Source: Electronic Materials and Processes Handbook

# 8

# Materials and Processes for Hybrid Microelectronics and Multichip Modules

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## 8.1 Introduction

Hybrid microelectronics technology is a distinct branch of electronics packaging technology and is primarily differentiated from other branches by the manner in which the interconnection patterns are generated. The foundation for the hybrid circuit is a substrate fabricated from one of the refractory ceramics. A metallization pattern is created on the substrate by one of the film technologies, forming the mounting pads and circuit traces to which we bond and interconnect additional active and passive devices as necessary. Another characteristic of hybrid technology is the ability to fabricate passive components. The thick and thin film technologies, for example, can be used to manufacture resistors with parameters superior to those of carbon resistors that are commonly used in conjunction with printed circuit boards.

The most commonly accepted definition of a hybrid circuit is a ceramic substrate metallized by one of the methods shown in Fig. 8.1, containing at least two components, one of which must be active. This definition is intended to exclude single-chip packages and circuits that contain only passive components such as resistor networks. By this definition, a hybrid circuit may range from a simple diode-resistor logic gate to a circuit containing in excess of 100 integrated circuits (ICs).

Multichip modules (MCMs) are close relatives of hybrid circuits. Although many of the assembly processes are common to those used to fabricate hybrid circuits, MCMs, as shown in Fig. 8.2, employ a wider range of substrate materials and metallization processes that provide a much higher packaging density.



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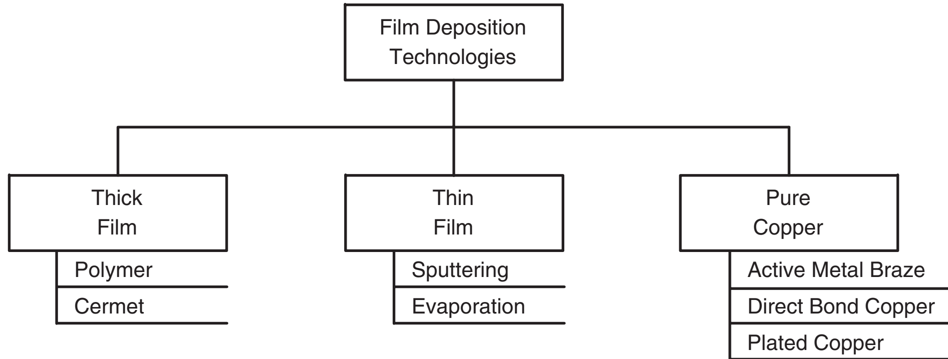


**Figure 8.1** Film deposition technologies.

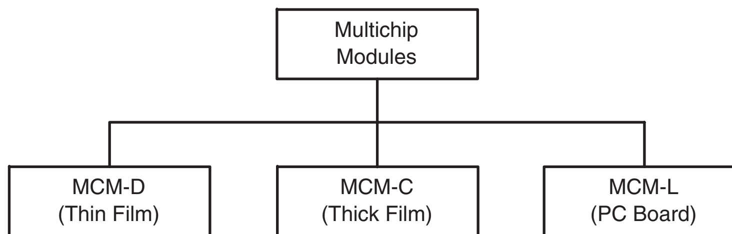


**Figure 8.2** Multichip module technologies.

This chapter describes the methods and properties of the various materials, metallization processes, and assembly methods used to manufacture hybrid circuits and MCMs. Also included are design guidelines, a discussion of reliability considerations, and applications of hybrid circuits.

## 8.2 Ceramic Substrates for Hybrid Circuits

The substrate is the foundation of an electronic circuit and must perform many functions. It acts as the platform upon which to mount components and must be compatible with the processes intended to metallize the substrate and to attach the components to the metallized traces. The substrate may also be an integral part of the overall circuit package.

The desirable properties of a substrate for electronic applications include

- *High electrical resistivity.* A substrate must have high electrical resistivity to isolate adjacent circuitry.
- *High thermal conductivity.* High thermal conductivity assists in transporting the heat generated by electronic components during normal operation away from the components.
- *Resistance to temperature.* Many of the processes used to metallize substrates and assemble the components take place at elevated temperatures.

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- *Inert to chemical corrosion.* Solvents, fluxes, and the like are harsh and must not attack the chemical structure of the substrate.
- *Cost.* The cost of the substrate material must be compatible with the cost of the end product.

The properties of ceramic substrates are advantageous for many microelectronic systems, ranging from simple, inexpensive circuits used in throwaway toys to elaborate multilayer structures used in space or medical applications. Only by understanding the properties of ceramic substrates can they be optimally utilized in this wide variety of applications.

Ceramics are crystalline in nature, with very few free electrons. They have high electrical resistivity, are chemically and thermally very stable, and have a high melting point. They are formed by the bonding of a metal and a nonmetal and may exist as oxides, nitrides, carbides, or silicides. An exception is diamond, which consists of pure carbon subjected to high temperature and pressure. Diamond substrates meet the criteria for ceramics and may be considered as such in this context.

The primary bonding mechanism in ceramics is ionic bonding. An ionic bond is formed by the electrostatic attraction between positive and negative ions. Atoms are most stable when they have eight electrons in the outer shell. Metals have a surplus of electrons in the outer shell, which are loosely bound to the nucleus and readily become free, creating positive ions. Similarly, nonmetals have a deficit of electrons in the outer shell and readily accept free electrons, creating negative ions. Figure 8.3 illustrates an ionic bond between a magnesium ion with a charge of +2 and an oxygen ion with a charge of –2, forming magnesium oxide (MgO). Ionically bonded materials are crystalline in nature and have both a high electrical resistance and a high relative dielectric

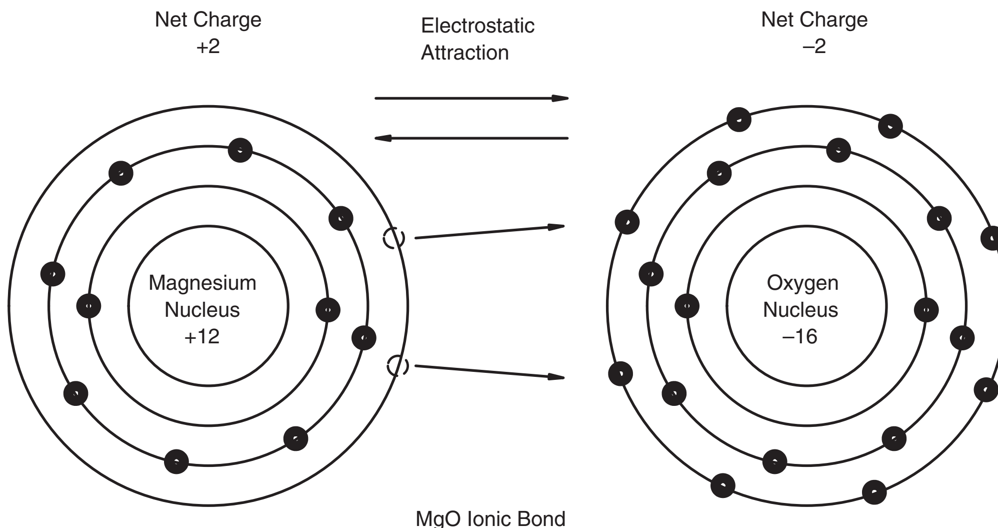


**Figure 8.3** Magnesium oxide ionic bond.

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constant. As a result of the strong nature of the bond, they have a high melting point and do not readily break down at elevated temperatures. For the same reason, they are very stable chemically and are not attacked by ordinary solvents and most acids.

A degree of covalent bonding may also be present, particularly in some of the silicon and carbon-based ceramics. The sharing of electrons in the outer shell forms a covalent bond. A covalent bond is depicted in Fig. 8.4, illustrating the bond between oxygen and hydrogen to form water. A covalent bond is also a very strong bond, and may be present in liquids, solids, and gases.

A composite is a mixture of two or more materials that retain their original properties but, in concert, offer parameters that are superior to either. Composites in various forms have been used for centuries. Ancient peoples, for example, used straw and rocks to increase the strength of bricks. Modern day structures use steel rods to reinforce concrete. The resulting composite structure combines the strength of steel with the lower cost and weight of concrete.

Ceramics are commonly used in conjunction with metals to form composites for electronic applications, especially thermal management. Ceramic-metal (cermet) composites typically have a lower TCE and a higher thermal conductivity than ceramics, and they are more ductile and more resistant to stress. These properties combine to make cermet composites ideal for use in high-power applications in which thermal management is critical.

## 8.3 Surface Properties of Ceramics

The surface properties of interest, surface roughness and camber, are highly dependent on the particle size and method of processing. Surface roughness is a measure of the surface microstructure, and camber is a measure of the devi-

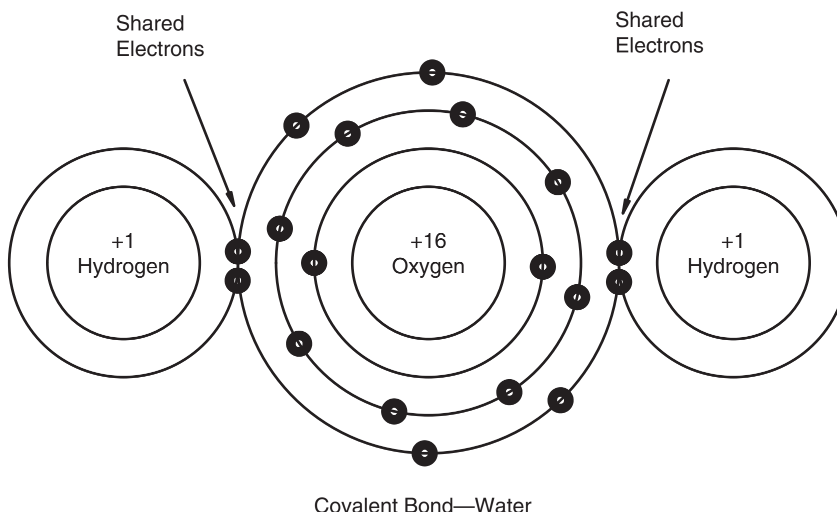


**Figure 8.4** Covalent bond between oxygen and hydrogen to form water.

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ation from flatness. In general, the smaller the particle size, the smoother the surface.

Surface roughness may be measured by electrical or optical means. Electrically, surface roughness is measured by moving a fine-tipped stylus across the surface. The stylus may be attached to a piezoelectric crystal or to a small magnet that moves inside a coil, inducing a voltage that is proportional to the magnitude of the substrate variations. The stylus must have a resolution of 25.4 nm (1 μin) to read accurately in the most common ranges. Optically, a coherent light beam from a laser diode or other source is directed onto the surface. The deviations in the substrate surface create interference patterns that are used to calculate the roughness. Optical profilometers have a higher resolution than the electrical versions and are used primarily for very smooth surfaces. For ordinary use, the electrical profilometer is adequate and is widely used to characterize substrates in both manufacturing and laboratory environments.

Camber and waviness are similar in form in that they are variations in flatness over the substrate surface. Referring to Fig. 8.5, camber can be considered to be an overall warpage of the substrate, whereas waviness is more periodic in nature. Both of these factors may occur as a result of uneven shrinkage during the organic removal/sintering process or as a result of nonuniform composition. Waviness may also occur because of a “flat spot” in the rollers used to form the green sheets.

Camber is measured in units of length/length, interpreted as the deviation from flatness per unit length, and is measured with reference to the longest dimension by placing the substrate through parallel plates set a specific distance apart. Thus, a rectangular substrate would be measured along the diagonal. A typical value of camber is 0.003 in/in (or 0.003 mm/mm), which for a 2-

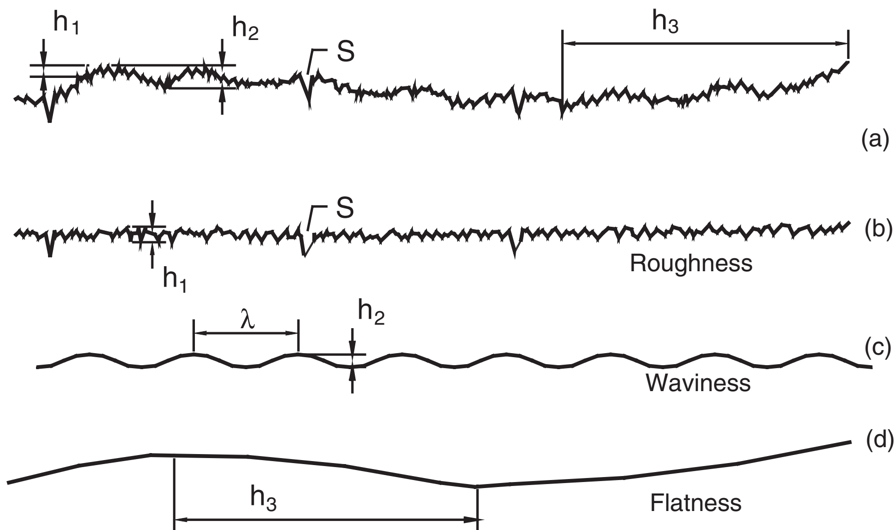


**Figure 8.5** Surface characteristics.

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× 2-in substrate, represents a total deviation of 0.003 × 2 × 1.414 = 0.0085 in. For a substrate that is 0.025 in thick, a common value, the total deviation represents one-third of the overall thickness!

## 8.4 Thermal Properties of Ceramic Materials

### 8.4.1 Thermal conductivity

The thermal conductivity of a material is a measure of the ability to carry heat and is defined as

$$q = -k\frac{dT}{dx} \tag{8.1}$$

where $k$ = thermal conductivity in W/m-°C
$q$ = heat flux in w/m$^2$
$\frac{dT}{dx}$ = temperature gradient in °C/m in steady state

The negative sign denotes that heat flows from areas of higher temperature to areas of lower temperature. A plot of thermal conductivity vs. temperature for selected materials is shown in Fig. 8.6.

### 8.4.2 Specific heat

The specific heat of a material is defined as

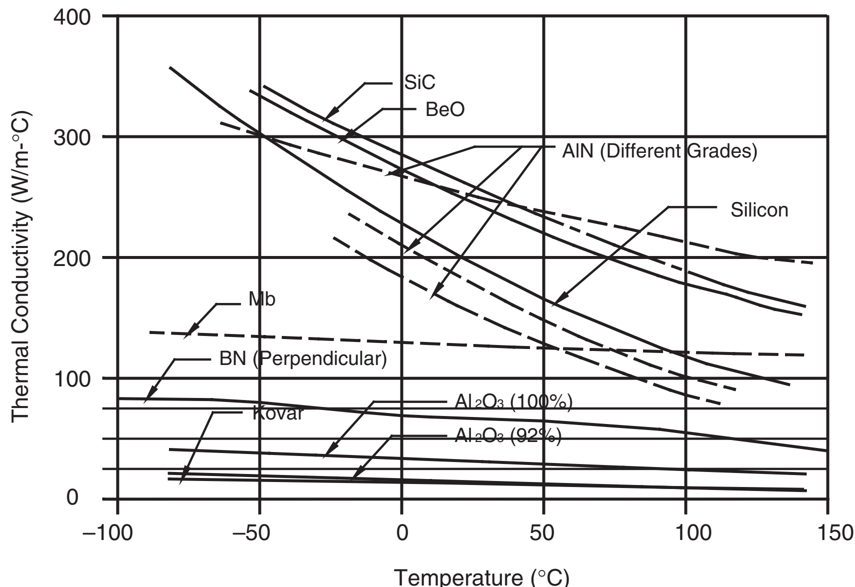


**Figure 8.6** Thermal conductivity vs. temperature for selected materials.

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$$c = \frac{dQ}{dT} \tag{8.2}$$

where $c$ = specific heat in W-sec/g-°C
$Q$ = energy in watt-sec
$T$ = temperature in kelvins (K)

The specific heat, $c$, is defined in a similar manner and is the amount of heat required to raise the temperature of one gram of material by one degree, with units of watt-sec/g-°C. The quantity "specific heat" in this context refers to the quantity, $c_V$, which is the specific heat measured with the volume constant, as opposed to $c_P$, which is measured with the pressure constant. At the temperatures of interest, these numbers are nearly the same for most solid materials. The specific heat is primarily the result of an increase in the vibrational energy of the atoms when heated, and the specific heat of most materials increases with temperature up to a temperature, called the Debye temperature, at which point it becomes essentially independent of temperature. The specific heat of several common ceramic materials as a function of temperature is shown in Fig. 8.7.

The heat capacity, $C$, is similar in form except that it is defined in terms of the amount of heat required to raise the temperature of a mole of material by one degree and has the units of watt-sec/mol-°C.

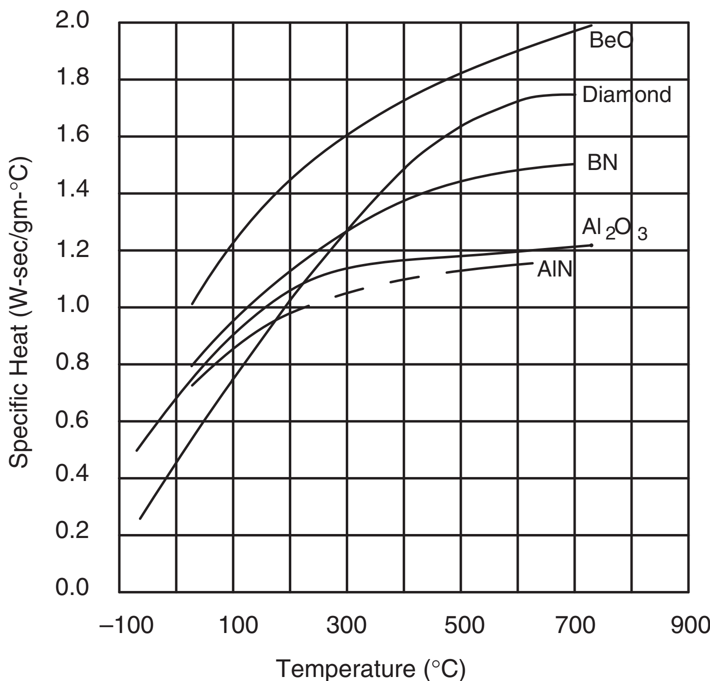


**Figure 8.7** Specific heat vs. temperature for selected ceramic materials.

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### 8.4.3 Temperature coefficient of expansion

The temperature coefficient of expansion (TCE) arises from the asymmetrical increase in the interatomic spacing of atoms as a result of increased heat. Most metals and ceramics exhibit a linear, isotropic relationship in the temperature range of interest, whereas certain plastics may be anisotropic in nature. The TCE is defined as

$$\alpha = \frac{\ell T_2 - \ell(T_1)}{\ell T_1 - (T_2 - T_1)} \tag{8.3}$$

where $\alpha$ = temperature coefficient of expansion in ppm/°C$^{-1}$
$T_1$ = initial temperature
$T_2$ = final temperature
$\ell(T_1)$ = length at initial temperature
$\ell(T_2)$ = length at final temperature

The TCE of most ceramics is isotropic. For certain crystalline or single-crystal ceramics, the TCE may be anisotropic, and some may even contract in one direction and expand in the other. Ceramics used for substrates do not generally fall into this category, as most are mixed with glasses in the preparation stage and do not exhibit anisotropic properties as a result. The temperature coefficient of expansion of several ceramic materials is shown in Table 8.1.

**TABLE 8.1 Temperature Coefficient of Expansion of Selected Ceramic Substrate Materials**

| Material | TCE (ppm/°C) |
|---|---|
| Alumina (96%) | 6.5 |
| Alumina (99%) | 6.8 |
| BeO (99.5%) | 7.5 |
| BN parallel | 0.57 |
| perpendicular | –0.46 |
| Silicon carbide | 3.7 |
| Aluminum nitride | 4.4 |
| Diamond, Type 11A | 1.02 |
| AlSiC (70% SiC loading) | 6.3 |

## 8.5 Mechanical Properties Of Ceramic Substrates

The mechanical properties of ceramic materials are strongly influenced by the strong interatomic bonds that prevail. Dislocation mechanisms, which create slip mechanisms in softer metals, are relatively scarce in ceramics, and failure may occur with very little plastic deformation (the small elongation that occurs

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before failure). Ceramics also tend to fracture with little resistance. They have a very high melting point, as shown in Table 8.2.

**TABLE 8.2 Melting Points of Selected Ceramics**

| Material | Melting point (°C) |
|---|---|
| SiC | 2700 |
| BN | 2732 |
| AlN | 2232 |
| BEO | 2570 |
| $Al_2O_3$ | 2000 |

### 8.5.1 Modulus of elasticity

The temperature coefficient of expansion (TCE) phenomenon has serious implications in the applications of ceramic substrates. When a sample of material has one end fixed, which may be considered to be a result of bonding to another material that has a much smaller TCE, the net elongation of the hotter end per unit length, or "strain" ($E$), of the material is calculated by

$$E = TCE \times \Delta T \tag{8.4}$$

where $E$ = strain in length/length
$\Delta T$ = temperature differential across the sample

Elongation develops a stress ($S$) per unit length in the sample as given by Hooke's law.

$$S = EY \tag{8.5}$$

where $S$ = stress in psi/in ($N/m^2/m$)
$Y$ = modulus of elasticity in $lb/in^2$ ($N/m^2$)

When the total stress (as calculated by multiplying the stress/unit length by the maximum dimension of the sample) exceeds the strength of the material, mechanical cracks will form in the sample that may even propagate to the point of separation. This analysis is somewhat simplistic in nature, but it serves to provide a basic understanding of the mechanical considerations. The modulus of elasticity of selected ceramics is summarized in Table 8.3, along with other mechanical properties.

### 8.5.2 Modulus of rupture

Ordinary stress-strain testing is not generally used to test ceramic substrates, because they do not exhibit elastic behavior to a great degree. An alternative

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**TABLE 8.3 Mechanical Properties of Selected Ceramics**

| Material | Modulus of elasticity (GPa) | Tensile strength (MPa) | Compressive strength | Modulus of rupture | Flexural strength | Density |
|---|---|---|---|---|---|---|
| Alumina (99%) | 370 | 500 | 2600 | 386 | 352 | 3.98 |
| Alumina (96%) | 344 | 172 | 2260 | 341 | 331 | 3.92 |
| Beryllia (99.5%) | 345 | 138 | 1550 | 233 | 235 | 2.87 |
| Boron nitride (normal) | 43 | 2410 | 6525 | 800 | 53.1 | 1.92 |
| Aluminum nitride | 300 | 310 | 2000 | 300 | 269 | 3.27 |
| Silicon carbide | 407 | 197 | 4400 | 470 | 518 | 3.10 |
| Diamond (Type 11A) | 1000 | 1200 | 11000 | 940 | 1000 | 3.52 |

test, the modulus of rupture (bend strength) test, is preferred. A sample of ceramic, either circular or rectangular, is suspended between two points, a force is applied in the center, and the elongation of the sample is measured. The stress is calculated by

$$\sigma = \frac{Mx}{I} \tag{8.6}$$

where $\sigma$ = stress in MPa
$M$ = maximum bending moment in N-m
$x$ = distance from center to outer surface in m
$I$ = moment of inertia in N-$m^2$

The expressions for $\sigma$, $M$, $x$, and $I$ are summarized in Table 8.4.

**TABLE 8.4 Parameters of Stress in Modulus of Rupture Test[1]**

| Cross section | $M$ | $c$ | $I$ |
|---|---|---|---|
| Rectangular | $\frac{FL}{4}$ | $\frac{y}{2}$ | $\frac{xy^3}{12}$ |
| Circular | $\frac{FL}{4}$ | R | $\frac{\pi R^2}{4}$ |

Referring to Fig. 8.8,[1] when these are inserted into Eq. (8.6), the result is

$$\sigma = \frac{3FL}{2xy^2} \quad \text{(Rectangular cross section)} \tag{8.7}$$

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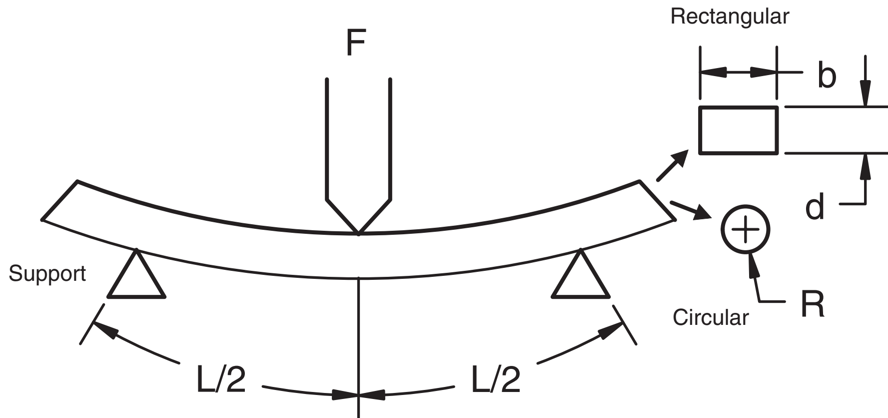


**Figure 8.8** Modulus of rupture test.

$$\sigma = \frac{FL}{\pi R^3} \text{ (Circular cross section)} \tag{8.8}$$

where $F$ = applied force in newtons
$x$ = long dimension of rectangular cross section in meters
$y$ = short dimension of rectangular cross section in meters
$L$ = length of sample in meters
$R$ = radius of circular cross section in meters

The modulus of rupture is the stress required to produce fracture and is given by

$$\sigma_r = \frac{3F_rL}{2xy^2} \text{ (Rectangular)} \tag{8.9}$$

$$\sigma_r = \frac{F_rL}{\pi R^3} \text{ (Circular)} \tag{8.10}$$

where $\sigma_r$ = modulus of rupture in n/m$^2$
$F_r$ = force at rupture

The modulus of rupture for selected ceramics is shown in Table 8.3.

### 8.5.3 Tensile and compressive strength

A force applied to a ceramic substrate in a tangential direction may produce tensile or compressive forces. If the force is tensile, in a direction such that the material is pulled apart, the stress produces plastic deformation as defined in Eq. (8.5). As the force increases past a value, referred to as the *tensile*

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*strength*, breakage occurs. Conversely, a force applied in the opposite direction creates compressive forces until a value referred to as the *compressive strength* is reached, at which point breakage also occurs. The compressive strength of ceramic materials is, in general, much larger than the tensile strength. The tensile and compressive strengths of selected ceramic materials are shown in Table 8.3.

In practice, the force required to fracture a ceramic substrate is much lower than predicted by theory. The discrepancy is due to small flaws or cracks residing within these materials as a result of processing. For example, when a substrate is sawed, small edge cracks may be created. Similarly, when a substrate is fired, trapped organic material may outgas during firing, leaving a microscopic void in the bulk. The result is an amplification of the applied stress in the vicinity of the void that may exceed the tensile strength of the material and create a fracture. If the microcrack is assumed to be elliptical in shape with the major axis perpendicular to the applied stress, the maximum stress at the tip of the crack may be approximated by[2]

$$S_M = 2S_O \leq \left(\frac{a}{\rho_t}\right)^{1/2} \tag{8.11}$$

where $S_M$ = maximum stress at the tip of the crack
$S_O$ = nominal applied stress
$a$ = length of the crack as defined in Fig. 8.9
$\rho_t$ = radius of the crack tip

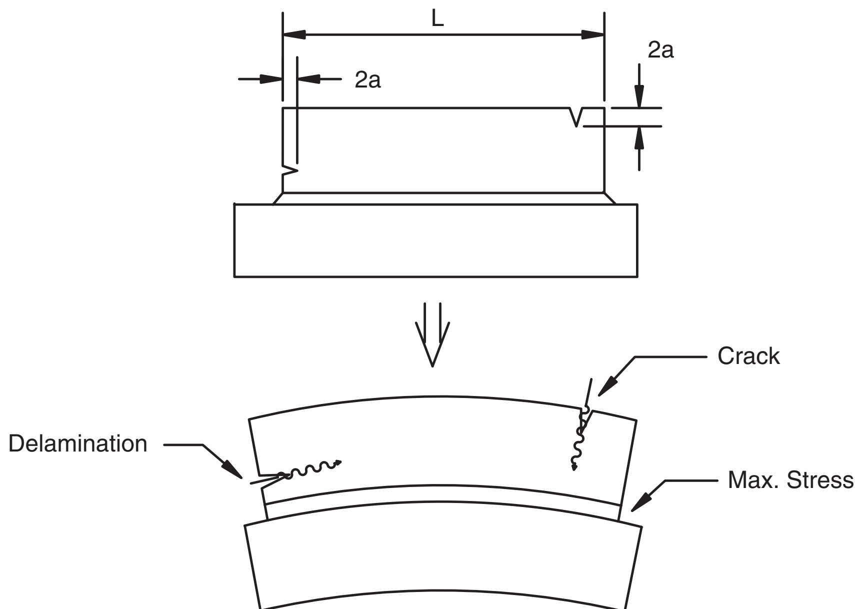


**Figure 8.9** Cracks and chip-outs in substrate.[5]

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The ratio of the maximum stress to the applied stress may be defined as

$$K_t = \frac{S_M}{S_O} = 2\left(\frac{a}{\rho_t}\right)^{1/2} \tag{8.12}$$

where $K_t$ = stress concentration factor

For certain geometries, such as a long crack with a small tip radius, $K_t$ may be much larger than 1, and the force at the tip may be substantially larger than the applied force.

Based on this analysis, a material parameter called the *plain strain fracture toughness*, a measure of the ability of the material to resist fracture, can be defined as

$$K_{IC} = ZS_C\sqrt{\pi a} \tag{8.13}$$

where $K_{IC}$ = plain strain fracture toughness in psi-in$^{1/2}$ or MPa-m$^{1/2}$
$Z$ = dimensionless constant, typically 1.2[2]
$S_C$ = critical force required to cause breakage

From Eq. (8.13), the expression for the critical force can be defined as

$$S_C = Z\frac{K_{IC}}{\sqrt{\pi a}} \tag{8.14}$$

When the applied force on the die caused by TCE or thermal differences exceeds this figure, fracture is likely. The plain strain fracture toughness for selected materials is presented in Table 8.5. It should be noted that Eq. (8.14) is a function of thickness up to a point but is approximately constant for the area-to-thickness ratio normally found in substrates.

