



Thermal Management Handbook

FOR ELECTRONIC ASSEMBLIES

Jerry E. Sergeant
Al Krum



THERMAL MANAGEMENT HANDBOOK

**for Electronic
Assemblies**

**Jerry Sergent
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CHAPTER 3

THERMAL PROPERTIES OF ELECTRONIC MATERIALS

Thomas C. Evans

3.1 INTRODUCTION

Packaging engineers have more material choices and thermal constraints to consider with each new product they design. Since higher performance drives integrated circuits, active, and passive components to generate more heat, selecting the right materials can be a key element of practicing good thermal management. Along with the thermal evaluation, there are four additional factors that must be considered as part of the final decision on any given material set.

1. Performance, including thermal, must increase.
2. Reliability must be the same, or even increased.
3. Available space for most new products is shrinking.
4. Cost must always be reduced.

Therefore, the design cycle should include a comparison of materials per the preceding criteria *and* a consideration of their overall effect on heat flow through the system.

To start the design of products that have good thermal performance, this chapter serves as a practical guide to material properties. Thermophysical values of thermal conductivity, specific heat, and thermal coefficient of expansion are presented along with density, modulus of elasticity, and tensile strength to provide a quick and easy-to-use reference. Specific data sheets from material suppliers should always be reviewed for comparison.

Many times there is confusion on how to classify a material, with the difference between trade names and generic classifications becoming blurred through misuse or indiscriminate substitution. Figure 3.1 summarizes most of the material types found in electronic products and serves as an overview for the tables of data. [1–3]

3.2 UNITS

Before presenting the actual data, the tabulation of thermal properties should start with an explanation of the most important terms and units. Tables 3.1 and 3.2 help the user interpret some of the typical units and the many different factors associated with them.

These are the standard base units of the SI (Système International d'Unités) system, set up in 1960 at the Eleventh General Conference on Weights and Measures. These units comprise a coherent form of the metric system, since all other units that may be used can be derived from these base units. [2,3]

