Electronic materials and components-Ceramic components

In other topics we deal fairly comprehensively with polymers and metals, but these aren’t the only materials that are used. Particularly in components, you will come across ceramics, a group of materials with a wide range of properties. Those that are best described as ‘glasses’, and those with magnetic properties, are both dealt with in Other passive components: this topic concentrates on their use for capacitors and resistors.

Some ceramics basics

The word ‘ceramic’ is derived from the Greek for potters’ clay, though the term is now used much more generally, to apply to a wide range of inorganic materials that are generally non-metallic and in most cases have been treated at high temperature at some stage during manufacture.

Ceramics can be classified into four main groups:

The amorphous ceramics that are generally referred to as ‘glasses’ – we shall meet these in Other passive components

Crystalline ceramics, which may be single phase materials like alumina, or mixtures of such materials – many electronic ceramics come into this category

Bonded ceramics, where individual crystals are bonded together by a glassy matrix, as with most clay-derived products

Cements, some of which are crystalline, whilst others contain both crystalline and amorphous phases.

The structures of ceramics fall into two main groups:

Simple crystal structures containing ionic or covalent bonds, or a mixture of the two. Examples are magnesium oxide (used for furnace linings) which is an ionic compound with cubic structure, and silicon carbide, with covalent bonds and a tetrahedral structure similar to that of diamond.

Alumina has a close packed hexagonal structure, with a mixture of covalent and ionic bonds, with one-third of the potential aluminium sites vacant in order to satisfy the valency requirements of the two elements.

Complex silicate structures: The majority of ceramic materials, in particular those derived from clay, sand or cement, contain the element silicon in the form of silicates. The arrangements are many, involving both chains of silicate ions

$(SiO_4)^{2-}$, double chains and links in sheet form. With the last of these, found in clays, cross-linking between adjacent sheets occurs when the clay is baked.

Generic manufacture methods

Many engineering ceramics are made from powders, by cold pressing the powder to produce a 'compact' which is strong enough to be handled. This compact is then sintered at a temperature high enough to cause fusion of the particle boundaries. The temperatures involved depend on the nature of the ceramic material and whether any 'glass formers' are included in the powder. With alumina for example, where materials are typically quoted at 96% or 99% purity, the balance consists of glass-formers, which help give the fired part a smooth surface finish, and reduce its porosity.

Until recently, most ceramic materials consisted of crystalline particles cemented together by glass, but sintering at sufficiently higher temperatures can produce wholly crystalline structures which maintain their strength at elevated temperatures.

Other ways of shaping ceramic products, such as the sheets of material used to make resistors and capacitors, include modifications of processes traditionally used with clay:

extrusion, where wet material is forced through a slit in a die

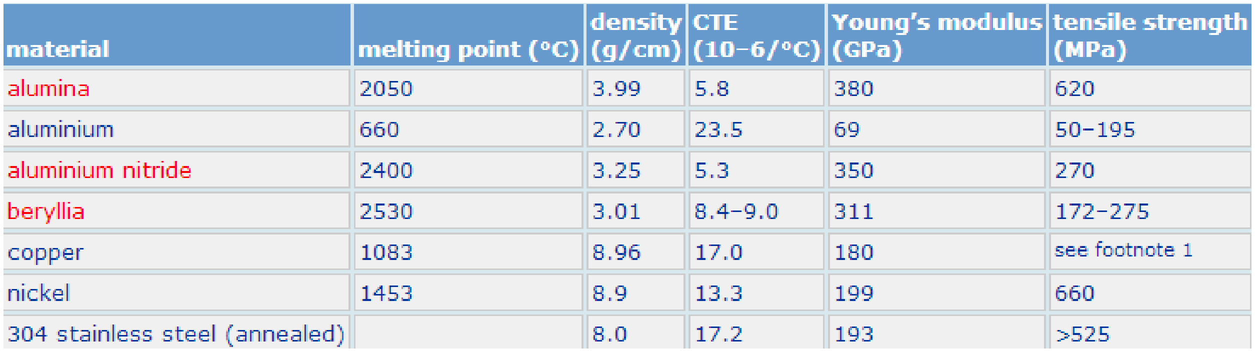
slip casting, which starts with a suspension of particles in water (the 'slip'), poured onto a surface of absorbent material, which takes up water, leaving a uniform layer of ceramic particles

Whether extruded, or cast as a sheet, the unfired ceramic has relatively little strength, and needs handling with care. It is, however, possible to carry out operations such as printing precious metal inks, which can be co-fired with the ceramic, and form part of the eventual structure. Any forming or cutting is best carried out while the ceramic is in the 'green' (or unfired) state, as the task is easy – you can cut a sheet of green ceramic with a razor blade; once fired, the ceramic will blunt the razor!