**TABLE 8.5 Fracture Toughness for Selected Materials**

| Material | Fracture toughness (MPa-m$^{1/2}$) |
|---|---|
| Silicon | 0.8 |
| Alumina (96%) | 3.7 |
| Alumina (99%) | 4.6 |
| Silicon carbide | 7.0 |
| Molding compound | 2.0 |

### 8.5.4 Hardness

Ceramics are among the hardest substances known, and their hardness is correspondingly difficult to measure. Most methods rely on the ability of one ma-

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terial to scratch another, and the measurement is presented on a relative scale. Of the available methods, the Knoop method is the most frequently used. In this approach, the surface is highly polished, and a pointed diamond stylus under a light load is allowed to impact the material. The depth of the indentation formed by the stylus is measured and converted to a qualitative scale called the "Knoop" or "HK" scale. The Knoop hardness of selected ceramics is given in Table 8.6.

**TABLE 8.6 Knoop Hardness for Selected Ceramics**

| Material | Knoop hardness (100 g) |
|---|---|
| Diamond | 7000 |
| Aluminum oxide | 2100 |
| Aluminum nitride | 1200 |
| Beryllium oxide | 1200 |
| Boron nitride | 5000 |
| Silicon carbide | 2500 |

### 8.5.5 Thermal shock

Thermal shock occurs when a substrate is exposed to temperature extremes over a short period of time. Under these conditions, the substrate is not in thermal equilibrium, and internal stresses may be sufficient to cause fracture. Thermal shock can be liquid-to-liquid or air-to-air, with the most extreme exposure occurring when the substrate is transferred directly from one liquid bath to another. The heat is more rapidly absorbed or transmitted, depending on the relative temperature of the bath, because of the higher specific heat of the liquid as opposed to air.

The ability of a substrate to withstand thermal shock is a function of several variables, including the thermal conductivity, the coefficient of thermal expansion, and the specific heat. Winkleman and Schott[3] developed a parameter called the *coefficient of thermal endurance* that qualitatively measures the ability of a substrate to withstand thermal stress.

$$F = \frac{P}{\alpha Y}\sqrt{\frac{k}{\rho c}} \tag{8.15}$$

where $F$ = coefficient of thermal endurance
$P$ = tensile strength in MPa
$\alpha$ = thermal coefficient of expansion in 1/K
$Y$ = modulus of elasticity in MPa
$k$ = thermal conductivity in W/m-K
$\rho$ = density in kg/m$^3$
$c$ = specific heat in W-sec/kg-K

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The coefficient of thermal endurance for selected materials is shown in Table 8.7. The phenomenally high coefficient of thermal endurance for BN is primarily a result of the high ratio of tensile strength to modulus of elasticity as compared to other materials. Diamond is also high, primarily because of the high tensile strength, the high thermal conductivity, and the low TCE.

**TABLE 8.7 Thermal Endurance Factor for Selected Materials at 25°C**

| Material | Thermal endurance factor |
|---|---|
| Alumina (99%) | 0.640 |
| Alumina (96%) | 0.234 |
| Beryllia (99.5%) | 0.225 |
| Boron nitride ("a" axis) | 648 |
| Aluminum nitride | 2.325 |
| Silicon carbide | 1.40 |
| Diamond (Type 11A) | 30.29 |

The thermal endurance factor is a function of temperature in that several of the variables, particularly the thermal conductivity and the specific heat, are functions of temperature. From Table 8.7, it is also noted that the thermal endurance factor may drop rapidly as the alumina-to-glass ratio drops. This is a result of the difference in the thermal conductivity and TCE of the alumina and glass constituents that increase the internal stresses. This is true of other materials as well.

## 8.6 Electrical Properties of Ceramics

The electrical properties of ceramic substrates perform an important task in the operation of electronic circuits. Depending on the applications, the electrical parameters may be advantageous or detrimental to circuit function. Of most interest are the resistivity, the breakdown voltage (or dielectric strength), and the dielectric properties, including the dielectric constant and loss tangent.

### 8.6.1 Resistivity

The electrical resistivity of a material is a measure of its ability to transport charge under the influence of an applied electric field. More often, this ability is presented in the form of the electrical conductivity, the reciprocal of the resistivity, as defined in Eq. (8.16).

$$\sigma = \frac{1}{\rho} \tag{8.16}$$

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where $\sigma$ = conductivity in siemens/unit length
$\rho$ = resistivity in ohm-unit length

The V-I relationship is governed primarily by injected carriers as opposed to thermal carriers (the opposite of the case with metals) and is given by

$$J = \mu \varepsilon E^2 \tag{8.17}$$

The electrical conductivity of ceramic substrates is extremely low. In practice, it is primarily the result impurities and lattice defects and may vary widely from batch to batch. The conductivity is also a strong function of temperature. As the temperature increases, the ratio of thermal to injected carriers increases. As a result, the conductivity increases and the V-I relationship follows Ohm's law more closely. Typical values of the resistivity of selected ceramic materials are presented in Table 8.8.

**TABLE 8.8 Electrical Properties of Selected Ceramic Substrates**

| Material | Property | | | |
|---|---|---|---|---|
| | Electrical resistivity (Ω-cm) | Breakdown voltage (AC kV/mm) | Dielectric constant | Loss tangent (@ 1 MHz) |
| Alumina (95%) | | 8.3 | | 0.0002 |
| 25°C | $>10^{14}$ | | 9.0 | |
| 500°C | $4 \times 10^9$ | | 10.8 | |
| 1000°C | $1 \times 10^6$ | | | |
| Alumina (99.5%) | | 8.7 | | 0.0001 |
| 25°C | $>10^{14}$ | | 9.4 | |
| 500°C | $2 \times 10^{10}$ | | 10.1 | |
| 1000°C | $2 \times 10^6$ | | | |
| Beryllia | | 6.6 | | |
| 25°C | $>10^{14}$ | | 6.4 | 0.0001 |
| 500°C | $2 \times 10^{10}$ | | 6.9 | 0.0004 |
| Aluminum nitride | $>10^{13}$ | 14 | 8.9 | 0.0004 |
| Boron nitride | $>10^{14}$ | 61 | 4.1 | 0.0003 |
| Silicon carbide* | $>10^{13}$ | 0.7 | 40 | 0.05 |
| Diamond (Type II) | $>10^{14}$ | 1000 | 5.7 | 0.0006 |

*Depends on method of preparation. May be substantially lower.

### 8.6.2 Breakdown voltage

The term *breakdown voltage* is very descriptive. Although ceramics are normally very good insulators, the application of excessively high potentials can

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dislodge electrons from orbit with sufficient energy to allow them to dislodge other electrons from orbit, creating an *avalanche effect.* The result is a breakdown of the insulation properties of the material, allowing current to flow. This phenomenon is accelerated by elevated temperature, particularly when mobile ionic impurities are present.

The breakdown voltage is a function of numerous variables, including the concentration of mobile ionic impurities, grain boundaries, and the degree of stoichiometry. In most applications, the breakdown voltage is sufficiently high that it is not an issue. However, there are two cases in which is must be a consideration.

1. At elevated temperatures created by localized power dissipation or high ambient temperature, the breakdown voltage may drop by orders of magnitude. Combined with a high potential gradient, this condition may be susceptible to breakdown.
2. The surface of most ceramics is highly "wettable," in that moisture tends to spread rapidly. Under conditions of high humidity, coupled with surface contamination, the effective breakdown voltage is much lower than the intrinsic value.

### 8.6.3 Dielectric properties

Two conductors in proximity with a difference in potential have the ability to attract and store electric charge. Placing a material with dielectric properties between them enhances this effect. A dielectric material has the capability of forming electric dipoles, displacements of electric charge, internally. At the surface of the dielectric, the dipoles attract more electric charge, thus enhancing the charge storage capability, or capacitance, of the system. The relative ability of a material to attract electric charge in this manner is called the *relative dielectric constant,* or *relative permittivity,* and is usually given the symbol K. The relative permittivity of free space is 1.0 by definition and the absolute permittivity is

$$\varepsilon_o = \text{permittivity of free space}$$

$$\varepsilon_o = \frac{1}{36\pi} \times 10^{-9} \frac{\text{farads}}{\text{meter}} \tag{8.18}$$

There are two common ways to categorize dielectric materials: as polar or nonpolar, and as paraelectric or ferroelectric. Polar materials include those that are primarily molecular in nature, such as water; nonpolar materials include both electronically and ionically polarized materials. Paraelectric materials are polarized only in the presence of an applied electric field and lose their polarization when the field is removed, whereas ferroelectric materials retain a degree of polarization after the field is removed. Materials used as ceramic substrates are usually nonpolar and paraelectric in nature. An exception is silicon carbide, which has a degree of molecular polarization.

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In the presence of an electric field that is changing at a high frequency, the polarity of the dipoles must change at the same rate as the polarity of the signal to maintain the dielectric constant at the same level. Some materials are excellent dielectrics at low frequencies, but the dielectric qualities drop off rapidly as the frequency increases. Electronic polarization, which involves only displacement of free charge and not ions, responds more rapidly to the changes in the direction of the electric field and remains viable up to about $10^{17}$ Hz. The polarization effect of ionic displacement begins to fall off at about $10^{13}$ Hz, and molecular and space charge polarizations fall off at still lower frequencies. The frequency response of the different types is shown in Fig. 8.10, which also illustrates that the dielectric constant decreases with frequency.

Changing the polarity of the dipoles requires a finite amount of energy and time. The energy is dissipated as internal heat, quantified by a parameter called the *loss tangent* or *dissipation factor*. Furthermore, dielectric materials are not perfect insulators. These phenomena may be modeled as a resistor in parallel with a capacitor. The loss tangent, as expected, is a strong function of the applied frequency, increasing as the frequency increases.

In alternating current applications, the current and voltage across an ideal capacitor are exactly 90° out of phase, with the current leading the voltage. In actuality, the resistive component causes the current to lead the voltage by an angle less than 90°. The loss tangent is a measure of the real or resistive com-

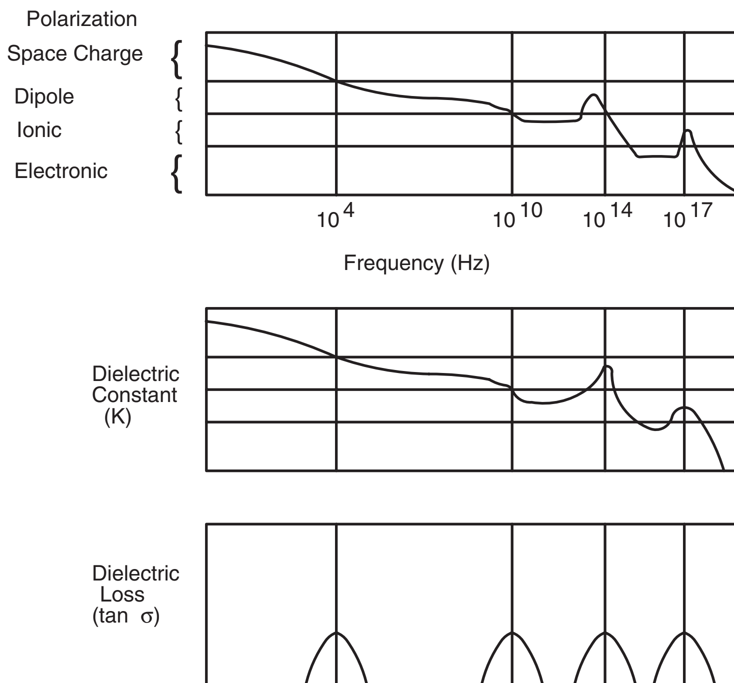


**Figure 8.10** Frequency effects on dielectric materials.

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ponent of the capacitor and is the tangent of the difference between 90° and the actual phase angle.

$$\text{Loss tangent} = \tan(90° - \delta) \quad (8.19)$$

where $\delta$ = phase angle between voltage and current

The loss tangent is also referred to as the *dissipation factor* (DF).

The loss tangent may also be considered as a measure of the time required for polarization. It requires a finite amount of time to change the polarity of the dipole after an alternating field is applied. The resulting phase retardation is equivalent to the time indicated by the difference in phase angles.

## 8.7 Properties of Substrate Materials

### 8.7.1 Aluminum oxide

Aluminum oxide, $Al_2O_3$, commonly referred to as alumina, is by far the most common substrate material used in the microelectronics industry, because it is superior to most other oxide ceramics in mechanical, thermal, and electrical properties. The raw materials are plentiful and low in cost and are amenable to fabrication by a wide variety of techniques into a wide variety of shapes.

Alumina is hexagonal close-packed with a corundum structure. Several metastable structures exist, but they all ultimately irreversibly transform to the hexagonal alpha phase. Alumina is stable in both oxidizing and reducing atmospheres up to1925°C.

Weight loss in vacuum over the temperature range of 1700°C to 2000°C ranges from $10^{-7}$ to $10^{-6}$ g/cm$^2$-sec. It is resistant to attack by all gases except wet fluorine to at least 1700°C. Alumina is attacked at elevated temperatures by alkali metal vapors and halogen acids, especially the lower-purity alumina compositions that may contain a percentage of glasses.

Alumina is used extensively in the microelectronics industry as a substrate material for thick and thin film circuits, for circuit packages, and as multilayer structures for multichip modules. Compositions exist for both high- and low-temperature processing. High-temperature cofired ceramics (HTCC) use a refractory metal, such as tungsten or molybdenum/manganese, as a conductor and fire at about 1800°C. The circuits are formed as separate layers, laminated together, and fired as a unit. Low-temperature cofired ceramics (LTCC) use conventional gold or palladium silver as conductors and fire as low as 850°C. Certain power MOSFETs and bipolar transistors are mounted on alumina substrates to act as electrical insulators and thermal conductors. The parameters of alumina are summarized in Table 8.9.

### 8.7.2 Beryllium oxide

Beryllium oxide (BeO, beryllia) is cubic close-packed and has a zinc blende structure. The alpha form of BeO is stable to above 2050°C. BeO is stable in dry atmospheres and is inert to most materials. It hydrolyzes at temperatures

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**TABLE 8.9 Typical Parameters of Aluminum Oxide**

| Parameter | Units | Test | Percentage (%) | | | |
|---|---|---|---|---|---|---|
| | | | 85 | 90 | 96 | 99.5 |
| Density | g/cm$^3$ | ASTM C20 | 3.40 | 3.60 | 3.92 | 3.98 |
| Elastic modulus | GPa | ASTM C848 | 220 | 275 | 344 | 370 |
| Poisson's ratio | | ASTM C848 | 0.22 | 0.22 | 0.22 | 0.22 |
| Compressive strength | MPa | ASTM C773 | 1930 | 2150 | 2260 | 2600 |
| Fracture toughness | MPa-m$^{0.5}$ | Notched beam | 3.1 | 3.3 | 3.7 | 4.6 |
| Thermal conductivity | W/m-°C | ASTM C408 | 16 | 16.7 | 24.7 | 31.0 |
| TCE | $10^{-6}$/°C | ASTM C372 | 5.9 | 6.2 | 6.5 | 6.8 |
| Specific heat | W-sec/g-°C | ASTM E1269 | 920 | 920 | 880 | 880 |
| Dielectric strength | AC kV/mm | ASTM D116 | 8.3 | 8.3 | 8.3 | 8.7 |
| Loss tangent (1 MHz) | | ASTM D2520 | 0.0009 | 0.0004 | 0.0002 | 0.0001 |
| Volume resistivity | 25°C<br>500°C<br>1000°C<br>Ω-cm | ASTM D1829 | $>10^{14}$<br>$4 \times 10^9$ | $>10^{14}$<br>$4 \times 10^8$<br>$5 \times 10^5$ | $>10^{14}$<br>$4 \times 10^9$<br>$1 \times 10^6$ | $>10^{14}$<br>$2 \times 10^{10}$<br>$2 \times 10^6$ |

greater than 1100°C with the formation and volatilization of beryllium hydroxide. BeO reacts with graphite at high temperatures, forming beryllium carbide.

Beryllia has an extremely high thermal conductivity, higher than aluminum metal, and is widely used in applications where this parameter is critical. The thermal conductivity drops rapidly above 300°C but is suitable for most practical applications.

Beryllia is available in a wide variety of geometries formed using a variety of fabrication techniques. While beryllia in the pure form is perfectly safe, care must be taken when machining BeO, however, as the dust is toxic if inhaled.

Beryllia may be metallized with thick film, thin film, or by one of the copper processes. However, thick film pastes must be specially formulated to be compatible. Laser or abrasive trimming of BeO must be performed in the presence of a vacuum to remove the dust. The properties of 99.5 percent beryllia are summarized in Table 8.10.

### 8.7.3 Aluminum nitride

Aluminum nitride is covalently bonded with a wurtzite structure and decomposes at 2300°C under 1 atm of argon. In a nitrogen atmosphere of 1500 psi, melting may occur in excess of 2700°C. Oxidation of AlN in even a low concen-

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**TABLE 8.10 Typical Parameters for 99.5 Percent Beryllium Oxide**

| Parameter | Units | Value |
|---|---|---|
| Density | g/cm$^3$ | 2.87 |
| Hardness | Knoop 100 g | 1200 |
| Melting point | °C | 2570 |
| Modulus of elasticity | GPa | 345 |
| Compressive strength | MPa | 1550 |
| Poisson's ratio | | 0.26 |
| Thermal conductivity | W/m-°C | |
| 25°C | | 250 |
| 500°C | | 55 |
| Specific heat | W-sec/g-K | |
| 25°C | | 1.05 |
| 500°C | | 1.85 |
| TCE | $10^{-6}$/K | 7.5 |
| Dielectric constant | | 6.5 |
| 1 MHz | | 6.6 |
| 10 GHz | | |
| Loss tangent | | |
| 1 MHz | | 0.0004 |
| 10 GHz | | 0.0004 |
| Volume resistivity | Ω-cm | |
| 25°C | | $>10^{14}$ |
| 500°C | | $2 \times 10^{10}$ |

tration of oxygen (<0.1 percent) occurs at temperatures above 700°C. A layer of aluminum oxide protects the nitride to a temperature of 1370°C, above which the protective layer cracks, allowing oxidation to continue. Aluminum nitride is not appreciably affected by hydrogen, steam, or oxides of carbon to 980°C. It dissolves slowly in mineral acids and decomposes slowly in water, It is compatible with aluminum to 1980°C, gallium to 1300°C, iron or nickel to 1400°C, and molybdenum to 1200°C.

Aluminum nitride substrates are fabricated by mixing AlN powder with compatible glass powders containing additives such as CaO and $Y_2O_3$, along with organic binders, and casting the mixture into the desired shape. Densification of the AlN requires very tight control of both atmosphere and temperature. The solvents used in the preparation of substrates must be anhydrous to minimize oxidation of the AlN powder and prevent the generation of ammonia during firing.[4] For maximum densification and maximum thermal conductivity, the substrates must be sintered in a dry reducing atmosphere to minimize oxidation.

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Aluminum nitride is primarily noted for two very important properties: a high thermal conductivity and a TCE closely matching that of silicon. Several grades of aluminum nitride with different thermal conductivities are available. The prime reason for the difference is the oxygen content of the material. It is important to note that even a thin surface layer of oxidation on a fraction of the particles can adversely affect the thermal conductivity. Only with a high degree of material and process control can AlN substrates be made consistent.

The thermal conductivity of AlN does not vary as widely with temperature as does that of BeO. Considering the highest grade of AlN, the crossover temperature is about 20°C. Above this temperature, the thermal conductivity of AlN is higher; below, 20°C, BeO is higher.

The TCE of AlN closely matches that of silicon, which is an important consideration when mounting large power devices. The second level of packaging is also critical. If an aluminum nitride substrate is mounted directly to a package with a much higher TCE, such as copper, the result can be worse than if a substrate with an intermediate, although higher, TCE were used. The large difference in TCE builds up stresses during the mounting operation that can be sufficient to fracture the die and/or the substrate.

Thick film, thin film, and copper metallization processes are available for aluminum nitride. Certain of these processes, such as direct bond copper (DBC) require oxidation of the surface to promote adhesion. For maximal thermal conductivity, a metallization process should be selected that bonds directly to AlN to eliminate the relatively high thermal resistance of the oxide layer.

Thick film materials must be formulated to adhere to AlN. The lead oxides prevalent in thick film pastes that are designed for alumina and beryllia oxidize the surface of AlN rapidly, causing blistering and a loss of adhesion. Thick film resistor materials are primarily based on $RuO_2$ and $MnO_2$

Thin film processes available for AlN include NiCr/Ni/Au, Ti/Pt/Au, and Ti/Ni/Au.[5] Titanium in particular provides excellent adhesion by diffusing into the surface of the AlN. Platinum and nickel are transition layers to promote gold adhesion. Solders such as Sn60/Pb40 and Au80/Sn20 can also be evaporated onto the substrate to facilitate soldering.

Multilayer circuits can be fabricated with W or Mb/Mn conductors. The top layer is plated with nickel and gold to promote solderability and bondability. Ultrasonic milling may be used for cavities, blind vias, and through vias. Laser machining is suitable for through vias as well.

Direct bond copper may be attached to AlN by forming a layer of oxide over the substrate surface, which may require several hours at temperatures above 900°C. The DBC forms a eutectic with aluminum oxide at about 963°C. The layer of oxide, however, increases the thermal resistance by a significant amount, partially negating the high thermal conductivity of the aluminum nitride. Copper foil may also be brazed to AlN with one of the compatible braze compounds. Active metal brazing (AMB) does not generate an oxide layer. The copper may also be plated with nickel and gold. The properties of aluminum nitride are summarized in Table 8.11.

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**TABLE 8.11 Typical Parameters for Aluminum Nitride (Highest Grade)**

| Parameter | Units | Value |
|---|---|---|
| Density | $g/cm^3$ | 3.27 |
| Hardness | Knoop 100g | 1200 |
| Melting point | °C | 2232 |
| Modulus of elasticity | GPa | 300 |
| Compressive strength | MPa | 2000 |
| Poisson's ratio | | 0.23 |
| Thermal conductivity | W/m-K | |
| 25°C | | 270 |
| 150°C | | 195 |
| Specific heat | W-sec/g-K | |
| 25°C | | 0.76 |
| 150°C | | 0.94 |
| TCE | $10^{-6}/K$ | 4.4 |
| Dielectric constant | | |
| 1 MHz | | 8.9 |
| 10 GHz | | 9.0 |
| Loss tangent | | |
| 1 MHz | | 0.0004 |
| 10 GHz | | 0.0004 |
| Volume resistivity | Ω-cm | |
| 25°C | | $>10^{12}$ |
| 500°C | | $2 \times 10^8$ |

### 8.7.4 Diamond

Diamond substrates are primarily grown by chemical vapor deposition (CVD). In this process, a carbon-based gas is passed over a solid surface and activated by a plasma, a heated filament, or a combustion flame. The surface must be maintained at a high temperature, above 700°C, to sustain the reaction. The gas is typically a mixture of methane ($CH_4$) and hydrogen ($H_2$) in a ratio of 1 to 2 percent $CH_4$ by volume.[6] The consistency of the film in terms of the ratio of diamond to graphite is inversely proportional to the growth rate of the film. Films produced by plasma have a growth rate of 0.1 to 10 μ/hr and are very high quality, while films produced by combustion methods have a growth rate of 100 to 1000 μ/hr and are of lesser quality.

The growth begins at nucleation sites and is columnar in nature, growing faster in the normal direction than in the lateral direction. Eventually, the columns grow together to form a polycrystalline structure with microcavities spread throughout the film. The resulting substrate is somewhat rough, with

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a 2- to 5-μ surface. This feature is detrimental to the effective thermal conductivity, and the surface must be polished for optimal results. An alternative method is to use an organic filler[7] on the surface for planarization. This process has been shown to have a negligible effect on the overall thermal conductivity from the bulk, and it dramatically improves heat transfer. Diamond substrates as large as 10 $cm^2$ and as thick as 1000 μ have been fabricated.

Diamond can be deposited as a coating on refractory metals, oxides, nitrides, and carbides. For maximum adhesion, the surface should be a carbide-forming material with a low TCE.[7]

Diamond has an extremely high thermal conductivity, several times that of the next highest material. The primary application is, obviously, in packaging power devices. Diamond has a low specific heat, however, and works best as a heat spreader in conjunction with a heat sink. For maximum effectiveness,[8]

$$t_D = 0.5 \rightarrow 1 \times r_h$$

$$r_D = 3 \times r_h$$

where $t_D$ = thickness of diamond substrate
$r_h$ = radius of heat source
$r_D$ = radius of diamond substrate

Applications of diamond substrates include heat sinks for laser diodes and laser diode arrays. The low dielectric constant of diamond, coupled with the high thermal conductivity, makes it attractive for microwave circuits as well. As improved methods of fabrication lower the cost, the use of diamond substrates is expected to expand rapidly. The properties of diamond are summarized in Table 8.12.

### 8.7.5 Boron nitride

There are two basic types of boron nitride (BN). Hexagonal (alpha) BN is soft and is structurally similar to graphite. It is white in color and is sometimes called *white graphite*. Cubic (beta) BN is formed by subjecting hexagonal BN to extreme heat and pressure, similar to the process used to fabricate synthetic industrial diamonds. Melting of either phase is possible only under nitrogen at high pressure.

Hot-pressed BN is very pure (>99 percent), with the major impurity being boric oxide (BO). Boric oxide tends to hydrolyze in water, degrading the dielectric and thermal shock properties. Calcium oxide (CaO) is frequently added to tie up the BO to minimize the water absorption. When exposed to temperatures above 1100°C, BO forms a thin coating on the surface, slowing further oxide growth.

Boron nitride in the hot-pressed state is easily machinable and may be formed into various shapes. The properties are highly anisotropic and vary considerable in the normal and tangential directions of the pressing force. The thermal conductivity in the normal direction is very high, and the TCE is very

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**TABLE 8.12 Typical Parameters for CVD Diamond**

| Parameter | Units | Value |
|---|---|---|
| Density | $g/cm^3$ | 3.52 |
| Hardness | Knoop 100 g | 7000 |
| Modulus of elasticity | GPa | 1000 |
| Compressive strength | MPa | 11000 |
| Poisson's ratio | | 0.148 |
| Thermal conductivity | W/m-K | |
| Normal | | 2200 |
| Tangential | | 1610 |
| Specific heat | W-sec/g-K | |
| 25°C | | 0.55 |
| 150°C | | 0.90 |
| TCE | $10^{-6}$/K | 1.02 |
| Dielectric constant | | |
| 1 MHz | | 5.6 |
| 10 GHz | | 5.6 |
| Loss tangent | | |
| 1 MHz | | 0.0001 |
| 10 GHz | | 0.0001 |
| Volume resistivity | Ω-cm | |
| 25°C | | $>10^{13}$ |
| 500°C | | $2 \times 10^{11}$ |

low, making BN an attractive possibility for a substrate material. However, it has not yet been proven possible to metallize BN,[9] thereby limiting the range of applications. It can be used in contact with various metals, including copper, tin, and aluminum, and may be used as a thermally conductive electrical insulator. Applications of BN include microwave tubes and crucibles. The properties of boron nitride are summarized in Table 8.13.

### 8.7.6 Silicon carbide

Silicon carbide (SiC) has a tetrahedral structure and is the only known alloy of silicon and carbon. Both elements have four electrons in the outer shell, with an atom of one bonded to four atoms of the other. The result is a very stable structure that is not affected by hydrogen or nitrogen up to 1600°C. In air, SiC begins decomposing above 1000°C. As with other compounds, a protective oxide layer forms over the silicon, reducing the rate of decomposition. Silicon carbide is highly resistant to both acids and bases. Even the so-called *white etch* (hydrofluoric acid mixed with nitric and sulfuric acids) has no effect.

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**TABLE 8.13 Typical Parameters for Boron Nitride**

| Parameter | Units | Value |
|---|---|---|
| Density | g/cm$^3$ | 1.92 |
| Hardness | Knoop 100 g | 5000 |
| Modulus of elasticity | GPa | |
| Normal | | 43 |
| Tangential | | 768 |
| Compressive strength | MPa | |
| Normal | | 110 |
| Tangential | | 793 |
| Poisson's ratio | | 0.05 |
| Thermal conductivity | W/m-K | |
| Normal | | 73 |
| Tangential | | 161 |
| Specific heat | W-sec/g-K | |
| 25°C | | 0.84 |
| 150°C | | 1.08 |
| TCE | $10^{-6}$/K | |
| Normal | | 0.57 |
| Tangential | | –0.46 |
| Dielectric constant | | |
| 1 MHz | | 4.1 |
| Loss tangent | | |
| 1 MHz | | 0.0003 |
| Volume resistivity | Ω-cm | |
| 25°C | | $1.6 \times 10^{12}$ |
| 500°C | | $2 \times 10^{10}$ |

Silicon carbide structures are formed by hot pressing, dry and isostatic pressing (preferred), CVD, or slip casting. Isostatic pressing using gas as the fluid provides optimal mechanical properties.

Silicon carbide in pure form is a semiconductor, and the resistivity depends on the impurity concentration. In the intrinsic form, the resistivity is less than 1000 W-cm, which is unsuitable for ordinary use. The addition of a small percentage (<1%) of BeO during the fabrication process[10] increases the resistivity to as high as $10^{13}$ W-cm by creating carrier-depleted layers around the grain boundaries.

