thermal conductivity of aluminum nitride can, theoretically, be raised to over 300 W/(m·K) (6). The dielectric constant of aluminum nitride is comparable to that of alumina, but the coefficient of thermal expansion is lower.

Single-crystal silicon has also been employed as substrate material, particularly in multichip module (MCM)-Si applications. As a substrate, silicon offers good thermal conductivity and matches the CTE of the devices mounted on it; it does, however, have a relatively high dielectric constant and is very brittle.

In applications in which electrical conductivity is required, metals, copper, tungsten, molybdenum, and Kovar [12606-16-5] are the preferred chip-carrier materials. Metals have excellent thermal conductivities. Tables 2 and 3 list the various materials used for substrates, along with their mechanical, electrical, and thermal properties.

4. Attachment Materials

Die attach, the process by which the die is anchored to the substrate, can be accomplished by either (*1*) introducing an adhesive between the backside of the die and the substrate, or (*2*) using an electrical connection procedure, such as TAB or solder bumping. One of the most important properties of the attachment material is its bonding strength, which ensures that the die and the substrate stay in place when subjected to the stresses imposed during manufacture, storage, and operation. The other important properties for attachment materials are tensile strength, shear strength, and fatigue endurance. If the attachment material must transmit heat from the die to the substrate, its thermal conductivity is also a critical material property. The electrical properties of the attachment materials assume importance when the attachment material serves as an ohmic contact.

4.1. Adhesive Connection. Adhesives can be classified as organic or inorganic. Inorganic materials, eg, soft solders, have the advantage of producing low contamination by-products, but require relatively high processing temperatures. Gold-based eutectics such as gold–tin (Au–Sn), gold–silicon (Au–Si), and gold–germanium (Au–Ge) have high strength and therefore offer excellent fatigue and creep resistance, but lack plastic flow which can lead to high stresses in the semiconductor due to the thermal expansion mismatch between the die and substrate (8). Their high cost also makes gold-based eutectics less popular. Organic compounds, on the other hand, have nearly the opposite characteristics. They can be effectively used on large dies since they can withstand large strains, but may be inappropriate for hermetic environments, due to out-gassing.

Epoxies are the most commonly used adhesives (qv). Silver and gold are sometimes added to an epoxy to improve its thermal conductivity. Polyimide, also used as an adhesive, has low shrinkage as well as low viscosity and can be cured at 180°C; its primary drawback is a tendency to absorb water, as much as 6% by weight.

Engineering rework is possible with eutectic and solder materials, but impossible with silver–glass. This constraint severely limits the usefulness of the material. Tables 4 and 5 give the electrical, mechanical, and thermal properties for various adhesives.

4.2. Wire Interconnect Materials. Wire-bonding is accomplished by bringing the two conductors to be joined into such intimate contact that the atoms of the materials interdiffuse (2). Wire is a fundamental element of interconnection, providing electrical connection between first-level (ie, the chip or die) and second-level (ie, the chip carrier, or the leadframe in a single-chip carrier) packages.

Characteristics of the wire materials, which are crucial to the strength of the wire bond, include wire dimensions, tensile strength, elongation, and contamination. Wire dimensions are important because the quality of the bond depends on the mass of the wire involved in making the bond. The tensile strength of the material is another significant factor for both ultrasonic and thermocompression bonds. Other important properties of wire and bond pad materials include shear and yield strength, elastic modulus, Poisson's ratio, hardness, CTE, elongation, fracture toughness, and fatigue endurance in tension and shear.

Gold and aluminum are the most commonly used wire materials, although copper and silver have also been used. Gold is mostly used in thermocompression bonding, aluminum in ultrasonic bonding. Both surface finish and cleanliness should be carefully controlled for gold-bonding wire to ensure a strong bond and prevent clogging of bonding capillaries. Pure gold can usually be drawn to an adequate breaking strength and proper elongation. Pure gold is very soft, small amounts of impurities can be added to make the gold wire workable. Beryllium-doped wire is stronger than copper-doped wire under most conditions by about 10 to 20%.

Because pure aluminum is typically too soft to be drawn into a fine wire, it is often alloyed with 1% silicon or 1% magnesium to provide a solid solution-strengthening mechanism. The resistance of Al-1% Mg wire to fatigue failure and to degradation of ultimate strength after exposure to elevated temperatures is superior to that of Al–1% Si wire.

Copper wires are used primarily because of their economy and resistance to sweep, ie, tendency of the wire to move in a plane perpendicular to its length, during plastic encapsulation (11–16). Because copper is harder than gold, more attention is needed during the bonding operation to prevent the chip from cratering. Table 6 lists the various properties for wire materials.

4.3. Tape-Automated Bonding (TAB). This is an approach to fine-pitch interconnections between the chip and the leadframe. The interconnections are patterned on a polymer tape; the chip to be bonded is positioned above the tape so that the metal tracks on the polymer tape correspond to the bonding sites on the chip. A thermocompression process is then used for bonding all joints in a single operation. Figure 4 shows an example of a TAB tape.

The basic elements of a tape-automated bond include metal plating, interface metallurgy, bumps, adhesive, and tape. Each of these elements requires materials containing unique properties. Metal plating should have excellent electrical conductivity for good performance and high thermal conductivity for heat dissipation. High toughness ensures that the material can stand more stress during thermal cycling in the bonding operation. In addition, metal plating should have good adherence to the plastic carrier and the capacity to be easily etched. Bump material should be soft and ductile.

Tape material, on the other hand, should have dimensional stability, good surface flatness, nonflammability, low shrinkage, low moisture absorption, a high tensile modulus, a low coefficient of thermal expansion, a high dielectric constant, and the capacities to withstand exposure to plating, etching, and soldering, as well as short-term elevated temperatures which are required during solder reflow and thermocompression bonding.

Copper is universally used as the metal plating for tape because it can be easily laminated with copper and the various plastic tapes. Copper is readily etched and has excellent electrical and thermal conductivity in both electrodeposited and rolled-annealed form. The tape metal plating is normally gold- or tin-plated to ensure good bondability during inner- and outer-lead bonding operations and to provide better shelf life and corrosion resistance.

Common materials for interface metallurgy are titanium or chromium for the adhesion layer, copper, nickel, tungsten, palladium, or platinum for the barrier layer, and gold for the bonding layer. To accommodate thermocompression bonding, soft gold is preferred. The solder bump in solder-reflow TAB is usually 95% lead and 5% tin by weight. Such a high lead solder has a 315°C melting point, which is higher than most other temperatures expected in the packaging process (17).

Possible tape materials include polyimide, polyester, polyethersulfone (PES), and polyparabanic acid (PPA) (18). Of these, polyimide is the most widely used material because its high melting point allows it to survive at temperatures up to 365°C. Although polyester is much cheaper than other materials, its use is limited to temperatures less than 160°C. PES and PPA, on the other hand, are half as costly as polyimide, and can survive maximum short-term temperatures of 220 and 275°C, respectively. PES has better dimensional stability than polyimide, absorbs less moisture, and does not tear as easily; however, it is inflammable and can be attacked by certain common solvents. Table 7 lists various plastic tapes and their properties. Common bump materials are gold, copper, and 95% Pb/5% Sn solder (see Tables 6 and 8 for properties; see also References 2 and 21).

4.4. Flip-Chip Materials. Flip-chip bonding is an interconnection technique in which the die is turned upside down and connected to the substrate by a medium that includes solder bumps, conduction polymers, and *z*-axis adhesives. Flip-chip bonds provide a high density, low inductance direct electrical path between the die and the substrate. Figure 5 shows the various layers of the flip-chip bond. Three classes of materials are used in making a flip-chip solder bump; they are solder, ball-limiting metallurgy (BLM), and top-surface metallurgy (TSM).

High melting point solders are used at the die level to permit the use of lower melting point solders for packaging at the board level without remelting the die-level interconnections. The strain-hardening exponent of the solder, which describes the strain induced in the solder by a given stress condition, is a material property that influences the thermal fatigue life.