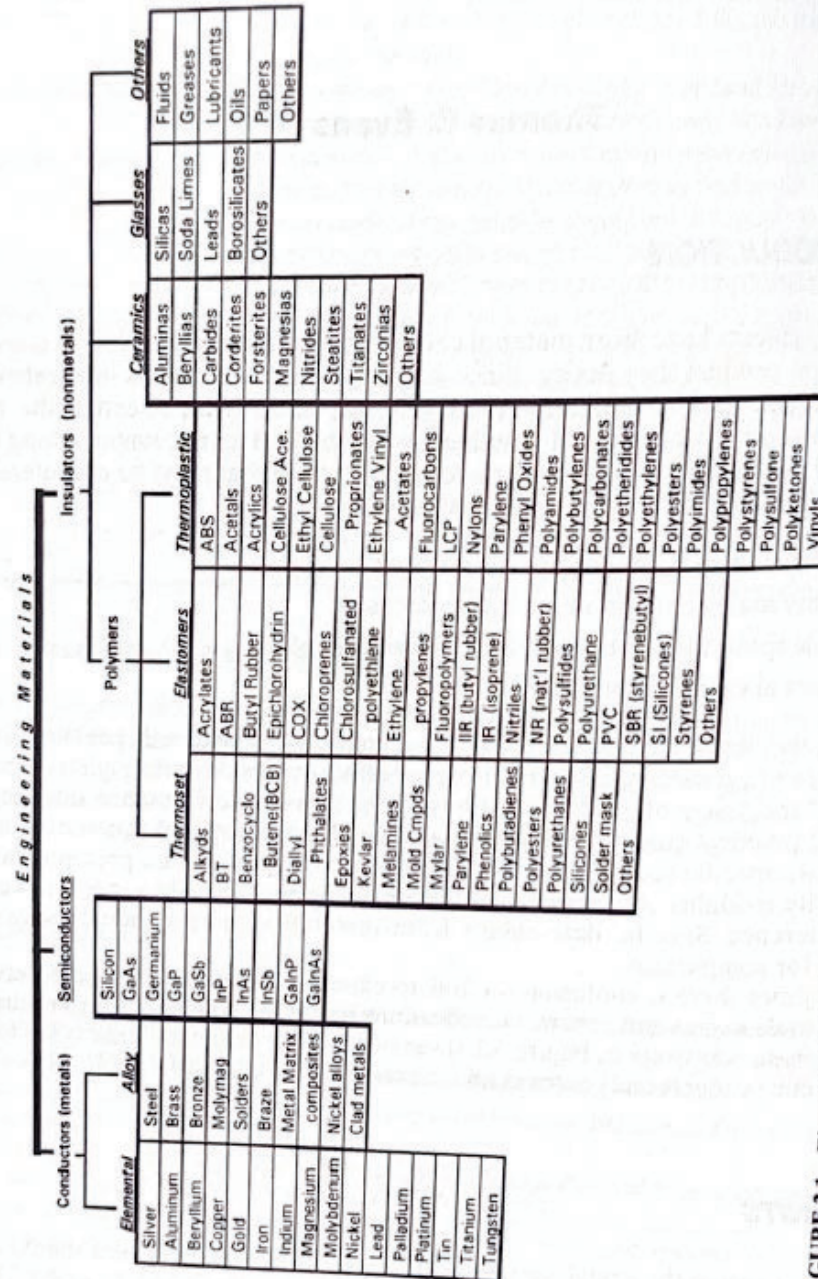


FIGURE 3.1 Electronic packaging materials classification.

TABLE 3.1 Common Units of Measurement

Quantity	Units	Symbol
Length	Meter	m
Mass	Gram	g
Time	Second	s
Temperature	Kelvin	K

TABLE 3.2 Multiplication Factors

Prefix	Symbol	Multiplying factor
Atto	a	10^{-18}
Femto	f	10^{-15}
Pico	p	10^{-12}
Nano	n	10^{-9}
Micro	u	10^{-6}
Milli	m	10^{-3}
Centi	c	10^{-2}
Hecto	h	10^2
Kilo	k	10^3
Mega	M	10^6
Giga	G	10^9
Tera	T	10^{12}

For reference, the application of energy through area, distance, and time determines the units listed in Table 3.3.

TABLE 3.3 Energy, Force, and Power Units

Force in newtons	(N)	=	$\text{m}\cdot\text{kg}/\text{s}^2$
Force over area	(Pa)	= N/m^2	= $\text{kg}/\text{m}\cdot\text{s}^2$
Energy in joules	(J)	= $\text{N}\cdot\text{m}$	= $\text{m}^2\cdot\text{kg}/\text{s}^2$
Power in watts	(W)	= J/s	= $\text{m}^2\cdot\text{kg}/\text{s}^3$

One additional note on standard units of temperature measurement is applicable. The thermodynamic scale of temperature is called the Kelvin scale. Absolute zero is 0 K, defined as the absence of all molecular movement. More familiar is the centigrade scale, which has 0°C equal to $+273.15\text{ K}$. Temperature differences are equivalent in either scale.

3.3 THERMAL AND PHYSICAL VALUES

Heat exists as energy in a solid material, with four methods of transfer or conduction. For insulators, phonon generation from the random vibration of atoms in a lattice structure is the largest contributor, but conductors transfer most of their thermal

energy from the translational motion of free electrons. Magnetic excitations and, in some cases, electromagnetic radiation can also contribute to heat transfer in solids. [6,7] From the different transfer methods and chemical structure, each material has a unique set of thermal and physical properties. The following are brief descriptions of thermophysical values used to describe common electronic materials.

3.3.1 Thermal Conductivity

Thermal conductivity is defined by the time rate of thermal energy (heat) transfer as it conducts between opposite faces of a cubic volume of material, and the temperature varies by 1 kelvin. Thermal conductivity indicates the efficiency of a material when heat flows from cooler to warmer regions and is defined as

$$q = -k \frac{dT}{dx} \quad (3.1)$$

where q = heat flux in W/m^2

k = thermal conductivity in W/(m-K)

dT/dx = temperature gradient, K/m in steady state

The negative sign denotes that heat flows from areas of higher temperature to areas of lower temperature, with lower thermal conductivity values indicating poor thermal performance. [6] It should be noted that thermal resistance is the inverse of thermal conductivity, and lower values of thermal resistance indicate a better thermal path.