Both thick and thin films can be used to metallize SiC, although some machining of the surface to attain a higher degree of smoothness is necessary for optimal results. The two parameters that make SiC attractive as a substrate are the exceptionally high thermal conductivity, second only to diamond, and the low TCE, which matches that of silicon to a higher degree than any other ceramic. SiC is also less expensive than either BeO or AlN. A possible disad-

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vantage is the high dielectric constant, 4 to 5 times higher than that of other substrate materials. This parameter can result in cross coupling of electronic signals or in excessive transmission delay. The parameters of SiC are summarized in Table 8.14.

**TABLE 8.14 Typical Parameters for Silicon Carbide**

| Parameter | Units | Value |
|---|---|---|
| Density | g/cm$^3$ | 3.10 |
| Hardness | Knoop 100 g | 500 |
| Modulus of elasticity | GPa | 407 |
| Compressive strength | MPa | 4400 |
| Fracture toughness | MPa-m$^{1/2}$ | 7.0 |
| Poisson's ratio | | 0.14 |
| Thermal conductivity | W/m-K | |
| 25°C | | 290 |
| 150°C | | 160 |
| Specific heat | W-sec/g-K | |
| 25°C | | 0.64 |
| 150°C | | 0.92 |
| TCE | $10^{-6}$/K | 3.70 |
| Dielectric constant | | 40 |
| Loss tangent | | 0.05 |
| Volume resistivity | Ω-cm | |
| 25°C | | $>10^{13}$ |
| 500°C | | $2 \times 10^9$ |

## 8.8 Composite Materials

Ceramics typically have a low thermal conductivity and a low TCE, whereas metals have a high thermal conductivity and a high TCE. It is a logical step to combine these properties to obtain a material with a high thermal conductivity and a low TCE. The ceramic in the form of particles or continuous fibers is mixed with the metal to combine the desirable properties of both. The resultant structure is referred to as a metal matrix composite (MMC).

The most common metals used in this application are aluminum and copper, with aluminum being more common due to lower cost. Fillers include SiC, AlN, BeO, graphite, and diamond. Compatibility of the materials is a prime consideration. Graphite, for example, has an electrolytic reaction with aluminum but not with copper.[11] Two materials will be described here: AlSiC,

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a composite made up of aluminum and silicon carbide, and Dymalloy®, a combination of copper and diamond.

### 8.8.1 Aluminum silicon carbide

Aluminum silicon carbide (AlSiC) is produced by forcing liquid aluminum into a porous SiC preform. The preform is made by any of the common ceramic processing technologies, including dry pressing, slip molding, and tape casting. The size and shape of the preform is selected to provide the desired volume fraction of SiC. The resulting combination has a thermal conductivity almost as high as that of pure aluminum, with a TCE as low as 6.1 ppm/°C. AlSiC is also electrically conductive, prohibiting its use as a conventional substrate.

The mechanical properties of the composite are determined by the ratio of SiC to aluminum as shown in Fig. 8.11.[10] A ratio of 70 to 73 percent of SiC by volume provides the optimal properties for electronic packaging.[10] This ratio gives a TCE of about 6.5 ppm/°C, which closely matches that of alumina and beryllia. This allows AlSiC to be used as a base plate for ceramic substrates, using its high thermal conductivity to best advantage.

AlSiC, being electrically conductive, may be readily plated with aluminum to provide a surface for further processing. The aluminum coating may be plated with nickel and gold to permit soldering, or it may be anodized where an insulating surface is required.[12] An alternative approach is to flame spray the AlSiC with various silver alloys for solderability.

Two other advantages of AlSiC are strength and weight. The aluminum is somewhat softer than SiC and reduces the propagation of cracks. The density is only about 1/3 that of Kovar®, and the thermal conductivity is over 12 times greater.

AlSiC has been used to advantage in the fabrication of hermetic single-chip and multichip packages and as heat sinks for power devices and circuits. Although difficult to drill and machine, AlSiC can be formed into a variety of

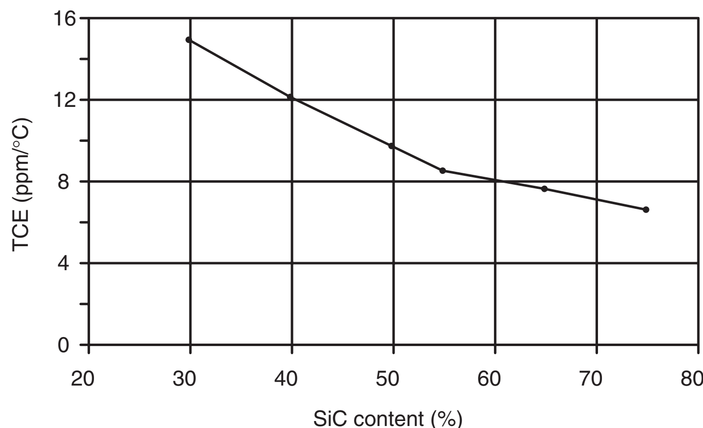


**Figure 8.11** TCE vs. SiC content for AlSiC.

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shapes in the powder state. It has been successfully integrated with patterned AlN to form a power module package.[12]

The TCE linearly increases with temperature up to about 350°C and then begins to decrease. At this temperature, the aluminum matrix softens, and the SiC matrix dominates. This factor is an important feature for power packaging. The parameters of AlSiC are summarized in Table 8.15.

**TABLE 8.15 Typical Parameters for AlSiC (70% SiC by Volume), SiC, and Aluminum**

| Parameter | Units | AlSiC | SiC | Al |
|---|---|---|---|---|
| Density | $g/cm^3$ | 3.02 | 3.10 | 2.70 |
| Modulus of elasticity | GPa | 224 | 407 | 69 |
| Thermal conductivity (25°C) | W/m-K | 192 | * | 55 |
| TCE | $10^{-6}$/K | 7.0 | 3.70 | 23 |
| Volume resistivity (25°C) | μΩ-cm | 34 | $>10^{13}$ | 2.8 |

*Depends on method of preparation and number/size of defects.

### 8.8.2 Dymalloy®

Dymalloy is a matrix of Type I diamond and Cu20/Ag80 alloy.[13] The diamond is ground into a powder in the 6- to 50-μm range. The powder is coated with W74/Rh26 to form a carbide layer approximately 100 Å thick followed by a 1000 Å coating of copper. The copper is plated to a thickness of several micrometers to permit brazing.

The powder is packed into a form and filled in a vacuum with Cu20/Ag80 alloy that melts at approximately 800°C. This material is selected over pure copper, which melts at a much higher temperature, to minimize graphitization of the diamond. The diamond loading is approximately 55 percent by volume. The parameters of Dymalloy are summarized in Table 8.16.

**TABLE 8.16 Typical Parameters for Dymalloy® (55% Diamond by Volume)**

| Parameter | Units | Value |
|---|---|---|
| Density | $g/cm^3$ | 6.4 |
| Tensile strength | MPa | 400 |
| Specific heat* | W-sec/g-°C | $0.316 + 8.372 \times 10^{-4}$ T |
| Thermal Conductivity | W/m–K | 360 |
| TCE† | $10^{-6}$/°C | $5.48 + 6.5 \times 10^{-3}$ T |

*Temperature in °C from 25 to 75°C
†Temperature in °C from 25 to 200°C

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## 8.9 Thick Film Technology

Thick film circuits as depicted in Fig. 8.12 are fabricated by screen printing conductive, resistive, and insulating materials in the form of a viscous paste onto a ceramic substrate. The printed film is dried to remove volatile components and exposed to an elevated temperature to activate the adhesion mechanism that adheres the film to the substrate. In this manner, by depositing successive layers as shown in Fig. 8.13, multilayer interconnection structures can be formed that may contain integrated resistors, capacitors, or inductors.

All thick film pastes have two general characteristics in common.

1. They are viscous fluids with a non-Newtonian rheology suitable for screen printing.
2. They are composed of two different multicomponent phases: a functional phase that imparts the electrical and mechanical properties to the finished film, and a vehicle phase that imparts the proper rheology.

There are numerous ways to categorize thick film pastes. One way is shown in Fig. 8.14, which depicts three basic categories: polymer thick films, refractory thick films, and cermet thick films. Refractory thick films are a special class of cermet thick films and are frequently categorized separately. These materials are designed to be fired at much higher temperatures (1500 to 1600°C) than conventional cermet materials and are also fired in a reducing atmosphere.

Polymer thick films consist of a mixture of polymer materials with conductor, resistor, or insulating particles. They cure at temperatures ranging from 85 to 300°C. Polymer conductors are primarily silver, with carbon being the most common resistor material. Polymer thick film materials are more com-

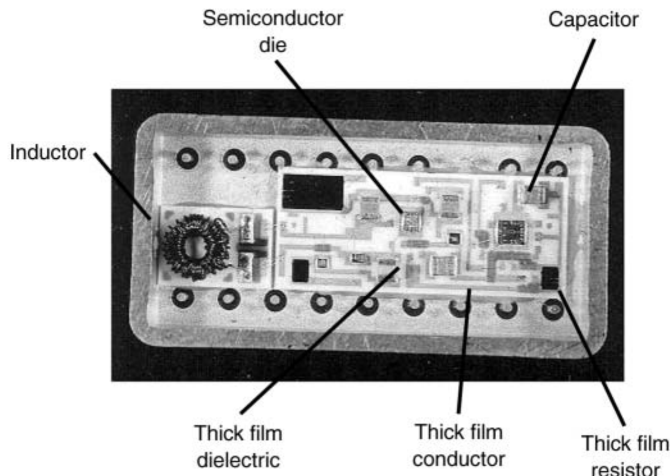


**Figure 8.12** Thick film hybrid circuit.

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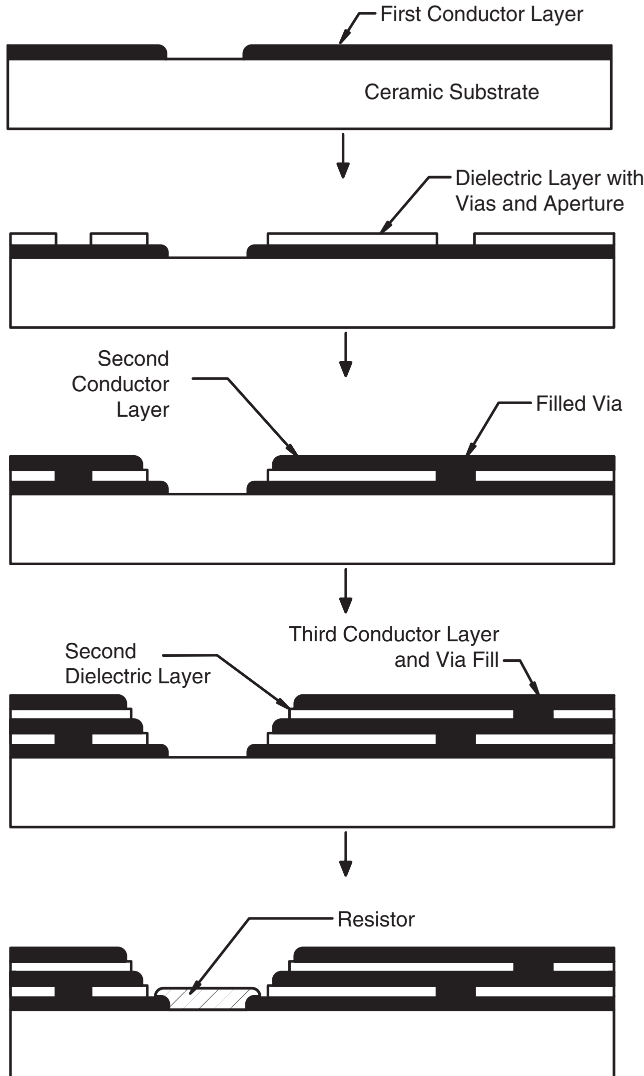


**Figure 8.13** Thick film multilayer fabrication steps.

monly associated with organic substrate materials, as opposed to ceramic, and will not be considered in further detail.

Cermet thick film materials in the fired state are a combination of glass ceramic and metal and are designed to be fired in the range 850 to 1000°C.

A conventional cermet thick film paste has four major constituents: an active element, which establishes the function of the film; an adhesion element, which provides the adhesion to the substrate and a matrix that holds the active particles in suspension; an organic binder, which provides the proper fluid properties for screen printing; and a solvent or thinner, which establishes the viscosity of the vehicle phase.

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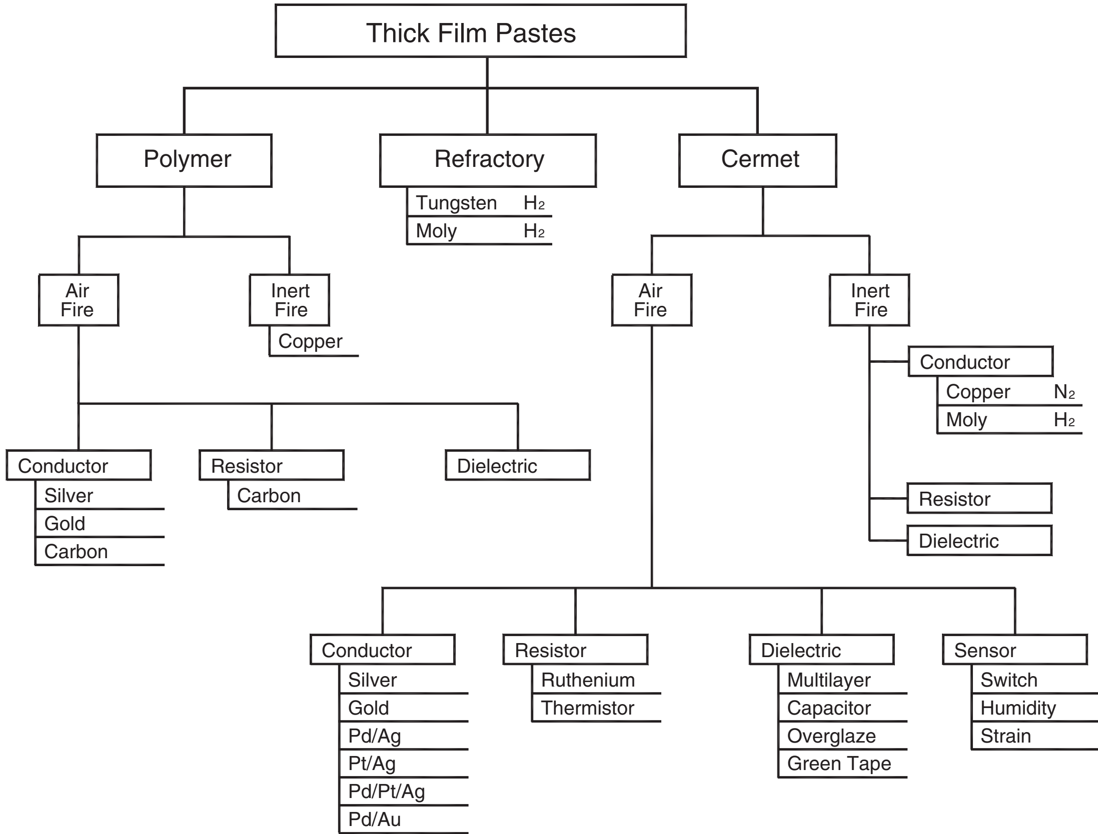


**Figure 8.14** Thick film paste matrix.

### 8.9.1 The active element

The active element within the paste determines the electrical properties of the fired film. If the active element is a metal, the fired film will be a conductor; if it is a conductive metal oxide, a resistor; and, if it is an insulator, a dielectric. The active element is most commonly found in powder form ranging from 1 to 10 μ in size, with a mean diameter of about 5 μ. Particle morphology can vary greatly depending on the method used to produce the metallic particles. Spherical, flaked, or circular shapes (both amorphous and crystalline) are available from powder manufacturing processes. Structural shape and particle morphology are critical to the development of the desired electrical performance, and extreme control on the particle shape, size, and distribution must be maintained to ensure uniformity of the properties of the fired film.

### 8.9.2 The adhesion element

There are two primary constituents used to bond the film to the substrate: glass and metal oxides, which may be used singly or in combination. Films

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that use a glass, or frit, are referred to as "fritted" materials and have a relatively low melting point (500 to 600°C). There are two adhesion mechanisms associated with the fritted materials: a chemical reaction and a physical reaction. In the chemical reaction, the molten glass chemically reacts with the glass in the substrate to a degree. In the physical reaction, the glass flows into and around the irregularities in the substrate surface, flowing into holes and voids and clinging to the small outcroppings of ceramic. The total adhesion is the sum of the two factors. The physical bonds are more susceptible to degradation by thermal cycling or thermal storage than the chemical bonds and are generally the first to fracture under stress. The glass also creates a matrix for the active particles, holding them in contact with each other to promote sintering and to provide a series of three-dimensional continuous paths from one end of the film to the other. Principal thick film glasses are based on $B_2O_3$-$SiO_2$ network formers with modifiers such as PbO, $Al_2O_3$, $Bi_2O_3$, ZnO, BaO, and CdO added to change the physical characteristics of the film, such as the melting point, the viscosity, and the coefficient of thermal expansion. $Bi_2O_3$ also has excellent wetting properties, both to the active element and to the substrate, and is frequently used as a fluxing agent. The glass phase may be introduced as a prereacted particle or formed in situ by using glass precursors such as boric oxide, lead oxide, and silicon. Fritted conductor materials tend to have glass on the surface, making subsequent component assembly processes more difficult.

A second class of materials utilizes metal oxides to provide the adhesion to the substrate. In this case, a pure metal, such as copper or cadmium, is mixed with the paste and reacts with oxygen atoms on the surface of the substrate to form an oxide. The conductor adheres to the oxide and to itself by sintering, which takes place during firing. During firing, the oxides react with broken oxygen bonds on the surface of the substrate, forming a Cu or Cd spinel structure. Pastes of this type offer improved adhesion over fritted materials, and are referred to as *fritless*, *oxide-bonded*, or *molecular-bonded* materials. Fritless materials typically fire at 950 to 1000°C, which is undesirable from a manufacturing aspect. Ovens used for thick film firing degrade more rapidly and need more maintenance when operated at these temperatures for long periods of time.

A third class of materials utilizes both reactive oxides and glasses. The oxides in these materials, typically Zn or Ca, react at lower temperatures but are not as strong as copper. A lesser concentration of glass than found in fritted materials is added to supplement the adhesion. These materials, referred to as *mixed bonded systems*, incorporate the advantages of both technologies and fire at a lower temperature.

### 8.9.3 The organic binder

The organic binder is generally a thixotropic fluid that serves two purposes: it holds the active and adhesion elements in suspension until the film is fired, and it gives the paste the proper fluid characteristics for screen printing. The organic binder is usually referred to as the *nonvolatile* organic, because it does

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not evaporate but begins to burn off at about 350°C. The binder must oxidize cleanly during firing, with no residual carbon that could contaminate the film. Typical materials used in this application are ethyl cellulose and various acrylics.

For nitrogen-fireable films, in which the firing atmosphere can contain only a few ppm of oxygen, the organic vehicle must decompose and thermally depolymerize, departing as a highly volatile organic vapor in the nitrogen blanket provided as the firing atmosphere. This is because oxidation into $CO_2$ or $H_2O$ is not feasible because of the oxidation of the copper film.

### 8.9.4 The solvent or thinner

The organic binder in the natural form is too thick to permit screen printing, which requires the use of a solvent or thinner. The thinner is somewhat more volatile than the binder, evaporating rapidly above about 100°C. Typical materials used for this application are terpineol, butyl carbitol, and certain of the complex alcohols into which the nonvolatile phase can dissolve. The low vapor pressure at room temperature is desirable to minimize drying of the pastes and to maintain a constant viscosity during printing. Additionally, plasticizers, surfactants, and agents that modify the thixotropic nature of the paste are added to the solvent to improve paste characteristics and printing performance.

To complete the formulation process, the ingredients of the thick film paste are mixed together in proper proportions and milled on a three-roller mill for a sufficient period of time to ensure that they are thoroughly mixed and that no agglomeration exists.

### 8.9.5 Fabrication of thick film paste

The fabrication process begins with the materials in powder form. Gold powders formed by precipitating gold out of a chemical solution are mixed with finely divided glass powder, typically formed by quenching molten glass and grinding the resulting particles. The gold powder morphology is chosen for proper combination of density, surface area, and purity. A large surface-to-volume ratio provides a large surface free energy to drive the sintering reaction and lower the processing temperatures. The glass is formulated to wet the gold (to enhance liquid phase sintering), adhere to the specific substrate, and to act as the “glue” to hold the fired film together. The particle size, distribution, and density must also be controlled to ensure proper packing and a high exothermic reaction at melting from a large surface energy component. The proper glass/gold mixture must be chosen to ensure chemical and thermal expansion compatibility with the desired substrate throughout the firing temperatures and during the cooling-down cycle. Additionally, small additions of other metals or oxides may be mixed with the glass and gold to impart improved mechanical or electrical properties, such as the addition of copper or copper oxide for the reactive bonding to alumina or rhodium to prevent blistering in gold.

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The vehicle is composed of a suitable solvent such as terpineol, xylene, or higher alcohols into which a thickening agent or gum is dissolved. Ethyl and methyl cellulose are common examples of gum thickeners. In addition, a wetting or hardening agent may be added to improve rheology or stability. For example, the surface of a dried but unfired film may be damaged if subjected to high-speed mechanical abrasion. The addition of a small amount of a film hardener eliminates this problem. High-contrast dyes can also be added to aid in automatic inspection or alignment.

The mixture is blended with a ball mill to reduce particle size of the glass frit or other brittle materials. The ball mill consists of a cylindrical container that is partly filled with a grinding media and the sample to be milled. The cylinder is rotated in a horizontal axis. The grinding medium, either tubular or spherical zirconia or $Al_2O_3$, cascades within the mill to produce a shear force to break down the particle size of the sample. The mill is rotated at a speed approximately 60 percent of the "critical speed," which is the speed at which the grinding media would be held at the container wall by centrifugal force. The critical speed is given by

$$\text{Speed}_{\text{critical}} = \frac{57.8}{\sqrt{R}} \text{ rpm} \tag{8.20}$$

In a typical ball mill load, only 50 percent of the overall volume of the mill is filled, with 50 percent of the filled portion being grinding medium. Particle size analysis is performed to determine the degree of milling progress. A schematic diagram of a ball mill is shown in Fig. 8.15.

In practice, the paste components are dispersed in a three-roll mill, as depicted in Fig. 8.16. The principle of three-roll milling is based on the high

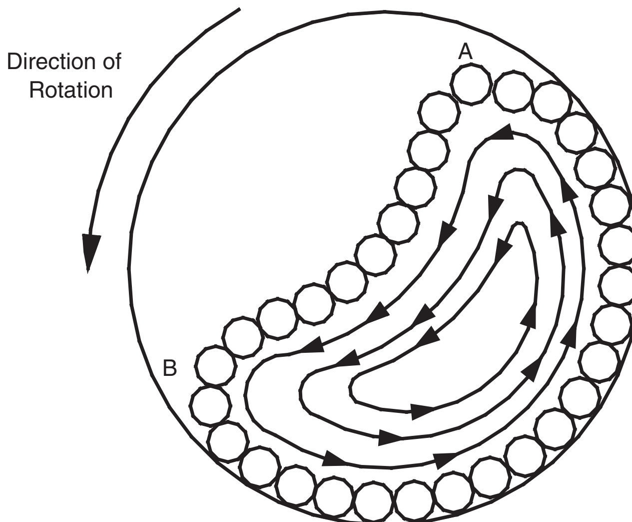


**Figure 8.15** Ball mill.

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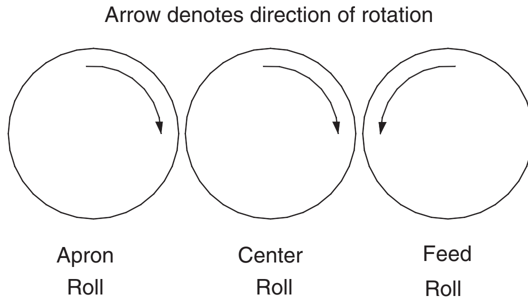


**Figure 8.16** Three-roll mill.

shear force obtained in a fluid contained in the gap of a counterrotating cylinder. Material is placed between the feed roll and the center roll. Because of the narrowing space between the rolls, the majority of paste is rejected from the nap region to the feed region. However, some material will pass through the nap region, experiencing the highest shear force. After exiting the nap region, the material remaining on the center roller moves into the nap region with the apron roll, which subjects the material to higher shear forces caused by the higher speed of the apron roll. A knife blade on the apron roll removes material remaining on the apron roll. This milling process can be redone to maximize the dispersion. The gap between the rollers can be mechanically set or maintained at a constant pressure under hydraulic pressure. Typically, the gap distance (on the order of a few mils), is far greater than the average particle size. Therefore, minimal particle size milling occurs. The function of roll milling is to maximize dispersion and to remove any entrapped air.

There are three important parameters that may be used to characterize a thick film paste.

- fineness of grind
- percent solids
- viscosity

### 8.9.6 Parameters of thick film paste

Fineness of grind is a measure of the particle size distribution and dispersion within the paste. A fineness-of-grind (FOG) gauge, as shown in Fig. 8.17, is a hard steel block with a tapered slot ground into one surface to a maximized depth, typically 50μ, with a micrometer scale marked along the groove. The paste is placed in the deep end and drawn down the block toward the shallow end by a tapered doctor blade. At the point where the largest particles cannot pass under the gap between the groove and the doctor blade, the film will begin to form streaks, or areas with no paste. The location of the first streak with respect to the scale denotes the largest particle, and the point where approximately half of the width of the groove is composed of streaks is the mean value of the particle size. At some point, essentially all of the particles will be trapped, which represents the smallest particle.

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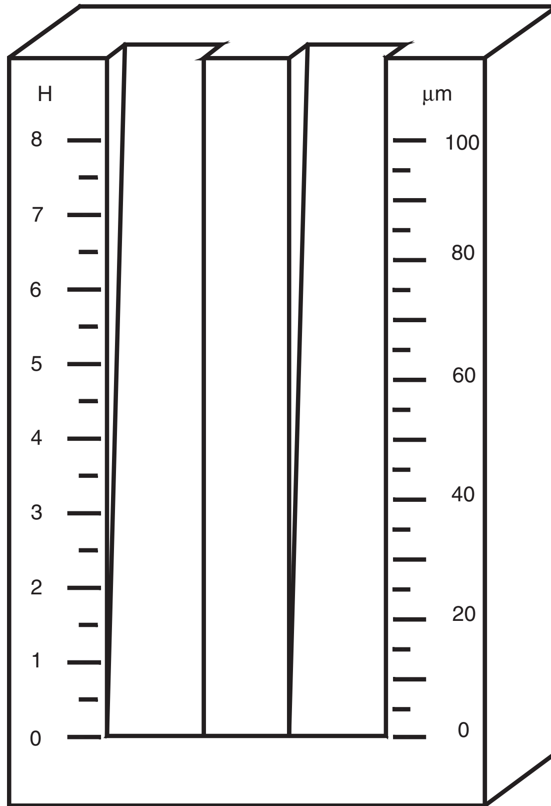


**Figure 8.17** Fineness-of-grind (FOG) gauge.

The percent solids parameter measures the ratio of the weight of the active and adhesion elements to the total weight of the paste. This test is performed by weighing a small sample of paste, placing it in an oven at about 400°C until all the organic material is burned away, and reweighing the sample. The percent solids parameter must be tightly controlled so as to achieve the optimal balance between printability and the density of the fired film. If the percent solids content is too high, the material will not have the proper fluid characteristics to print properly. If it is too low, the material will print well, but the fired print may be somewhat porous or may lack definition. A typical range for percent solids is 85 to 92 percent by weight. By volume, of course, the ratio is somewhat lower because of the lower density of the vehicle as compared to the active and adhesion elements.

The viscosity of a fluid is a measure of the tendency of the fluid to flow and is the ratio of the shear rate of the fluid in $sec^{-1}$ to the shear stress in force/unit area. The unit of viscosity is the poise, measured in dynes/$cm^2$-sec. Thick film pastes typically have the viscosity expressed in centipoise (cP), although the actual viscosity may be in the thousands of poise. An alternate unit of viscosity is the pascal-sec (Pas). One pascal-sec is equivalent to 0.001 cP.

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In an ideal or "Newtonian" fluid, the relationship between shear rate and shear stress is linear, and the graph passes through the origin. Newtonian fluids are not suitable for screen printing, because the force of gravity assures that some degree of flow will always be present. As a basis for comparison, the flow properties of water approach those of Newtonian fluids.

To be suitable for screen printing, a fluid must have certain characteristics.

- The fluid must have a yield point, or minimum pressure required to produce flow, which must obviously be above the force of gravity. With a finite yield point, the paste will not flow through the screen at rest and will not flow on the substrate after printing.
- The fluid should be somewhat *thixotropic* in nature. A thixotropic fluid is one in which the shear rate /shear stress ratio is nonlinear. As the shear rate (which translates to the combination of squeegee pressure, velocity, and screen tension) is increased, the paste becomes substantially thinner, causing it to flow more readily. The corollary of this term is *pseudoplastic*. A pseudoplastic fluid is one in which the shear rate does not increase appreciably as the force in increased.
- The fluid should have some degree of hysteresis so that the viscosity at a given pressure depends on whether the pressure is increasing or decreasing. Preferably, the viscosity should be higher with decreasing pressure, as the paste will be on the substrate at the time and will have a lesser tendency to flow and lose definition.