As well as a barrier, functioning as the BLM adhesive layer must have excellent adhesion to both the metallization pad and the passivation layer. The solder-wetting layer of the BLM must have good solderability and the ability to prevent interdiffusion between the solder and the metallization pad. The oxidation-barrier layer provides an inert surface during bonding and protects the BLM metal layers from oxidation during storage. In contrast, the upper layer of the TSM structure must have good wetting properties, because it contacts the solder, and should have an adequate shelf life prior to die attachment. This layer is usually a metal that increases the wettability and makes the surface suitable for solder reflow.

The most widely used high melting point solder for flip-chip bonding is 95% lead–5% tin solder (mp ~315°C); eutectic 60% lead–40% tin solder (mp ~183°C) is used to attach dies to organic substrates such as polyimide films and glass–epoxy printed circuit boards. Lead–indium alloys offer significant fatigue-life enhancement over lead–tin solder alloys (22), showing parabolic dependence between the indium concentration and fatigue life. Alloys of 3–5% indium provide a compromise between fatigue-life enhancement and resistance against corrosion (23).

The BLM layer uses a glue layer of chromium or titanium. These metals stick well to other metals and most dielectrics, but they are not solderable. Copper, nickel, and silver have been used as the solder-wetting layer for BLM in applications involving 95% lead–5% tin solders. Gold is commonly used as the oxidation layer on account of its resistance to oxidation and its excellent solderability.

5. Case Materials

A case provides mechanical support and protection for the devices, interconnects, and substrate mounted in it; it also helps to dissipate heat during component operation and offers protection to the contents of the package from environmental stresses, contaminants, and, in the case of hermetic packages, moisture.

Cases can be classified as either hermetic or nonhermetic, based on their permeability to moisture. Ceramics and metals are usually used for hermetic cases, whereas plastic materials are used for nonhermetic applications. Cases should have good electrical insulation properties. The coefficient of thermal expansion of a particular case should closely match those of the substrate, die, and sealing materials to avoid excessive residual stresses and fatigue damage under thermal cycling loads. Moreover, since cases must provide a path for heat dissipation, high thermal conductivity is also desirable.

5.1. Ceramics and Metals. Among ceramics, the most commonly used material is alumina, which has good electrical resistivity (~10^{12} Ω·cm). The coefficient of thermal expansion of alumina fairly matches that of commonly used sealing glasses. Alumina cannot be used in high power applications due to its low thermal conductivity; for these hybrid applications, other ceramics, such as beryllia, aluminum nitride, or silicon carbide, are used. Although beryllia has a high thermal conductivity, it is toxic and must be handled with care, a precaution that also increases its processing costs. A comparatively low cost alternative to beryllia is aluminum nitride, which has a high thermal conductivity and a coefficient of thermal expansion matching that of silicon.

Kovar, one of the most commonly used metals for hermetic cases, is composed of 54% iron, 29% nickel, and 17% cobalt. It has a good CTE (5.1–5.9 ppm/°C), matching that of the commonly used sealing glasses (5.25–6.96 ppm/°C). Its thermal conductivity, however, is lower than that of the copper alloys. As a result, Kovar is not effective as a heat dissipator in high power applications. Instead, copper tungsten, which has a high thermal conductivity, is used for such applications. However, copper alloys pose a problem when sealing a lid to a copper case with electrical resistance welding, because the high thermal conductivity of copper causes the heat generated during the welding process to dissipate quickly. Tables 2 and 3 give properties of many materials used for cases.

5.2. Plastic Encapsulant Materials. A PEM encapsulant is generally an electrically insulating plastic material formulation that protects an electronic device and die-leadframe assembly from the adverse effects of handling, storage, and operation (see EMBEDDING). Various molding compounds are used as encapsulants. The molding compound is a proprietary multicomponent mixture of an encapsulating resin with various types of additives. The principal active and passive (inert) components in a molding compound include curing agents or hardeners, accelerators, inert fillers, coupling agents, flame retardants, and stress-relief additives.

ASTM D883 defines a filler as "...a relatively inert material added to a plastic to modify its strength, permanence, working properties, or other qualities or to lower costs." Fillers (qv) that modify the properties and characteristics of epoxies are employed in epoxy resins for a variety of reasons. Their principal functions are to control viscosity, reduce shrinkage and the coefficient of thermal expansion, effect a cost reduction, and color the epoxy resins.

The binder system of a plastic encapsulant consists of an epoxy resin, a hardener or curing agent, and an accelerating catalyst system. The conversion of epoxies from the liquid (thermoplastic) state to tough, hard, thermoset solids is accomplished by the addition of chemically active compounds known as curing agents. Flame retardants (qv), usually in the form of halogens, are added to the epoxy resin backbone because epoxy resins are inherently flammable.

The polymeric encapsulating resin, modified by additives, must possess adequate mechanical strength, adhesion to package components, manufacturing and environmental chemical resistance, electrical resistance, CTE matching, as well as thermal and moisture resistance in the use-temperature range.

Epoxy resins cannot be used alone as encapsulants because of their high coefficient of thermal expansion and low thermal conductivity. Inert inorganic fillers are added to the molding compound to lower the coefficient of thermal expansion, increase thermal conductivity, raise the elastic modulus, prevent resin bleed at the molding-tool parting line, and reduce encapsulant shrinkage during cure, reducing residual thermomechanical stress. Curing agents and accelerators perform the primary function of setting the extent and rate of resin polymerization. The toughness and stress-relaxation response of the epoxy resins can be enhanced by adding flexibilizers and stress-relief agents.

Thermosetting-encapsulation compounds, based on epoxy resins (qv) or, in some niche applications, organosilicon polymers, are widely used to encase electronic devices. Polyurethanes, polyimides, and polyesters are used to encase modules and hybrids intended for use under low temperature, low humidity conditions. Modified polyimides have the advantages of thermal and moisture stability, low coefficients of thermal expansion, and high material purity. Thermoplastics are rarely used for PEMs, because they are low in purity, require unacceptably high temperature and pressure processing conditions, and lead to moisture-induced stresses.

All epoxy resins contain compounds from the epoxide, ethoxylene, or oxirane groups, in which an oxygen atom is bonded to two adjacent (end) bonded carbon atoms. In electrical and electronic applications, three types of epoxy resins are commonly used: diglycidyl ethers of bisphenol A (DGEBA) or bisphenol F (DGEBF), phenolic and cresol novolaks, and cycloaliphatic epoxides. DGEBF is less viscous than DGEBA. Liquid DGEBAs synthesized from petrochemical derivatives are most common and are readily adaptable for electrical and electronic device encapsulation. The epoxy novolaks, essentially synthesized in the same way as DGEBA, are primarily solids; because of their relatively superior performance at elevated temperatures, they are widely used as molding compounds. The cycloaliphatic epoxides or peracid epoxides, usually cured with dicarboxylic acid anhydrides, offer excellent electrical properties and resistance to environmental exposure. Reference 10 compiles the mechanical and electrical properties of the various epoxies (see also EPOXY RESINS).

Silicones (qv) have an advantage over organic resins in their superior thermal stability and low dielectric constants. Polyurethanes, when cured, are tough and possess outstanding abrasion and thermal shock resistance. They also have favorable electrical properties and good adhesion to most surfaces. However, polyurethanes are extremely sensitive to and can degrade after prolonged contact with moisture; as a result, they are not as commonly used as epoxies and silicones (see URETHANE POLYMERS).

Additives. Historically, the filler that exhibits the optimum combination of required properties has been crystalline silica or alpha quartz. A typical crystalline silica-filled molding compound, loaded to 73% by weight, offers a coefficient of thermal expansion of about 32 ppm/°C, a thermal conductivity of around 15 kW/m·K and good abrasion and moisture resistance, electrical properties, and dimensional stability. Crystalline silica has been replaced by ground-fused silica, which provides lower density and viscosity. Thermal conductivity can be increased by a factor of about five with the addition of fillers such as alumina and copper. Generally, an increase in filler concentration increases thermal conductivity, which can also be enhanced by the addition of other filler materials, such as aluminum nitride, silicon carbide, magnesium oxide, and silicon nitride (24). In low stress epoxy resins, spherical silica particles are usually blended with crushed silica, thus increasing the filler loading with a nonlinear increase of viscosity as well as further lowering the coefficient of thermal expansion.