Experimental study of the thermal conductivity of solids was started by Benjamin Franklin in the mid-eighteenth century. In 1753, he pointed out the different abilities of different materials "to receive and convey away the heat." Exactly 100 years later, Weidemann and Franz used a steady-state test method originally suggested by Franklin to determine the relative thermal conductivity of several metals [7]

Today, measurement of thermal conductivity can be accomplished by direct or indirect methods. ASTM has a direct method C408-88 which uses a copper rod in vacuum, placing the sample in the middle and measuring temperatures along the length as heat is pumped down the rod. E1461-92 is the indirect method using a thermal pulse or flash of heat. [6] By combining the thermal diffusivity values with the density and specific heat capacity, the thermal conductivity can be calculated as

$$\lambda = \alpha C_p \rho \quad (3.2)$$

where λ = thermal conductivity in W/(m-K)

α = thermal diffusivity in m^2/s

C_p = specific heat capacity in $(\text{W-s})/(\text{g-K})$

ρ = density g/m^3

3.3.2 Thermal Capacity and Specific Heat

Materials can absorb energy in the form of heat and release it. *Thermal capacity* is defined as the amount of thermal energy required to raise the temperature of one mole of material by 1 kelvin. One mole of material is equal to 6.023×10^{23} atoms or molecules.

$$C = \frac{dQ}{dt} \quad (3.3)$$

where C = heat capacity in W-s/mol-K
 Q = energy in W-s
 T = temperature in K

A more common expression is the *specific heat*, which is the thermal capacity divided by the mass and has units of W-s/g-K. Specific heat can be measured at constant volume or at constant pressure, but for the temperatures and solid materials of interest, these values are practically equivalent.

For metals, semiconductors, and ceramics, specific heat values over temperature change gradually, but the heat capacities of plastic polymers exhibit an incremental increase at the glass transition temperature T_g . The T_g of plastic polymers represents a threshold below which the plastic is hard and rigid, and above this temperature, the plastic becomes flexible and rubbery.

Differential calorimetry in accordance with ASTM standard test methods E1296-90 and E968-63 determines the specific heat by comparing thermal energy content of an empty sample container, a sapphire crystal (standard), and the actual sample. [6]

3.3.3 Thermal Coefficient of Expansion (TCE)

TCE is a result of asymmetrical changes in the interatomic spacing of atoms due to increased energy content in the form of heat. Most metals and ceramics exhibit a linear, isotropic relationship in the temperature range of interest, while plastics are generally anisotropic in nature due to behaviors above and below T_g . TCE values for plastic polymers are usually several times larger above the T_g than below it. The temperature coefficient of expansion is defined as

$$\alpha = \frac{L(T_2) - L(T_1)}{L(T_1)(T_2 - T_1)} \quad (3.4)$$

where α = temperature coefficient of expansion, $1/^\circ\text{C}$

T_1 = initial temperature

T_2 = final temperature

$L(T_1)$ = length at initial temperature

$L(T_2)$ = length at final temperature

The term α is often multiplied by 10^6 with corresponding units of parts per million length change per kelvin, ppm/K.

Direct measurement at room temperature and elevated temperature (per ASTM standard test method C372-88) has the sample accurately measured on a thermally conductive plate at room temperature, then measured again at a higher temperature after thermal equilibrium has been reached. [6]

From a historical perspective, material expansion and contractions have been observed and even feared for quite some time. "From ghoulies and ghosties, and long leggety beasties and things that go bump in the night, Good Lord deliver us" is an old Scottish prayer. One can imagine hearing strange noises in the middle of the night, as cool night air in Scotland caused homes and furnishings to contract.

The first serious attempt to measure dimensional change over temperature was performed in 1730, to obtain more accurate clocks. As a professor of astronomy, Petrus

van Musschenbroek of Utrecht determined that pendulums made of iron gave the best results. Clocks using brass, copper, or lead pendulums had inaccurate timekeeping over the course of even a single day. Investigating further, he found changes in the length of the pendulum from daily temperature variations. [7]

3.3.4 Modulus of Elasticity (E)

The modulus of elasticity is the measure of rigidity or stiffness of a material, which can be described as the plastic deformation under load. In more technical terms, E is the ratio of stress below the proportional limit, compared to the corresponding strain, and can be represented by the slope of the initial stress-strain curve. If a tensile stress of 13.8 MPa results in an elongation of 1.0 percent, the modulus of elasticity is 13.8 divided by 0.01, or 1380 MPa. [5,8] E can be represented by

$$\sigma = Ee \quad (3.5)$$

where σ = stress in psi or N/m²

E = modulus of elasticity in psi or N/m²

e = strain, in m/m, the net elongation (contraction/unit length)

The units are generally listed as GPa.