The shear rate versus shear stress curve for a thixotropic paste with these characteristics is shown in Fig. 8.18. A third variable (time) should also be

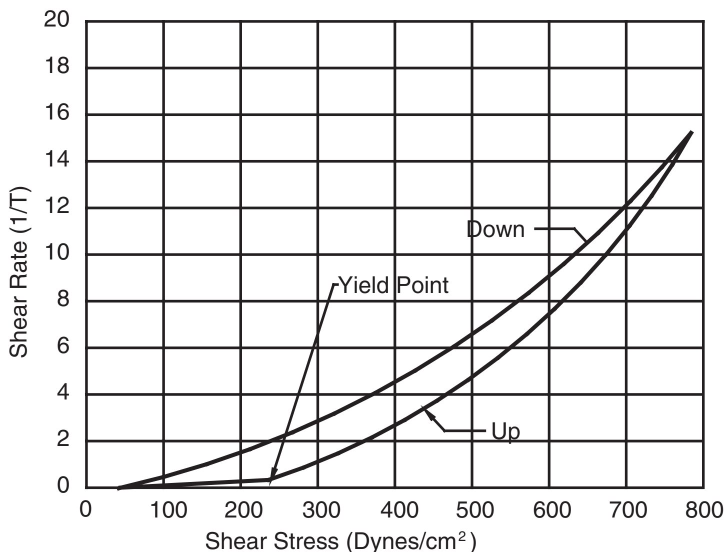


**Figure 8.18** Typical viscosity curve for thixotropic paste.

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considered in this figure. In practice, a finite and significant amount of time elapses between the application of the force and the time when the steady-state viscosity is attained. During the printing process, the squeegee velocity must be sufficiently slow to allow the viscosity of the paste to lower to the point at which printing is optimized. After the print, sufficient time must be allowed for the paste to increase to nearly the rest viscosity (leveling). If the paste is placed in the drying cycle prior to leveling, the paste will become still thinner as a result of the increased temperature, and the printed film will lose line definition.

Under laboratory conditions, the viscosity of the paste may be measured with a cone-and-plate or spindle viscometer. The cone-and-plate viscometer consists of a rotating cylinder with the end ground to a specific angle. A sample of paste is placed on a flat plate, and the cylinder is inserted into the paste parallel to the plate. The cylinder is rotated at a constant velocity, and the torque required to maintain this velocity is converted to viscosity. The spindle method utilizes a cylinder of known volume filled with paste. A spindle of known size is rotated at a constant speed inside the cylinder, and the torque measurement is converted to viscosity, as with the cone-and-plate unit. The spindle method provides a more consistent reading, because the boundary conditions can be more tightly controlled, and it is the most common method of characterizing thick film pastes in a development or manufacturing facility.

It is important to understand the limitations of viscometers for laboratory use. These are not analytical tools, in that a viscometer reading may be directly translated to the settings on the screen printer. Most viscometers of this type are designed to operate at two speeds, which would yield only two points on the curve in Fig. 8.18. This limits the utilization of the viscometer to simply compare one paste with another. When used for this purpose, the measurement conditions must be identical; the same type spindle in the same volume of paste must be used, and the sample must be at the same temperature if the correlation is to be meaningful.

Viscosity can be readily lowered by addition of an appropriate solvent. This is frequently required when the paste jar has been opened a number of times or if paste has been returned to the jar from the screen. If the original viscosity is recorded, the paste can be returned to the original viscosity with the aid of the viscometer. Increasing the viscosity is more difficult, requiring the addition of more nonvolatile vehicle followed by remilling of the paste.

Cermet thick film pastes are divided into three broad categories: conductors, resistors, and dielectrics. Each of these categories may have several subcategories that describe materials for a specific application.

## 8.10 Thick Film Conductor Materials

Thick film conductors must perform a variety of functions in a hybrid circuit.

- The most fundamental function is to provide electrically conductive traces between the nodes of the circuit.

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- They must provide a means to mechanically mount components by solder, epoxy, or direct eutectic bonding.
- They must provide a means for the electrical interconnection of components to the film traces and to the next higher assembly.
- They must provide a means of terminating thick film resistors.
- They must provide electrical connections between conductor layers in a multilayer circuit.

Thick film conductor materials are of three basic types: air fireable, nitrogen fireable, and those that must be fired in a reducing atmosphere. Air-fireable materials are made up of noble metals that do not readily form oxides. The basic metals are gold and silver, which may be used in the pure form or alloyed with palladium and/or platinum. Nitrogen-fireable materials include copper, nickel, and aluminum, with copper being the most common. The refractory materials, molybdenum, manganese, and tungsten, are intended to be fired in a reducing atmosphere consisting of a mixture of nitrogen and hydrogen.

### 8.10.1 Gold conductors

Gold has many varied requirements in thick film circuits, as shown in Table 8.17. It is most often used in applications in which a high degree of reliability is required, such as military and medical applications, or wherein gold wire bonding is desirable for reasons of speed. The assembly processes (i.e., soldering, epoxy bonding, and wire bonding) used with gold thick films must be selected with care if reliability is to be maintained at a high level. For example, gold readily alloys with tin and will leach rapidly into certain of the tin-bearing solders, such as the lead-tin (Pb/Sn) alloys. Gold and tin also form brittle intermetallic compounds with a high electrical resistivity. Where Pb/Sn solders are to be used for component or lead attachment, gold must be alloyed with platinum or palladium to minimize leaching and intermetallic compound formation. Gold also forms intermetallic compounds with the aluminum that is commonly used as the contact material on semiconductor devices and for wire bonding. The diffusion coefficient of aluminum into gold is much higher than that of gold into aluminum, with the diffusion rate increasing rapidly with temperature. Consequently, when an Au-Al interface occurs, as when an aluminum wire is bonded to a gold thick film conductor, the aluminum will diffuse into the gold wire, leaving voids in the interface (Kirkendall voids) that weaken the bond strength and increase the electrical resistance. This phenomenon is accelerated at temperatures above about 170°C and represents a reliability risk. The addition of palladium alloyed with the gold lowers the rate of aluminum diffusion significantly and improves the reliability of aluminum wire bonds.

### 8.10.2 Silver conductors

Silver is often used in commercial applications where cost is a factor. Like gold, silver leaches into Pb/Sn solders, although at a slower rate. Pure silver

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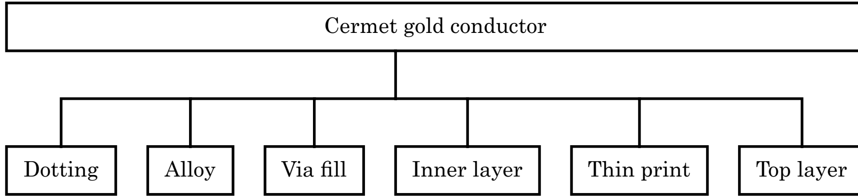
**TABLE 8.17 Requirements for Gold in a Thick Film Circuit**




may be used in applications wherein the exposure to Pb/Sn solder in the liquidus state is minimized and may also be nickel plated to further inhibit leaching.

Silver also has a tendency to migrate when an electrical potential is applied between two conductors in the presence of water in its liquid form. As shown in Fig. 8.19, positive silver ions dissolve into the water from the positive conductor. The electric field between the two conductors transports the Ag ions to the negative conductor, where they recombine with free electrons and precipitate out of the water onto the substrate as metallic silver. Over time, a continuous silver film grows between the two conductors, forming a conductive path. While other metals, including gold and lead, will migrate under the proper conditions, silver is the most notorious because of its high ionization potential.

Alloying silver with palladium and/or platinum slows down both the leaching rate and the migration rate, making it practical to use these alloys for soldering. Palladium/silver conductors are used in most commercial applications and are the most common materials found in hybrid circuits. However, the addition of palladium increases both the electrical resistance and the cost. A ratio of four parts silver to one part palladium is frequently used, providing a good compromise between performance and cost.

### 8.10.3 Copper conductors

Copper-based thick films were originally developed as a low-cost substitute for gold, but copper is now being selected when solderability, leach resistance, and low resistivity are required. These properties are particularly attractive for power hybrid circuits. The low resistivity allows the copper conductor traces to

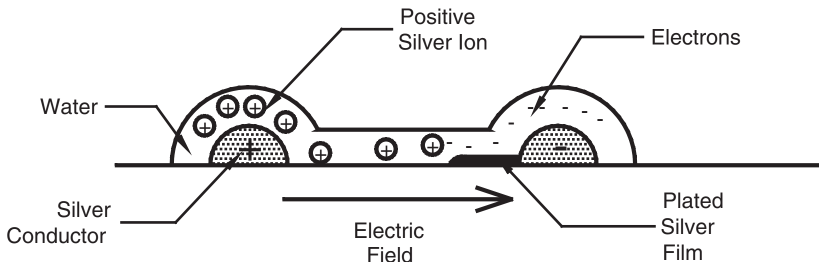



**Figure 8.19** Silver migration.

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handle higher currents with a lower voltage drop, and the solderability allows power devices to be soldered directly to the metallization for better thermal transfer.

Copper thick film systems are known to exhibit the following problems:

- The requirement for a nitrogen atmosphere (<10 ppm oxygen) has created problems when scaling up from a prototype effort to high-volume production. Organic materials used in air-fireable systems combine with oxygen in the furnace atmosphere and "burn" off, whereas those used in copper paste systems "boil" off (or "unzip") and must be carried away by the nitrogen flow. It has proven difficult to maintain a consistent, uniform nitrogen blanket in the larger furnaces required for production, which has required collaboration between furnace manufacturers, paste manufacturers, and users to come up with special, innovative furnace designs for copper firing. Although some furnaces may be used for both nitrogen and air firing in prototype quantities, it is not practical to switch back and forth for production.
- Because of the large print areas normally required for dielectric materials, the problem of organic material removal is amplified when these materials are used to manufacture multilayer circuits. Consequently, multilayer dielectric materials designed to be used with copper are generally more porous than those designed for air-fireable materials, and, as a result, it has proven difficult to manufacture dielectric materials that are hermetic. This generally has required three layers of dielectric material between conductor layers to minimize short circuits and leakage, as opposed to the normal two required for air-fireable systems.
- Many resistor materials, particularly in the high ohmic range, have not proven to be as stable as air-fireable resistors when fired at temperatures below 980°C.

Refractory thick film materials, typically tungsten, molybdenum, and titanium, may also be alloyed with each other in various combinations. These materials are designed to be cofired with ceramic substrates at temperatures ranging up to 1600°C and are postplated with nickel and gold to allow component mounting and wire bonding. The properties of thick film conductors are summarized in Table 8.18.

## 8.11 Thick Film Resistor Materials

Thick film resistors are formed by mixing metal oxide particles with glass particles and firing the mixture at a temperature/time combination sufficient to melt the glass and sinter the oxide particles together. The resulting structure consists of a series of three-dimensional chains of metal oxide particles embedded in a glass matrix. The higher the metal oxide-to-glass ratio, the lower will be the resistivity of the fired film and vice versa.

Thick film resistor materials are blended approximately to Lichtenecker's logarithmic mixing rule,

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**TABLE 8.18 Thick Film Conductor Capabilities**

| | Au wire bonding | Al wire bonding | Eutectic bonding | SN/PB solder | Epoxy bonding |
|---|---|---|---|---|---|
| Au | Y | N | Y | N | Y |
| Pd/Au | N | Y | N | Y | Y |
| Pt/Au | N | Y | N | Y | Y |
| Ag | Y | N | N | Y | Y |
| Pd/Ag | N | Y | N | Y | Y |
| Pt/Ag | N | Y | N | Y | Y |
| Pt/Pd/Ag | N | Y | N | Y | Y |
| Cu | N | Y | N | Y | N |

$$\log R_m = V_j \sum_{j=1}^{n} \log R_j \tag{8.21}$$

where $R_m$ = bulk resistivity of the mixture
$V_j$ = volume fraction of the individual component
$R_j$ = bulk resistivity of the component

Referring to Fig. 8.20, the electrical resistance of a material in the shape of a rectangular solid is given by the classic formula,

$$R = \frac{\rho_B L}{WT} \tag{8.22}$$

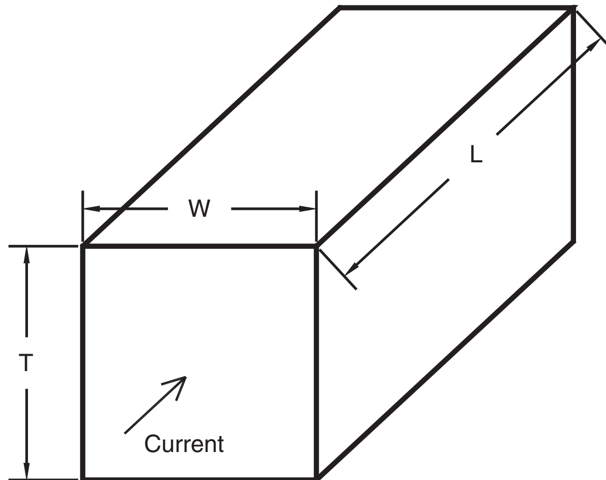


**Figure 8.20** Definition of resistance.

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where $R$ = electrical resistance in ohms
$\rho_B$ = bulk resistivity of the material in ohms-length
$L$ = length of the sample in the appropriate units
$W$ = width of the sample in the appropriate units
$T$ = thickness of the sample in the appropriate units

A "bulk" property of a material is one that is independent of the dimensions of the sample.

When the length and width of the sample are much greater than the thickness, a more convenient unit to use is the "sheet" resistivity, which is equal to the bulk resistivity divided by the thickness.

$$\rho_s = \frac{\rho_B}{T} \tag{8.23}$$

where $\rho_S$ = sheet resistivity in ohms/square/unit thickness

The sheet resistivity, unlike the bulk resistivity, is a function of the dimensions of the sample. Thus, a sample of a material with twice the thickness as another sample will have half the sheet resistivity, although the bulk resistivity is the same. In terms of the sheet resistivity, the electrical resistance is given by

$$R = \frac{\rho_s L}{W} \tag{8.24}$$

For a sample of uniform thickness, if the length is equal to the width (i.e., the sample is a square), the electrical resistance is the same as the sheet resistivity independent of the actual dimensions of the sample. This is the basis of the units of sheet resistivity, "ohms/square/unit thickness." For thick film resistors, the standard adopted for unit thickness is 0.001 in or 25 μ of dried thickness. The dried thickness is chosen as the standard as opposed to the fired thickness for convenience in process control. The dried thickness can be obtained in minutes, whereas obtaining the fired thickness can take as much as an hour. The specific units for thick film resistors are Ω/❑/0.001 in of dried thickness, or simply Ω/❑.

One of the difficulties in developing a conduction model has been the large number of variables that influence the conduction process, including the particle size, the particle shape, the substrate, and the type of glass. It is correspondingly difficult to manufacture thick film resistor pastes. The same ingredients mixed in the same proportions and milled in the same fashion will not always produce the same results, particularly where the TCR is concerned. When the TCR is not within specification, a modifier, usually a metal oxide, must be added and the paste remilled. For this reason, a paste with a low TCR is generally more expensive, even though it may contain the same basic ingredients as one with a higher TCR.

A group of thick film materials with identical chemistries that are blendable is referred to as a "family" and will generally have a range of values from

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10 Ω/❑ to 1 MΩ/❑ in decade values, although intermediate values are available as well. There are both high and low limits to the amount of material that may be added. As more and more material is added, a point is reached at which there is not enough glass to maintain the structural integrity of the film. With conventional materials, the lower limit of resistivity is about 10 Ω/❑. Resistors with a sheet resistivity below this value must have a different chemistry and often are not blendable with the regular family of materials. At the other extreme, as less and less material is added, a point is reached at which there are not enough particles to form continuous chains, and the sheet resistance rises very abruptly. Within most resistor families, the practical upper limit is about 2 MΩ/❑. Resistor materials are available to about 20 MΩ/❑, but these are not amenable to blending with lower-value resistors.

The active phase for resistor formulation is the most complex of all thick film formulations because of the large number of electrical and performance characteristics required. The most common active material used in air-fireable resistor systems is ruthenium, which can appear as $RuO_2$ (ruthenium dioxide) or $BiRu_2O_7$ (bismuth ruthenate). With the addition of TCR modifiers, these materials can be formulated to provide a temperature coefficient of resistance [as defined in Eq. (8.33)] of ±50 ppm with a stability of better than 1 percent after 1000 hr at 150°C.

Certain properties of thick film resistors as a function of ohmic value are predictable with qualitative conduction models.[14]

- High-ohmic-value resistors tend to have a more negative TCR than low-ohmic-value resistors. This is not always the case in commercially available systems, a result of the presence of TCR modifiers, but it always holds true in pure metal oxide-glass systems.
- High-ohmic-value resistors exhibit substantially more current noise than low-ohmic-value resistors as defined in MIL-STD-202. Current noise is generated when a carrier makes an abrupt change in energy levels, as it must when it makes the transition from one metal oxide particle to another across the thin film of glass. When the metal oxide particles are directly sintered together, the transition is less abrupt, and little or no noise is generated.
- High-ohmic-value resistors are more susceptible to high-voltage pulses and static discharge than are low-ohmic-value resistors. The high-voltage impulse breaks down the thin film of glass and forms a sintered contact, permanently lowering the value of the resistor. The effect of static discharge is highly dependent on the glass system used. Resistors from one manufacturer may drop by as much as half when exposed to static discharge, while others may be affected very little. This can be verified experimentally by heating a previously pulsed resistor to about 200°C. The value increases somewhat, indicating a regrowth of the glass oxide layer.

### 8.11.1 Electrical properties of thick film resistors

The electrical properties of resistors can be divided into two categories.

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1. Time-zero (as-fired) properties
   - temperature coefficient of resistance (TCR)
   - voltage coefficient of resistance (VCR)
   - resistor noise
   - high-voltage discharge
2. Time-dependent (aged) properties
   - high-temperature drift
   - moisture stability
   - power handling capability

### 8.11.2 Time-zero properties

**8.11.2.1 Temperature coefficient of resistance (TCR).** Referring to Eq. (8.40), all real materials exhibit some change in resistance with temperature, and most are nonlinear to a greater or lesser degree. Figure 8.21 shows a graph of resistance versus temperature for a typical material. The TCR is a function of temperature and is defined as the slope of the curve at the test temperature, *T*.

$$TCR(T) = \frac{dR(T)}{dT} \tag{8.25}$$

Referring again to Fig. 8.21, the TCR is often linearized over a range of temperatures as depicted in Eq. (8.26).

$$TCR = \frac{\Delta R}{\Delta T} \tag{8.26}$$

In general, this result is a small number expressed as a decimal with several preceding zeroes. For convenience, Eq. (8.41) is typically normalized to

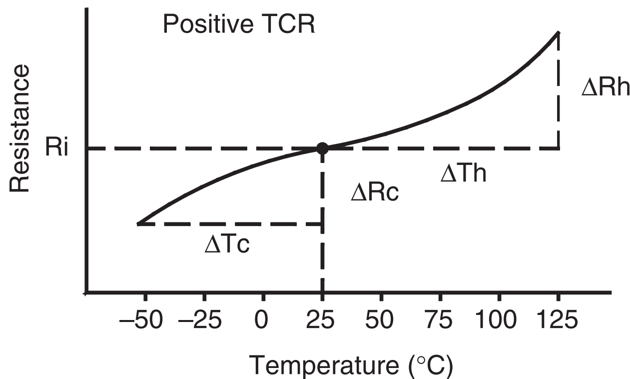


**Figure 8.21** Typical resistance vs. temperature curve for a thick film resistor.

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the initial value of resistance and is multiplied by 1 million to produce a whole number as shown in Eq. (8.27).

$$TCR = \frac{R(T_2) - R(T_1)}{R(T_1)(T_2 - T_1)} \times 10^6 \text{ ppm/°C} \tag{8.27}$$

where $R(T_2)$ = resistance at a temperature $T_2$
$R(T_1)$ = resistance at a temperature $T_1$

Most paste manufacturers present the TCR as two values.

1. The average from 2 to 125°C (the "hot" TCR)
2. The average from 25 to –55°C (the "cold" TCR)

An actual resistor paste carefully balances the metallic, nonmetallic, and semiconducting fractions to obtain a TCR as close to zero as possible. This is not a simple task, and the "hot" TCR may be quite different from the "cold" TCR. While linearization does not fully define the curve, it is adequate for many design applications.

It is important to note that the TCR of most materials is not linear, and the linearization process is at best an approximation. For example, the actual TCR of most thick film resistor materials at temperatures below –40°C tends to drop very rapidly and may be somewhat below the linearized value. The only completely accurate method of describing the temperature characteristics of a material is to examine the actual graph of temperature versus resistance. The TCR for a material may be positive or negative. By convention, if the resistance increases with increasing temperature, the TCR is positive. Likewise, if the resistance decreases with increasing temperature, the TCR is negative.

In general, metals exhibit positive TCRs, and nonmetals exhibit negative TCRs. In metals, the electron cloud is more disordered with increasing thermal energy, and resistance increases. Nonmetals (or semiconductors), which have electrons firmly bonded to crystal locations, become more mobile with energy and are better conductors as temperature is increased. They have a negative TCR.

While the absolute TCR of a resistor is critical to the operation of an electronic circuit, in some cases, the ratio of resistance change between two resistors is even more important. For example, assume that two resistors with a value of 1 kΩ have TCRs of +75 ppm and –40 ppm, respectively, at 0°C. After a change in temperature of +100°C, the respective values of resistance would be 1008 Ω and 996 Ω. The ratio of these two resistors at 100°C is

$$\frac{R_1}{R_2} = \frac{1008}{996} = 1.012$$

which translates to a net TCR of 115 ppm/°C, or the algebraic difference of the TCRs of the individual resistors.

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Now consider that the TCRs of the two resistors are 200 ppm/°C and 175 ppm/°C, substantially higher in magnitude than the previous example. For this case, $R_1 = 1020\ \Omega$ and $R_2 = 1018\ \Omega$ at 100°C, and the ratio is

$$\frac{R_1}{R_2} = \frac{1020}{1018} = 1.002$$

which is equivalent to a TCR of only 24.6 ppm/°C for the ratio.

It is therefore possible to have low TCR tracking with high absolute TCR if both resistors move in the same direction with temperature variations. In many circuit designs, this parameter is more important than a low absolute TCR. Following these guidelines can enhance the TCR tracking of two resistors:

- Resistors made from the same value paste will track more closely than resistors made from different decades.
- Resistors of the same length will track more closely than resistors of different lengths.
- Resistors printed with the same thickness will track more closely than resistors of different thicknesses.

Typical TCRs for decade values of thick film paste are shown in Fig. 8.22.

**8.11.2.2 Voltage coefficient of resistance (VCR).** Certain resistor materials also exhibit sensitivity to high voltages or, more specifically, to high electric fields as defined in Eq. (8.28). Note that the form of this equation is very similar to that of the TCR.

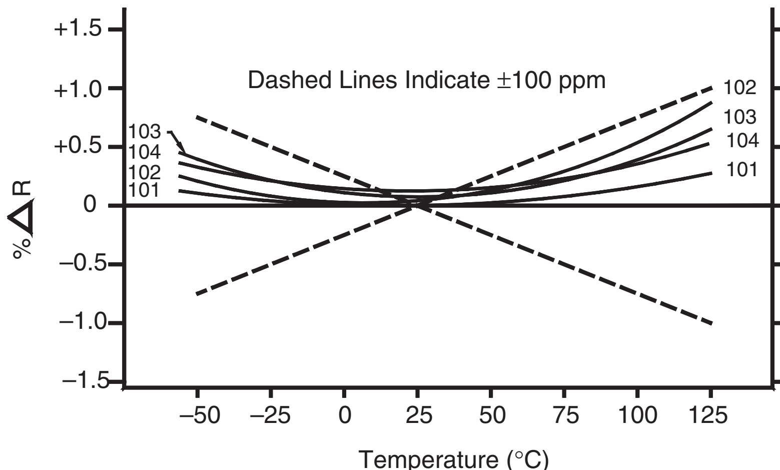


**Figure 8.22** Typical TCR of resistor paste decades.

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$$VCR = \frac{R(V_2) - R(V_1)}{R(V_1)(V_2 - V_1)} \times 10^6 \text{ ppm/V} \tag{8.28}$$

where $R(V_1)$ = resistance at $V_1$
$R(V_2)$ = resistance at $V_2$
$V_1$ = voltage at which $R(V_1)$ is measured
$V_2$ = voltage at which $R(V_2)$ is measured

Because of the semiconducting component in resistor pastes, the VCR is invariably negative. That is, as $V_2$ is increased, the resistance decreases. Also, because higher resistor decade values contain more glass and oxide constituents and are more semiconducting, higher paste values tend to have more negative VCRs than lower values.

Finally, the VCR is dependent on resistor length. The voltage effect on a resistor is a gradient, and it is the volts/unit length rather than the absolute voltage that causes resistor shift. Therefore, long resistors show less voltage shift than short resistors, for similar compositions and voltage stress. Typical VCRs of thick film resistors are shown in Fig. 8.23.

**8.11.2.3 Resistor noise.** On a fundamental level, noise occurs when an electron is moved to a higher or lower energy level. The greater the potential difference between the energy levels, the greater the noise. Metals with many available electrons in the "electron cloud" have low noise, whereas semiconducting materials have fewer free electrons and exhibit higher noise.

There are two primary noise sources present in thick film resistors: thermal, or "white" noise, and current, or "pink" noise. The thermal noise is gener-

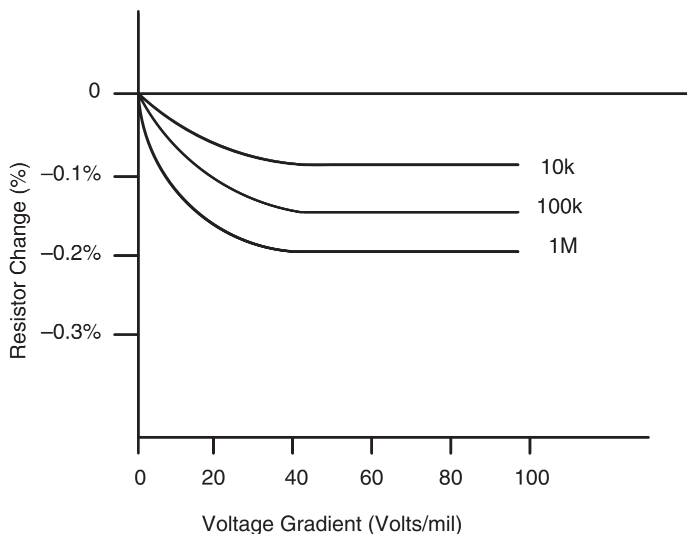


**Figure 8.23** Typical VCR of resistor paste decades.

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ated by the random transitions between energy levels as a result of heat and is present to some degree in all materials. Current noise occurs as a result of a transition between boundaries in a material, such as grain boundaries, where the energy levels may undergo abrupt changes from one region to another. In thick film resistors, the prime source of current noise is the thin layer of glass that may exist between the active particles.

The frequency spectrum of thermal noise is independent of frequency and is expressed in dB/Hz. The total noise is calculated by multiplying the noise figure by the bandwidth of the system. Current noise, on the other hand, has a frequency spectrum proportional to the inverse of the frequency, or $1/f$, and is expressed in units of dB/decade. The level of current noise in most applications is insignificant after the frequency exceeds 10 to 20 kHz.

In applications in which the noise level is of significance, these guidelines may help to improve performance:

- High-value resistors exhibit a higher noise level than low-value resistors.
- Large-area resistors exhibit a lower noise level.
- Thicker resistors exhibit a lower noise level.

Noise information is particularly important for low-signal applications as well as a quality check on processing. A shift in noise index, with constant resistor value, geometry, and termination, indicates a process variation that must be investigated. For example, thin or underfired resistors generate higher noise than normal. The conductor–resistor interface can also be an important noise generator if it is glassy or otherwise imperfect. Finally, poor or incomplete resistor trimming also generates higher noise. A resistor noise test is an excellent method of measuring a resistor attribute that is not easily obtained by other methods. Typical noise characteristics of thick film resistors are shown in Fig. 8.24.

## 8.11.3 Time-dependent properties

**8.11.3.1 High-temperature drift.** Thick film resistors in the untrimmed state exhibit a slight upward drift in value, primarily as a result of stress relaxation in the glasses that make up the body of the resistor. In properly processed resistors, the magnitude of the drift over the life of the resistor is measured in fractions of a percent and is not significant for most applications. At high temperatures, however, the drift is accelerated and may affect circuit performance in resistors that have not been properly fired or terminated or that are incompatible with the substrate.

To characterize the drift parameters, accelerated testing is frequently performed. A standard test condition is 125°C for 1000 hr at normal room humidity, corresponding to test condition S of MIL-STD-883C, method 1005.4 This test is considered to be equivalent to end-of-life conditions. More aggressive testing conditions are 150°C for 1000 hr or 175°C for 40 hr.

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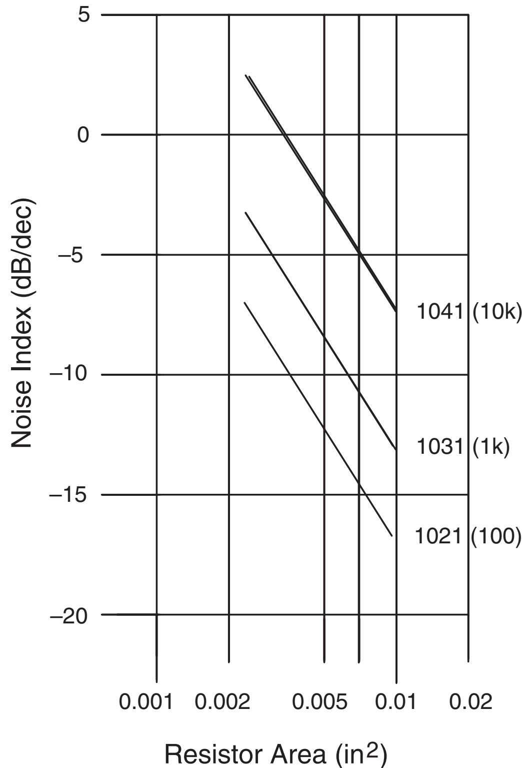


**Figure 8.24** Effect of resistor area on noise level.

**8.11.3.2 Moisture stability.** Resistance drift in the presence of moisture is a discriminating and important test. The most common test condition is 85 percent relative humidity and 85°C. Past studies indicate that this condition accelerates failure in thick film circuits by a factor of almost 500, compared to normally stressed circuits in the field. Humidity testing of resistors and circuits is more expensive than simple heat aging, but all the evidence indicates that it is a good predictor of reliability.