Ceramic properties

Ceramics are hard and reasonably strong: Table 1 gives some typical values, from which it can be seen that, weight for weight, alumina is stronger than stainless steel. However, ceramics are more rigid (higher Young's modulus). More crucially, they have almost no ductility, because of the directional nature of the covalent bonds. Without ductility, stress concentrations are prevented from being relieved by plastic flow, so ceramics tend to fracture readily.

Table 1: Mechanical properties of selected electronic materials (ceramics are shown in red)



material	**melting point (°C)**	**density (g/cm)**	**CTE (10−6/°C)**	**Young's modulus (GPa)**	**tensile strength (MPa)**
alumina	2050	3.99	5.8	380	620
aluminium	660	2.70	23.5	69	50−195
aluminium nitride	2400	3.25	5.3	350	270
beryllia	2530	3.01	8.4−9.0	311	172−275
copper	1083	8.96	17.0	180	see footnote 1
nickel	1453	8.9	13.3	199	660
304 stainless steel (annealed)		8.0	17.2	193	>525

1 The tensile strength of copper depends on its treatment history: typical values are 125 MPa for cast copper (50% elongation), 220 MPa for annealed wrought copper (56% elongation), and 386 MPa for cold-drawn copper (6% elongation).

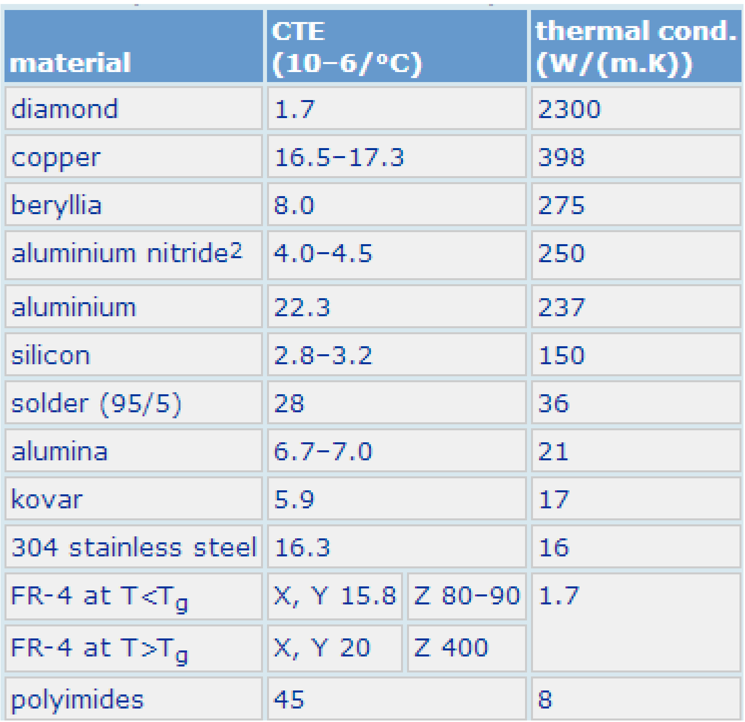
Internal imperfections such as porosity reduce both strength and ductility. Because most engineering ceramics are compacted from powders, some porosity is inevitable, so most ceramics are very brittle.

Ceramics also tend to suffer from the presence of micro-cracks, which act as stress raisers, and tensile stresses must generally be kept low if sudden failure is to be avoided. Also, because the number of faults will vary from specimen to specimen, in ceramics there can be a much bigger scatter of measured strengths than with metals.

Creep only takes place in crystalline ceramics at relatively high temperatures. However, non-crystalline glasses have low softening temperatures, and considerable creep occurs at moderate temperatures.

Most ceramics are non-conductors of electricity, and have many uses because of this. They are particularly useful because they are reasonable conductors of heat. Table 2 shows alumina to be a very much better conductor of heat than FR-4 laminate, and comparable in performance to leadframe materials and solder. Other ceramics have substantially better characteristics, comparable to metals, but their specification and use is outside the scope of this module.