3.3.5 Tensile Strength

Tensile strength is the amount of stress applied to stretch a material to its breaking point. In tensile testing, the ratio of maximum load to original cross-sectional area is also called the *ultimate strength*. [5,8] Units are listed as MPa. Both the tensile strength and E depend upon the purity and processing of seemingly equivalent materials.

It is beyond the scope of this book to detail all the important factors having an effect on thermal and physical properties. For instance, two metal samples can have identical constituents but different tempers which affect mechanical strength. Temper is determined by the annealing (heat and cooling rates) of the original material. Looking at polymers, samples may have equivalent molecular weights, but slightly different types or amounts of crosslinking. Crosslinking generally has a large effect on values of mechanical strength and T_g .

3.4 CONVERSION FACTORS

Comparisons between numbers are often complicated by the fact that values have different units to describe them. Conversion factors for various English and mgs (meter/gram/second) units are listed in Table 3.4. [5,9]

3.5 MATERIAL THERMAL AND PHYSICAL VALUES

Many times references differ in the actual values of the physical constants. It might be hoped that test standards and handbooks would better address this issue, but for whatever reason, that does not seem to be the case. Material purity can be another

TABLE 3.4 Units and Conversion Factors

Length, area, and volume	Work, energy, and power
1 inch = 25.4 mm = 0.0254 m	1 inch-lb (force) = 0.113 J = 0.113 Nm
12 inches = 1 foot	1 ft-lb = 1.365 J
1 foot = 305 mm = 0.305 m	1 BTU = 778 ft-lb = 252 calories = 1,055 J
1 inch ² = 645 mm ² = 0.6452 × 10 ⁻³ m ²	1 BTU/hr = 0.293 W
1 foot ² = 92,900 mm ² = 0.0929 m ²	1 calorie (cal) = 4.186 J
1 inch ³ = 16,400 mm ³ = 16.4 × 10 ⁻⁶ m ³	1 erg = 10 ⁻⁷ J
1 foot ³ = 0.0283 m ³	1 ft-lb/s = 1.356 W
	1 ft-lb/min = 0.0226 W
	1 W-s = 1 J
Mass and density	Thermal conductivity
1 lb (mass) = 0.45359 kg	1 BTU/hr-ft-°F = 1.7303 W/m-K
1 lb/in ³ = 2,768 kg/m ³	1 BTU/hr-in-°F = 0.1442 W/m-K
1 lb/ft ³ = 16.0185 kg/m ³	1 W/in-K = 39.3 W/m-K
Force and stress	1 cal/s-cm-K = 418.4 W/m-K
1 lb (force) = 4.448 N	Specific heat
1 lb*in ² (psi) = 6,894.76 N/m ²	1 cal/g-°C = 4.17 W-s/g-°C
1 lb*ft ² (psf) = 47.9 N/m ²	1 BTU/lb-°F = 4.1867 W-s/g-°C)
1 MPa = 10 ⁶ N/m ² = 1 N/mm ²	
1 dyne = 10 ⁻⁵ N	
1 dyne = 2.248 × 10 ⁻⁶ lb	

reason for differences between sources, and it is not always presented with the thermal data. Values reported in this chapter are for 300 K and should be expected to vary between 5 and 10 percent from the true value. [10-12] The properties of metals, ceramics and glasses, polymers, and semiconductors are presented in Tables 3.5, 3.6, 3.7, and 3.8, respectively.

3.6 LAMINATE SUBSTRATES AND PRINTED CIRCUIT BOARDS (PCBS)

It can be fairly difficult to determine the thermal conductivity for a specific design of an organic laminate. Several factors contribute to differences between even fairly similar layouts and must be accounted for when performing a thermal analysis. Some of the same factors can also affect ceramic substrates, but not as much as an organic-based one.

