Printed circuit boards-Alternative board materials

Resin types

The phenolic-paper and epoxy-glass laminates which come under the generic NEMA descriptions of FR-2 and FR-4, materials have been described in some detail under Basic board materials, although it must be emphasised that these terms are used of two groups of laminate materials which vary greatly between suppliers. However, any base laminate consists of resin plus reinforcement, and its properties are determined both by the materials and their 'lay-up'.

The choice of resin binder affects chemical and environmental performance as well as electrical and mechanical properties.

More is said about lay-up, particularly as it relates to FR-4 materials, in Geoff Layhe's booklet Multilayer bonding – what's it all about.

The first two resins summarised in this section are by far the most widely used, but other materials and mixtures of materials are continually being introduced for specialist applications. Also, although it is usual to employ a single resin system in any construction for ease of process control, different types of resin can be combined within a single multilayer board.

Phenolic

Phenolic resins are thermoset materials produced by a condensation reaction between phenol and formaldehyde: the polymer grows by combining two large molecules and releasing a third small molecule, usually water. Depending on the product formulation, a curing agent may be used.

In alcohol or aqueous solution, phenolic resins will penetrate and saturate paper and similar materials, cross-linking throughout the reinforcement after thermal exposure to provide the desired mechanical strength, electrical and thermal properties, and chemical resistance.

Plasticised phenolic resin, with flame-retardant additive, is usually the lowest cost option, but has limited performance and temperature range.

Epoxy and modified epoxy

Epoxy resins are the most commonly used materials, because of their good mechanical and electrical properties. From the board manufacturer's perspective, epoxy resins are generally relatively inexpensive, and they:

dissolve readily in safe and inexpensive solvents, so are easy to use for impregnating

adhere well to both copper foil and electroless copper

bond well to glass fibre finished with epoxy-silane

drill easily (bits are deflected by the glass fibres, rather than the resin)

can be formulated to be flame-retardant.

Note that the term ‘epoxy’, which describes the type of chemical bond, covers a range of materials with widely differing characteristics and costs. The simplest epoxies are ‘difunctional’ blends, manufactured by reacting epichlorohydrin and bisphenol A with flame-retardant additive: such resins are adequate for most double-sided boards.

For more demanding applications, electrical, chemical and moisture resistance properties can be improved by adding more cross-linking to the system, by incorporating ‘tetrafunctional’ or ‘multifunctional’ epoxies. However, this may make the material more brittle and less flame retardant.

These multifunctional materials/blends were developed to fill the niche between lower-cost regular epoxies and high-performance resins, and give an extended operational temperature range at lower cost than polyimide.

BT resins

BT resins are heat-resistant thermosets, made of bismaleimide triazine resin, co-reacted with epoxy, to give a resin system with some flexibility. The proportions in the blend are varied to produce different properties: a resin with 10% bismaleimide by weight is used for general purpose circuit boards, as it has a similar curing temperature to epoxy resins.

The enhanced heat resistance of BT resins comes from their ring structure rather than increasing the density of cross links. This means that they have relatively good bond strength and are less brittle than epoxies. BT resins also have a low proportion of polar groups, giving lower dielectric constant than FR-4, low loss, low dissipation factor, and excellent insulation resistance after moisture absorption: in humid conditions, their service life is several times that of conventional glass epoxy boards.

Polyimide

Where FR-4 has too low an operating temperature, there are other materials with similar constructions, reinforced with multiple plies of woven glass cloth, but using different impregnation resins. Polyimide resins have long been used[1] for severe applications, because they have high operating temperature ratings (250–260°C), good thermal conductivity (twice that of FR-4), and low CTE at up to soldering temperatures. They are favoured by military users as they will withstand the thermal stress of multiple repair cycles.

[1] Under the trade name Kapton®, polyimide was first commercialised by DuPont in 1965, initially in film form as insulation for motors and wires and as high-temperature pressure-sensitive tape.