For many electronic and electrical applications, electrically conductive resins are required. Most polymeric resins exhibit high levels of electrical resistivity. Conductivity can be improved, however, by the judicious use of fillers; eg, in epoxy, silver (in either flake or powdered form) is used as a filler. Sometimes other fillers such as copper are also used, but result in reduced efficiency. The popularity of silver is due to the absence of the oxide layer formation, which imparts electrical insulating characteristics. Consequently, metallic fibers such as aluminum are rarely considered for this application.

Epoxidized phenol novolak and cresol novolak are the most common curing agents. The composition of the resin and hardener system is optimized for each specific application; eg, incorporating phenol novolaks in the matrix resin can increase cure speed.

In epoxy molding compounds, the principal stress-relief agents used are silicones, acrylonitrile–butadiene rubbers, and poly(butyl acrylate) (PBA). Silicone elastomers, with their high purity and high temperature properties, are the preferred agents. Silicone elastomers, interface-modified with poly(methyl methacrylate) (PMMA), have uniform domain sizes (1–100 μm) and inhibit passivation layer cracking, aluminum line deformation, and package cracking.

One of the more important flame retardants is homologous brominated DGEBA (diglycidyl ethers of bisphenol A). When used with a normal nonhalogenated resin, they impart self-extinguishing properties and achieve flame retardancy via the bromine liberated at the decomposition temperature. Previously, halogen additives were used as hardeners and/or fillers, but these tended to lower the heat-distortion temperature. Halogenated epoxy resins can be used without sacrificing properties. Antimony trioxide used as a filler is another common flame retardant, but its cost is higher; homologous brominated DGEBA epoxy and heterogenous antimony oxides can also be used together (24).

6. Lead Materials

Leads serve as the input–output interconnections between the component package and the mounting platform. Sometimes leads also aid in the dissipation of heat generated in the package. In the case of plastic packages, leads are formed from the leadframe, which also acts as a heat-dissipation path and a mechanical support for the die.

Because they serve as a path for electrical signals, leads should have good electrical conductivity. They should also have good corrosion resistance, since corrosion products can change the electrical properties of the lead, and because leads are soldered to the board, they should be wettable by solder. The coefficient of thermal expansion should closely match that of the die material for leadframes, substrate, and sealing glass. Other important properties of leads are yield strength and fatigue properties. Good thermal conductivity is also desirable to enhance the path for heat dissipation.

Alloy 42 (42% Ni–58% Fe) and Kovar are lead materials commonly used in ceramic chip carriers. The coefficients of thermal expansion of both materials match moderately well with those of silicon and ceramic substrate materials (3.4–7.4 ppm/°C). In addition, both materials have high fatigue strength; Alloy 42 has a fatigue strength of 620 MPa, compared with only 380–550 MPa for most copper alloys (3). Copper alloys are particularly suitable for leadframes in plastic packages because they have higher electrical and thermal conductivities than either Kovar or Alloy 42. Copper alloys also exhibit better solderability characteristics than Kovar or Alloy 42. Table 9 gives the key properties for various lead and leadframe materials.

7. Solder Materials

Solders are alloys that have melting temperatures below 300°C, formed from elements such as tin, lead, antimony, bismuth, and cadmium. Tin–lead solders are commonly used for electronic applications, showing traces of other elements that can tailor the solder properties for specific applications.

Alloy selection depends on several factors, including electrical properties, alloy melting range, wetting characteristics, resistance to oxidation, mechanical and thermomechanical properties, formation of intermetallics, and ionic migration characteristics (26). These properties determine whether a particular solder joint can meet the mechanical, thermal, chemical, and electrical demands placed on it.

Tin−lead solders are popular because of their melting range (180−230°C), good wetting characteristics, and affordable prices. Their thermal conductivity ranges from 43−50 W/(m·K. In general, lead takes little part in the reactions at the interface, but affects the solidus temperature of the alloy. Tin is more reactive and affects metallurgical reactions with metals. Solders having high land content possess higher solidus temperatures and are used for high temperature applications. Other metals are also added to tin−lead solders for specific applications. Silver is added (62% Sn−36% Pb−2% Ag) for soldering silver-coated surfaces because it reduces silver dissolution and creep. Antimony is added to improve solder strength. Table 8 lists the electrical and mechanical properties of various tin−lead solders. Tin−indium solders provide good solderability, ductility, and thermal fatigue properties; they are used for soldering glasses and ceramics.

8. Printed Circuit Board Materials

A printed circuit board (PCB) typically consists of a copper circuit pattern created on a copper-clad composite laminate by lithography and electoplating technologies (2). A typical printed circuit board serves the electronic system in three ways: mechanically, by providing support to the components and the conductors; thermally, by offering a thermal conduction path to dissipate heat generated by the devices mounted on it; and electrically, by serving as an insulator for the conductors. Chemical properties also need to be considered, since moisture absorption and chemical attack can both degrade the material properties.

Most of the laminates used for rigid printed circuit boards have been classified, by the National Electrical Manufacturers Association (NEMA), according to the combination of properties that determine the suitability of a laminate for a particular use. Fiber reinforcements make laminate-effective properties orthotropic.

E-glass−epoxy laminates, by far the most widely used circuit board materials, have been designated FR-4 (fire retardant epoxy-glass cloth) by NEMA. The glass-transition temperature, T_g, for FR-4 ranges from 120 to 135°C, which is acceptable for most commercial PCB applications. The advantages of FR-4 are ease of processing, punchability, machinability, low cost, and availability. E-glass−epoxy laminates provide an in-plane thermal expansion closely matched to that of inner-layer copper, with a fiber volume fraction in the range of 0.28−0.30 (27). E-glass−bismaleimide triazine (BT) resin laminates offer similar advantages as FR-4 laminates as well as sustained insulation resistance against moisture absorption (28). E- glass–polyimide laminate has a higher glass-transition temperature (260°C), and is used for military applications.

Ceramic laminates withstand a harsher environment than organic laminates. They also have good thermal conductivities, higher flexural strength, and a better match of coefficients of thermal expansion with the components mounted on them, ensuring good board interconnection reliability under cyclic thermal loading. The disadvantages of ceramic laminates are their relatively high cost, high dielectric constant, and high density. Table 10 gives the properties of various laminate materials.

9. Conformal Coating Materials

Conformal coatings are protective coatings applied to circuit board assemblies. They protect the interconnect conductors, solder joints, components, and the board itself; they reduce permeability to moisture, hostile chemical vapors, and solvents in the coating. Use of conformal coatings eliminates dendritic growth between conductors, conductor bridging from moisture condensation, and reduction in insulation resistance by water absorption.

The critical property for conformal coatings is resistance to chemicals, moisture, and abrasion. Other properties, such as the coefficient of thermal expansion, thermal conductivity, flexibility, and modulus of elasticity, are significant only in particular applications. The dielectric constant and loss tangent of the conformal coating are important for high speed applications.

Materials for coating must last as long as the product itself, be easy to apply and rework, and be cost-effective. Various materials are used for conformal coatings. Polyurethanes are the most widely used and offer good resistance to moisture, fungus, abrasion, solvent and chemical. In addition, they have good adhesion, low shrinkage, flexibility, and elasticity, and are particularly suited to applications requiring good humidity resistance. However, polyurethanes are difficult to rework due to their high chemical resistance, and are unsuitable for high frequency and high temperature applications due to the strong dependence of their dielectric constants and loss tangents on these variables.

Acrylic resins have excellent moisture resistance, dielectric properties, and reworkability, but poor abrasion resistance. Their dielectric constant, which decreases with increasing frequency, makes them attractive candidates for high frequency applications.