For typical substrates or PCBs, the area covered by copper traces or planes, the thickness of the copper, and the number of vias greatly influence thermal performance. If one area of a board has more copper traces, or more vias, the local thermal conductivity may be much greater. Therefore, in critical applications, the thermal analysis should not treat the substrate/PCB as a bulk material. [13,14] Important material and geometric factors affecting thermal conductivity of a given laminate substrate or PCB follow:

1. Number of metallization layers
2. Area coverage of metallization versus substrate/board size
3. Thickness of metallization

TABLE 3.5 Properties of Metals and Alloys

Metal		Thermal conductivity, W/mK	Specific heat, Ws/gK	Thermal coefficient of expansion, ppm/K	Density, g/cc	Modulus of elasticity, GPa	Tensile strength, MPa
Lead frames							
Clad metal							
Substrates							
Metallization							
Packages							
Joining							
Ag (silver) 99.99%		427	0.23	19.2	10.5	72	125
Ag filled epoxy (varies with filler and metal)		2-2.5		45 (<88 C) 20 (>88 C)		3.5	
Ag/Pd thick film		150		14			
Alloy 42		14.6	0.477	4.5	8.12	148	569
Al (aluminum) 99.99+		237	0.91	23	2.702	69	50-110
Al 1100H18		218					
Al 6063 T6		201					
Al 6061 T0		173				70	
Al 6061 T6		156		23.4	2.71		
Al 5052		139		23.6	2.72		
Al 2024 and 7075		121-130					
Au (gold) 99.99+%		318	0.13	14.3	18.9	80	130
88% Au/12% Ge (hard solder)		88		11	15		233
80% Au/20% Sn (hard solder)		57	0.015	13.9	15	59	198
97% Au/3% Si (hard solder)		94	0.147	12	15.7	83	253
Au/Pt thick film		130		10			
Ba (barium)		18.4					
Be (beryllium)		200	1.88	11.6	1.85	119	
Bi (bismuth)		5.3					
B (boron)		27					
Brass, red (85 Cu/15 Zn)		151	0.38		8.8		
Brass, yellow (65/35)		119	0.38		8.3		

TABLE 3.5 Properties of Metals and Alloys (Continued)

Metal		Thermal conductivity, W/mK	Specific heat, Ws/gK	Thermal coefficient of expansion, ppm/K	Density, g/cc	Modulus of elasticity, GPa	Tensile strength, MPa
Lead frames							
Clad metal							
Substrates							
Metallization							
Packages							
Joining							
Ni (nickel) 99.8%		91	0.44	13	8.9	214	345-760
Pb (lead)		35	0.129	29	11.3	14	
95% Pb/5% Sn (soft solder)		32.3	0.134	28	11	7.4	55
92.5% Pb/2.5% Ag/5% In (soft solder)		39		25	12		
90% Pb/10% Sn (soft solder)		36		28		19	30
88% Pb/10% Sn/2% Ag (soft solder)		37		29			
Pd (palladium)		71	0.24	11.7	12	57.4	
Pt (platinum) 99.99+%		72	0.13	8.9	21.4	147	125
Sb (antimony)		24					
Sn (tin)		65	0.23	21	7.32	41	
60% Sn/40% Pb (soft solder)		50	0.18	24.2	9.29	18-25	43
63% Sn/37% Pb (soft solder)		51	0.18	24.1	9.25		45
Stainless steel							
SS AISI-347		13.8	0.423			190-200	500-800
Carbon steel AISI-1010		64	0.434	11.3	7.861	192	750
Ta (tantalum)		58					
Ti (titanium)		22	0.52	8.6	4.4	110	
W (tungsten)		201	0.13	4.5	19.4	344	1825-4050
80% W/20% Cu		248	0.184	7	15.7	330	5.5
90% W/10% Cu		170	0.16-0.21	6.5	17	330	4.9
Zn (zinc)		116					