The main disadvantage is their high cost, but polyimides also tend to absorb water, causing changes in electrical properties. For the fabricator, polyimides are difficult to work with, especially in multi-layer processing. Whilst their high glass transition temperature virtually eliminates drill smear caused by heat during the drilling process, polyimide materials have a lower inter-laminar bond strength than epoxy systems, so care has to be taken when drilling and routing.

Cyanate ester

Cyanate ester resin systems have good electrical properties and thermal performance, and are designed to have a lower dielectric constant than both epoxy and polyimide. Although costly, they are a cheaper alternative to polyimide for operation at up to about 220°C. Based on triazine, cyanate ester systems usually contain a small amount of epoxy to aid cross-linking. They are reported as tending to be tougher, offer better adhesion, and be easier to process than some of the alternatives. However, moisture absorption is a serious problem both in board fabrication and during population and soldering, causing delamination in all operations above 100°C. “Most fabricators do not relish manufacturing boards with this material”.

PTFE

Fluoropolymers, such as DuPont’s Teflon®, offer the lowest dielectric constant (2.0) of all normally available resin systems, and form the main component in many special microwave composites. Unfortunately, the resin itself is quite soft, has a high CTE, and requires special preparation in order to get acceptable levels of adhesion. This last is not surprising, since PTFE is used to make non-stick coatings!

Thermoplastics

All the resins listed so far have been thermosets, but some thermoplastics are also used in printed circuit assemblies:

Polyethylene terephthalate (PET), commonly referred to as ‘polyester’, is used in low-cost, high-volume applications such as membrane touch switches and automotive behind-the-dash cluster circuits, mainly where leads are attached mechanically, rather than by soldering, and the board is not subjected to high temperatures. FR-6 is an example of a polyester laminate.

Poly Ether Sulphone (PES) is an example of a material which is sufficiently stable at high temperature for use in soldered electronic assembly, either as a conventional board or as a three dimensional moulding.

Resin choices

The choice of polymer used to form the dielectric and prepreg layers has a major influence on the electrical, thermal, mechanical and environmental performance of the board. It is however only one of the influences, since the data from which Table 1 was complied related inevitably to completed laminates, rather than the resins themselves. When you research values for laminate parameters, bear in mind that often those quoted will be for copolymers, such as BT epoxy, rather than straight resins, and the inclusion of additives may have substantial effects on the dielectric properties.

Table 1: Properties of various resins in laminate form

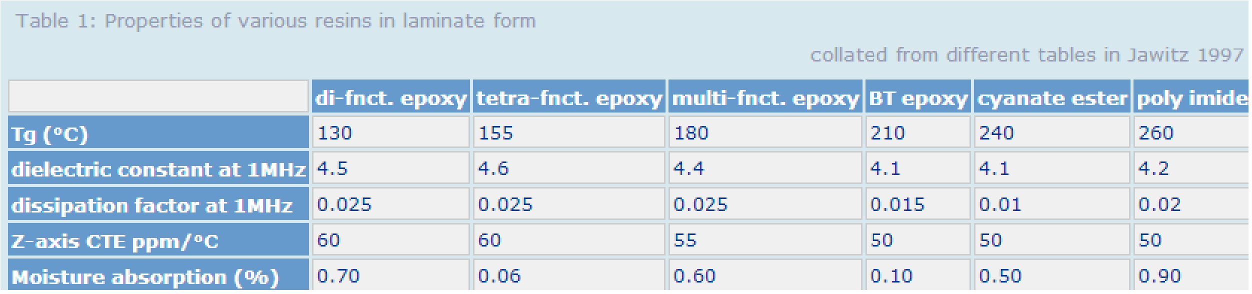


Table 1: Properties of various resins in laminate form

collated from different tables in Jawitz 1997

	di-fnct. epoxy	tetra-fnct. epoxy	multi-fnct. epoxy	BT epoxy	cyanate ester	poly imide
Tg (°C)	130	155	180	210	240	260
dielectric constant at 1MHz	4.5	4.6	4.4	4.1	4.1	4.2
dissipation factor at 1MHz	0.025	0.025	0.025	0.015	0.01	0.02
Z-axis CTE ppm/°C	60	60	55	50	50	50
Moisture absorption (%)	0.70	0.06	0.60	0.10	0.50	0.90

Even more important for many users is the effect that differences in raw material costs and processing issues have on the final price of the board! The price and performance properties of the most common resin materials used are compared in

Table 2, which was compiled from BS6221: Part 22: for all but the phenolic-paper laminate, woven glass fibre is used for the reinforcement.