Epoxies provide excellent chemical, moisture, and abrasion resistance. However, because a solvent can sometimes dissolve the epoxy present in the laminate, rework on an epoxy coating requires heat or abrasion to remove the coating.

Silicone-based coatings are well suited for high temperature and high speed applications. They are flexible, tough, and resistant to thermal and oxidative deterioration. They have good surface resistance and are fungus- and flame resistant. However, they possess a high coefficient of thermal expansion and have poor adhesion.

Table 11 gives the properties for various commercial parylenes (*para*-xylylene). These materials have excellent moisture and chemical resistance as well as good electrical and mechanical properties. They are noted for their ability to penetrate small spaces by vapor deposition (see XYLYLENE POLYMERS).

10. Connector Materials

Connectors are third-level interconnections between daughter boards, between subassemblies, between systems, and to peripherals. The connector assembly normally consists of insert, pin, and contact materials. Platings and/or lubricants are often used to reduce wear and improve contact resistance between the pin and the contact. The insert material must provide support and insulation for the pin and contacts. The coefficient of thermal expansion of the material and the mold shrinkage should be low to ensure pin-to-pin dimensional stability in high density connectors. At higher pin densities, the volumetric and surface resistivity should be high for proper electrical performance. Flexibility is essential for a snap fit. Properties required of metals used for pin and contacts are low electrical resistivity, high strength, wear resistance, corrosion resistance, and a high modulus of elasticity. A low dielectric constant is required for high speed connectors.

Polymers are used as inserts for pins and contacts. Important properties of the commonly used insert materials have been compiled (31). Polysulfones are high temperature thermoplastics that have high rigidity, low creep, excellent thermal stability, flame resistance, low loss tangents, and low dielectric constants. The principal weakness of polysulfones is their low chemical resistance.

Commonly used materials for pins and contacts are brass, beryllium copper, phosphor–bronze, and copper–nickel. Beryllium copper, a popular contact material, has good spring properties, corrosion resistance, high strength, hardness, fatigue endurance, and wear resistance. Phosphor–bronze, made with a large percentage of tin, is resistant to fatigue, wear, and corrosion, and has a high tensile strength and a high capacity to absorb energy. Properties of commonly used pin and contact materials are given in Tables 12 and 13.

11. Cable and Flex Circuit Materials

A cable or flex circuit is often employed as an interconnection between electronic circuits that are not easily connected by other means. The interconnection density obtained with a cable or flex circuit is lower than that achieved with a backpanel.

Properties desired in cable insulation and flexible circuit substrate materials include mechanical flexibility, fatigue endurance, and resistance to chemicals, water absorption, and abrasion. Both thermoplasts and thermosets are used as cable-insulating materials. Thermoplastic materials possess excellent electrical characteristics and are available at relatively low cost.

Copper is by far the most widely used conductor material. It has high electrical conductivity, thermal conductivity, solderability, and resistance to corrosion, wear, and fatigue. Annealed copper conductors can withstand flex and vibration stresses normally encountered in use.

Commonly used materials for cable insulation are poly(vinyl chloride) (PVC) compounds, polyamides, polyethylenes, polypropylenes, polyurethanes, and fluoropolymers. PVC compounds possess high dielectric and mechanical strength, flexibility, and resistance to flame, water, and abrasion. Polyethylene and polypropylene are used for high speed applications that require a low dielectric constant and low loss tangent. At low temperatures, these materials are stiff but bendable without breaking. They are also resistant to moisture, chemical attack, heat, and abrasion. Table 14 gives the mechanical and electrical properties of materials used for cable insulation.

BIBLIOGRAPHY

CITED PUBLICATIONS

1. J. Dally, *Packaging of Electronic Systems: A Mechanical Engineering Approach,* McGraw-Hill Book Co., Inc., New York, 1990.
2. M. Pecht, *Handbook of Electronic Package Design,* Marcel Dekker, Inc., New York, 1991.
3. M. Pecht, *Integrated Circuit, Hybrid, and Multichip Module Package Design Guidelines: A Focus on Reliability,* John Wiley & Sons, Inc., New York, 1994.
4. D. R. Lide, *Handbook of Chemistry and Physics,* 7th ed., CRC Press, Inc., Boca Raton, Fla., 1990.
5. C. A. Harper, *Electronic Packaging and Interconnection Handbook,* McGraw-Hill Book Co., Inc., New York, 1991.
6. N. Iwase, K. Anzai, and K. Shinozaki, *Solid State Technol.* **29**(10), 135–138 (Oct. 1986).
7. A. H. Kumar and R. R. Tummala, *Int. J. Hybrid Microelectronics,* **14**(4), 137–150 (Dec. 1991).
8. R. K. Shukla and N. P. Mecinger, *Solid State Technol.* **29**(7), 67–74 (July 1985).
9. F. B. Beach and R. Olson, in M. L. Minges and co-workers, eds., *Electronic Materials Handbook,* Vol. 1, ASM International, Materials Park, Ohio, 1989.
10. M. L. Minges and co-workers, eds., *Electronic Materials Handbook,* Vol. 1, ASM International, Materials Park, Ohio, 1989.
11. K. Atsumi and co-workers, “Ball Bonding Technique for Copper Wire,” *36th Proceedings of the IEEE Electronic Components Conference,* Seattle, Wash., May 5–7, 1986, 312–317.
12. J. Hirota and co-workers, “The Development of Copper Wire Bonding for Plastic Molded Semiconductor Packages,” *35th Electronic Component Conference Proceedings,* Washington, D.C. 1985, 116–121.
13. J. Kurtz, D. Cousens, and M. Dufour, *34th IEEE Electronic Components Conference,* New Orleans, La., May 14–16, 1984, 1–5.
14. L. Levine and M. Shaeffer, *Semiconductor Int.* **9**(8), 126–129 (Aug. 1986).
15. J. Onuki, M. Koizumi, and I. Araki, *IEEE Transactions on Components, Hybrids, and Manufacturing Technology,* Vol. 10, CHMT-10, Dec. 1987, 550–555.
16. S. T. Riches and N. R. Stockham, *Proceedings of the 6th European Microelectronics Conference (ISHM),* Bournemouth, U.K., June 3–5, 1987, 27–33.

17. C. Speerschneider and J. Lee, *Solid State Technol.,* **32**(7) (July 1989).
18. J. Lyman, *Packag. Prod. Ed.,* 175–182 (Dec. 1975).
19. J. H. Lau, S. J. Erasmus, and D. W. Rice, in Ref. 9, 274–296.
20. *Solder Alloy Data-Mechanical Properties of Solders and Soldered Joints,* I.T.R.I. Pub. No. 656, International Tin Research Institute.
21. *Metal Foil for Printed Wiring Applications,* IPC-MF-150, Institute for Interconnecting and Packaging Electronic Circuits, Lincolnwood, Ill., 1991.
22. L. S. Goldmann, *Proceeding of the 27th Electronic Components Conference,* Arlington, Va., 1977, 25–29.
23. T. R. Howard, *IBM J. Res. Dev.* **3,** 372–378 (1982).
24. R. K. Rosler, in Ref. 9, 810–816.
25. J. Crane and J. F. Breedis, in Ref. 9, 483–492.
26. M. G. Pecht, *Soldering Processes and Equipment,* John Wiley & Sons, Inc., New York, 1993.
27. C. L. Guiles, *CTE Materials for PWBs,* IPC Technical Paper 914, IPC Seminar Meeting, San Diego, Calif., 1990.
28. G. Morio, N. Ikeguchi, and S. Ayano, *Electronic Packaging Prod.* **25**(12), 30–33 (Dec. 1985).
29. F. L. Gray, in Ref. 9, 611–629.
30. S. J. Mumby, *J. Electronic Mater.* **18**(2), 241–250 (Mar. 1989).
31. W. T. Shugg, *Handbook of Electrical and Electronic Insulating Materials,* Van Nostrand Reinhold Co., Inc., New York, 1986.
32. G. L. Ginsberg, ed., *Connectors and Interconnection Handbook,* Vols. 1–3, The Electronic Connector Study Group, Inc., Camden, N.J., 1978.