Table 2: Thermal characteristics of selected electronic



material	CTE (10−6/°C)		thermal cond. (W/(m.K))
diamond	1.7		2300
copper	16.5−17.3		398
beryllia	8.0		275
aluminium nitride[2]	4.0−4.5		250
aluminium	22.3		237
silicon	2.8−3.2		150
solder (95/5)	28		36
alumina	6.7−7.0		21
kovar	5.9		17
304 stainless steel	16.3		16
FR-4 at $T<T_g$	X, Y 15.8	Z 80−90	1.7
FR-4 at $T>T_g$	X, Y 20	Z 400	
polyimides	45		8

Aluminium nitride (AlN) is a stable covalent compound with low thermal expansion that makes it useful in electronics as a heat sink material. Unfortunately, the material cannot be sintered in air and exhibits considerable variations in thermal performance due to the presence of oxide in the structure. However, it does not present the same toxic hazards as beryllia.

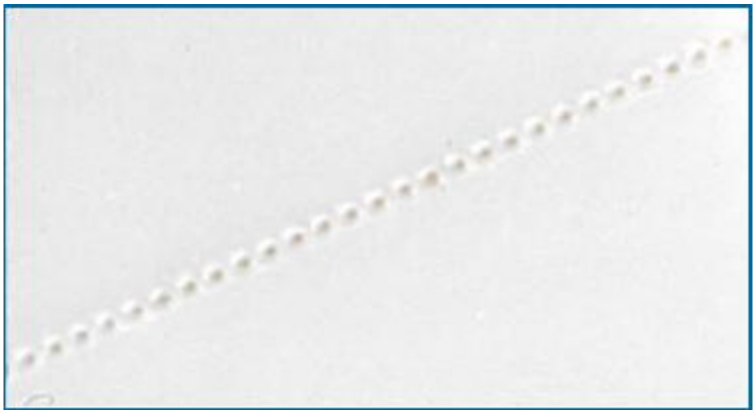
Alumina has other uses within electronic packaging, because it is not permeable to gas, provided that it is correctly sintered. Ceramics therefore are the basis of many advanced packages. Their use in this way uses the fact that layers of ceramic can be co-fired to form a robust joint, making package assembly possible, and the structure allows enough penetration by glass to make it possible to metallise ceramic using glass threads containing precious metals. It is materials of this sort, referred to as ‘thick film inks’ which are used both in package manufacture and in making chip resistors.

Resistors

Most chip resistors are of the so-called ‘thick film’ construction, where patterns of inks containing glass frit and a mix of metals and oxides are printed onto a ceramic substrate and converted to adherent, stable films by firing at high temperature (typically 850ºC).

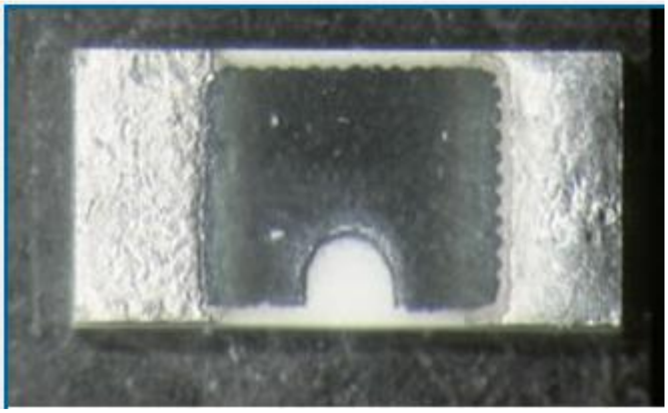
The usual substrate is a high purity alumina[3] sheet which is first laser-scribed in two directions at right angles to provide crack lines for breaking out the individual resistors at a later stage in production. The internal metal electrodes, usually of palladium-silver, but sometimes of gold, are printed across the appropriate cracks and fired on.

[3] Alumina (Al_2O_3) is produced from the bauxite ore which is also the source of metallic aluminium. The crushed ore is digested with hot caustic under pressure, the solution filtered, and aluminium hydroxide precipitated by passing carbon dioxide through the solution. The resulting pure hydroxide is dried and calcined at 1100°C where it decomposes to give pure alumina.