Table 2: Relative cost and performance of common PCB laminate materials

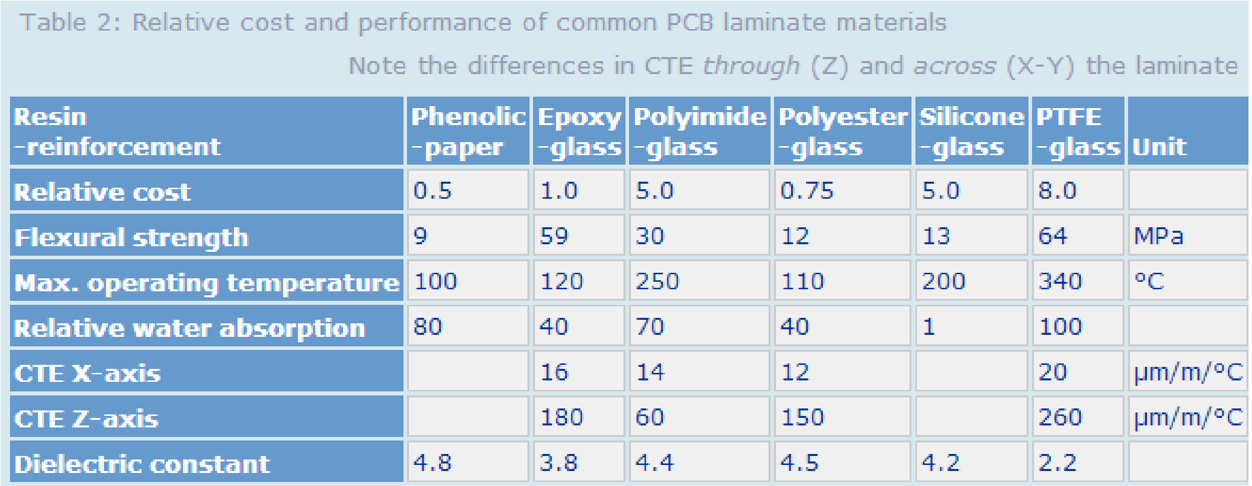


Table 2: Relative cost and performance of common PCB laminate materials

Note the differences in CTE *through* (Z) and *across* (X-Y) the laminate

Resin -reinforcement	**Phenolic -paper**	**Epoxy -glass**	**Polyimide -glass**	**Polyester -glass**	**Silicone -glass**	**PTFE -glass**	**Unit**
Relative cost	0.5	1.0	5.0	0.75	5.0	8.0	
Flexural strength	9	59	30	12	13	64	MPa
Max. operating temperature	100	120	250	110	200	340	°C
Relative water absorption	80	40	70	40	1	100	
CTE X-axis		16	14	12		20	µm/m/°C
CTE Z-axis		180	60	150		260	µm/m/°C
Dielectric constant	4.8	3.8	4.4	4.5	4.2	2.2	

Caution: Remember that the cost guidelines in Table 2 are just that; rough guides to relative pricing. They should not be relied upon for accurate estimates, as prices are volume-related and also very sensitive to many aspects of design.

Reinforcement materials

Reinforcement materials are the 'backbone' of a laminate structure. They provide the strength and dimensional stability required to make the laminate a viable interconnection structure. They also contribute to the electrical properties of the laminate and can influence manufacturability if not selected with care.

Whilst some of the low-cost laminates use multiple plies of paper, glass fabric continues to be the most widely used reinforcement in rigid laminates as it has:

good electrical properties

good dimensional stability

good chemical resistance

low water absorption

high tensile strength

good heat resistance

The glass is formed from a melt into filaments of 3.5 µm–20 µm diameter which are then spun into strands of 50 to 800 filaments. Whilst some board types use a mat of chopped fibres, for most boards the strands are twisted and woven into a fabric. An organic surface 'finish' is applied to the glass as a 'coupling agent' to aid the bond to the impregnation resin.