GENERAL REFERENCES

B. Ellis, *Chemistry and Technology of Epoxy Resins,* Chapman and Hall, Glasgow, U.K., 1993.

M. G. Pecht, L. Nyugen, and E. B. Hakim, *Plastic Encapsulated Microelectronics: Materials, Processes Quality, Reliability and Applications,* John Wiley & Sons, Inc., New York, 1995.

MICHAEL PECHT
University of Maryland at College Park
ASOHK PRABHU
Nitto Denko America Inc.

Table 1. **Properties[a] of Semiconductor and Die Materials**

Material	Dielectric constant at high frequency	Density, kg/m^3	Knoop hardness, kg/mm^3	Thermal conductivity, W/(m·k)	Melting point, °C
Si	11.9	2330	850–1150	124–148	1685
Ge	16.0	5320–5360	750–780	2.0–3.4	958–1231
Te		6230–6240		990–2300	723
diamond	5.7	3500–3530	7000–8800	283	>3823
SiC	10.0	3210	2200–2950	67–80	3070
InP	12.4	4787	420–535	29	1344
InAs	14.6	5775	220–225	16	1216
InSb	17.7	3810	510	84	808
AlAs	8.5–10.9	2420–2850	430–560	92	>1873
AlP		4218	360–408	46–60	>1773
AlSb	11.6	5316	535–765	44–58	1323
GaAs	11.0–14.4	4130	950–964	75–79	1511
GaP	13.1	5619	450	27–33	1738
GaSb	11.1	4135–4820	55	40.1	985
CdS	15.7	5660–5810		31.6	1750
CdSe	5.4	6200	61	6	1512
CdTe	10.0	3980–4100	180	25–46	1365
ZnS	72–10.2	5420	138	14.0	2122
ZnSe	5.2–8.9	6340	92	10.8	1790
ZnTe	5.9–9.2	7500–7610		2.3	1511
PbS	9.0–10.4	8100–8150		1.7	1386
PbSe	17.0	8160–8164		2.3	1338
PbTe	24.0–161				1190

[a] Other properties, eg, strength, resistivity, heat capacity, and thermal expansion, are given in the reference (2,4) from which this table is compiled.

Table 2. **Mechanical Properties of Substrates**[a]

Material	Tensile strength, MPa[b]	Compressive strength, MPa[b]	Flexural strength, MPa[b]	Elastic modulus, GPa[c]	Density, kg/m^3	Hardness[d]	Impact strength, J[e]
BeO	230		250–490	345	3000	100 K	
SiC	17.24	490	440–460	412	3160	2800 K	65
AlN		392–441	360–490	310–343	3260	1200 K	
Si			580	190	2330	850–950 K	
Si_3N_4	96.5–965		275–932	314	2400–3440		
SiO_2	96.5–386		30–100	69	2190–2320		
Al_2O_3 85%	124.11	1620	290	221	3970	9 MH	8.5–8.8
Al_2O_3 95%	127.4–193.0	2069–2413	310–338	296–317	3970	9 MH	8.8–10.3
Al_2O_3 99.8%	206.9	2758	350–414	386	3970	93.5 RA	9.5
Al_2O_3 silicate	17.24	276	62	55.2	3970	6 MH	4.5
diamond			71.4		3500–3530	7000–8800 K	
quartz	48.3	1103		71.7	2200	5 MH	
steatite	55.2–69.0	448–896	110–165	90–103	2500–2700		0.4–0.5
forsterite	55.2–69.0	414–690	124–138	90–103	2700–2900		0.04–0.05
titanate	27.6–69.0	276–827	69–152	69–103	3500–5500		0.4–0.7
cordierite	55.2–69.0	138–310.3	10.3–48.0	13.8–34.0	1600–2100		0.3–0.34
mullite			125–275	175			
molybdenum	655			324	10,240		
10% Cu–90% W	489.5		1062	331	17,300	427 K	
tungsten	310–1517		28.3	345	19,300	485 K	
Kovar	522–552			138	8360	68 RB	

[a] Refs. (2, 4), and 7.

[b] To convert MPa to psi, multiply by 145.

[c] To convert GPa to psi, multiply by 145,000.

[d] K = Knoop; MH = Moh; RA = Rockwell A; B = Brinnell.

[e] To convert J to ft·lb, divide by 1.356.

Table 3. **Thermal[a] and Electrical[b] Properties of Substrates[c]**

Material	Thermal conductivity, W/(m·K)	CTE, ppm/°C	Heat capacity, J/(kg·K)	Dielectric constant at 1 MHz	Dielectric strength, kV/mm
BeO	150–300	6.3–7.5	1047–2093	20–42	0.04
SiC	120–270	3.5–4.6	675	8.5–10	0.55
AlN	82–320	4.3–4.7	745	11.9	
Si	125–148	2.33	712	6–10	196.8
Si_3N_4	25–35	2.8–3.2	691	3.5–4.0	196.8
SiO_2	1.5	0.6		4.5–10	0.33
Al_2O_3	15–33	4.3–7.4	765	5.7	
quartz	43	1.0–5.5	816–1193	4.6	
diamond	2000–2300	1.0–1.2	509	5.5–7.5	7.9–15.7
steatite	2.1–2.5	8.6–10.5		6.2	7.9–11.8
forsterite	2.1–4.2	11		15–12,000	2.0–11.8
titanate	3.3–4.2	7–10		4.5–5.5	1.6–9.8
cordierite	1.3–4.0	2.5–3.0	770	6.6–6.8	
mullite	5.0–6.7	4.0–4.2			
molybdenum	138	3.0–5.5	251		
10% Cu–90% W	209.3	6.0	209		
tungsten	174–177	4.5	132		
Kovar	15.5–17.0	5.87	439		

[a] Maximum use temperatures exceed 1000°C except for SiO_2 (>800°C); melting points range from 1450°C (Kovar) to 3660°C (tungsten).

[b] Resistivity for nonmetallic materials is 10^4–10^{14} Ω·m; for metals the order of magnitude is 10^{-8} Ω·m.

[c] Refs. (2,4), and 7.

Table 4. **Electrical and Thermal Properties of Attachment Materials**[a]

Materials	Volume resistivity, Ω·m	Dielectric constant at 1 MHz	Dielectric strength, kV/mm	Dissipation factor at 1 MHz	Thermal conductivity, W/(m·k)	CTE, ppm/°C	Maximum use temperature, °C
silicone	10^{13}–10^{15}	2.9–4.0	15.8–27.6	0.001–0.002	6.4–7.5	262–300	260
polyure-thane	0.3×10^{9}	5.9–8.5	12.9–27.6	0.05–0.06	1.9–4.6	90–450	65.6
acrylic	7×10^{11}						93.3
epoxy novolak	10^{13}–10^{16}	3.4–3.6		0.016			
epoxy phenolic	6.1×10^{14}	3.4	15.8	0.32	25.0–74.7	33	87.8
epoxy bisphenol A	10^{14}–10^{16}	3.2–3.8		0.013–0.024			
epoxy silicone					13–26	60–80	260
cyano-acrylate							82.2
polyimide					0.2	40–50	

[a] Refs. (2,9), and 10.

Table 5. **Mechanical Properties of Attachment Materials**[a]

Material	Tensile strength, MPa[b]	Shear strength, MPa[b]	Elongation, %	Modulus of elasticity, GPa[c]	Specific gravity	Hardness[d]
silicone	10.3		100–800	0.06–2.21	1.02–1.2	20–90 A
urethane	5.5–55	15.5	250–800	0.172–34.5	1.1–1.6	10 A–80 D
acrylic	12.4–13.8		100–400	0.69–10.3	1.09	40–90 A
epoxy silicone		11.7				
epoxy novolak	55.0–82.7	26.2	2–5	2.76–3.45	1.2	
epoxy bisphenol A	43–85		4.40–11.0	2.7–3.3	1.15	106 RM
polyimide		16.5		3.0		
epoxy polyimide		41				
epoxy polyurethane (50:50)	34		10			

[a] Ref. 2.