**8.11.3.3 Power-handling capability.** Drift resulting from high power is primarily caused by internal resistor heating. It is different from thermal aging in that the heat is generated at the point-to-point metal contacts within the resistor film. When a resistor is exposed to elevated temperature, the entire bulk of the resistor is uniformly heated. Under power, local heating can be much greater than the surrounding area. Because lower-value resistors have more metal and, therefore, many more contacts, low-value resistors tend to drift less than higher-value resistors under similar loads. For most resistor systems, the shape of the power aging curve is a "rising exponential" as shown in Fig. 8.25.

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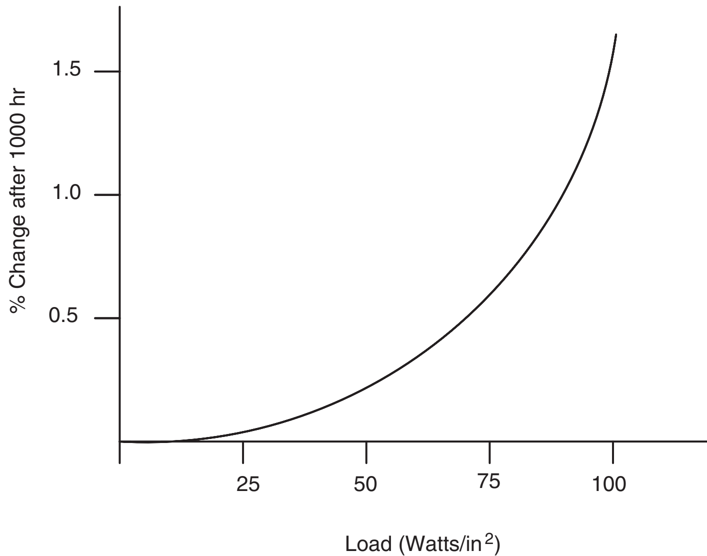


**Figure 8.25** Load life of a typical thick film resistor under extreme power stress.

The most generally accepted power rating of thick film resistors to achieve a drift of less than 0.5 percent over the resistor life is 50 W/in$^2$ of active resistor area. If more drift can be tolerated, the resistor can be rated at up to 200 W/in$^2$, as catastrophic failure will not occur until this rating is exceeded by a factor of several times. Typical properties of thick film resistors are shown in Table 8.19.

**TABLE 8.19 Typical Characteristics of Thick Film Resistors**

| Parameter | Value* |
|---|---|
| Tolerances, as fired | ±10–20% |
| Tolerances, laser trimmed | ±0.5–1.0% |
| TCRs (–55 to +125°C) | |
| 5 to 100 kΩ/❑ | ±100–150 ppm/°C |
| 100 kΩ/❒ to 10 MΩ/❒ | ±150–750 ppm/°C |
| Resistance drift after 1000 hr at 150°C, no load | ±0.3% |
| Resistance drift after 1000 hr at 85°C, with 25 W/in$^2$ | 0.25–0.3% |
| Resistance drift, short-term overload (2.5 times rated voltage) | <0.5% |
| Voltage coefficient | –20 ppm/V-in |
| Noise (Quan-tech) | |
| 100 Ω/❒ | –30 to –20 dB |
| 100 Ω/❒ | 0 to + 20 dB |
| Power rating | 40–50 W/in$^2$ |

*Selected materials may exceed these ratings.

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### 8.11.4 Process considerations for thick film resistors

The process windows for printing and firing thick film resistors are extremely critical in terms of both temperature control and atmosphere control. Small variations in temperature or time at temperature can cause significant changes in the mean value and distribution of values. In general, the higher the ohmic value of the resistor, the more dramatic will be the change. As a rule, high ohmic values tend to decrease as temperature and/or time is increased, while very low values (<100 Ω/❑) may tend to increase.

Thick film resistors are very sensitive to the firing atmosphere. For resistor systems used with air-fireable conductors, it is critical to have a strong oxidizing atmosphere in the firing zone of the furnace. In a neutral or reducing atmosphere, the metallic oxides composing the active material will reduce to pure metal at the temperatures used to fire the resistors, dropping resistor values sometimes by more than an order of magnitude. Again, high-ohmic-value resistors are more sensitive than low-ohmic-value devices. Atmospheric contaminants, such as vapors from hydrocarbons or halogenated hydrocarbons, will break down at firing temperatures, creating a strong reducing atmosphere. For example, one of the breakdown components of hydrocarbons is carbon monoxide, one of the strongest reducing agents known. Concentrations of fluorinated hydrocarbons in a firing furnace of only a few ppm can drop the value of a 100 kΩ resistor to below 10 kΩ. As a rule of thumb, no solvents, halogenated or carbon based, should be permitted in the vicinity of a furnace used to fire thick film materials.

## 8.12 Thick Film Dielectric Materials

Thick film dielectric materials are used primarily as insulators between conductors, either as simple crossovers or in complex multilayer structures. Small openings, or vias, may be left in the dielectric layers so that adjacent conductor layers may interconnect. In complex structures, as many as several hundred vias per layer may be required. In this manner, complex interconnection structures may be created. Although the majority of thick film circuits can be fabricated with only three layers of metallization, others may require several more. If more than three layers are required, the yield begins dropping dramatically with a corresponding increase in cost.

Dielectric materials used in this application must be of the devitrifying or recrystallizable type. These materials in the paste form are a mixture of glasses that melt at a relatively low temperature. During firing, when they are in the liquid state, they blend together to form a uniform composition with a higher melting point than the firing temperature. Consequently, on subsequent firings, they remain in the solid state, which maintains a stable foundation for firing sequential layers. By contrast, vitreous glasses always melt at the same temperature and would be unacceptable for layers to either "sink" and short to conductor layers underneath or "swim" and form an open circuit. Additionally, secondary loading of ceramic particles is used to enhance devitrification and to modify the temperature coefficient of expansion (TCE).

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Dielectric materials have two conflicting requirements in that they must form a continuous film to eliminate short circuits between layers. At the same time, they must maintain openings as small as 0.010 in. In general, dielectric materials must be printed and fired twice per layer to eliminate pinholes and prevent short circuits between layers.

The TCE of thick film dielectric materials must be as close as possible to that of the substrate to avoid excessive bowing, or warpage, of the substrate after several layers. Excessive bowing can cause severe problems with subsequent processing, especially if the substrate must be held down with a vacuum or if it must be mounted on a heated stage. In addition, the stresses created by the bowing can cause the dielectric material to crack, especially if it is sealed within a package. Thick film material manufacturers have addressed this problem by developing dielectric materials that have an almost exact TCE match with alumina substrates. Where a serious mismatch exists, matching layers of dielectric must be printed on the bottom of the substrate to minimize bowing, which obviously increases the cost. The effects of a TCE mismatch for two different dielectrics, one recrystallizable and one specially formulated to match the TCE of alumina, are shown in Table 8.20.

**TABLE 8.20 Substrate Bowing (%) vs. Number of Layers**

| | Number of layers | | | |
|---|---|---|---|---|
| Dielectric | 2 | 4 | 6 | 8 |
| Two crystalline fillers | 0.6 | 0.8 | 1.2 | 2.4 |
| Recrystallizable | 1.6 | 5.5 | – | – |

Dielectric materials with higher dielectric constants are also available for manufacturing thick film capacitors. These generally have a higher loss tangent than chip capacitors and utilize a great deal of space. While the initial tolerance is not good, thick film capacitors can be trimmed to a high degree of accuracy.

Another consideration for selecting a thick film dielectric is the compatibility with a resistor system. As circuits become more complex, the necessity of printing resistors on dielectric as opposed to directly on the substrate becomes greater. In addition, it is difficult to print resistors on the substrate in the proximity of dielectric several dielectric layers. The variations in the thickness affect the thickness of the substrate and, therefore, affect the spread of the resistor values.

## 8.13 Overglaze Materials

Dielectric overglaze materials are vitreous glasses designed to fire at a relatively low temperature, usually around 550°C. They are designed to provide mechanical protection to the circuit, to prevent contaminants and water from

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spanning the area between conductors, to create solder dams, and to improve the stability of thick film resistors after trimming.

Noble metals, such as gold and silver, are somewhat soft by nature. Gold, in particular, is the most malleable of all metals. When subjected to abrasion or to scraping by a sharp object, the net result is likely to be a bridging of the metal between conductors, resulting in a short circuit. A coating of overglaze can minimize the probability of damage and can also protect the substrates when they are stacked during the assembly process.

Contaminants that are ionic in nature, combined with water in the liquid form, can accelerate metal migration between two conductors. An overglaze material can help to limit the amount of contaminant actually contacting the surface of the ceramic and can help to prevent a film of water from forming between conductors. A ceramic substrate is a very "wettable" surface in that it is microscopically very rough, and the resulting capillary action causes the water to spread rapidly, creating a continuous film between conductors. A vitreous glass, being very smooth by nature, causes the water to "bead up," much like on a waxed surface, helping to prevent the water from forming a continuous film between conductors, thereby inhibiting the migration process.

When soldering a device with many leads, it is imperative that the volume of solder under each lead be the same. A well designed overglaze pattern can prevent the solder from wetting other circuit areas and flowing away from the pad, keeping the solder volume constant. In addition, overglaze can help to prevent solder bridging between conductors.

Overglaze material has long been used to stabilize thick film resistors after laser trim. In this application, a green or brown pigment is added to enhance the passage of an yttrium-aluminum-garnet (YAG) laser beam. Colors toward the shorter-wavelength end of the spectrum, such as blue, tend to reflect a portion of the YAG laser beam and reduce the average power level at the resistor. There is some debate as to the effectiveness of overglaze in enhancing the resistor stability, particularly with high ohmic values. Several studies have shown that, although overglaze is undoubtedly helpful at lower values, it can actually increase the resistor drift of high-value resistors by a significant amount.

## 8.14 Screen Printing

Three fundamental processes are required to produce a thick film circuit; screen printing, drying, and firing. The screen printing process applies the paste to the substrate, the drying process removes the volatile solvents from the paste before firing, and the firing process activates the adhesion mechanism, adhering the print to the substrate.

Thick film paste is applied to the substrate by screen printing through a stainless steel mesh screen. During the design process, artwork corresponding to each of the individual layers is generated. These artworks are used to expose a screen coated with a photosensitive material, or *emulsion*, to generate the pattern. The emulsion not protected by the dark areas of the film is hardened by the UV light, and the protected portions may be simply washed away

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with water, leaving openings in the emulsion corresponding to the dark areas in the film.

Commercial screen printers are designed to hold the screen parallel to and in proximity with the substrate. A squeegee is used to provide the force necessary to force the paste through the openings onto the substrate. The process sequence is as follows:

- The screen is placed in the screen printer
- The substrate is placed directly under the screen
- Paste is applied to the top of the screen

The squeegee is activated and travels across the surface of the screen, forcing the paste through the openings onto the substrate. In this manner, the paste can be applied in very precise geometries, allowing complex interconnection patterns to be generated.

Screen printing has been used for thousands of years to generate designs. In ancient China, silk was one of the first materials used as a mesh. A pattern was created in the silk using pitch or similar materials to block out unwanted areas, and dye was forced through the pattern by hand onto cloth or other surfaces to create colored patterns. By performing several sequential screenings with different colors and patterns, complex decorative patterns could be formed.

Silk continued to be one of the most common materials used until the development of synthetic materials, and the term "silk screening" is still commonly used to describe the screen printing process. The development of synthetic fibers, such as nylon, made possible greater control of the mesh materials, and the added development of photosensitive materials used for creating the patterns allowed screen printing to become much more precise, repeatable, and controllable.

Today, in the hybrid microelectronics industry, the primary mesh material is stainless steel, which adds an additional degree of control and precision over nylon in addition to added resistance to wear and stretching. The crude hand methods of printing have evolved to sophisticated, microprocessor-controlled machines that are self-aligning, have the ability to measure the thickness of the film, and have the ability to adjust the printing parameters to compensate for variations in the properties of the paste.

Still, of all the processes used to manufacture thick film hybrid microcircuits, the screen printing process is the least analytical. Because of the large number of variables involved, it is not possible to measure the parameters of the paste and convert them to the proper printer settings to produce the desired results. Many of the variables are not in the direct control of the process engineer and may change as the printing process proceeds. For example, the viscosity of the paste may change during printing because of solvent evaporation.

There are two basic methods of screen printing: the contact process and the off-contact process. In the contact process, the screen remains in contact with the substrate during the print cycle and then is separated abruptly by either lowering the substrate or raising the screen. In the off-contact process, the

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screen is separated from the substrate by a small distance and is stretched by the squeegee until it contacts the substrate only at a point directly under the squeegee. Once the squeegee passes, the screen "snaps back," leaving the paste on the substrate. In general, the best line definition is obtained with the off-contact process, and most printing of thick film pastes is performed in this manner. The contact process is generally used when a stencil is utilized to print solder paste. The stencil, being solid metal, cannot be stretched continually in the same manner as a screen without permanent deformation.

In the printing process, the paste is applied to the screen, and the squeegee is activated, sweeping across the screen. The pressure from the squeegee forces the paste through the openings in the screen onto the substrate. The rough substrate surface creates somewhat more surface tension than does the smooth wires of the screen mesh, causing the paste to stay on the substrate when the squeegee passes. The process is facilitated by the thixotropic nature of the paste. As the squeegee applies force to the paste, it becomes thinner and flows more readily. As the squeegee passes, the paste becomes thicker again and retains the line definition on the substrate.

## 8.15 Drying Thick Film Paste

Two organic components compose the vehicle in the printed film: the volatile component and the nonvolatile component. Immediately after printing, thick film materials are simply discrete particles of glass or metal suspended in a thickened vehicle and are somewhat tacky and fragile. The volatile component must be removed at a low temperature prior to firing. The volatile solvents evaporate rapidly at temperatures above 100°C and may cause extreme voiding of the fired film if exposed to elevated temperatures.

After printing, parts are usually allowed to "level" in air for a period of time (usually, 5 to 15 min). The leveling process permits screen mesh marks to fill in and some of the more volatile solvents to evaporate slowly at room temperature. The leveling process is critical to the precision of the fired film. The viscosity drops considerably during the printing process as a result of the thixotropic nature of the paste. Immediately after printing, the viscosity is still quite low and requires a period of time to return to a higher viscosity before drying. If the film is exposed to elevated temperatures immediately after printing, the viscosity will drop still lower, and the paste may spread across the substrate, degrading the definition of the printed film.

After leveling, the parts are force dried at temperatures ranging from 70 to 150°C for about 15 min. Drying is usually accomplished in a low-temperature, moving-belt dryer. For smaller or laboratory operations, drying may be accomplished in batch, forced-air dryers or even by placing the substrates on a hotplate. In a production environment, it is important to have an exhaust system to remove the solvent vapor from the environment. Certain of the solvents have a strong odor and may also adversely affect the atmosphere in a firing furnace if allowed to remain in the immediate area.

There are two important considerations in drying: the cleanliness of the atmosphere and the drying rate. Drying must be accomplished in a clean room

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(<Class 100,000) to prevent dust and lint particles from accumulating in the dried film. During firing, the particles will burn away, leaving voids in the film. The rate of temperature rise during the drying process must be controlled to prevent cracking of the film as a result of rapid solvent evaporation.

Drying removes the most volatile fraction of the paste. Perhaps 90 percent of the solvents and gums are removed in the drying step. Such solvents may be terpineol, butyl carbitol, higher alcohols such as decanol and octanol, or xylene. Because of the potentially toxic nature of these solvents, drying must be carried out under a hood or other extraction device. Because each paste system has its own solvents, gums, and wetting agents, the paste manufacturer will recommend the exact drying schedule for their materials.

## 8.16 Firing Thick Film Paste

After drying, the parts are placed on a moving belt or conveyor furnace. As with the drying profile, each paste manufacturer develops precise profiles for its products and should be consulted for the most current information.

A thick film furnace must provide the following:

1. A clean furnace environment
2. A uniform and controllable temperature profile
3. A uniform and controllable atmosphere

To provide for both a clean environment and a controllable atmosphere, all modern thick film furnaces have impervious muffles. Both metal and quartz muffles are used, and both are satisfactory when properly designed. Larger production furnaces and multi-atmosphere furnaces all must use metal muffles (usually Inconel), because a large cross section of impervious quartz is too expensive to fabricate. Thick film furnaces are designed to operate under 1000°C, and resistive heated furnaces use wound nichrome heating elements.

In some designs, traditional firebrick insulation has been replaced with lightweight foam insulation. Lightweight insulation has many advantages over heavy brick. Because lightweight insulation does not absorb moisture to the same extent as brick, the furnace may be turned off if not being used. This is not recommended with brickwork furnaces, because the evaporating steam will damage the bricks. Given the high cost of electricity in many parts of the country today, the ability to shut a furnace down if it is not being used offers a tremendous cost saving. Conversely, in the case of brickwork furnaces, the furnace may be "banked" to a somewhat lower temperature if not being used, but it must not be turned off.

Lightweight insulation, by nature, has lower thermal mass and responds to temperature changes more rapidly than brick. In fact, it can be integrated with the heating elements, making it is possible to use a single furnace for two or more profiles. A traditional furnace could take up to 12 hr to stabilize from an 850 to a 600°C profile. A furnace made with foam or fiber insulation can stabilize in one or two hours.

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## 8.17 Thick Film—Summary

It is apparent that cermet thick film materials are complex structurally and electrically. More than 120 variables related to material properties and processes have been identified with thick film resistors alone. Clearly, it is impossible to control all these variables in a manufacturing environment. To achieve the best results, it is important that the user know how the various constituents interact and the role each plays in the final product. Although the user need not know all the ingredients making up a particular paste, it is critical that the degree of compatibility with other pastes to be used in the circuit be assured. Very few hybrid circuits can be made with only one thick film paste, and if one or more of the pastes are incompatible with the others, unexpected reactions can occur that result in circuit failure. Usually, the only source of information, other than direct experimentation, is the paste manufacturer. A close working relationship with the manufacturer is a vital element toward creating a successful operation.

## 8.18 Thin Film Technology

The thin film technology, in contrast to the thick film technology, is a subtractive technology in that the entire substrate is coated with several layers of metallization, and the unwanted material is etched away in a succession of photoetching processes. The use of photolithographic processes to form the patterns enables much narrower and more precisely defined lines than can be formed by the thick film process. This feature promotes the use the thin film technology for high-density and high-frequency applications.

Thin film circuits typically consist of three layers of material deposited on a substrate as shown in Fig. 8.26. The bottom layer serves two purposes: it is the resistor material, and it provides the adhesion to the substrate. The middle layer acts as an interface between the resistor layer and the conductor layer, either by improving the adhesion of the conductor or by preventing diffusion of the resistor material into the conductor. The top layer acts as the conductor layer.

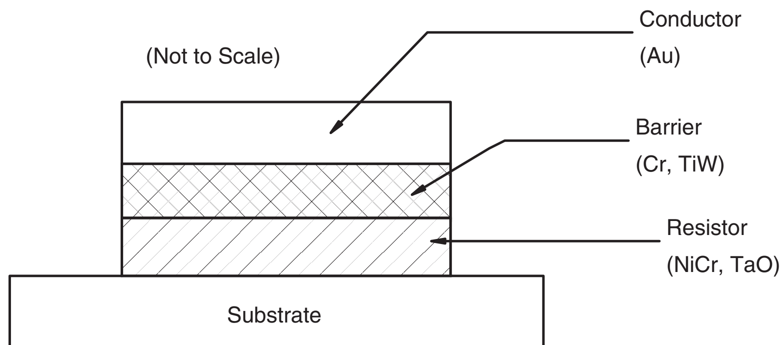


**Figure 8.26** Thin film structure.

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## 8.19 Deposition Technology

The term *thin film* refers more to the manner in which the film is deposited onto the substrate than to the actual thickness of the film. Thin films may be deposited by one of the vacuum deposition techniques or by electroplating.

### 8.19.1 Sputtering

Sputtering is the prime method by which thin films are applied to substrates. In ordinary triode sputtering, as shown in Fig. 8.27, a current is established in a conducting plasma formed by striking an arc in a partial vacuum of approximately 10 μ pressure. The gas used to establish the plasma is typically an inert gas, such as argon, that does not react with the target material. The substrate and a target material are placed in the plasma with the substrate at ground potential and the target at a high potential, which may be AC or DC. The high potential attracts the gas ions in the plasma to the point at which they collide with the target with sufficient kinetic energy to dislodge microscopically sized particles with enough residual kinetic energy to travel the distance to the substrate and adhere.

The adhesion mechanism of the film to the substrate is an oxide layer that forms at the interface. The bottom layer must therefore be a material that oxidizes readily. The adhesion is enhanced by presputtering the substrate surface by random bombardment of argon ions prior to applying the potential to the target. This process removes several atomic layers of the substrate sur-

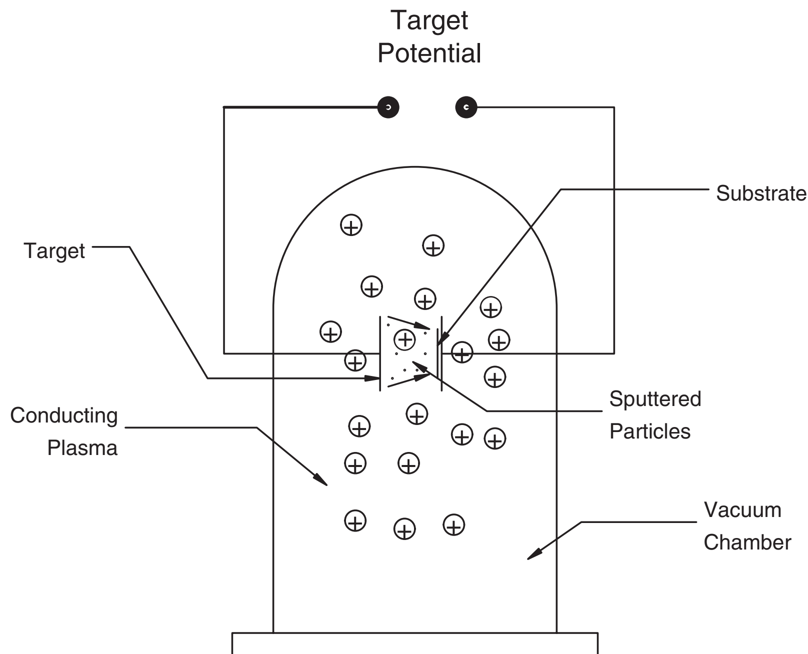


**Figure 8.27** Triode sputtering.

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face, creating a large number of broken oxygen bonds and promoting the formation of the oxide interface layer. The oxide formation is further enhanced by the residual heating of the substrate that results from the transfer of the kinetic energy of the sputtered particles to the substrate when they collide.

Ordinary triode sputtering is a very slow process, requiring hours to produce usable films. By utilizing magnets at strategic points, the plasma can be concentrated in the vicinity of the target, greatly speeding up the deposition process. The potential applied to the target is typically RF energy at a frequency of approximately 13 MHz. The RF energy may be generated by a conventional electronic oscillator or by a magnetron. The magnetron is capable of generating considerably more power with a correspondingly higher deposition rate.

By adding small amounts of other gases, such as oxygen and nitrogen, to the argon, it is possible to form oxides and nitrides of certain target materials on the substrate. This technique, called *reactive sputtering*, is used to form tantalum nitride, a common resistor material.

### 8.19.2 Evaporation

The evaporation of a material into the surrounding area occurs when the vapor pressure of the material exceeds the ambient pressure, and it can take place from either the solid state or the liquid state. In the thin film process, the material to be evaporated is placed in the vicinity of the substrate and heated until the vapor pressure of the material is considerably above the ambient pressure as depicted in Fig. 8.28. The evaporation rate is directly proportional to the difference between the vapor pressure of the material and the ambient pressure and is highly dependent on the temperature of the material.

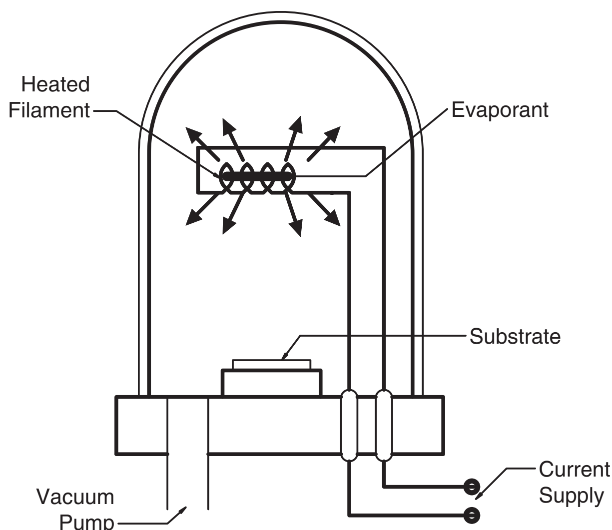


**Figure 8.28** The evaporation process.

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Evaporation must take place in a relatively high vacuum (<$10^{-6}$ torr) for three reasons.

1. To lower the vapor pressure required to produce an acceptable evaporation rate, thereby lowering the required temperature required to evaporate the material.
2. To increase the mean free path of the evaporated particles by reducing the scattering due to gas molecules in the chamber. Furthermore, the particles tend to travel in more of a straight line, improving the uniformity of the deposition.
3. To remove atmospheric contaminants and components, such as oxygen and nitrogen, that might tend to react with the evaporated film.

At $10^{-6}$ torr, a vapor pressure of $10^{-2}$ torr is required to produce an acceptable evaporation rate. A list of common materials, their melting points, and the temperature at which the vapor pressure is $10^{-2}$ torr are shown in Table 8.21.

**TABLE 8.21 Melting Points and $P_v = 10^{-2}$ Torr Temperatures of Selected Metals Used in Thin Film Applications**

| Temperature | Melting point (°C) | Temperature at which $P_v = 10^{-2}$ torr (°C) |
|---|---|---|
| Aluminum | 659 | 1220 |
| Chromium | 1900 | 1400 |
| Copper | 1084 | 1260 |
| Germanium | 940 | 1400 |
| Gold | 1063 | 1400 |
| Iron | 1536 | 1480 |
| Molybdenum | 2620 | 230 |
| Nickel | 1450 | 1530 |
| Platinum | 1770 | 2100 |
| Silver | 961 | 1030 |
| Tantalum | 3000 | 3060 |
| Tin | 232 | 1250 |
| Titanium | 1700 | 1750 |
| Tungsten | 3380 | 3230 |

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The "refractory" metals (metals with a high melting point), such as tungsten, titanium, and molybdenum, are frequently used as carriers or "boats" to hold other metals during the evaporation process. To prevent reactions with the metals being evaporated, the boats may be coated with alumina or other ceramic materials.

If it is assumed that the evaporation takes place from a point source, the density of the evaporated particles assumes a cosine distribution from the normal as shown in Fig. 8.29. The distance of the substrate from the source then becomes a compromise between deposition uniformity and deposition rate; if the substrate is closer (farther away), the deposition is greater (lesser), and the deposition is less (more) uniform over the face of the substrate.

In general, the kinetic energy of the evaporated particles is substantially less than that of sputtered particles. This requires that the substrate be heated to about 300°C to promote the growth of the oxide adhesion interface. This may be accomplished by direct heating of the substrate mounting platform or by radiant infrared heating.

There are several techniques by which evaporation can be accomplished. The two most common of these are resistance heating and electron-beam (E-beam) heating.

Evaporation by resistance heating usually takes place from a boat made with a refractory metal, a ceramic crucible wrapped with a wire heater, or a wire filament coated with the evaporant. A current is passed through the element, and the heat generated heats the evaporant. It is somewhat difficult to monitor the temperature of the melt by optical means because of the propensity of the evaporant to coat the inside of the chamber, and control must be done by empirical means. Closed-loop systems exist that can control the deposition rate and the thickness, but these are quite expensive. In general, adequate results can be obtained from the empirical process if proper controls are used.

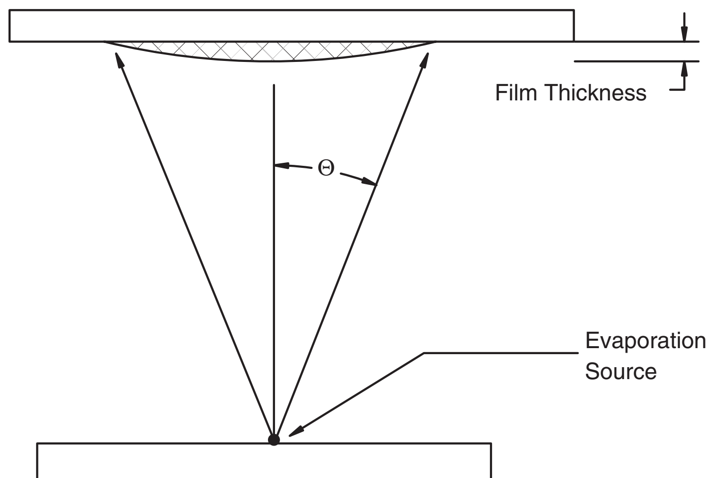


**Figure 8.29** Evaporation from a point source.

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The E-beam evaporation method takes advantage of the fact that a stream of electrons accelerated by an electric field tends to travel in a circle when entering a magnetic field. This phenomenon is utilized to direct a high-energy stream of electrons onto an evaporant source. The kinetic energy of the electrons is converted into heat when they strike the evaporant. E-beam evaporation is somewhat more controllable, because the resistance of the boat is not a factor, and the variables controlling the energy of the electrons are easier to measure and control. In addition, the heat is more localized and intense, making it possible to evaporate metals with higher $10^{-2}$ torr temperatures and lessening the reaction between the evaporant and the boat.