The laminate is built up in layers, combining glass cloths of different weights and weaves, and using different proportions of resin, in order to give the required thickness and surface finish and to optimise performance and cost. This aspect of board manufacture is extremely complex.

Fibre-glass cloth made with 'E-glass' is most common. This glass has a very low content of soluble ionic components, and is available in a variety of weave styles and thicknesses. Depending on the application, 'S-glass' may be preferred for its lower dielectric constant (4.5–5.2, as against 5.8–6.3 for E-glass). Quartz cloth is very expensive and extremely difficult to drill, so its use is confined to high-performance applications, for tight dimensional tolerances and low CTE.

Non-woven materials

So far we have being looking mostly at materials that are based either on paper or on woven glass with conventional weaves, with warp and weft threads of similar construction. In the latter, the woven structure tends to give a non-flat surface finish. The usual method of achieving a smooth surface is to use outer layers of fine glass fabric, although this adds to the cost and complexity of laminate manufacture. One alternative is to use 'resin-rich' prepregs, so that the surface becomes levelled by resin flow; you may also encounter special weaves, with comparatively many more strands in one direction than the other, that are intrinsically flatter.

However, any woven laminate inevitably has some repeating structure with elements of different dielectric constant. This produces slight variations of dielectric constant throughout the volume of the laminate, which can adversely affect electrical performance at high frequencies.

An alternative to a woven cloth, which improves homogeneity, is a matte reinforcement, with a more random orientation. The most common type is 'chopped-strand' matte, made from fibres chopped into 25–150 mm lengths and distributed evenly. 'Continuous strand' matte consists of continuous strands of fibre in a random spiral orientation.

This 'non-woven' structure is used for aramid fibre reinforcement, which produces an epoxy laminate that is lighter, and has a lower CTE and dielectric constant, than one made with woven glass. Aramid boards2 such as DuPont's Thermount® are also easier to process by laser ablation, a technique used for the very smallest holes as an alternative to conventional drilling. With laser drilling, the optical qualities of the glass affect the quality of the hole.

2 Epoxy-Thermount high-temperature laminates are well suited to Chip-On-Board and other high-density applications, although their fairly high CTE in the Z direction below glass transition can put PTH reliability at risk, and conventional drilling and routing of the laminate are difficult because the fibres are tough. The laminate is also substantially more expensive than an equivalent reinforced with glass fibre.

Non-woven matte made from fibreglass is also used for board manufacture. It has a flatter surface than woven glass-cloth, and can be made in a wide range of thicknesses. Unfortunately laminates produced from non-woven matte are less robust than those made from woven glass, and their use is generally restricted to being components of a composite material.

Composite materials

When we looked at laminates based on paper, you will have noticed that these are substantially cheaper, but have performance limitations. For example, they are not compatible with through-hole processes. They are, however, much easier to punch and drill; the comparative difficulty with woven glass coming both from the brittle and abrasive nature of the glass, which quickly blunts press tools and bits, and from the woven structure, drill bits tending to be deflected by the glass fibres themselves or by the non-flat surface finish.

Fortunately, it is possible to create ‘composite electronic materials’ (whence ‘CEM’) which combine some of these desirable properties, and create reduced-cost products with comparatively good performance. For example:

CEM-1 has a paper core and surfaces of woven glass cloth, all impregnated with epoxy resin. This construction gives CEM-1 punching properties similar to those of FR-2, but with an environmental performance nearer to that of FR-4.

CEM-3 is similarly impregnated with epoxy resin and has woven glass cloth surfaces, but its core of non-woven matte fibreglass is more compatible than CEM-1 with through-hole plating. CEM-3 is much more suitable than FR-4 for punching and scoring, and its smoother surface gives better fine-line capability.

CEM-3 in particular is something that you are likely to come across as a cost-reduced substitute for FR-4 in applications such as home computers, car electronics, and home entertainment products. ‘Improved’ CEM-3 materials are becoming nearer to FR-4 in properties, but with slightly higher CTE and lower flexural strength.