[b] To convert MPa to psi, multiply by 145.

[c] To convert GPa to psi, multiply by 145,000.

[d] A = Shore A; D = Shore D; RM = Rockwell M.

Table 6. **Properties of Wire and Bond Pad Materials**[a]

Property	Aluminum [7429-90-5]	Copper [7440-50-8]	Gold [7440-57-5]
specific heat, (W·s)/(g·°C)	0.9	0.385	0.129
thermal conductivity, W/(cm·C)	2.37	4.03	3.19
specific gravity	2.7	9.0	19.3
melting point, °C	660	1083	1064
electrical resistivity, Ω·cm	2.65×10^{-6}	1.7×10^{-6}	2.2×10^{-6}
temperature coefficient of electrical resistivity, Ω·cm/°C	4.3×10^{-9}	6.8×10^{-9}	4×10^{-9}
elastic modulus, GPa[b]	34.5	1324	77.2
yield strength, MPa[c]	10.34	68.95	172.38
ultimate tensile strength, MPa[c]	44.82	220.64	206.85
coefficient of thermal expansion, ppm/°C	46.4	16.12	14.2
Poisson's ratio	0.346	0.339	0.291
hardness, Brinnell	17	37	18.5
elongation, %	50	51	4

[a] At 27°C (3).

[b] To convert GPa to psi, multiply by 145,000.

[c] To convert MPa to psi, multiply by 145.

Table 7. **Properties of Plastic Films**[a]

Plastic film	Melting point, °C	Moisture absorption, %	Tensile strength, MPa[b]	Ultimate elongation, %	Coefficient of thermal expansion, 10^{-6}/K	Dissipation factor at 1 kHz	Dielectric constant at 1 kHz	Dielectric strength, MV/m	Cost factor
polyimide (Kapton)	none	3.0	230	72	18–50	0.0018–0.0026	3.4–3.5	150–300	17.0
polyester (Mylar)	180	<0.8	170	120	31	0.005	3.25	300	1.0
polytetrafluoroethylene (Teflon)	328	<0.01	28	350	12.2	0.0002	2.0	17	9.2
fluorinated ethylene–propylene (Teflon)	280	<0.01	21	300	9.7	0.0002	2.0	255	16.0
polyamide (Nomex)	482	3.0	75	10	38–154	0.007	2.0	18	1.9
poly(vinyl chloride)	163	<0.5	35	130	63	0.009	3.0	40	0.36
poly(vinyl fluoride) (Tedlar)	299	<0.05	70–130	110–300	50	0.02	8.5–10.5	140	3.5
polyethylene	121	<0.01	21	>300	198	0.0003	2.2	20	0.17
polypropylene	204	<0.005	170	250	104–184	0.0003	2.1	160	0.48
polycarbonate	132	0.35	62	110	68	1.0000	3.2	16	1.32
polysulfone	190	0.22	68	95	56	0.001	3.1	295	3.33
polyparabanic acid (PPA)	299	1.8	97	10	51	0.004	3.8	235	8.0
polyether sulfone (PES)	203		84			0.001	3.5		4.5

[a] Ref. 19.

[b] To convert MPa to psi, multiply by 145.

Table 8. **Mechanical and Electrical Properties of Solder Materials**[a]

Materials	Density, g/mL	Hardness[b]	Electrical conductivity, % IACS	Electrical resistivity, μΩ·cm	Young's modulus, GN/m^{2c}
99% Sn–1% Cu	7.31	9 HB			
97% Sn–3% Cu	7.34	11 HB			
96.5% Sn–3.5% Ag	10.38	14.8 HV	14	12.31	
95% Sn–5% Sb	7.25	15 HB	11.9	14.5	49.99
60% Sn–40% Pb	8.52	16 HV	11.5	14.99	29.99
50% Sn–50% Pb	8.89	14 HV	10.9	15.8	
42% Sn–58% Bi	8.72	22 HB	4.5	34.5	
40% Sn–60% Pb	9.28	12 HV	10.1	17.07	23.03
62% Sn–36% Pb–2% Ag	8.50				22.96
40% Sn– 58% Pb–2% Sb	9.23		9.2		
1% Sn–97.5% Pb–1.5% Ag	11.28	13 HB			

[a] Ref. 20.

[b] Brinnell (HB) or Vickers (HV).

[c] To convert GN/m^2 (GPa) to psi, multiply by 145,000.

Table 9. **Properties of Lead–Lead Frame Alloys**[a]

Symbol	Nominal composition, %	Thermal conductivity, W/(m·K)	Electrical resistivity, μΩ·cm	Yield bend fatigue strength[b], MPa[c]
		Cu–Fe		
C19400	Fe 2.35; P 0.03; Zn 0.12	260	2.54	475
C19500	Fe 1.5; Co 0.8; P 0.05; Sn 0.6	200	3.44	
C19700	Fe 0.6; P 0.2; Mg 0.04	320	2.16	450
C19210	Fe 0.10; Mg 0.034	340	2.03	380
		Cu–Cr		
CCZ	Cr 0.55; Zr 0.25	340	2.03	430
EFTEC647	Cr 0.3; Sn 0.25; Zn 0.2			
		Cu–Ni–Si		
C7025	Ni 3.0; Si 0.65; Mg 0.15	160	4.31	620
KLF 125	Ni 3.2; Si 0.7; Sn 1.25; Zn 0.3	140	4.89	
C19010	Ni 1.0; Si 0.2; P 0.03	240	2.87	585
		Cu–Sn		
C50715	Sn 2.0; Fe 0.1; P 0.03	140	4.89	550
C50710	Sn 2.0; Ni 0.2; P 0.05	120	5.75	450
		Others		
C15100	Zr 1.0; Cu 99.0	380	1.81	380
C15500	Mg 0.11; P 0.06; Cu 99.83	344	1.99	
		Fe–Ni		
ASTM F30 (Alloy 42)	Ni 42; Fe 58	12	70	620
		Fe–Ni–Co		
ASTM F15 (Kovar)	Ni 29; Co 17; Fe 54	40	49	

[a] Ref. 25.

[b] Load bend fatigue strength of alloys capable of withstanding 4–5 cycles before failure in 0–90–0 degree cycles, which is above the three-cycles-to-failure minimum in MIL-STD-883; values pertain to a 0.25-mm thick strip that has been sheared to 0.45-mm width.

[c] To convert MPa to psi, multiply by 145.

Table 10. **Properties of Selected PWB Laminate Materials**[a]

Laminate	T_g, °C	CTE below T_g, ppm/°C		Water uptake, MIL-P-13949F, mg	Dielectric constant at 1 MHz	Dissipation factor at 1 MHz	Tensile strength, MPa[b]	Modulus of elasticity, GPa[c]	Thermal conductivity, W/(m·K)
measurement direction		*x, y*	*z*		*z*	*z*	*x, y*	*x, y*	*z*
E-glass–epoxy	120	12–16	60–80	10	4.7	0.021	276	17.4	0.35
E-glass–polyimide	220–300	11–14	60–80	25	4.5	0.018	345	19.6	0.35
E-glass–PTFE	75	24	261		2.3	0.006	68–103	1.0	0.26
quartz–polyimide	260	6–12	34	25	3.6	0.010		27.6	0.13
quartz–Quatrex	185		62		3.5			18.6	
Kevlar-49–Quatrex	185	3–8	105	10	3.7	0.030		22–28	0.16
Kevlar-49–polyimide	180–200	3–8	83	25	3.6	0.008		20–27	0.12

[a] Refs. (2,29), and 30.

[b] To convert MPa to psi, multiply by 145.

[c] To convert GPa to psi, multiply by 145,000.