### 8.19.3 Comparison between sputtering and evaporation

Evaporation allows a rapid deposition rate, but there are certain disadvantages as compared with sputtering.

1. It is difficult to evaporate alloys such as NiCr because of the difference between the $10^{-2}$ torr temperatures. The element with the lower temperature tends to evaporate somewhat faster, causing the composition of the evaporated film to be different from the composition of the alloy. To achieve a particular film composition, the composition of the melt must contain a higher portion of the material with the higher $10^{-2}$ torr temperature, and the temperature of the melt must be tightly controlled. By contrast, the composition of a sputtered film is identical to that of the target.
2. Evaporation is limited to the metals with lower melting points. Refractory metals and ceramics are virtually impossible to deposit by evaporation.
3. Reactive deposition of nitrides and oxides is very difficult to control.

### 8.19.4 Electroplating

Electroplating is accomplished by applying a potential between the substrate and the anode, which are suspended in a conductive solution of the material to be plated. The plating rate is a function of the potential and the concentration of the solution. In this manner, most metals can be plated to a conducting surface.

In the thin film technology, it is a common practice to sputter a film of gold that is only a few angstroms (Å) thick and to build up the thickness of the gold film by electroplating. This is considerably more economical and results in much less target usage. For added savings, some companies apply photoresist to the substrate and electroplate gold only where actually required by the pattern.

### 8.19.5 Photolithographic processes

In the photolithographic process, the substrate is coated with a photosensitive material and exposed to ultraviolet light through a pattern formed on a glass plate. The photoresist may be of the positive or negative type, with the positive type being prevalent because of its inherently higher resistance to the etchant materials. The unwanted material not protected by the photoresist may be removed by *wet* (chemical) etching or by *dry* (sputter) etching.

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In general, two masks are required, one corresponding to the conductor pattern and the other corresponding to a combination of both the conductor and resistor patterns, generally referred to as the *composite* pattern. As an alternative to the composite mask, a mask containing only the resistor pattern plus a slight overlap onto the conductor to allow for misalignment may be used. The composite mask is preferred, because it allows a second gold etch process to be performed to remove any bridges or extraneous gold that might have been left from the first etch.

Although chemical etching remains the most common method of etching thin films, more and more companies are turning to sputter etching despite the added capital equipment required. In this technique, the substrate is coated with photoresist, and the pattern is exposed in exactly the same manner as with chemical etching. The substrate is then placed in a plasma and connected to a potential. In effect, the substrate acts as the target during the sputter etching process, with the unwanted material being removed by the impingement of the gas ions on the exposed film. The photoresistive film, being considerably thicker than the sputtered film, is not affected. Sputter etching has two major advantages over chemical etching.

1. There is virtually no undercutting of the film. The gas ions strike the substrate in approximately a cosine distribution with respect to the normal direction of the substrate. This means that virtually no ions strike the film tangentially, leaving the edges intact. This results in more uniform line dimensions, which further results in better resistor uniformity. By contrast, the rate of the chemical etching process in the tangential is the same as in the normal direction, which results in the undercutting of the film by a distance equal to the thickness converted into heat when the ions strike the evaporant. E-beam evaporation is somewhat more controllable.
2. The potent chemicals used to etch thin films are no longer necessary, resulting in fewer hazards to personnel and no disposal problems.

The major impediment to the use of sputter etching is the investment in capital equipment. Most of the new systems have this as an option, and, as more users invest in new equipment or start a new thin film operation, this method will become more widely used.

## 8.20 Thin Film Materials

The sputtering process may deposit virtually any inorganic material, but the outgassing of most organic materials is too extensive to allow sputtering to take place. A wide variety of substrate materials are also available, but these generally must contain an oxygen compound to permit adhesion of the film.

### 8.20.1 Thin film resistors

Materials used for thin film resistors must perform a dual role in that they must also provide the adhesion to the substrate, which narrows the choice to

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materials that form oxides. The resistor film begins forming as single points on the substrate in the vicinity of substrate faults or other irregularities that might have an excess of broken oxygen bonds. The points expand into islands that, in turn, join to form continuous films. The regions where the islands meet are called *grain boundaries,* which are a source of collisions for the electrons. The more grain boundaries that are present, the more negative will be the TCR. Unlike thick film resistors, however, the boundaries do not contribute to the noise level. Furthermore, laser trimming does not create microcracks in the glass-free structure, and the inherent mechanisms for resistor drift are not present in thin films. As a result, thin film resistors have better stability, noise, and TCR characteristics than thick film resistors.

The most common resistor material types are nichrome (NiCr), tantalum nitride (TaN), and chrome disilicide. Although NiCr has excellent stability and TCR characteristics, it is susceptible to corrosion by moisture if not passivated by sputtered quartz or by evaporated silicon monoxide (SiO). TaN, on the other hand, may be passivated by simply baking the film in air for a few minutes. This feature has resulted in the increased use of TaN at the expense of NiCr, especially in military programs. The stability of passivated TaN is comparable to that of passivated NiCr, but the TCR is not as good unless annealed for several hours in a vacuum to minimize the effect of the grain boundaries. Both NiCr and TaN have a relatively low maximum sheet resistivity on alumina—about 400 Ω/❑ for NiCr and 200 Ω/❑ for TaN. This requires complex patterns to achieve a high value of resistance, resulting in a large required area and the potential for low yield. Chrome disilicide has a maximum sheet resistance of 1000 Ω/❑ and overcomes this limitation to a large extent. The stability and TCR of chrome disilicide are comparable to those of TaN.

The TaN process is the most commonly used because of its inherently high stability. In this process, $N_2$ is introduced into the argon gas during the sputtering process, forming TaN by reacting with pure Ta atoms on the surface of the substrate. Heating the film in air at about 425°C for 10 min forms a film of TaO over the TaN that is virtually impervious to further $O_2$ diffusion at moderately high temperatures. The film helps to maintain the composition of the TaN film and stabilizes the value of the resistor. TaO is essentially a dielectric, and, during the stabilization of the film, the resistor value is increased. The amount of increase for a given time and temperature is dependent on the sheet resistivity of the film. Films with a lower sheet resistivity increase proportionally less than those with a higher sheet resistivity. The resistance increases as the film is heated longer, making it possible to control the sheet resistivity to a reasonable accuracy on a substrate-by-substrate basis.

### 8.20.2 Barrier materials

When Au is used as the conductor material, a barrier material between the Au and the resistor is required. When gold is deposited directly on NiCr, the Cr has a tendency to diffuse through the Au to the surface, which interferes with both wire bonding and eutectic die bonding. To alleviate this problem, a thin

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layer of pure Ni is deposited over the NiCr. In addition, the Ni improves the solderability of the surface considerably.

The adhesion of Au to TaN is very poor. To provide the necessary adhesion, a thin layer of 90Ti/10W may be used between the Au and the TaN.

### 8.20.3 Conductor materials

Gold is the most common conductor material used in thin film hybrid circuits because of the ease of wire and die bonding and the high resistance of the gold to tarnish and corrosion. Aluminum and copper are also frequently used in certain applications. It should be noted that copper and aluminum will adhere directly to ceramic substrates, but gold requires one or more intermediate layers, because it does not form the necessary oxides for adhesion.

### 8.20.4 Thin film substrates

Although the substrate gets quite warm during the deposition process, the temperature does not approach that of the thick film firing process. This enables a wider choice of substrate materials for the thin film process, permitting such materials as glass and low-temperature ceramics to be used.

Still, the prime material remains high purity (99.5%) alumina, with sapphire, a form of alumina, used in critical high-frequency applications. Substrates for thin film applications must have a smoother surface than for thick film, about 3 to 4 μin CLA. Substrates with an as-fired finish are preferred to polished substrates because of the surface pitting typically created during the polishing process.

The surface finish is crucial for consistent and reliable results because, even with a 3 to 4 μin finish, the thickness of the deposited film is significantly less than the variations found in the finish, and the stability of resistors is worse. In addition, the conductor is also thinner in spots, and this contributes to wire and die bond failures.

Certain of the newer materials, such as AlN, are more likely to be used initially in the thin film process, rather than thick film, because no special treatment of the substrate is required.

## 8.21 Comparison of Thick Film and Thin Film

Although the thin film process provides better line definition, smaller line geometry, and better resistor properties, several factors contribute to its relatively infrequent use as compared to thick film.

1. Because of the added labor involved, the thin film process is almost always more expensive than the thick film process. Only when a number of thin film circuits can be fabricated on a single substrate can thin film compete in price.

2. Multilayer structures are extremely difficult to fabricate. Although they are a possibility with multiple deposition and etching processes, this is a

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very expensive and labor-intensive process and is limited to a very few applications.

3. The designer, in most cases, is limited to a single sheet resistivity. This requires a large area to fabricate both large- and small-value resistors.

A common practice is to use thin film arrays on thick film substrates where dictated by performance or space limitations. The use of thin film and thick film deposition on the same substrate has been reported in the literature, but it is not widely employed. A comprehensive comparison of the thick and thin film processes is shown in Table 8.22.

**TABLE 8.22 Comparison of Thick Film and Thin Film**

| Thin film | Thick film |
|---|---|
| 50 to 24,000 Å | 24,000 to 240,000 Å (1 mil) |
| Indirect (subtractive) process—evaporate, photoetch | Direct process—screen, dry, and fire |
| Problems with disposal and handling of dangerous chemicals, etchants, developers, plating solutions | No chemical etchants or plating solutions used |
| Problems with recovery of precious metals from etching solutions | No recovery of precious metals |
| Multilayering difficult; usually only one layer; multilayer using polyimide as dielectric for multichip module circuits | Low-cost multilayering process |
| Limited to low sheet resistivity materials; NiCr and TaN, 100 to 300 Ω/❑ | Wide range of resistor values by using several pastes with different sheet resistivities, from 1 Ω/❑ to 20 MΩ/❑ |
| Resistors susceptible to chemical corrosion | Rugged resistors able to withstand harsh environments and high temperatures |
| Low-TCR resistors, 0 ± 50 ppm | TCRs ±50 to 300 ppm/°C |
| Line definition to 1 mil; 0.1 mil possible with sputter etching | Line definition 5 to 10 mils |
| High-cost batch process | Low-cost process, continuous, conveyorized |
| Initial equipment investment high (>$2 million) | Initial equipment investment low (<$500,000) |
| More precise line definition; better for RF signals | Line definition not good for RF |
| Wire bondability better; homogeneous material; plating bath impurities can affect wire bonds | Wire bondability affected by impurities in paste; conductors are heterogeneous |

## 8.22 Copper Metallization Technologies

The thick film and thin film technologies are limited in their ability to deposit films with a thickness greater than 1 mil (25 μm). This factor directly affects the ohmic resistance of the circuit traces and affects their ability to handle

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large currents or high frequencies. The copper metallization technologies provide conductors with greatly increased conductor thickness, which offer improved circuit performance in many applications. There are three basic technologies available to the hybrid designer: direct bond copper (DBC), active metal braze (AMB), and the various methods of plating copper directly to ceramic.

### 8.22.1 Direct bond copper

Copper may be bonded to alumina ceramic by placing a film of copper in contact with the alumina and heating to about 1065°C, just below the melting point of copper, 1083°C. At this temperature, a combination of 0.39 percent $O_2$ and 99.61 percent Cu form a liquid that can melt, wet, and bond tightly to the surfaces in contact with it when cooled to room temperature. In this process, the copper remains in the solid state during the bonding process, and a strong bond is formed between the copper and the alumina with no intermediate material required. The metallized substrate is slowly cooled to room temperature at a controlled rate to avoid quenching. To prevent excessive bowing of the substrate, copper must be bonded to both sides of the substrate to minimize stresses caused by the difference in TCE between copper and alumina.

In this manner, a film of copper from 5 to 25 mils thick can be bonded to a substrate and a metallization pattern formed by photolithographic etching. For subsequent processing, the copper is usually plated with several hundred microinches of nickel to prevent oxidation. The nickel-plated surface is readily solderable, and aluminum wire bonds to nickel constitute one of the most reliable combinations.[15] Aluminum wire bonded directly to copper is not as reliable and may result in failure on exposure to heat and/or moisture.[16]

Multilayer structures of up to four layers have been formed by etching patterns on both sides of two substrates and bonding them to a common alumina substrate. Interconnections between layers are made by inserting oxidized copper pellets into holes drilled or formed in the substrates prior to firing. Vias may also be created by using one of the copper plating processes.

Bonding a copper sheet larger than the ceramic substrate and etching a lead frame at the same time as the pattern may create integral leads extending beyond the substrate edge.

The line and space resolution of DBC are limited by the difficulty of etching thick layers of metal without substantial undercutting. Although the DBC technology does not have a resistor system, the thick film technology can be used in conjunction with DBC to produce integrated resistors and areas of high-density interconnections.

Aluminum nitride can also be used with copper, although the consistency of such factors as grain size and shape are not as good as with aluminum oxide at this time. Additional preparation of the AlN surface is required to produce the layer of oxide required to produce the bond. This can be accomplished by heating the substrate to about 1250°C in the presence of oxygen.

Direct bond copper offers considerable advantages when packaging power circuits. The thick layer of copper can handle considerable current without ex-

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cessive voltage drops and heat generation, and it allows the heat to spread rapidly outward from semiconductor devices, which dramatically lowers the thermal impedance of the system. The layer of copper on the bottom also contributes to heat spreading.

### 8.22.2 Plated copper technology

Although a copper film can be mechanically bonded to a rough substrate surface, the adhesion is usually inadequate for most applications. The various methods of plating copper to a ceramic all begin with the formation of a conductive film on the surface. This film may be vacuum deposited by thin film methods, screen printed by thick film processes, or deposited with the aid of a catalyst. A layer of electroless copper may be plated over the conductive surface, followed by a layer of electrolytic copper to increase the thickness.

A pattern may be generated in the plated surface by one of two methods. Conventional photolithographic methods may be used to etch the pattern, but this may result in undercutting and loss of resolution when used with thicker films. To produce more precise lines, a dry film photoresist may be utilized to generate a pattern on the electroless copper film that is the negative of the one required for etching. The traces may then be electroplated to the desired thickness using the photoresist pattern as a mold. Once the photoresist pattern is removed, the entire substrate may be immersed in an appropriate etchant to remove the unwanted material between the traces. Plated copper films created in this manner may be fired at an elevated temperature in a nitrogen atmosphere to improve adhesion.

### 8.22.3 Active metal brazing copper technology

The active metal brazing (AMB) process utilizes one or more of the metals in the IV-B column of the periodic table (e.g., titanium, hafnium, and zirconium) to act as an activation agent with ceramic. These metals are typically alloyed with other metals to form a braze that can be used to bond copper to ceramic. One such example is an alloy of 70Ti/15Cu/15Ni, which melts at 960 to 1000°C. Numerous other alloys can also be used.[14]

The braze may be applied in the form of a paste, a powder, or a film. The combination is heated to the melting point of the selected braze in a vacuum to minimize oxidation of the copper. The active metal forms a liquidus with the oxygen in the system that acts to bond the metal to the ceramic. After brazing, the copper film may be processed in much the same manner as DBC.

## 8.23 Comparison of Copper Metallization Technologies

The DBC and AMB processes are advantageous for applications in which a thicker copper layer is beneficial. In particular, these technologies are highly suitable for use in power circuits, where their ability to handle high currents and to aid heat dissipation can be utilized. Plated copper is most applicable to applications in which fine lines and precise geometries are required, such as

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RF circuits. Design guidelines for each of these technologies is given in Table 8.23.

## 8.24 Summary of Substrate Metallization Technologies

The applications of the various substrate metallization technologies rarely overlap. Given a particular set of requirements, the choice is usually very apparent. Table 8.24 illustrates the properties of the different technologies.

## 8.25 Assembly of Hybrid Circuits

There are two basic methods of assembling hybrid circuits: the "chip-and-wire" approach, in which semiconductor devices in the unpackaged form are mechanically attached to the substrate metallization by epoxy, solder, or eutectic bonding, and electrically connected by wire bonding; and the "surface mount" approach, in which packaged devices are soldered to the substrate, making both the electrical and mechanical connections simultaneously. These methods are not mutually exclusive, and it is very common to combine these approaches on a single substrate. This treatise is primarily concerned with the chip-and-wire technology.

### 8.25.1 Chip-and-wire technology

Semiconductor devices in the unpackaged state are very delicate. The metallization patterns are extremely thin and easily damaged, even with normal handling. The input/output (I/O) terminals are electrically open, and an electrical charge has no path to ground, making the die extremely susceptible to damage by electrostatic discharge (ESD). ESD can be generated from a variety of sources, as shown in Table 8.25. The die must be handled with extreme care, using a vacuum pickup (as opposed to tweezers) designed to dissipate electrical charge. Operators must be properly grounded, and ionized air blowers may be necessary when especially susceptible devices are being mounted.

### 8.25.2 Direct eutectic bonding of semiconductor devices

Silicon forms a eutectic composition with gold in the ratio of 94 percent gold and 6 percent silicon by weight, which melts at 370°C. Gold is the only metal that has a sufficiently low eutectic temperature in combination with silicon to be practical. By contrast, the eutectic temperature of silicon and silver is nearly 800°C.

In the eutectic bonding process, the substrate is preheated to about 200°C to minimize thermal shock and then transferred to a heated stage at about 400°C. The silicon die is picked up by a heated collet to further minimize thermal shock. The collet is sized to match the size of the die and is connected to a small vacuum pump for the purpose of holding the die in place. The collet is also connected to a motor capable of providing mechanical scrubbing to assist in making the bond. The die is picked up by the collet and transported to the

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**TABLE 8.23 Comparison of Design Rules for Pure Copper Metallization**

| Technology | Line width (in) | | Etch factors* (in) | Registration† (in) | Copper thickness ‡ (in) | | | Via diameters (in) | | Integral leads from edge of substrate | Camber** (in/linear in) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Min. | Typ. | | | Min. | Typ. | Max. | Min. | Typ. | | |
| Direct bond copper | 0.015 | 0.020 | 0.004 to 0.008†† | ±0.008 | 0.005 | 0.012 | 0.050 | 0.016 | 0.064 | ‡‡ | ± 00.004 |
| Plated copper | 0.002 | 0.005 | 0.0005 | ± 0.005 | 0.001 | 0.002 | 0.005 | 0.005 | 0.025 | †† | ± 0.003 |
| Active metal braze | 0.015 | 0.020 | 0.004 to 0.006** | ± 0.005 | 0.008 | 0.010 | 0.012 | ‡‡ | †† | *** | ± 0.004 |

*The width of the artwork pattern determines final conductor width. Etching will reduce the original artwork width by several mils, depending on copper thickness. Therefore, the artwork must have a wider dimension to compensate.
†The artwork is registered to a feature on the ceramic substrate, usually a corner of the ceramic surface.
‡Copper layers can be lapped to a lesser thickness after metallization.
**Assume that both ceramic sides have copper metallization. Then camber depends on differences in percentage of ceramic surface area coverage by copper.
††0.020-in pullback required from ceramic edge.
‡‡Not possible
***0.100 $in^2$ required on ceramic for integral leads

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**TABLE 8.24 Comparison of Hybrid Metallization Technologies**

| Technology | Ceramic selection | Metallization description | Adhesion mechanism | Geometry (typical) | Electrical and thermal | Hybrid assembly | Reliability | Cost |
|---|---|---|---|---|---|---|---|---|
| Thick film | Usually oxide, most types possible | Metal + glass | Chemical + mechanical | 0.010 in (250 μm lines and more than 0.0005 in (12 μm) thickness | Adequate | Good; solder rework can be a problem | Good; well understood | Variable; can use expensive precious metals |
| Thin film | All types | Pure metal, requires adhesion layers | Mechanical + chemical | 0.002 in (50 μm) lines and less than 0.0005 in (12 μm) thickness | Adequate | Adequate, not easily soldered | Good, well understood | High for equipment, process, and materials |
| Direct bond copper | More selective, oxide based | Pure copper | Chemical + mechanical | 0.020 in (400 μm) lines and 0.008 in to 0.020 in (200 to 500 μm) thickness | Good | Good | Good, well understood | Reasonable |
| Plated copper | All types | Pure, copper, usually thin adhesion layer | Mechanical (chemical?) | 0.004 in (100 μm) lines and 0.0005 in to 0.005 in (12 to 125 μm) thickness | Good | Good | Less understood | Reasonable |
| Active metal braze copper | All types | Pure copper, with braze adhesion layer | Chemical + mechanical | 0.020 in (400 μm) lines and 0.008 in to 0.020 in (200 to 500 μm) thickness | Good | Good | Adequate | Reasonable |



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**TABLE 8.25 Typical Electrostatic Voltages[17]**

| Event | Relative humidity, % | | |
|---|---|---|---|
| | 10 | 40 | 55 |
| Walking across carpet | 35,000 | 15,000 | 7,500 |
| Walking across vinyl floor | 12,000 | 5,000 | 3,000 |
| Motions of bench worker | 6,000 | 800 | 400 |
| Remove DIPs from plastic tubes | 2,000 | 700 | 400 |
| Remove DIPS from vinyl trays | 11,500 | 4,000 | 2,000 |
| Remove DIPs from styrofoam | 14,500 | 5,000 | 3,500 |
| Remove bubble pack from PWBs | 26,000 | 20,000 | 7,000 |
| Pack PWBs in foam-lined box | 21,000 | 11,000 | 5,500 |

desired metallization pattern on the substrate. Simply placing the die in contact with the heated substrate will not automatically form the bond; the materials must be in the proper proportion. This is accomplished by mechanically scrubbing the die into the gold metallization. During the scrubbing process, the eutectic alloy will be formed at some random point along the interface, which will then become molten. This, in return, will rapidly dissolve more material until the entire interface is liquid and the bond is formed. Devices larger than $0.020 \times 0.020$ in tend to crack when mechanically scrubbed and require a gold-silicon preform to make the bond.

The eutectic process makes a very good bond, mechanically, electrically and thermally, but the high bonding temperature is an extreme disadvantage for a variety of reasons, and this process is generally used only in single-chip applications. Where a metallurgical bond is required, solder is the preferred process. Semiconductor devices intended for solder bonding are typically metallized with a titanium/nickel/silver alloy on the bottom.

### 8.25.3 Organic bonding materials

The most common method of mechanically bonding active and passive components to a metallized substrate is with epoxy. Most epoxies for hybrid circuit applications have a filler added for electrical and/or thermal conductivity, with silver being the most common. Silver has a high electrical conductivity, and a smaller proportion of silver to epoxy is required to produce a given resistivity than other metals. Silver epoxy, therefore, has a higher mechanical strength, because a higher ratio of epoxy to filler is present for a given volume. Other conductive filler materials include gold, palladium-silver for reduced silver migration, and tin-plated copper. Nonconductive filler materials include aluminum oxide, beryllium oxide, and magnesium oxide for improved thermal conductivity.

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Epoxy may be dispensed by screen printing, pneumatic dispensing through a nozzle, and die transfer. Screen printing requires a planar surface, whereas pneumatic dispensing and die transfer may be used with irregular surfaces. If many die are to be mounted on a single substrate, screen printing is the preferred method, because epoxy can be applied to all mounting pads in a single pass of the screen printer with a more uniform and repeatable cross section.

If large surfaces such as substrates are to be mounted, liquid epoxies are difficult to use. For this application, a large sheet of glass cloth can be impregnated with epoxy, which is then B-staged, or partially cured, to produce a solid structure of epoxy generally referred to as a *preform*. Heating the preform further will soften the partially cured epoxy to facilitate bonding and will then complete the curing process. The sheet may then be cut into smaller pieces and used to mount large components and substrates. If high thermal conductivity is required, the mesh may be made from silver wire, and silver epoxy may be used.

Epoxy as a die attach material suffers from two major disadvantages.

1. The thermal and electrical resistances are quite high as compared to direct methods of bonding such as soldering or eutectic bonding.
2. The operating temperature is limited to about 150°C, as many epoxies begin breaking down and outgassing at temperatures above this figure.

These factors inhibit the use of epoxy in mounting power devices, in applications where a high processing temperature is required, where performance at a high ambient temperature is required, and where a low bond resistance is needed. One phenomenon that can occur when the epoxy is operated at elevated temperatures near or above the glass transition temperature ($T_g$) is the settling of the filler away from the device interface, leaving a thin layer of resin at the bond line and increasing the electrical resistance of the bond to the point at which circuit failure occurs. Another failure mechanism that can occur is silver migration, which can be accelerated by water absorption of a resin with a relatively high mobile ion content.

Other materials utilized for die bonding include polyimide and certain of the thermoplastic materials. Polyimide is stable out to around 350°C unless filled with silver, which acts as a catalyst to promote adhesion loss. Polyimides are typically dissolved in a solvent, such as xylene, requiring a two-step curing process. The first step, at a low temperature, evaporates the solvent, and the second step, at an elevated temperature, cross-links the polyimide. Thermoplastic materials are particularly advantageous in high-volume applications, because the cure cycle is much shorter than that of either epoxy or polyimide. Properties of selected die attach materials are shown in Table 8.26.

### 8.25.4 Solder attachment

In the soldering process, an alloy of two or more metals is melted at the interface of two metal surfaces. The molten solder dissolves a portion of the two

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**TABLE 8.26 Properties of Selected Organic Die Attach Materials**

| | Advantages and limitations of various adhesive types | |
|---|---|---|
| Type | Advantages | Limitations |
| Phenolics | Very high bond strength | Used mostly for structural applications, possibly corrosive, difficult to process at low temperatures |
| Polyurethanes | Easy to rework | Not suitable for temperatures above 120°C; relatively high outgassing, some decomposition |
| Polyamides | Easy to rework | High moisture absorption, high outgassing, variations in electrical insulation properties, especially when exposed to high humidity |
| Polyimides | Very high temperature stability | High cure temperatures, require solvents as vehicles |
| Silicones | High-temperature stability, easy to rework, high purity, low outgassing | Moderate-to-poor bond strength, high CTE |
| Epoxies | Some easy to rework by thermomechanical means, some low outgassing, easy to process, can be filled to 60 to 70 percent with a variety of conductive or nonconductive fillers | Depending on type of curing agent used and degrees of cure, outgassing, catalyst leaching, and corrosivity |
| Cyanoacrylates | Very rapid setting (<10 sec); very high initial bond strengths | Bond strengths often degrade under moist or elevated temperature (>150°C) conditions |

surfaces and, when the solder cools, a junction, or "solder joint," is formed, joining the two metal surfaces.

For the solder joint to occur, both metal surfaces and the solder must be clean and free from surface oxides so that the solder is able to "wet" both surfaces as shown in Fig. 8.30. Removal of the oxides is accomplished by the use of a "flux," an organically based acid. Fluxes are categorized by their strength and by the requirement for cleaning. Fluxes requiring solvent cleaning are rapidly being phased out because of environmental regulations, and the so-called "no-clean" fluxes, which remain on the circuit after the soldering process, are seeing extensive use in commercial applications. Water-soluble fluxes are still widely used in the printed circuit board industry. Surfaces that are

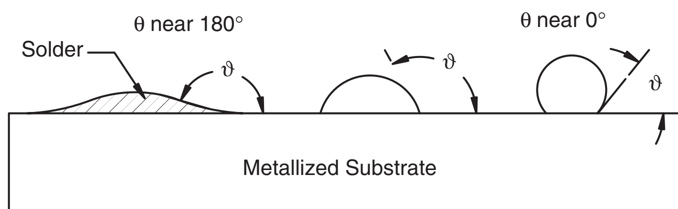


**Figure 8.30** Degrees of wetting.

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heavily oxidized before soldering may require the use of a stronger flux such as an resin mildly activated (RMA) flux.

Solder materials are selected primarily for their compatibility with the surfaces to be soldered, their reliability under conditions of temperature extremes, and their melting point. Solders are generally divided into two categories: "hard" solders, which have a melting point above about 500°C and are often referred to as "brazes," and "soft" solders, which have a lower melting point. Soft solders are used primarily in the assembly process, whereas hard solders are used in lead attachment and package sealing.

Soft solders may also be divided into two categories: eutectic and noneutectic solders. Eutectic solders have the lowest melting point and are typically more rigid in the solid state than other solders with the same constituents. This is partly a result of the fact that eutectic solders go directly from the liquid to the solid state without going through a "plastic" region. Their lower melting point makes them very attractive in many applications, and their use is quite common. Some of the more common solders and their characteristics are listed in Table 8.27.

The compatibility of the solder with the material in the metal surfaces must be a prime consideration when selecting a solder, in particular the tendency of the metal to "leach" into the solder and the tendency to form intermetallic compounds that might prove detrimental to reliability. Leaching is the process by which a material is absorbed into the molten solder to a high degree. While a certain degree of leaching must occur to produce the solder joint, excessive leaching can cause the metallization pattern to vanish into the molten solder, creating an open circuit. Tin-bearing solders used in conjunction with gold or silver conductors are especially prone to this phenomenon, because these materials have a strong affinity with tin. A thick or thin film gold or silver conductor will dissolve into a tin-lead solder in a matter of seconds. The addition of platinum and/or palladium to the thick film conductor materials will greatly enhance the leach resistance to tin-bearing solders, but it must still be a consideration. The leach resistance is proportional to the amount of Pt and Pd added, but this has the adverse effect of adding to both the cost and the electrical resistance. Soldering at the lowest possible temperature for the shortest possible time consistent with forming the solder joint can minimize leaching. The addition of a small amount of silver to the solder lowers the melting point slightly, and, with proper control of the soldering temperature, the silver already present in the solder partially saturates the solution, further inhibiting leaching. Soldering directly to gold requires the use of AuSn, PbIn, or other solders that do not leach gold. The added Au in the AuSn combination inhibits leaching of the gold in the film.