Building a laminate with different materials has to be approached with caution, especially if different resin systems are to be combined, when chemical compatibility has to be considered, as well as adhesion and CTE match. However, the basic idea is very flexible, and is something to which we will return in Technology Awareness.

Selecting a laminate

Before selecting the material most suitable for the intended application, it is important both to appreciate the wide variety of types of laminates that are available and to understand how they are made, where they are used, and the advantages and disadvantages of each.

In Table 3 we have listed the most common of these copper-clad laminates, with descriptions and comment about each. It must be remembered, however, that all are generic types, and in consequence there are considerable variations in cost and performance within each category. For example, variants of FR-4 may vary very widely in glass transition temperature.

In the tables, we have used the most common (NEMA) descriptors for the general-purpose laminates, even though you may well have to specify them by their IPC-4101 or BS EN 60249 descriptions, as explained in the final section of Properties of laminates.

Table 3: Laminate designations and materials

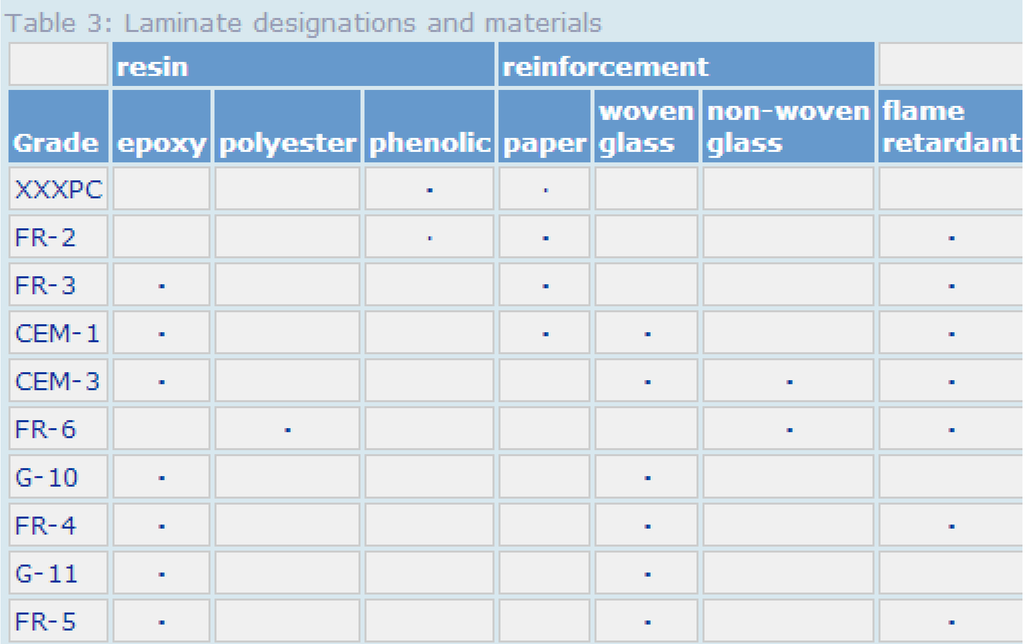


Table 3: Laminate designations and materials

	resin			reinforcement			
Grade	**epoxy**	**polyester**	**phenolic**	**paper**	**woven glass**	**non-woven glass**	**flame retardant**
XXXPC			·	·			
FR-2			·	·			·
FR-3	·			·			·
CEM-1	·			·	·		·
CEM-3	·				·	·	·
FR-6		·				·	·
G-10	·				·		
FR-4	·				·		·
G-11	·				·		
FR-5	·				·		·

Table 3 has tabulated the construction of each of these common materials; Table 4 describes what they look like, their principal characteristics, and what typical applications are.