Overlapping pits on a ceramic substrate form a laser scribe line

The resistive element, normally based on ruthenium dioxide, is similarly printed between these electrodes and again fired. The resistive value as-fired is always lower than the target so that each resistor can be adjusted upwards to the precise value required. Computer controlled laser trimming is used to vaporise a narrow channel in the resistive element whilst the increasing resistance is being monitored. The central area is then glazed, to protect the resistive element with a glass film (Figure 1).



Early chip resistor shows concept: this example has been

adjusted by air-abrasion

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Figure 1: Chip resistor construction

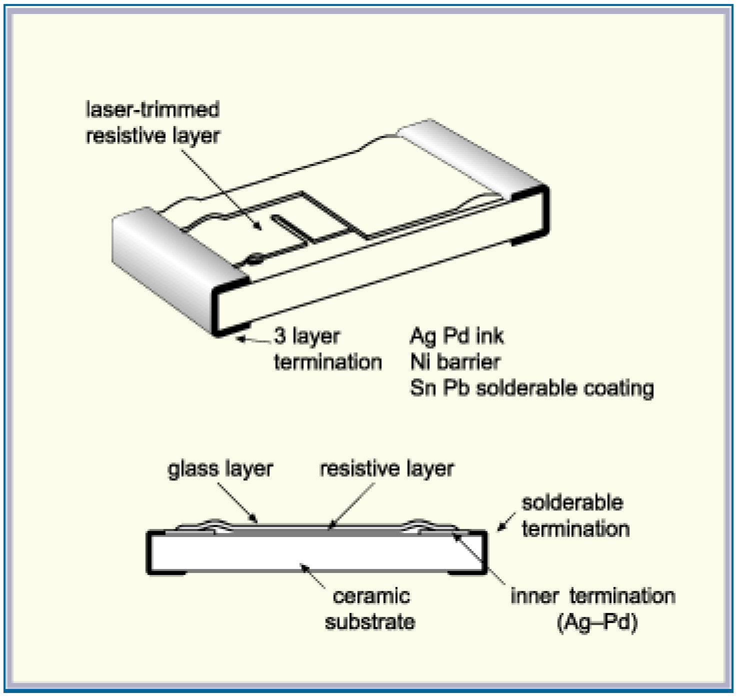
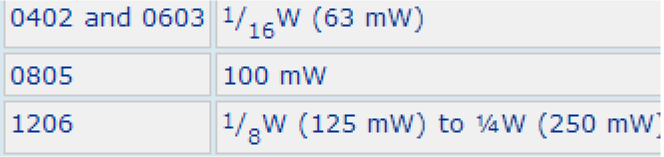


Figure 1: Chip resistor construction

A completed and coded chip resistor

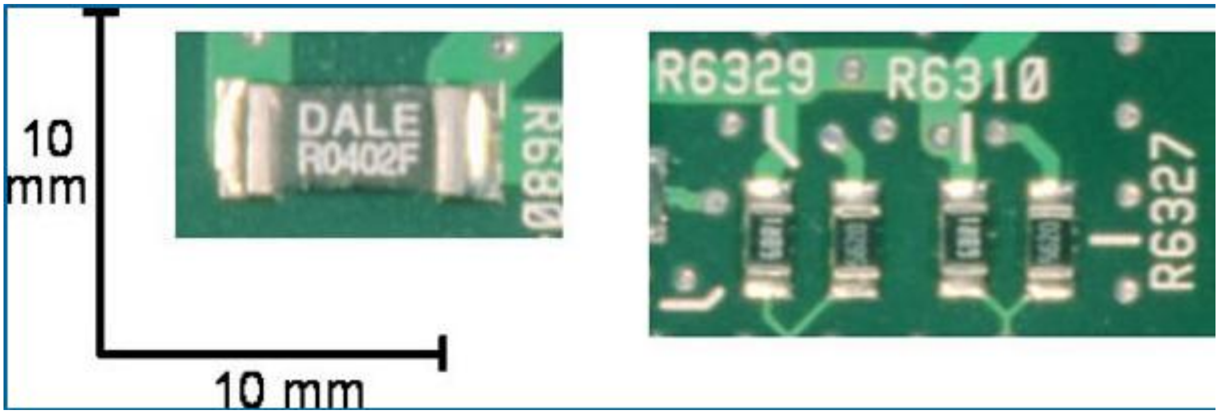
Such resistors typically range from 1W to 10MW with a choice of tolerances in the range ±0.5% to ±20%. Because resistors are individually adjusted, the spread of values within a batch will normally be very much closer than the nominal tolerance, ±1% of mean value being typical of what is achieved with ±5% parts.