TABLE 3.6 Properties of Ceramics, Glasses, and Metal Matrix Composites

Ceramic, glass, and metal matrix composites (MMC)	Thermal conductivity, W/mK	Specific heat, Ws/gK	Thermal coefficient of expansion, ppm/K	Density, g/cc	Modulus of elasticity, GPa	Tensile strength, MPa
AlN	140-220	0.74	4.4	3.26	300	310
Alumina 96%	21	0.88	6.5	3.8	344	172
Alumina 99.5%	37	0.88	6.8	3.9	370	500
Barium Titanate	1.25		8.1	5.5		
BeO 99.5% (very temperature dependent)	250	1.04	7.5	2.9	345	138
BN (hex)	60 12-100 (hot press) 1300 (single crystal)		0.4-3.8	1.9-2.2	43	
Borosilicate glass	1.02		3.2	2.1	63	
Cofired multilayer ceramic	15		6-6.5			380
Cordierite ($2\text{MgO} \cdot 2\text{Al}_2\text{O}_3 \cdot 5\text{SiO}_2$)	2.5		2.5	2.7		300
Diamond; type IIA	2000					
Diamond; type IIB	1300					
Diamond film	100-1200	2		3.5	1000	
Ferrite	6.2					
Forsterite ($2\text{MgO} \cdot \text{SiO}_2$)	3.3		9.8	2.9	96	55
Glass, pyrex	1.02	0.837		2.23		
LTCC	3		5-7	2.9		152
Magnesium titanate	41.8		7.5	3.6		
Mullite ($3\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$)	5		4	3.1	175	186
SiC aluminum MMC (70% SiC loading)	170		6.3	3	250	300
Graphite aluminum MMC	4.08		5.8	2.5	145	
Boron aluminum MMC (20% loading)	4.65 (x,y) 0.43 (z)		12.7	2.6	186	

TABLE 3.6 Properties of Ceramics, Glasses, and Metal Matrix Composites (Continued)

Ceramic, glass, and metal matrix composites (MMC)	Thermal conductivity, W/mK	Specific heat, W/gK	Thermal coefficient of expansion, ppm/K	Density, g/cc	Modulus of elasticity, GPa	Tensile strength, MPa
Quartz	2		1	2.6		
Quartz fiber	1.1	0.23	0.54	2.2	7.4	200
SiC	270	0.675	3.7	3.2	407	28
SiO ₂ (vitreous)	0.5-2		0.5	2.2	73	
SiN	27	0.691	2.3			
Alpha Si3N4	80 (single crystal) 10-33 (hot press)		3	3.2	310	
Spinel (MgO·Al ₂ O ₃)	15		7.6			
Stearite (MgO·SiO ₂)	2.5		8.2	2.7	96	55
Titania (TiO ₂)	5		8.3	4		

TABLE 3.7 Properties of Polymer Materials

Polymers		Thermal conductivity, W/mK	Specific heat, Ws/gK	Thermal coefficient of expansion, ppm/K	Density, g/cc	Modulus of elasticity, GPa	Tensile strength, MPa
Plastics							
Laminates							
Glass Weave							
Coating and Films							
ABS (acrylonitrile-butadiene-styrene)		0.17-0.38	1.26	32-60	1.01-1.07	2.1	21-48
Acetals		0.3	1.5	42-53	1.42		61-68
Acrylics		0.06	1.5	30-60	1.19		34-75
Alkyds		0.7-1.0	1.3	20-50	2		20-65
BCB (benzocyclobutene)				45-70		2.3	82
BT (bismaleimide-triazine) laminate		0.17-0.21		13-15 (x,y) 40-50 (z)	1.3		80-84
Chlorotrifluoroethylene		0.17-0.25		36			41
CR (chloroprene-neoprene)		0.19		34		0.002	25-38
CSM (chlorosulfonated polyethylene)		0.11		27			4-24
DAP (diallyl phthalates)		0.36		27			68
EPDM and EPM (ethylene propylene polymers)		0.25		83-105			4-24
Epoxies		0.17-1.0	1.7	10-35			27-186
Epoxy fiberglass laminate (FR-4 types)		0.8 (x,y) 0.3 (z)	1.0-1.3	16-20 (x,y) 50-70 (z)	1.8-2.0	17.4	250
Fluoroelastomers		0.1-2.2			1.4-2.2		13
G10 epoxy fiberglass laminate		0.294				15.2	241
E-glass fiber		0.89	0.82	5	2.54	7.4	350
S-glass fiber		0.9		2.8	2.49	8.6	475

TABLE 3.7 Properties of Polymer Materials (Continued)