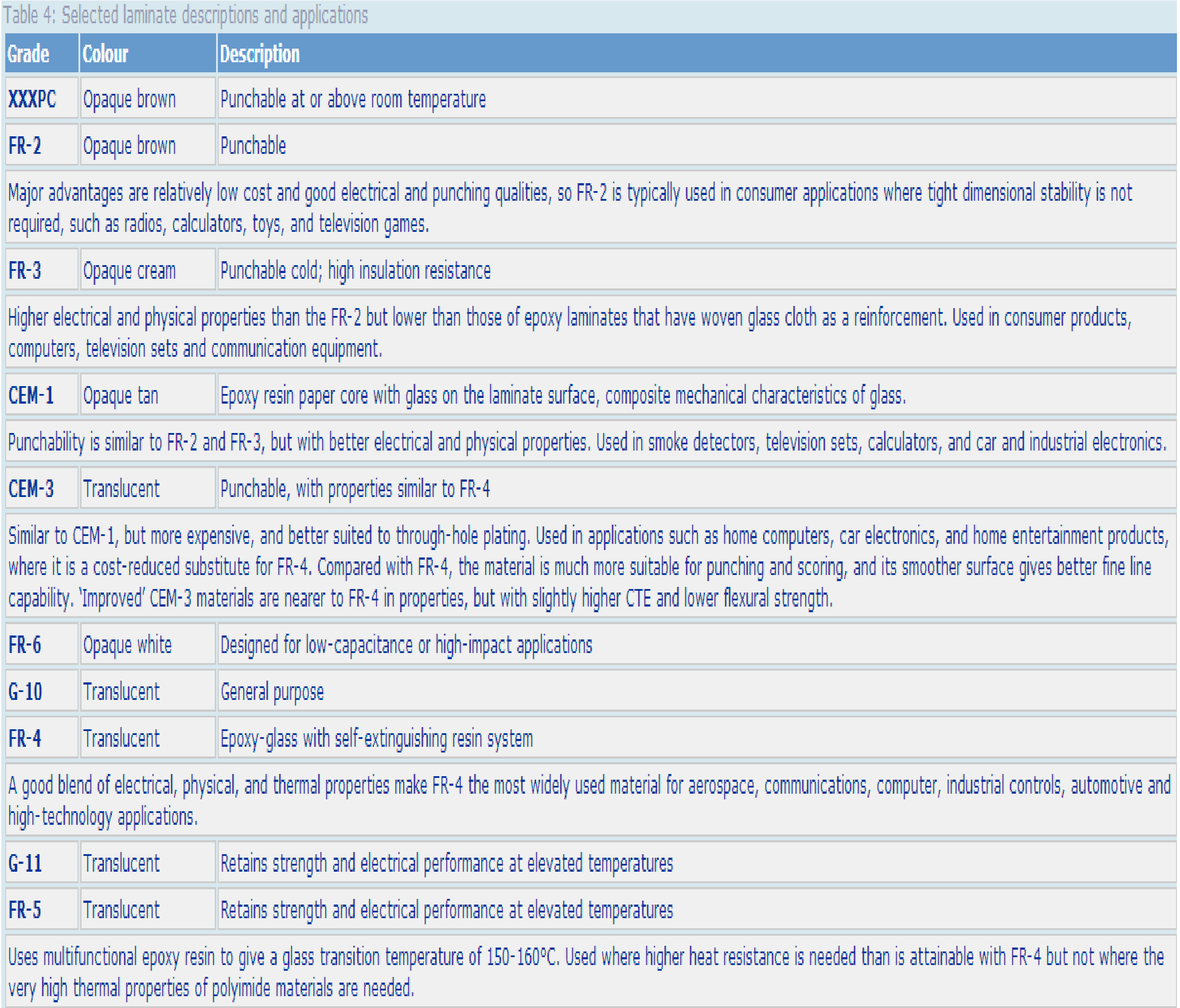
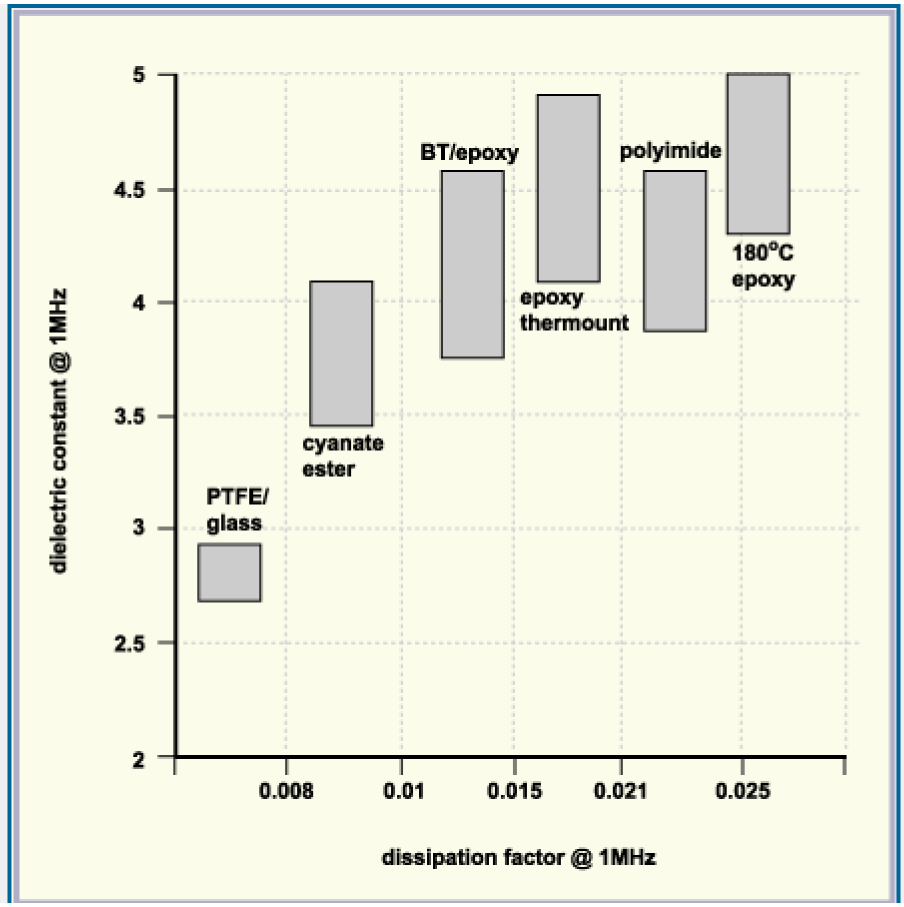