Intermetallic compound formation is also a consideration. Certain compounds have a high electrical resistance and are susceptible to mechanical failure when exposed to temperature cycling or storage at temperature extremes. Tin forms intermetallic compounds with both gold and copper, and indium also forms intermetallic compounds with copper. The most commonly used solders are the tin-lead solders, which are used extensively on copper and the PdAg and PtAg alloys.

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**TABLE 8.27 Processing Temperatures of Selected Organic and Metallic Attachment Materials**

| Organic attachment materials | | |
|---|---|---|
| Material | Temperature, °C | |
| Polyimide | 259–300* | |
| Epoxy | 150 | |
| Metallic attachment materials | | |
| Alloy | Liquidus, °C† | Solidus, °C |
| In52/Sn48‡ | 118 | 118 |
| Sn62.5/Pb36.1/Ag1.4‡ | 179 | 179 |
| Sn63/Pb37‡ | 183 | 183 |
| In60/Pb40 | 185 | 174 |
| Sn60/Pb40 | 188 | 183 |
| Sn96.5/Ag3.5‡ | 221 | 221 |
| Pb60/Sn40 | 238 | 183 |
| Pb70/Sn27/Ag3 | 253 | 179 |
| Pb92.5/Sn5/Ag2.5 | 280 | 179 |
| Sn90/Ag10 | 295 | 221 |
| Pb90/Sn10 | 302 | 275 |
| Au88/Ge12‡ | 356 | 356 |
| Au96.4/Si3.6‡ | 370 | 370 |
| Ag72/Cu28‡ | 780 | 780 |

*Polyimide materials require a precure step at 70°C to remove solvents.
†The processing temperature of most alloys is ≥20°C above the liquidus.
‡Eutectic composition.

Lead-free solders, such as the tin/silver combinations, are becoming more widely used. Apart from environmental concerns, the tin/silver solders have proven to be more resilient to extensive temperature cycling conditions. Table 8.28 shows the comparative fatigue characteristics of various solders.

In the soldering process, it is desirable to minimize the exposure of the part to elevated temperatures. High temperatures accelerate the rate of chemical reactions that may be detrimental to the reliability of the circuit. Furthermore, excessive exposure of metal surfaces to liquid solder increases the rate of formation of intermetallic compounds and also increases leaching.

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**TABLE 8.28 Comparative Fatigue Characteristics of Solder Alloys**

| Performance | Composition | Performance | Composition |
|---|---|---|---|
| Worst | Sn63/Pb37<br>Sn60/Pb40 | Fair | In99/Cu1<br>Sn90/Pb10<br>Sn99.25/Cu0.75 |
| Poor | Sn62/Pb36/Ag2<br>Sn65/In35<br>Sn42/Bi58<br>Sn50/In50<br>Sn50/Pb50 | Good | Sn99/Sb1<br>Pb50/In50<br>Sn100 |
| | | Excellent | Sn96/Ag4<br>Sn95/Sb5 |

Solders for microelectronic applications are generally in the form of a paste, with the solder in powder form mixed with an appropriate flux and a dispensing vehicle. Solder in paste form may be screen printed or dispensed pneumatically. The part is placed in the wet solder paste prior to soldering manually or by an automatic pick-and-place system.

The most effective method of soldering is to place the part in conjunction with the solder paste into a tunnel furnace with several heated zones. By controlling the speed of the belt and the temperature of the individual zones, a time-temperature relationship, or "profile," can be established that will optimize the soldering process. Heating of the part may be accomplished by resistance heating, by infrared (IR) heating, or by a combination of both.

The use of a nitrogen or forming gas blanket during the soldering process to prevent oxidation of the solder and/or the surfaces aids greatly in soldering, particularly to nickel, and improves the wetting of tin-bearing solders. The formation of a gas blanket can be easily accomplished by connecting a gas source to the furnace and by the use of baffles at the ends of the furnace to minimize the intrusion of air into the heated region. A typical profile has a duration of several minutes and has a plateau just below the melting point of the solder for a period of time followed by a rapid rise in temperature, or "spike," above the melting point for a short duration and a gradual decline down to room temperature. In general, the duration of the spike should be held as short as possible, consistent with good solder flow and wetting, to minimize such effects as leaching of conductor materials and the effect of high temperatures on the components.

### 8.25.5 Wire bonding

Ohmic contacts to semiconductor devices are typically made with aluminum, because that material diffuses well into the silicon structure at a moderate temperature. Wire bonding is used to make the electrical connections from the aluminum contacts to the substrate metallization or to a lead frame; from other components, such as chip resistors or chip capacitors, to substrate metallization; from package terminals to the substrate metallization; or from one point on the substrate metallization to another.

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There are two basic methods of wire bonding: thermocompression wire bonding, which uses primarily gold wire; and ultrasonic wire bonding, which uses primarily aluminum wire. Thermocompression wire bonding, as the name implies, utilizes a combination of heat and pressure to form an intermetallic bond between the wire and a metal surface. In thermocompression bonding (Fig. 8.31), a gold wire is passed through a hollow capillary, generally

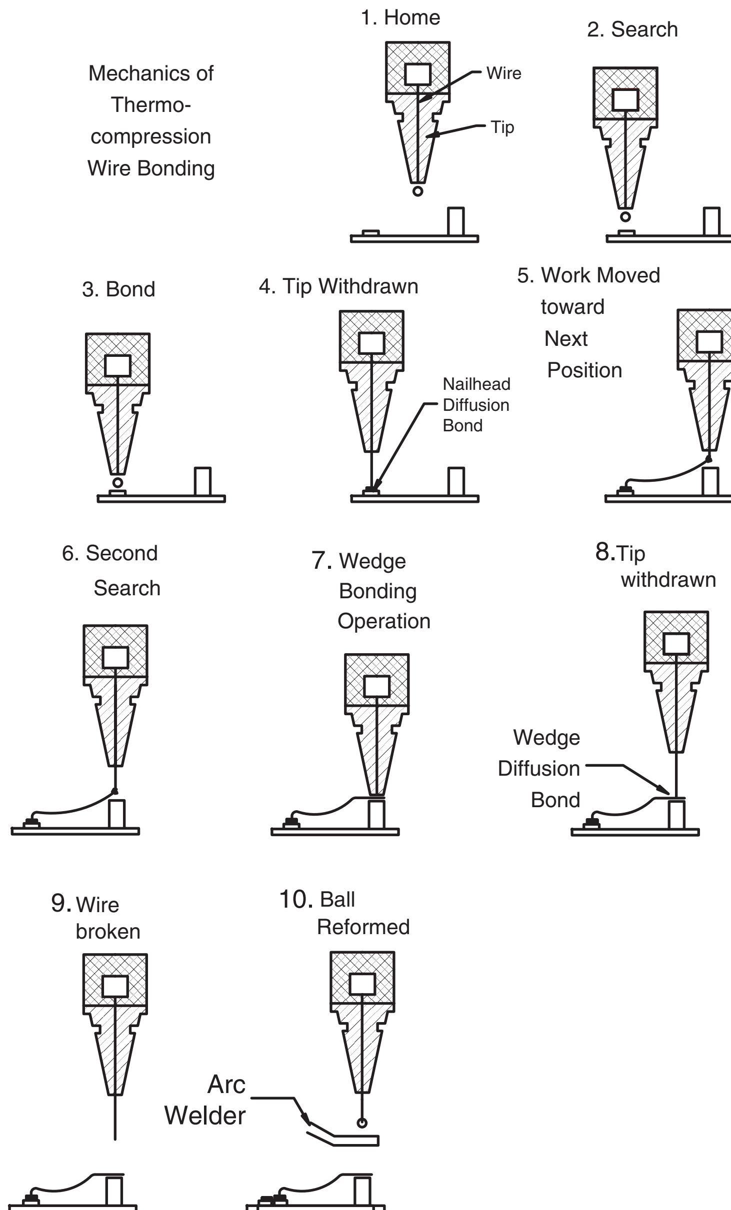


**Figure 8.31** Thermocompression bonding sequence.

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made from a refractory metal such as tungsten, and a ball is formed on the end by means of an electrical arc. The substrate is heated to about 300°C, and the ball is forced into contact with the bonding pad on the device with sufficient force to cause the two metals to bond. The capillary is then moved to the bond site on the substrate, feeding the wire as it goes, and the wire is bonded to the substrate by the same process, except that the bond is in the form of a "stitch" as opposed to the "ball" on the device.

The wire is then clamped and pulled to break just above the stitch, and another ball is formed as above. Thermocompression bonding is rarely used for a variety of reasons.

- The high substrate temperature precludes the use of epoxy for device mounting.
- The temperature required for the bond is above the threshold temperature for gold-aluminum intermetallic compound formation. The diffusion rate for aluminum into gold is much greater than for gold into aluminum. The aluminum contact on a silicon device is very thin and, when it diffuses into the gold, voids (called *Kirkendall voids*) are created in the bond area, increasing the electrical resistance of the bond and decreasing the mechanical strength.
- The thermocompression bonding action does not effectively remove trace surface contaminants that interfere with the bonding process.

The ultrasonic bonding process (Fig. 8.32) uses ultrasonic energy to vibrate the wire against the surface to combine the atomic lattices together at the surface as depicted in Fig. 8.33. Localized heating at the bond interface caused by the scrubbing action, aided by the oxide on the aluminum wire, assists in forming the bond. The substrate itself is not heated. Intermetallic compound formation is not as critical as with the thermocompression bonding process, because both the wire and the device metallization are aluminum. Kirkendall voiding on an aluminum wire bonded to gold substrate metallization is not as critical, given that there is substantially more aluminum available to diffuse than on device metallization. Ultrasonic bonding makes a stitch on both the first and second bonds. For this reason, ultrasonic bonding is somewhat slower than thermocompression, because the capillary must be aligned with the second bond site when the first bond is made. Ultrasonic bonding to package leads may be difficult if the leads are not tightly clamped, because the ultrasonic energy may be propagated down the leads instead of being coupled to the bond site.

The use of thermosonic bonding largely overcomes the difficulties noted with thermocompression bonding. In this process, used with gold wire, the substrate is heated to 150°C, and ultrasonic energy is coupled to the wire through the transducer action of the capillary, scrubbing the wire into the metal surface and forming a ball-stitch bond from the device to the substrate, as in thermocompression bonding.

Thermosonic gold bonding is the most widely used bonding technique, primarily because it is faster than ultrasonic aluminum bonding. Once the ball

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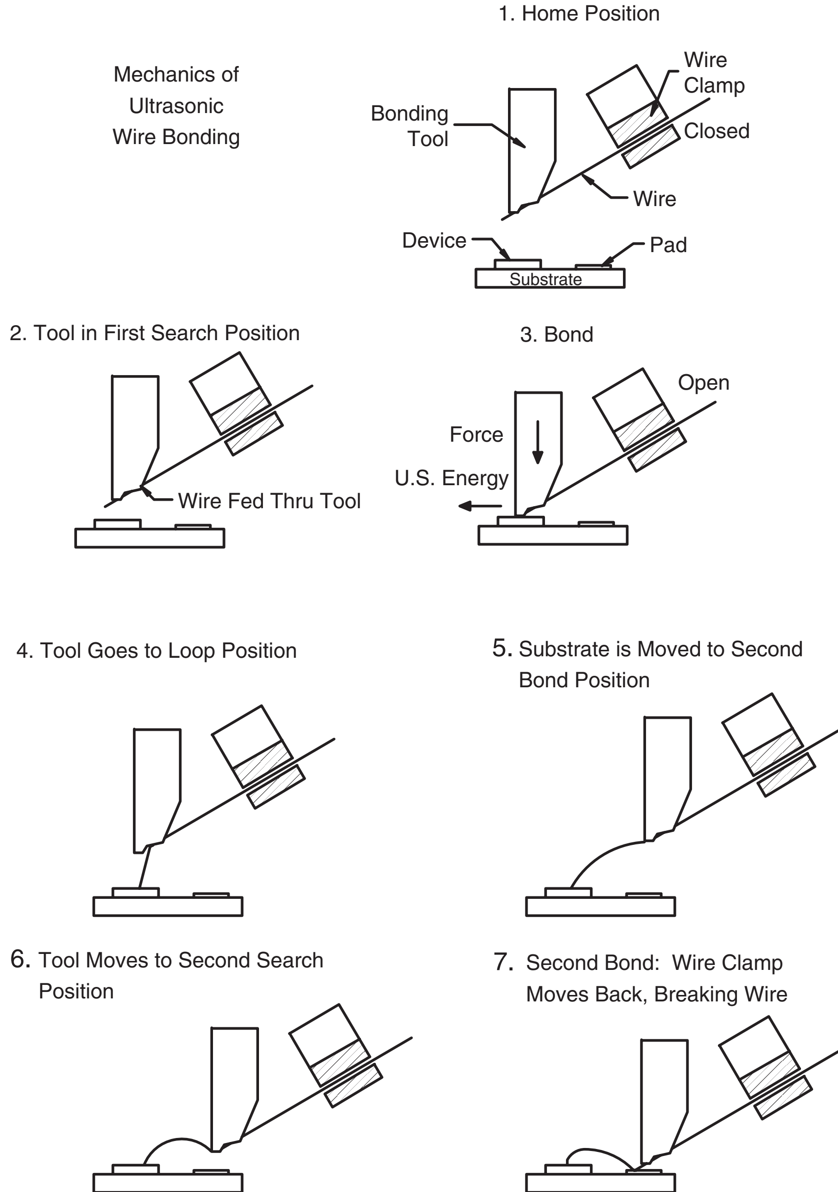


**Figure 8.32** Ultrasonic bonding sequence.

bond is made on the device, the wire may be moved in any direction without stress on the wire, which greatly facilitates automatic wire bonding, as the movement need only be in the x and y directions. An example of thermosonic bonding is shown in Fig. 8.34.

By contrast, before the first ultrasonic stitch bond is made on the device, the circuit must be oriented so that the wire will move toward the second bond

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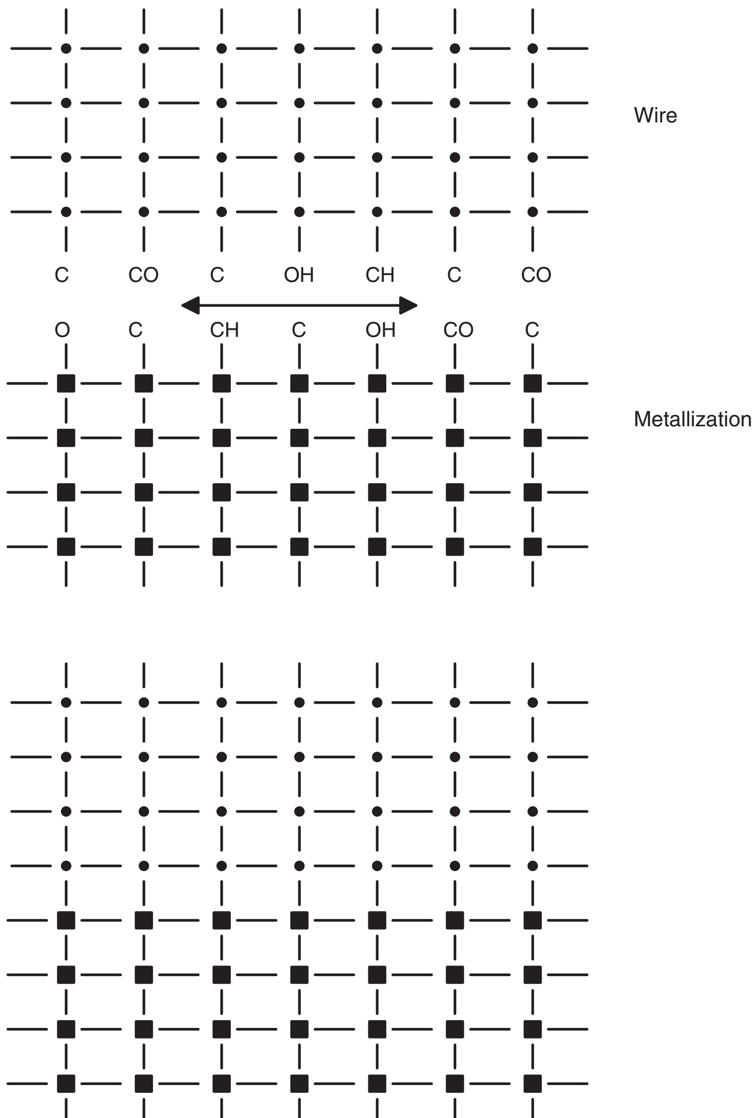


**Figure 8.33** Lattice formation in ultrasonic bonding.

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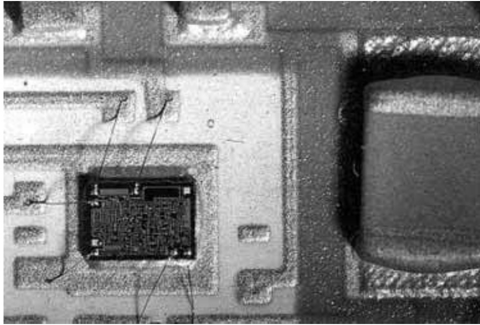

**Figure 8.34** Thermosonic wire bonding.

site only in the direction of the stitch. This requires rotational movement, which not only complicates the design of the bonder but increases the bonding time as well.

Attempts at designing an aluminum ball bonder have not proven successful to date, because of the difficulty in making a ball on the end of the wire. Aluminum bonding is commonly used in hybrids or chip carriers where the package-sealing temperature may exceed the threshold temperature for the formation of intermetallic compounds, in power hybrids where the junction temperature is high, and in applications where large wires are required. Gold wire is difficult to obtain in diameters above 0.002 in, whereas aluminum wire is available up to 0.022 in. An example of power devices bonded with large aluminum wire is shown in Fig. 8.35.

Automatic thermosonic gold bonding equipment now exists that can bond up to four wires per second under optimal conditions. The actual rate depends on the configuration of the bonding pattern and the number of devices to be bonded. The utilization of an automatic bonder with pattern recognition is strongly dependent on the accuracy of the device placement and on the quality of the substrate metallization. If the devices are not placed within a few mils of the bond site and within a few degrees of rotation, the pattern recognition

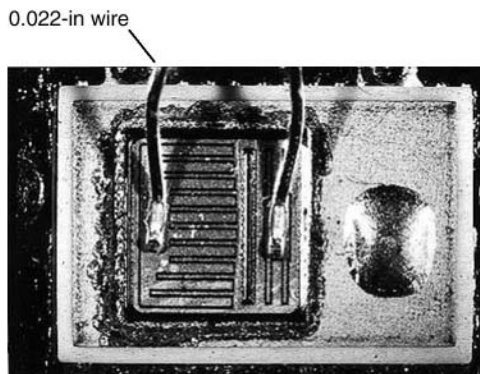


**Figure 8.35** Large aluminum wire bonding.

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system will not be able to locate the device, resulting in lost production time while the operator feeds in the coordinates. An ideal stitch bond is shown in Fig. 8.36.

The substrates must be kept very clean and should be handled only with finger cots during the assembly process. In storage, the substrates should be kept in a clean, dry area. Thin film metallization makes the best bonding surface, because it is uniform in thickness and is almost pure gold. There exists a considerable variation in bondability among the various thick film gold conductors, and bonding studies under a variety of conditions must be an integral part of the selection process of a thick film gold material. Thick film gold for use with aluminum wire must contain palladium to improve the strength of the bond under conditions of thermal aging. The same principle applies to aluminum bonding on palladium-silver materials. As the palladium-to-silver ratio is increased, the reliability of the bonds increases.

The integrity of the wire bonds may be tested by placing a small hook under the wire and pulling at a constant rate of speed, usually very slow, until the bond fails. The amount of force required is the *bond strength*. The mode of failure is just as important as the actual bond strength. There are five points at which a bond can fail.

1. The ball (or stitch) at the device may fail.
2. The wire may break just above the stitch at the device end.
3. The wire may break in the center.
4. The wire may break just above the stitch at the substrate end.
5. The stitch at the substrate may lift.

Of the five options, number three is the most desirable, with two and four following in turn. If an excessive number of lifts occur, particularly at the device end, a serious bonding problem may be indicated. Some of the more common bonding problems and their possible causes are listed below.

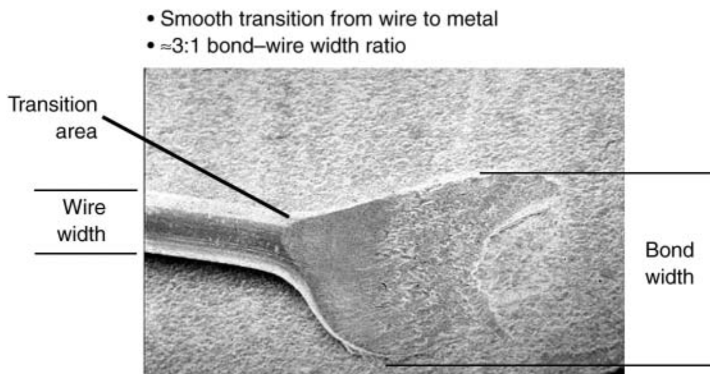


**Figure 8.36** Ideal stitch bond.

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- *Excessive bond lifts at the device.* This problem may be a result of one of three factors: improper bond setup, contamination on the device, or incomplete etching of the glass passivation on the device.
- *Excessive bond breaks just above the device.* This is probably caused by either a worn bonding tool or by excessive bonding pressure, both of which can crimp the wire and create a weak point.
- *Excessive bond breaks just above the substrate.* This is probably caused by excessive bonding pressure. This may result from improper bonding setup, which in turn may be due to contamination or to poor substrate metallization. A worn bonding tool may result in the wire being nicked, creating a possible failure point.
- *Excessive stitch lifts at the substrate.* This may be the result of a worn bonding tool, poor bonder setup, or poor device metallization.

The wire size is dependent on the amount of current that the wire is to carry, the size of the bonding pads, and the throughput requirements. Table 8.29 provides the wire size for a specified current for both gold and aluminum wire. For applications where current and bonding size is not critical, 0.001-in wire is the most commonly used size. Although 0.0007-in wire is less expensive, it is difficult to thread through a capillary and bond without frequent breaking and consequent line stoppages.

**TABLE 8.29 Maximum Current for Wire Size**

| | | Maximum current | |
|---|---|---|---|
| Material | Diameter (in) | L < 0.040 in | L > 0.040 in |
| Gold | 0.001 | 0.949 | 0.648 |
| | 0.002 | 2.683 | 1.834 |
| Aluminum | 0.001 | 0.696 | 0.481 |
| | 0.002 | 1.968 | 1.360 |
| | 0.005 | 7.778 | 5.374 |
| | 0.008 | 15.742 | 10.876 |
| | 0.012 | 28.920 | 19.981 |
| | 0.015 | 40.417 | 27.924 |
| | 0.022 | 71.789 | 49.600 |

## 8.26 Packaging

Packaging for individual devices or complete hybrid assemblies can be characterized as shown in Table 8.30 with examples depicted in Fig. 8.37. There are

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many driving forces and considerations in the choice of technology for packaging and the subsequent next level assembly technologies.

**TABLE 8.30 Characterizations of Package Types**

| Leads | Type |
|---|---|
| Through-hole | Hermetic |
| Plug-in<br>Dual-in-line (DIP)<br>Pin grid array (PGA)<br>TO types | Metal<br>Ceramic |
| Surface mount | Nonhermetic |
| Flat package<br>Ball grid array (BGA) | Plastic molded<br>Conformal coated |

### 8.26.1 Hermetic packages

A true hermetically sealed package would prevent intrusion of contaminants (liquid, solid, or gas) for an indefinite period of time. In practice, however, this is not realistic. Even in a perfectly sealed structure, diffusion phenomena will occur over time, allowing the smaller molecules, such as helium or water vapor, to penetrate the barrier medium and ultimately reach equilibrium within the package interior. A hermetic package is defined as one in which the leak rate of helium after pressurization is below a specified rate with reference to the package size as shown in Table 8.31.

A hermetic package must either be metal, ceramic, or glass. Organic packages, or packages with an organic seal, may initially pass the pressurization

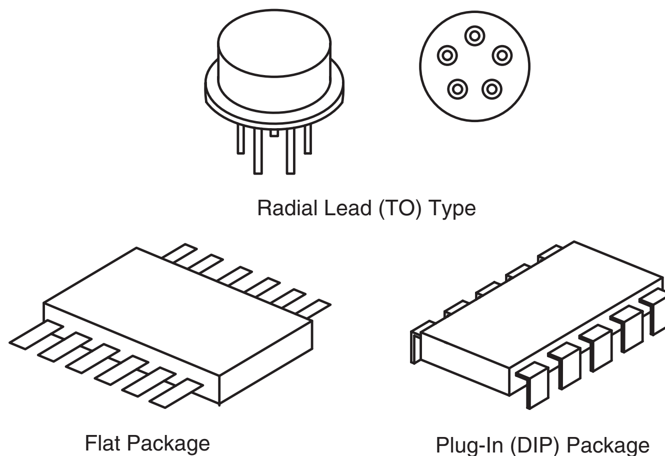


**Figure 8.37** Package types.

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**TABLE 8.31 Acceptable Leak Rates for Hermetic Packages per MIL-STD-883**

| Package volume ($cm^3$) | PSIG | Bomb condition exposure time (hr) | Maximum dwell (hr) | Reject limit (atm-$cm^3$/sec-He) |
|---|---|---|---|---|
| $V < 0.05$ | $75 \pm 2$ | 2.0, +0.2, –0 | 1 | $5 \times 10^{-8}$ |
| $0.05 \leq V < 0.5$ | $75 \pm 2$ | 4.0 +0.4, –0 | 1 | $5 \times 10^{-8}$ |
| $0.5 \leq V < 10.0$ | $45 \pm 2$ | 2.0, +0.2, –0 | 1 | $1 \times 10^{-7}$ |
| $1.0 \leq V < 10.0$ | $45 \pm 2$ | 4.0 +0.4, –0 | 1 | $5 \times 10^{-8}$ |
| $10.0 \leq V < 20.0$ | $45 \pm 2$ | 10.0, +1.0, –0 | 1 | $5 \times 10^{-8}$ |

test described above but will allow water vapor to pass back and forth from the atmosphere to the package interior. Therefore, they are not truly hermetic. Interconnections through a metal package may be insulated by glass-to-metal seals utilizing glass that matches the coefficient of expansion to that of the metal.

A hermetic package allows the circuit mounted inside to be sealed in a benign environment—generally nitrogen, which is obtained from a liquid nitrogen source. Nitrogen of this type is extremely dry, with a moisture content of less than 10 ppm. As a further precaution, the open package with the enclosed circuit mounted inside is subjected to an elevated temperature, usually 150°C, in a vacuum, to remove absorbed and absorbed water vapor and other gases prior to sealing. For added reliability, the moisture content inside a package should not exceed 5000 ppm. This figure is below the dew point of 6000 ppm at 0°C, ensuring that any water that precipitates out will be in the form of ice, which is not as damaging as water in the liquid form.

A hermetic package adds considerably to the reliability of a circuit by guarding against contamination, particularly of the active devices. An active device is susceptible to a number of possible failure mechanisms, such as corrosion and inversion, and may be attacked by something as benign as distilled, deionized water, which can leach phosphorous out of the passivating oxide to form phosphoric acid. This, in turn, can attack the aluminum bonding pads.

### 8.26.2 Metal packages

The most common type of hermetic package is the metal package, which is fabricated primarily from ASTM F-15 alloy, Fe52Ni29Co18 (known also as Kovar®). The so-called bathtub type package is fabricated by forming a sheet of the F-15 alloy over a set of successive dies. Holes for the leads are then punched in the bottom for plug-in packages and in the side for flat packages. A layer of oxide is then grown over the package body. Beads of borosilicate glass, typically Corning 7052 glass, are placed over the leads and in the holes in the package body. Heating the structure above the melting point of the glass (approximately 500°C) forms a reactive glass-to-metal seal. The molten glass dis-

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solves some of the oxides on the alloy (primarily iron oxide), which, on cooling, provides the adhesion mechanism (see Fig. 8.38). The glass-to-metal seal formed in this manner has four distinctive layers.

1. Metal
2. Metal oxide
3. Metal oxide dissolved in glass
4. Glass

After the glass-to-metal seals have been formed, the oxide not covered by the glass must be removed and the metal surface plated to allow the package to be sealed and to allow the package leads to be soldered to the next higher assembly. The prime plating material is electrolytic nickel, although gold is frequently plated over the nickel to aid in sealing and to prevent corrosion. In either case, the package leads are plated with gold to allow wire bonding and to improve solderability. Although electroless nickel has better solderability, it tends to crack when the leads are flexed.

The glass-to-metal seal formed in this manner provides an excellent hermetic seal, and the close match in TCE between the glass and the F-15 alloy (approximately $5.0 \times 10^{-6}$/°C) maintains the hermeticity through temperature cycling and temperature storage. A cross section of metal package types is shown in Figs. 8.39 through 8.41.