Table 11. **Typical Properties of Parylene Coatings**[a]

Properties	Parylene-N	Parylene-C	Parylene-D
density, g/cm^3	1.11	1.289	1.418
tensile modulus, GPa[b]	2.4	3.2	2.8
tensile strength, MPa[c]	45	70	75
yield strength, MPa[c]	42	55	60
elongation to break, %	30	200	10
yield elongation, %	2.5	2.9	3
hardness, Rockwell R scale	85	80	
melting point, °C	420	290	380
CTE at 25°C, ppm/°C	69	35	
specific heat capacity at 25°C, J(g·K)	1.3	1.0	
thermal conductivity at 25°C, W(m·K)	0.12	0.082	
dielectric constant			
at 60 Hz	2.65	3.15	2.84
1 kHz	2.65	3.10	2.82
1 MHz	2.65	2.95	2.80
loss tangent			
at 60 Hz	0.0002	0.02	0.004
1 kHz	0.0002	0.019	0.003
1 MHz	0.0006	0.013	0.002
dielectric strength, 25-μm thick, MV/m			
sort time	275	220	215
step by step	235	186	
volume resistivity,[d] MΩ	14	8.8	2
surface resistivity,[d] Ω	10^{13}	10^{14}	10^{16}
water absorption, %	<0.1	<0.1	<0.1
gas permeability at 25°C, mol/(Pa·s·m)			
N_2	15.4	2.0	9.0
O_2	78.4	14.4	64.0
CO_2	429.0	15.4	26.0
H_2S	1590	26.0	2.9
SO_2	3790	22.0	9.53
Cl_2	148	0.7	1.1

[a] Ref. 9.

[b] To convert GPa to psi, multiply by 145,000.

[c] To convert MPa to psi, multiply by 145.

[d] At 23°C and 50% rh.

Table 12. **Copper-Based Metal Alloys**[a]

Property[b]	Alloy 260[c] brass	Alloy 172[c] beryllium–copper[d]	Alloy 510, grade A, phosphor–bronze	Alloy 638	Alloy 725	Alloy 762, nickel–silver
nominal composition, %	Cu 70 Zn 30	Cu 98.1 Be 1.9	Cu 94.81 Sn 5.0	Cu 95 Al 2.8 Si 1.8 Co 0.4	Cu 88.2 Ni 9.5 Sn 2.3	Cu 59.25 Zn 28.75 Ni 12
electrical conductivity at 20°C, MΩ	0.163	0.128	0.087	0.058	0.064	0.050
thermal conductivity at 20°C, W(m·K)	121	109–130	68.6	40.6	54.4	41.8
density at 20°C, g/cm^3	8.54	8.260	8.86	8.29	8.89	8.70
modulus of elasticity, GPa[e]	112	130	112	117	135	127
yield strength, 0.2% offset, MPa[f]	70–220	109	150	410–470	180	200
annealed	290–410	123	330–480	530–630	400–510	410–580
half hard	460–530	127	520–620	640–720	520–560	580–680
hard	580–630		650–760	700–790	550–650	710–770
spring	600–690		690–770	750 min	630–720	720 min

[a] Ref. 32.

[b] At 0.020-mm grain size except in the case of Alloy 638, which is the standard annealed condition.

[c] Designation of Copper Development Association.

[d] All property data for beryllium–copper are for material after age-hardening heat treatment.

[e] To convert GPa to psi, multiply by 145,000.

[f] To convert MPa to psi, multiply by 145.

Table 13. **Properties of Nickel-Based Alloys**[a]

Alloy	Nominal composition, %	Tensile strength, MPa[b]	Yield strength, MPa[b]	Elongation, %	Electrical conductivity, MΩ·cm
nickel 200[c]	99 Ni	379–758	103–689	55–10	0.106
nickel 270	99.97 Ni	344–655	103–620	50–4	0.134
Duranickel 301[c]	93 Ni 4.5 Al	620–1448	209–1206	55–15	0.024
beryllium–nickel 440[d]	98 Ni 2 Be	655–1861	275–1586	30–8	0.027

[a] Ref. 32.

[b] To convert MPa to psi, multiply by 145.

[c] Modulus of elasticity = 206 GPa (29.9×10^6 psi).

[d] Modulus of elasticity = $186 - 207$ GPa ($27 - 30 \times 10^6$ psi).

Table 14. **Mechanical and Electrical[a] Properties of Cable Insulating Materials[b]**

Insulation	Common designation	Tensile strength, MPa[c]	Elongation, %	Specific gravity	Dielectric strength, kV/mm	Dielectric constant at 1 kHz	Dissipation factor at 1 kHz
poly(vinyl chloride)	PVC	16.6	260	1.2–1.5	15.8	5–7	0.02
polyethylene	PE	9.6	300	0.92	18.9	2.3	0.005
polypropylene		41.4	25	1.4	29.5	2.54	0.006
cross-linked polyethylene	IMP	20.7	120	1.2	27.6	2.3	0.005
polytetrafluoro-ethylene	TFE	20.7	150	2.15	18.9	2.1	0.0003
fluorinated ethylene–propylene	FEP	20.7	150	2.15	19.9	2.1	0.0003
chlorotrifluoro-ethylene	Kel-F	34.5	120	2.13	17.0	2.45	0.025
poly(vinylidene fluoride)	Kynar	49.0	300	1.76	50.4 (8 mil)	7.7	0.02
silicone rubber	Silicone	5.5–12.6	100–800	1.15–1.38	22.6–27.6	3.0–3.6	0.003
polychloroprene	Neoprene	1.0–27.6	600–700	1.23	32.0	9.0	0.03
butyl rubber	Butyl	4.8–10.3	500–700	0.92	23.6	2.3	0.003
fluorocarbon rubber	Viton	16.6	350	1.4–1.95	19.7	4.2	0.14
polyurethane	Urethane	34.5–55.2	100–600	1.24–1.26	17.7–19.7	6.7–7.5	0.055
polyamide	nylon	27.6–48.3	300–600	1.10	15.2	4–10	0.02
polyimide film	Kapton	124.1	707	1.42	212.6 (8 mil)	3.5	0.003
polyester film	Mylar	89.6	185	1.39	102.4	3.1	0.15
polyalkene		13.8–48.3	200–300	1.76	73.6	3.5	0.028
polysulfone		69.0	50–100	1.24	16.73	3.13	0.0011
polyimide-coated TFE	TFE/ML	20.7	150	2.2	18.9	2.2	0.0003
polyimide-coated FEP	FEP/ML	20.7	150	2.2	18.9	2.2	0.0003

[a] Volume resistivity ranges from 10^{10}–10^{18} Ω·cm.

[b] Ref. 5.

[c] To convert MPa to psi, multiply by 145.