Table 4: Selected laminate descriptions and applications

<table>
<tr><th>Grade</th><th>Colour</th><th>Description</th></tr>
<tr><td>XXXPC</td><td>Opaque brown</td><td>Punchable at or above room temperature</td></tr>
<tr><td>FR-2</td><td>Opaque brown</td><td>Punchable</td></tr>
<tr><td colspan="3">Major advantages are relatively low cost and good electrical and punching qualities, so FR-2 is typically used in consumer applications where tight dimensional stability is not required, such as radios, calculators, toys, and television games.</td></tr>
<tr><td>FR-3</td><td>Opaque cream</td><td>Punchable cold; high insulation resistance</td></tr>
<tr><td colspan="3">Higher electrical and physical properties than the FR-2 but lower than those of epoxy laminates that have woven glass cloth as a reinforcement. Used in consumer products, computers, television sets and communication equipment.</td></tr>
<tr><td>CEM-1</td><td>Opaque tan</td><td>Epoxy resin paper core with glass on the laminate surface, composite mechanical characteristics of glass.</td></tr>
<tr><td colspan="3">Punchability is similar to FR-2 and FR-3, but with better electrical and physical properties. Used in smoke detectors, television sets, calculators, and car and industrial electronics.</td></tr>
<tr><td>CEM-3</td><td>Translucent</td><td>Punchable, with properties similar to FR-4</td></tr>
<tr><td colspan="3">Similar to CEM-1, but more expensive, and better suited to through-hole plating. Used in applications such as home computers, car electronics, and home entertainment products, where it is a cost-reduced substitute for FR-4. Compared with FR-4, the material is much more suitable for punching and scoring, and its smoother surface gives better fine line capability. 'Improved' CEM-3 materials are nearer to FR-4 in properties, but with slightly higher CTE and lower flexural strength.</td></tr>
<tr><td>FR-6</td><td>Opaque white</td><td>Designed for low-capacitance or high-impact applications</td></tr>
<tr><td>G-10</td><td>Translucent</td><td>General purpose</td></tr>
<tr><td>FR-4</td><td>Translucent</td><td>Epoxy-glass with self-extinguishing resin system</td></tr>
<tr><td colspan="3">A good blend of electrical, physical, and thermal properties make FR-4 the most widely used material for aerospace, communications, computer, industrial controls, automotive and high-technology applications.</td></tr>
<tr><td>G-11</td><td>Translucent</td><td>Retains strength and electrical performance at elevated temperatures</td></tr>
<tr><td>FR-5</td><td>Translucent</td><td>Retains strength and electrical performance at elevated temperatures</td></tr>
<tr><td colspan="3">Uses multifunctional epoxy resin to give a glass transition temperature of 150-160°C. Used where higher heat resistance is needed than is attainable with FR-4 but not where the very high thermal properties of polyimide materials are needed.</td></tr>
</table>