Three types of lids are commonly used on metal packages: the domed lid, the flat lid, and the stepped lid. These are also fabricated with ASTM F-15 alloy with the same plating requirements as the packages. The domed lid is designed for use with platform packages and may be projection welded or soldered. The flat lid is designed for use with the tub package and is primarily soldered to the package. The stepped lid is fabricated by photoetching a groove in a solid sheet of F-15 alloy such that the flange is about 0.004 in thick. This lid is designed to be seam welded to a tub package. When lids are designed for

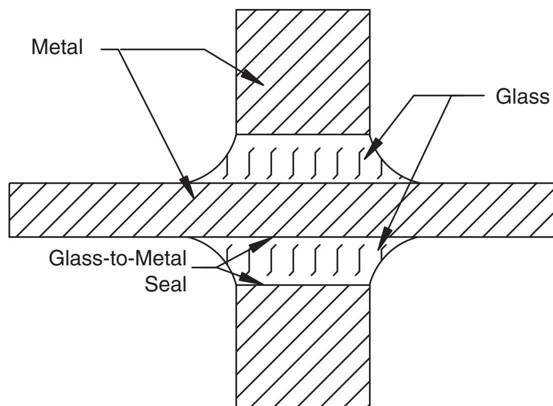


**Figure 8.38** Glass-to-metal seal.

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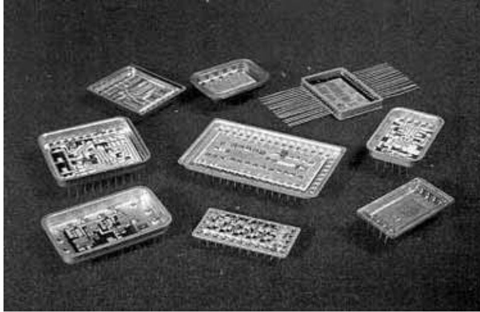

**Figure 8.39** Metal packages, platform and "bath-tub."

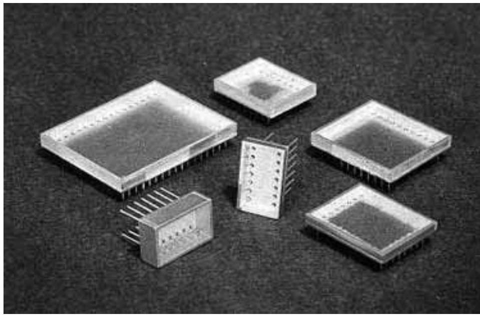

**Figure 8.40** Metal packages, through-hole.

**Figure 8.41** Flat ("butterfly") package.

soldering, a preform of the desired solder material is generally attached to the outer perimeter of the bottom of the lid.

### 8.26.3 Methods of sealing metal packages

A flat or stepped lid may be soldered to the package by hand by the use of a heated platen or in a furnace. Although the platen is somewhat faster, the metal package acts as a heat sink, simultaneously drawing heat away from the seal area and raising the temperature inside the package unless the glass beads used for insulating the leads extend entirely around the periphery of the package—an obviously impractical arrangement. In addition, leaks through the solder, or "blow holes," caused by a differential in pressure be-

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tween the inside and outside of the package, will occur unless the ambient pressure outside the package is increased simultaneously with the pressure that is created inside by heating the package. Because of the temperature rise inside the package, it is risky to use epoxy to mount components unless the glass beads extend around the periphery of the package as described above. Solder sealing may be accomplished in a conveyor-type furnace that has a nitrogen atmosphere. The nitrogen prevents the oxidation of the solder and also provides a benign environment for the enclosed circuit. Furnace sealing requires a certain degree of fixturing to provide pressure on the lid.

Parallel seam welding (Fig. 8.42) is accomplished by the generation of a series of overlapping spot welds by passing a pair of electrodes along the edge of the lid. The alignment of the lid to the package is quite critical and is best accomplished outside the sealing chamber, with the lid being tacked to the package in two places by small spot welds. A stepped lid greatly facilitates the process and improves the yield, because it requires considerably less power than a flat lid of greater thickness. The sealing process is relatively slow compared to other methods, but a package sealed by parallel seam welding can be easily delidded by grinding the edge of the lid away. Because the lid is only about 0.004 in thick in the seal area, this may be readily accomplished with a single pass of a grinding wheel. With minimal polishing of the seal area of the package, another lid may be reliably attached.

Certain classes of packages with a flange on the package may be sealed by a process called *projection* or *one-shot* welding. In this process, an electrode is placed around the flange on the package and a large current pulse is passed through the lid and the package, creating a welded seam. Heavy-duty resistance welding equipment capable of supplying 500 lb of pressure and 12,000 A per linear inch of weld is required for these packages. The major advantages of one-shot welding are process time and a less-expensive package. The major disadvantage is the difficulty of removing the lid and repairing the circuit inside. Delidding a projection-welded package is a destructive process, and the package must be replaced.

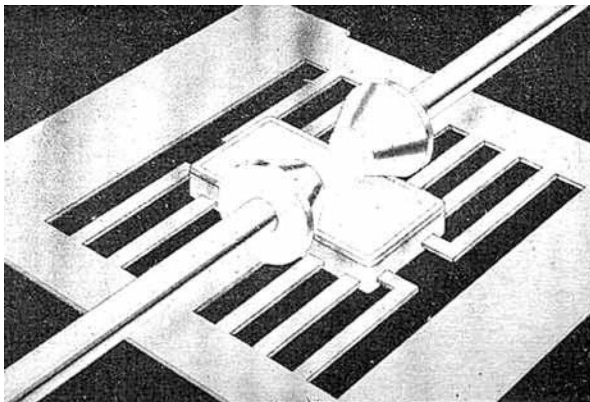

**Figure 8.42** Parallel seam welding.

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### 8.26.4 Ceramic packages

**Figure 8.43** Leadless ceramic chip carrier (internal).

Ceramic packages in this context are considered to be structures that permit a thick or thin film substrate to be mounted inside in much the same manner as a metal package. Ceramic structures that have metallization patterns, which allow direct mounting of components, are referred to as *multichip ceramic packages*. Ceramic packages for hybrid circuits generally consist of three layers of alumina. The bottom layer may or may not be metallized, depending on how the substrate is to be mounted. A ring of alumina is attached to the bottom layer with glass, and a lead frame is sandwiched between this ring and a top ring with a second glass seal. The top ring may be metallized to allow a solder seal of the lid or may be left bare to permit a glass seal. Various types of ceramic packages are shown in Figs. 8.43 through 8.45.

### 8.26.5 Methods of sealing ceramic packages

The most common method of sealing ceramic packages is solder sealing. During the manufacturing process, a coating of a refractory metal or combination of metals, such as tungsten or an alloy of molybdenum and manganese, is fired onto the ceramic surface around the periphery of the seal area. On completion, the surface area is successively nickel plated and gold plated. A lid made from ASTM F-15 alloy is plated in the same manner and soldered onto the package, usually with an alloy of Au80Sn20, in a furnace with a nitrogen atmosphere.

A less expensive, but also less reliable, method of sealing is to use a glass with a low melting point to seal a ceramic lid directly to a ceramic package. This avoids the use of gold altogether, lowering the material cost considerably.

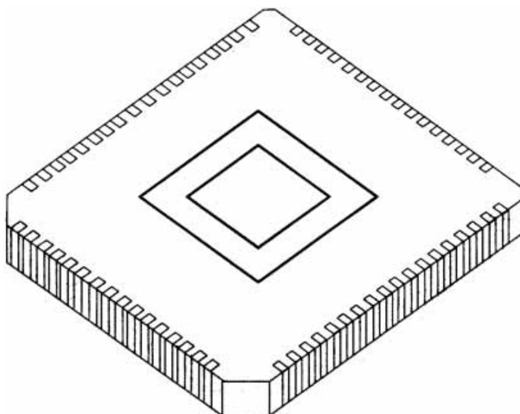

**Figure 8.44** Leadless ceramic chip carrier (external).

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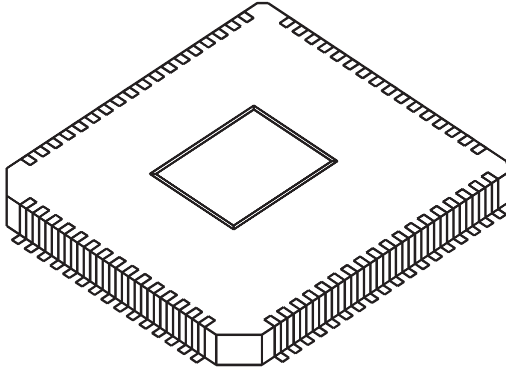

**Figure 8.45** Leaded ceramic chip carrier.

The glass requires a temperature of about 400°C for sealing, as opposed to about 300°C for the AuSn solder. The glass seal is somewhat susceptible to mechanical and thermal stress, particularly at the interface between the glass and the package.

These two techniques have a common problem: it is difficult to remove the lid for repair without rendering the package useless for further sealing. An alternative approach seeing increased use is to braze a ring of ASTM F-15 alloy that has been nickel and gold plated as described above onto the sealing surface of the ceramic package. It is then possible to use parallel seam welding, with its inherent advantages for repair. This approach is also frequently used for ceramic multilayer packages designed for multichip packaging.

### 8.26.6 Nonhermetic packaging approaches

The term *nonhermetic* package encompasses a number of configurations and materials, all of which ultimately allow the penetration of moisture and/or other contaminants to the circuit elements. Most techniques involve encapsulation with one or more polymer materials, with the most common being the molding and fluidized bed approaches.

Both injection and transfer molding techniques employ thermoplastic polymers, such as acrylics or styrenes, to coat the circuit. In transfer molding, the material is heated and transferred under pressure into a closed mold in which the circuit has been placed; in injection molding, the material is heated in a reservoir and forced into the mold by piston action.

The fluidized bed technique uses an epoxy powder kept in a constant state of agitation by a stream of air. The circuit to be coated is heated to a temperature above that of the melting point of the epoxy and is placed in the epoxy powder. The epoxy melts and clings to the circuit, with the thickness controlled by the time and the preheat temperature.

Both methods are used to encapsulate hybrids and individual devices, and both are amenable to mass production techniques. The overall process may be performed at a cost of only a few cents per circuit. The coatings are quite rug-

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ged mechanically, are resistant to many chemicals, and have a smooth, hard surface suitable for marking.

### 8.26.7 Plug-in packages

Plug-in packages have leads protruding from the bottom with a lead spacing of 0.100 in. A special case of plug-in packages is the DIP package. Standard DIP packages are used to package individual die and have two rows of leads on 0.100-in centers, separated with each row being 0.300 in apart. Other package types designed for hybrid use (platform or bathtub) often are found to have a lead configuration consistent with the DIP design for commonality with test mounting sockets. An example is shown in Fig. 8.40.

Plug-in packages are designed for through-hole insertion into printed wiring boards. In addition to DIP packages, a single-in-line (SIP) packaging technique was developed for resistor and capacitor components and networks. For all plug-in packages, the leads provide a convenient method for ensuring clearance on assembly and providing a degree of compliance into the mechanical stress established by assembly or expansion coefficient mismatch between the package and the mounting substrate. DIP packages were the mainstay of discrete device packaging while device complexity was low. However, with the advent of very large scale integration (VLSI) devices and high I/O counts, the 100-mil lead centers required the development of very large packages. A standard 40-pin device required a length exceeding 2.00 in, and higher pin counts became increasingly difficult to package in DIP form.

### 8.26.8 Small-outline package

A small-outline (SO) package is shown in Fig. 8.46. The leads on the SO package are on 0.050-in centers, as opposed to 0.100-in centers for the DIP package. The SO has a low profile and occupies less than 50 percent of the area of the DIP. It weighs about one-tenth that of a DIP. The SO package family in-

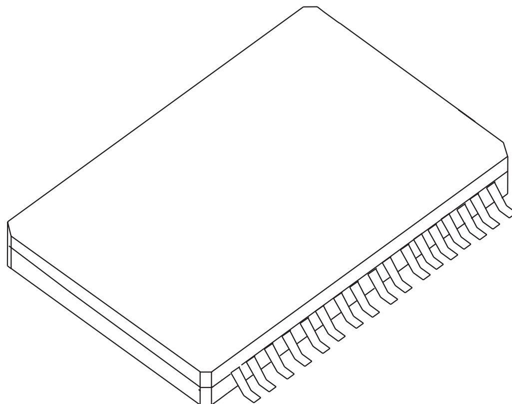

**Figure 8.46** Small-outline package.

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cludes packaging of passive devices; packages that contain ICs, known as SOIC packages; and packages that contain transistors, known as SOTs. Both plastic and ceramic SO packages are available.

### 8.26.9 Ceramic chip carriers

A special case of the ceramic package is the hermetic chip carrier as shown in Figs. 8.43 through 8.45. The wire bonding pads are routed to the outside between layers of ceramic and are connected to semicircular contacts called *castellations*. The most common material is alumina, which is metallized with a refractory metal during fabrication and then successively plated with nickel and gold. Most multilayer chip carriers are designed to be sealed with solder, usually Au80/Sn20.

Configurations of chip carriers for military applications have been standardized by JEDEC in terms of size, lead count, lead spacing, and lead orientation, although nonstandard carriers can be used for specialized applications. The most common lead spacing is 0.050 in, with high lead count packages having a spacing of 0.040 in.

The removal of heat from chip carriers in the standard "cavity-up" configuration has been a problem, because the only path for heat flow is along the bottom of the carrier and out to the edge of the carrier, where it flows down to the substrate through the solder joints. This problem can be alleviated to a certain extent by printing pads on the bottom of the carrier, which are soldered directly to the substrate. This lowers the thermal impedance by a factor of several times. If this does not prove adequate, carriers with the cavity pointing down can be utilized. In this configuration, the chip is mounted on the top of the carrier in the upside-down position, the lid is mounted in a recess on the bottom of the carrier, and a heat sink is mounted to the top to enable the heat to be removed by convection. Beryllia and aluminum nitride chip carriers are being used to package high-power devices,

Devices mounted in chip carriers can be thoroughly tested and burned in before mounting on a substrate or printed circuit board. This process can be highly automated and is frequently done in military applications. Sockets exist for standard sizes that make contacts to the castellations without the necessity of solder.

Chip carriers have proven to be a viable approach for packaging hybrid circuits of minimal size. Although available with pin counts up to 128, chip carriers have proved to be a reliability risk when the pin count is greater than 84, because the net expansion of the carrier at temperature extremes (and therefore the stress on the solder joints) is proportional to its size. Furthermore, the temperature at which chip carriers may be used on PC boards is limited because of the difference in the coefficient of expansion (TCE) between the carrier and board material.

As the solder joint is made higher, the difference in TCE becomes less significant. The highest solder column that can be made by ordinary means is about 0.007 in. Above this height, a molten solder column begins collapsing of its own weight. Power cycling, in which the device in the carrier is powered on

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and off at periodic intervals, has proven to be a serious reliability risk, even more than temperature cycling, when power devices are mounted. While the device in the carrier is being power cycled, the carrier and the board are in a nonequilibrium state with respect to temperature. This causes considerable stress on the solder joints, ultimately resulting in failure from metal fatigue.

### 8.26.10 Packages for power hybrid circuits

As the power requirements of package materials have become more demanding, ASTM F-15 alloy and alumina become less attractive because of their relatively low thermal conductivity. Copper, molybdenum, copper-clad materials, aluminum nitride, and beryllia have all been used to manufacture packages. This requires some innovation on the part of the package manufacturer to develop methods of sealing and through-hole connections, given that copper is not amenable to seam welding or glass-to-metal sealing.

One type of power package uses a cavity machined from a solid block of copper, plated with nickel and gold, with a stainless steel seal ring brazed around the perimeter as shown in Fig. 8.47. The leads are made from copper-cored Alloy 52 material with a ceramic insulator. The insulator is generally metallized on the outside with an alloy of MbMn successively plated with Ni and Au. The pins are individually soldered to the package body with 80Au/20Sn solder. This package is compatible with conventional seam welding and offers the best thermal conductivity of the various configurations when oxygen-free high-conductivity (OFHC) copper is used. The copper must be processed such that the cold-worked mechanical properties are not destroyed to enable the package to withstand the constant acceleration test. This limits the temperature range that the package can see during processing and use.

An alternative method of attaching the leads to the package is to use a glass with a low melting point, such as potash soda barium glass, which has a dif-

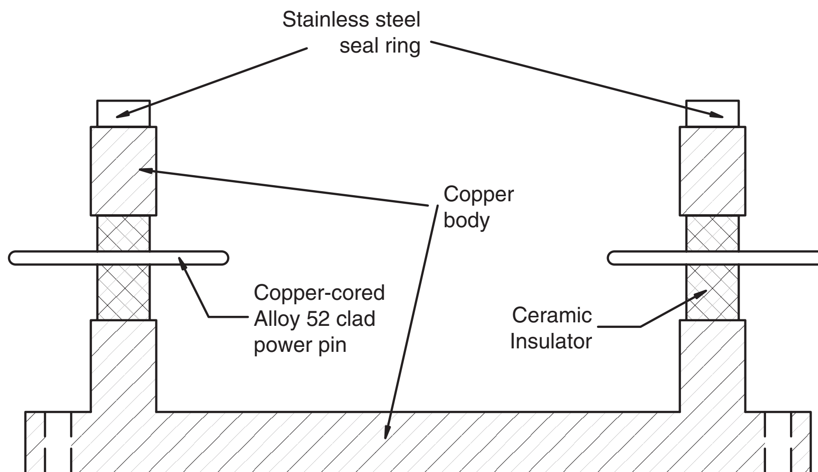


**Figure 8.47** Solid copper package.

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ferent temperature coefficient of expansion (TCE) from that of the package material such that a compression seal is formed.

Another approach uses a copper base that has an ASTM F-15 lead frame brazed to it and is plated with Ni and Au. This package can use conventional glass-to-metal sealing in the manufacturing process and is compatible with parallel seam welding. This package must be less than 1 × 1 in and must use a copper base less than 0.060 in thick because of the large TCE mismatch between copper and ASTM F-15 alloy.

## 8.27 Multichip Modules

Multichip modules are an extension of the hybrid technology. They permit a higher packaging density than can be attained with other approaches, allowing a silicon-to-substrate area ratio of greater than 30 percent. There are three branches of the MCM technology as depicted in Table 8.32:[17] MCM-L, based on a laminated printed circuit board structure; MCM-C, based on cofired ceramic structures; and MCM-D, which utilizes deposited conductors and dielectrics.

**TABLE 8.32 Types of Multichip Modules**

| | |
|---|---|
| MCM–L | Substrates formed by *laminating* layers of printed circuit board material to form multilayer interconnection structures |
| MCM–C | Substrates formed by cofired *ceramic* or glass/ceramic structures, similar to the thick film process |
| MCM–D | Interconnections formed by depositing alternate layers of conductors and dielectrics onto an underlying substrate, similar to the thin film process |

### 8.27.1 The MCM-L technology

The MCM-L technology is based on printed circuit board technology. Multilayer structures are formed by etching patterns in copper foil laminated to both sides of resin-based organic panels ("cores") that are laminated together with one or more layers of the basic resin in between to act as an insulator. Interconnections between layers may be formed by "through" vias, which extend all the way through the board; "blind" vias, which extend from the surface part way through the board; or "buried" vias, which connect only certain of the inner layers and do not extend to the surface in either direction as shown in Fig. 8.48. Through vias may be drilled and plated after laminating, whereas blind and buried vias must be drilled and plated prior to laminating.

A number of materials may be used to fabricate MCM-L structures as shown in Table 8.33.[18] The criteria for selection will vary with the application. Cyanate ester, for example, has a very low dielectric constant and excellent high-frequency characteristics.

Design guidelines for MCM-L substrates are presented in Table 8.34. Printed circuit boards for MCM applications must be suitable for wire bond-

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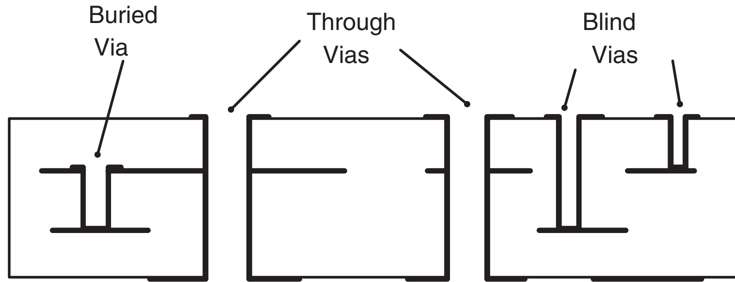


**Figure 8.48** Buried, through, and blind vias.

**TABLE 8.33 Properties of MCM–L Substrate Materials**

| Property | Units | Bismaleimide-triazine/epoxy | Polyimide | Cyanate ester | Sycar |
|---|---|---|---|---|---|
| | | Physical | | | |
| Water absorption | % | 1.3 | 0.35 | 0.8 | 0.02 |
| Specific gravity | | | 1.7 | | 1.6 |
| Chemical resistance (solvents) | | Excellent | Excellent | Excellent | Excellent |
| | | Mechanical | | | |
| Glass transition temperature by DMA ($T_g$) | °C | 175–200 | 220–280 | 180–260 | 180 |
| Coefficient of thermal expansion (z-axis)* | in/in/°C | $7.0 \times 10^{-5}$ 25–2208°C | $3.5 \times 10^{-5}$ 25–220°C | $8.1 \times 10^{-5}$ 25–245°C | $8.5 \times 10^{-5}$ 25–190°C |
| Coefficient of thermal expansion (x-y axis)* | in/in/°C | | $1.4 \times 10^{-5}$ 25–220°C | $1.5 \times 10^{-5}$ 25–245°C | $1.5 \times 10^{-5}$ 25–190°C |
| Dimensional stability (x-y axis) after elevated temperature | in/in | 0.0005 | 0.0005 | 0.0003 | 0.00036 |
| Flexural strength (>0.020 in) | psi | | | | |
| Lengthwise | | | 80,000 | | 50,000 |
| Crosswise | | | 65,000 | | 43,000 |

*CTE can be lowered by selection of alternative fibers such as Keviar or by use of constraining metal cores such as Cu-In-Cu.

ing. This is accomplished by selectively plating nickel and gold on the copper traces as required. The difference in gold thickness is a result of the different bonding mechanism between gold and aluminum wire. Gold wire bonding is accomplished by thermosonic bonding and is fundamentally a gold-to-gold bond, whereas aluminum wire bonding is accomplished by ultrasonic bonding and is an aluminum-nickel bond. Gold plating for aluminum bonding is thin-

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**TABLE 8.34 Design Guidelines for MCM–L Substrates**

| Parameter | Value |
|---|---|
| Minimum metal spacing | 0.003 in |
| Minimum trace width/maximum trace thickness | 0.003/0.0018 in |
| Minimum Pth pad diameter | 0.015 in |
| Surface layer nickel thickness, μ n | 30+ |
| Aluminum/gold wire bonding, μin | 100–200 |
| Surface layer gold thickness, μin | 10+ |
| Aluminum wire bonding, μin | 10–40 |
| Gold wire bonding, μin | 50–100 |
| Minimum blind via diameter | 0.006 in |
| Minimum finished hole diameter | 0.010–0.000 in |
| Minimum buried via diameter | 0.006 in |
| Minimum via pitch (no tracks) | 0.015 in |

ner, because it acts only to keep the nickel from oxidizing and interfering with the bonding process.

### 8.27.2 The MCM-C technology

MCM-C multilayer structures are fabricated from ceramic or ceramic/glass materials, with alumina being the primary base. There are two basic types of MCM-C substrates: high-temperature cofired ceramic (HTCC) and low-temperature cofired ceramic (LTCC). Both processes begin with thin sheets of unfired material, approximately the consistency of putty. The sheets are referred to as *green tape*. Green tape is created by mixing the base powder with an organic vehicle and forming it into sheets by doctor blading or other means. Vias are punched in the green tape where interconnections between layers are to be made and filled with thick film paste designed specifically for via filling. The individual layers are printed with thick film paste to create the metallization patterns, aligned with the other layers, and laminated at elevated temperature and pressure. The laminated structures are then subjected to a lengthy bake-out cycle to remove the organic material and cofired at an elevated temperature to form a monolithic structure.

The HTCC and the LTCC processes differ in two primary ways: the firing temperatures and the thick film materials.[5] HTCC ceramics are designed to be fired at approximately 1600°C, which requires the use of refractory metals such as tungsten and molybdenum/manganese alloys as the conductors, and the firing process must take place in a reducing atmosphere to avoid oxidation of the metals. The top and bottom metallization layers are plated with nickel

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and gold to permit die and wire bonding. LTCC materials primarily consist of glass/ceramics and are designed to be fired at much lower temperatures, in the range of 850 to 1050°C. This permits the use of standard thick film materials, such as silver and gold, which have much lower sheet resistivity than the refractory metals and do not require subsequent processing for assembly. A comparison of the HTCC and LTCC processes is shown in Table 8.35.

**TABLE 8.35 Comparison of HTCC and LTCC MCM–C Substrates**

| Parameter | Units | Cofired ceramic ($Al_2O_3$) | Cofired glass/ceramic |
|---|---|---|---|
| Line width | µm (min.) | 100 | 100 |
| Via diameter | µm (min.) | 125 | 125 |
| Number of metal layers | | 1–75 | 1–75 |
| Conductor resistance | mΩ/❑ | 8–12 | 3–20 |
| Relative permeability | @ 1 MHz | 9–10 | 5–8 |
| Dissipation factor | @ 1 MHz | $5–15 \times 10^{-4}$ | $15–30 \times 10^{-4}$ |
| Insulation resistance | Ω -cm | $> 10^{14}$ | $10^{12}–10^{15}$ |
| Breakdown voltage | V/25 µm | 550 | 800 |
| Resistor values | Ω | N/A | 0.1–1 M |
| Coefficient of thermal expansion | ppm/°C | 6.5 | 3–8 |
| Thermal conductivity | W/m-°C | 15–20 | 2 –6 |
| Camber | mils/in | 1–4 | Conforms to setter |
| Surface roughness | µin | 10–25 | 8–10 |
| Flexural strength | MPa | 275–40 | 150–250 |

As a result of the organic burnout, the substrates shrink during firing. The shrinkage is very predictable, however, and may be accounted for during the design stage. This property is very critical when selecting a via fill material. The shrinkage of the via fill material must match that of the ceramic to prevent open circuits between layers.

Resistors and capacitors that are compatible with the LTCC green tape process may also be fabricated.[19] A distinction is made here between a sandwiched resistor, which is formed between two layers of green tape, and a buried resistor, which is printed on an alumina substrate and covered with layers of green tape. The resistor pastes developed for this process show a high degree of stability after several refirings at high temperatures and exhibit TCRs comparable to those of standard materials (<100 ppm/°C). Although the accuracy of untrimmed resistors is adequate for many digital circuit applications, buried resistors printed and fired on the substrate may be

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laser trimmed prior to lamination with green tape. These show excellent stability under conditions of high-temperature storage, temperature cycling, and harsh environments, because they are covered with hermetic dielectric.

### 8.27.3 The MCM-D technology

The MCM-D technology utilizes processes similar to those used to fabricate thin film hybrid circuits. The conductors are primarily sputtered or plated metals, gold, aluminum, or copper deposited on a variety of substrate materials, including ceramic and silicon. The dielectric materials are primarily used in the liquid state and are applied by spinning. Vias may be opened in the dielectric film by applying photoresist and etching or by using photosensitive dielectric materials. A list of common dielectric materials is shown in Table 8.36.[20]

MCM-D structures can be made much denser than the other types as a result of the photoetching process. Line widths of 10 μ and via diameters of 15 μ are common.

### 8.27.4 Summary

Multichip modules are an important part of the repertoire of the packaging engineer for at least two reasons.

1. By utilizing the increased density available with this technology, more functionality can be incorporated into a smaller volume with all the advantages that this ability encompasses.
2. The variety of materials enables the substrate/interconnection structures to be more nearly tailored to a particular application.

A comparison of the various MCM technologies is given in Table 8.37.

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**TABLE 8.36 Properties of Selected Commercial Polymer Dielectrics**

| Vendor | Material | Photosensitive | Wet etchable? | Dielectric constant | CTE (ppm) | $T_g$ (°C) | Flexural modulus (GPa) | Tensile strength (MPa) | Elongation (%) |
|---|---|---|---|---|---|---|---|---|---|
| Amoco | UD–4212 | | Y | 2.9 | 50 | 300 | | 110 | 15–20 |
| Ciba-Geigy | PROB–400 | Y | | 3.3 | 40 | | 3.5 | 124 | 10 |
| Dow | BCB–3002 | | | 2.7 | 52 | >350 | 3.3 | 80 | 8 |
| | BCB–19010 | Y | | 2.7 | 52 | >350 | | | |
| DuPont | PI–2555 | | | 3.3 | 40 | >320 | 2.4 | 130 | 15 |
| | PI–2611D | | | 2.9(z), 3.9 (x, y) | 20.3* | >400 | 8.9 | 340 | 25 |
| | PI–2722 | Y | | 3.3 | 40 | 310 | – | 130 | 15 |
| | PI–2741 | Y | | 2.9(z) | 10* | 365 | | 330 | 50 |
| | PI–1111 | | Y | 2.8(z) | 19* | 385 | | 300 | 55 |
| Hitachi | PIQ–13 | | | 3.4 | 45–48 | >350 | | 116 | 10 |
| | PI–L100 | | | | 3* | | | 385 | 35 |
| | PL–2315 | Y | | 3.3 | 40 | – | 3.5 | 124 | 10 |
| Nat'l. Starch | EL–5010 | | | 3.2 | 38 | 214 | | 154 | 7 |
| Toray | UR–3800 | Y | | 3.3 | 45 | 280 | 3.4 | 145 | 30 |

*Properties are anisotropic.

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**TABLE 8.37 Comparison of MCM Technologies**

| Parameter | Units | MCM–L | MCM–C | MCM–D |
|---|---|---|---|---|
| Description | | High-density laminated printed circuit board | Cofired low dielectric constant ceramic substrate | Thin film on silicon |
| Maximum wiring density | cm/cm$^2$ | 300 | 800 | 250–750 |
| Minimum line width | µm | 60–100 | 75–100 | 8–25 |
| Line space | µm | 625–2250 | 50–450 | 25–75 |
| Maximum substrate dimension | mm | 700 | 245 | 50–225 |
| Dielectric constant | | 3.7–4.5 | 5–5.9 | 3.5 |
| Pinout grid | mm | Array 2.54 | Array 1.00–2.54 (staggered) | Peripheral 0.63 |
| Maximum number of wiring layers | | 46 | 63 | 8 |
| Via grid | µm | 1250 | 125–450 | 25–75 |
| Via diameter | µm | 150–500 | 50–100 | 8–25 |


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