Polymers						
	Thermal conductivity, W/mK	Specific heat, Ws/gK	Thermal coefficient of expansion, ppm/K	Density, g/cc	Modulus of elasticity, GPa	Tensile strength, MPa
Plastics	0.5	0.26	-5 (along axis) 60 (radial)	1.4	13	400
Laminates						
Glass Weave						
Coating and Films						
Aramid fiber						
IIR (butyl rubber)	0.1			0.92		13
IR (isoprene)	0.11			0.92-1.04		17-32
Kapton	0.156	1.086				172
LCP (liquid crystal polymer)			20-43	1.4-1.9		140-300
Mylar	0.19					
Plastic package mold compounds	0.07-0.10	0.7-0.9	17 (<140° C) 68 (>140° C)	1.9	0.017	20-100
NBR (nitriles elast.)	0.24		39			8-24
NR (natural rubber, polyisoprene)	0.14		37		0.001-0.008	16-28
Nylon	0.25	1.7	11-80	1.1	2.76	0.6-2.8
Parylene (vapor deposited)	0.13		35			68
Phenolics	0.1-1.0	1.2-2.0	8-22			21-117
Phenyl oxides	0.19-2.0		10-45			41-124
Polyamides	0.069-0.15	0.067-0.14	12-84			34-179
Polyamide-imides	0.26		30			152-221
Polybutadienes			37			13-16
Polybutylenes	0.18-0.29		60-95			
Polycarbonate	0.19	1.3	67-70	1.2		62-138
Polyesters; thermoplastic	0.19-0.38	0.8-1.9	10-50			55-172
Polyesters; thermoset	0.21-0.87	0.8-1.9	10-60			0.6-60

Polyetherimides		11-31	96-200
Polyethylene			
low density	0.21		
medium density	0.35	2.3	14
high density	0.4	2.3	20
	0.5	2.3	28
Polyimides	0.11	1.3	27-158
Polyimide/glass laminate	0.2		
		15-35 (x,y)	3-7
		40-50 (z)	
Polyimide/quartz laminate	0.30-0.35	11-14 (x,y)	21
		60-80 (z)	
Polyketones	0.4	18-47	24-225
Polyphenylene oxide	0.16	38-70	4.6-5.3
Polypropylene	0.12-0.17	38-90	23-97
Polyphthalamide	0.07-0.11	80-330	10
Polystyrene	0.13	50-80	48
Polysulfides	0.08-0.29	27-49	3.4-12
Polysulfones	0.26	56	11-210
PTFE (polytetrafluoroethylene)	0.26	20-120	17-34
Polyurethanes	0.31	100-200	1.2-60
PVC (polyvinylchloride)	0.13-0.21	70-250	41-82
SI (silicone coolymers)	0.25	450	2-10
Solder mask		(60-90 coating)	0.062
Styrenes	0.21	70	
Teflon (polytetrafluoroethylene)	0.13	20-120	
Thermal grease (depends on filler)	0.25		1.5-3.8
	0.1-1.5		

3.15

TABLE 3.8 Properties of Semiconductor Materials

Semiconductors	Thermal conductivity, W/mK	Specific heat, Ws/gK	Thermal coefficient of expansion, ppm/K	Density, g/cc	Modulus of elasticity, GPa	Tensile strength, MPa
Silicon (Si) 99.5%–99.95%	150	0.712	2.8	2.33	129	81–128
Gallium arsenide (GaAs)	45	0.32	5.87	5.316	85	
Ge	77		5.7	5.33		
GaP	133		5.3	4.13		
GaSb	33		6.9	5.6		
InP	97		4.4	4.79		
InAs	35		5.3	5.7		
InSb	19		5	5.8		

4. Number and size of vias
5. Filled versus unfilled vias
6. Individual substrate/PCB layer thickness

A method of calculating the thermal conductivity that accommodates some of the preceding factors is developed in Eq. (3.6): [15]

$$k_{\text{SUBS}} = \frac{0.25t_B + 13.65Ct_t}{t_B} \quad (3.6)$$

where k_{SUBS} = thermal conductivity of the PCB or ceramic in W/m-K
 t_B = substrate thickness in mm
 C = decimal percent conductor coverage
 t_t = trace thickness in oz of Cu

Example The PCB is 1.57 mm thick and contains two 0.5-ounce copper signal layers of approximately 50 percent coverage, and one 1.0-ounce copper ground plane of approximately 75 percent coverage.

$$C = (2 \times 0.5 + 0.75)/3 = 0.583$$

$$t_t = 2 \times 0.5 + 1 = 2$$

$$k_{\text{SUBS}} = \frac{(0.25 \times 1.57) + (13.65 \times 0.583) \times 2}{1.57} = 10.4 \text{ W/m-K}$$

3.7 TEMPERATURE VARIATION

Almost all physical constants vary with temperature, and the thermal values of electronic materials are no exception. Generally, conductivity varies by 10 percent for