Materials for high-frequency applications

Materials with lower values of permittivity are increasingly needed for high-frequency applications. Figure 1 plots both permittivity and loss characteristics for a range of materials, from which it can be seen that lower values and losses than conventional epoxy-glass boards are really only available by using laminates based on cyanate esters or PTFE.



The most common high-frequency materials are made from PTFE mechanically reinforced by glass fibre to improve mechanical stability and reduce cold flow of the material. However, woven reinforcements tend to produce anisotropic dielectric properties, so randomly distributed short micro-fibres are used to give better results. Improved dimensional stability and thermal conductivity is sought by adding ceramic fillers to the micro-fibre reinforcement.

Foil materials

In Basic board materials we introduced the manufacturing process for electrodeposited copper foil, the main material used for rigid boards3. Depending on your customer base, you may, however, encounter two different materials, both of which are composite foils. The first of these is promoted for reducing handling damage, and the second for reducing CTE.

3 Rolled foils are used for flexible circuits, a topic we will be introducing in Unit 9

CAC (Copper Aluminium Copper) uses an aluminium separator sandwiched between two sheets of copper foil. The internal copper surfaces are processed to be free of any particles or dents larger than 5µm and are protected by the aluminium from exposure to airborne particles and resin dust. During multilayer lamination, the copper foils release from the aluminium separator sheet and become the outer layers of the printed circuit boards above and below.

The improved surface gives higher yields on high density, fine line circuits, and combining three layers in one gives savings in manual handling and cleaning. Having a supporting foil (separators come in thicknesses between 0.18 mm and 0.50 mm) is also a good approach when using difficult-to-handle thin foils.

Other materials may be laminated by the proprietary processes involved, but aluminium is generally preferred. However, the process is far from common on account of the high cost of the materials.

Copper-invar-copper4 is a sandwich of invar, an iron alloy containing a high percentage of nickel, between two layers of copper. It is metallurgically bonded in the rolling process which also reduces the thickness to as little as 150 µm. Typically the ratio of copper to invar is 12.5%/75%/12.5% which gives the composite foil a CTE of about 5.5 ppm/°C. Since CIC also has a very high modulus, it is effective in constraining the overall movement of boards in which layers of CIC are embedded.

4 There are always dangers with acronyms. If you search for CIC on the web, you will not have the same clear experience as with CAC: CIC may be a learned society (Chemical Institute of Canada) or the smallest type of hearing aid (Completely-in-the-canal)!

For severe environment applications, CIC is commonly used as combined heat sink and restraining layer, for example, when ceramic packages need to be mounted on multilayer boards with matching thermal expansion. However, such applications also often demand polyimide laminates, and bonding CIC to these is inherently difficult because of the shear forces caused by differences in CTE during heating and cooling. Until special surface treatment was developed to enhance bonding to polyimide, practical uses of this combination of materials were severely limited.

Author: Martin Tarr

Source: http://www.ami.ac.uk/courses/topics/0233_abm/index.html