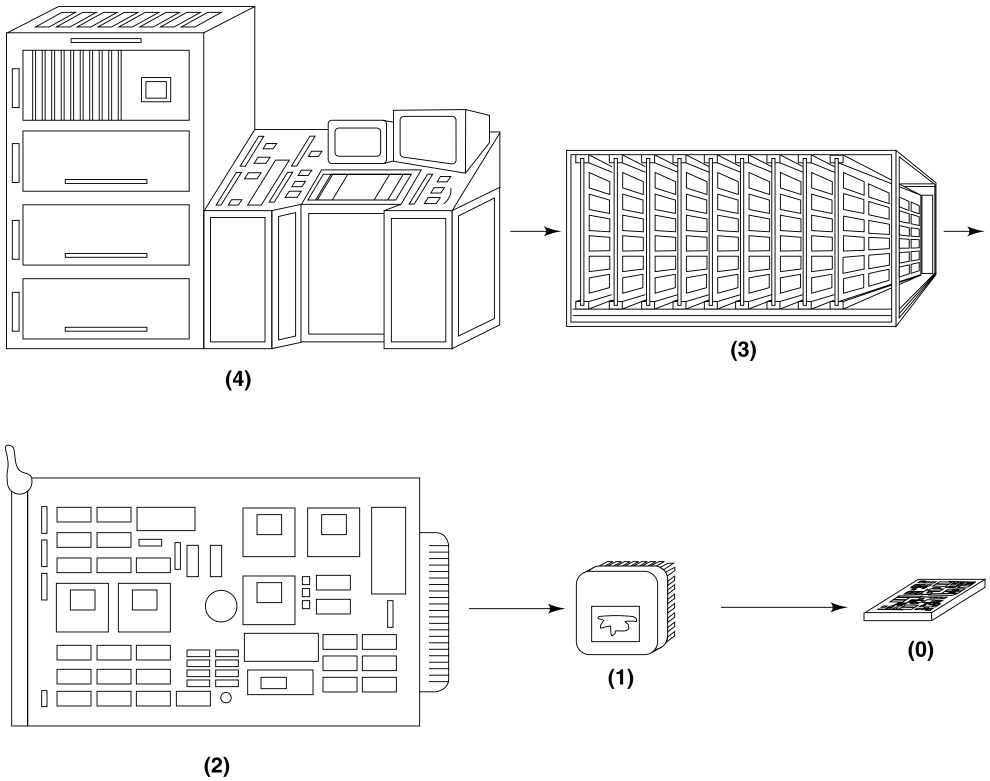

Fig. 1. The different levels of electronic packaging: **(0)** chip; **(1)** chip carrier; **(2)** printed circuit board (electronic card assembly); **(3)** rack; and **(4)** system (2).

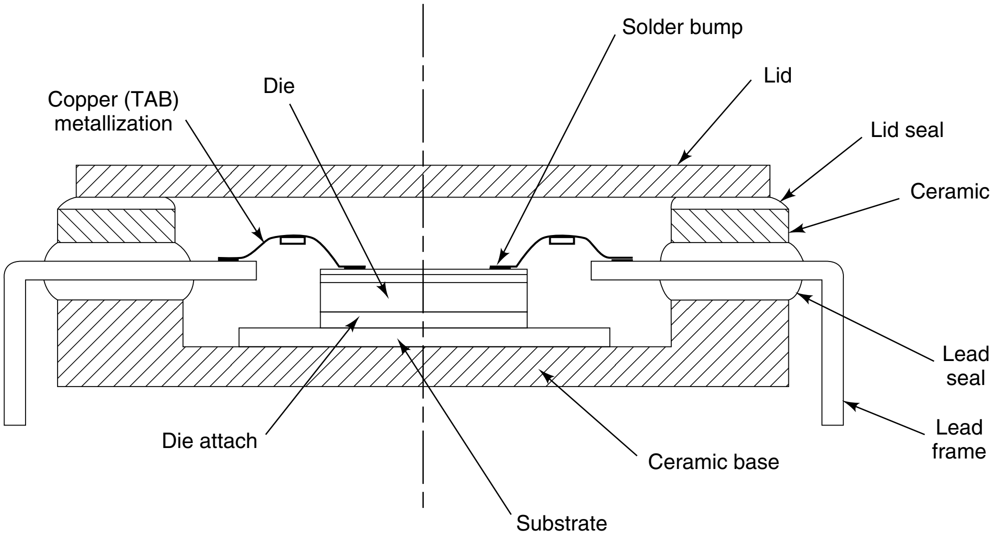

Fig. 2. Ceramic package with TAB interconnect (3).

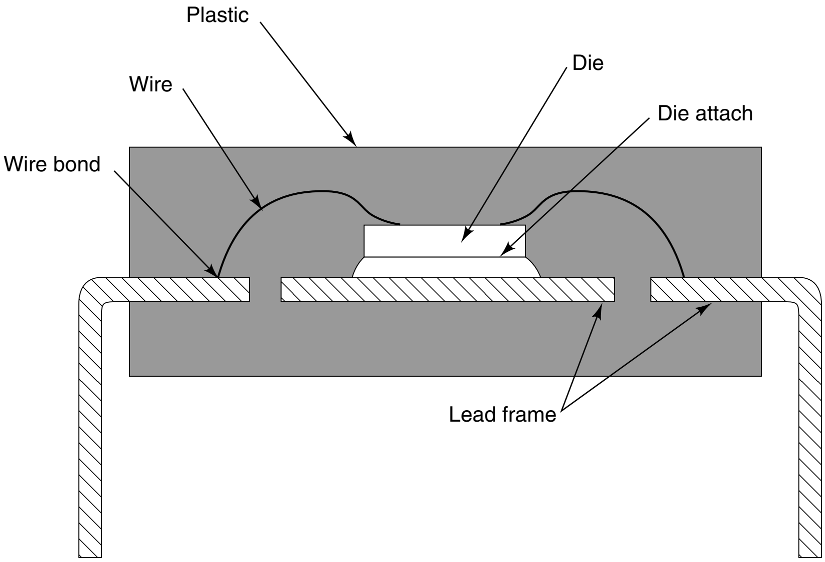

Fig. 3. Plastic package with wire bond interconnect (3).

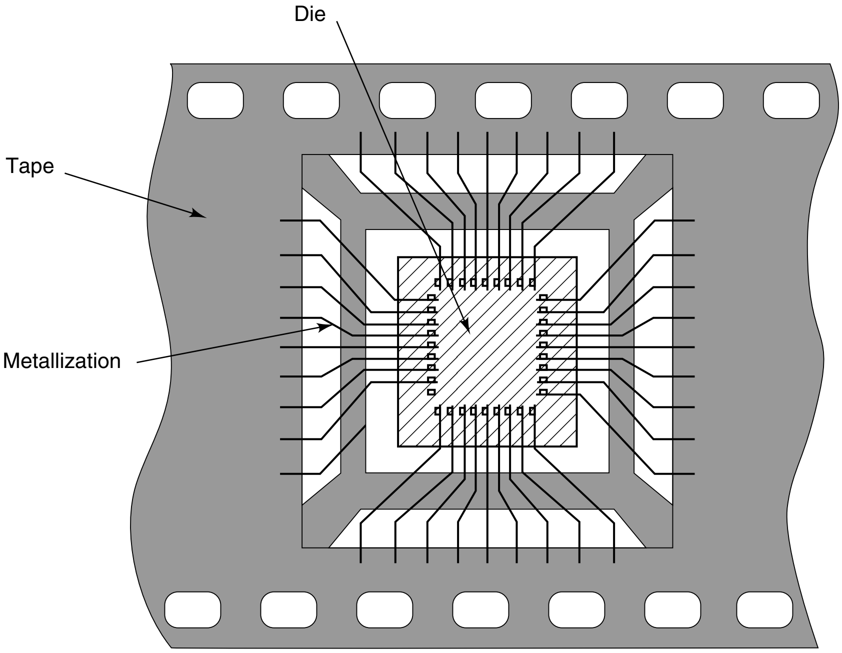

Fig. 4. Example of a TAB tape (3).

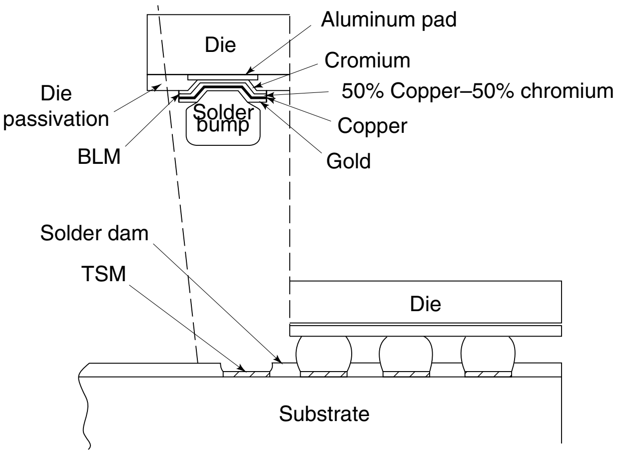

Fig. 5. Various layers in a flip-chip bond, where BLM = ball-limiting metallurgy and TSM = top-surface metallurgy (3).