Power ratings over an operating range of approximately -40ºC to +70ºC depend on the resistor size



0402 and 0603	$^{1}/_{16}$W (63 mW)
0805	100 mW
1206	$^{1}/_{8}$W (125 mW) to ¼W (250 mW)

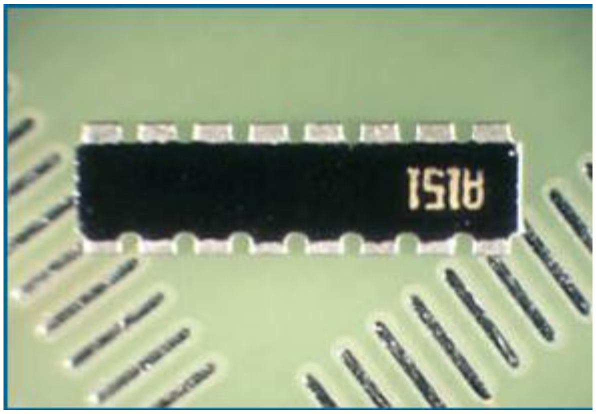
Different sizes and ratings of chip resistor



The temperature coefficient of this type of resistor is low, typically less than ±0.02%/ºC, making thick film resistors fairly stable components. However, for critical applications, precision chip resistors are available. These are manufactured using a different technology.

Resistor networks

Resistor networks, consisting of several thick-film or thin-film resistors on one substrate, are produced in a variety of package outlines. The earliest of these formats were DIL (Dual-In-Line) and SIL (Single-In-Line), but leadless chip styles have also been developed, and flat-pack styles are now very common. These are similar in concept to the SO-IC but frequently on a smaller pitch.



Leadless chip resistor network

Whilst custom networks were once favoured, for most applications the networks contain identical resistors of one of the standard resistance values (see The component driver -: Implications for board design). The two most common arrays have either separate resistors, or resistors with one side of each connected to a common pin (Figure 2).

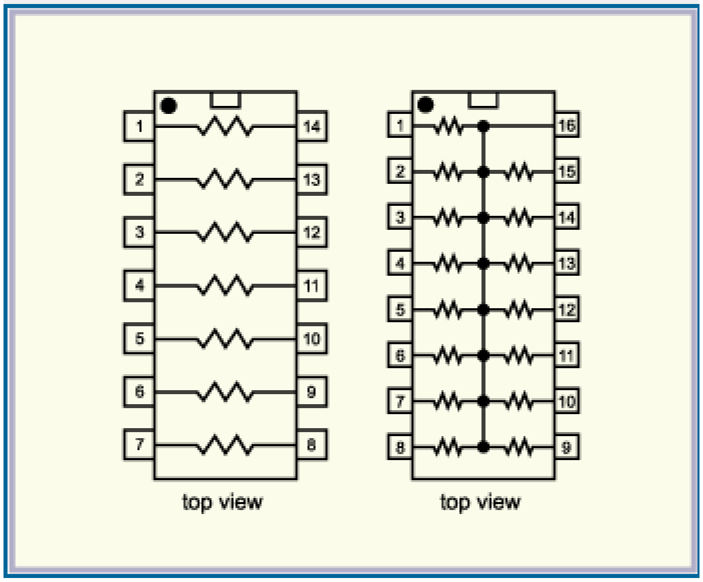


Figure 2: Standard configurations for resistor networks

Ceramic capacitors

The type of chip capacitor that predominates because of its useful range is the multilayer ceramic chip (MLC). The basis of this structure is shown in Figure 3. In a typical process, thick film capacitor electrodes are screen printed onto sheets of doped barium titanate ceramic using an interleaved pattern. These sheets are stacked under pressure, dried, cut to size and sintered at a temperature around 1300°C. The electrodes must be of a metal with a melting point that is higher than the sintering temperature, and platinum (1774°C) or palladium (1552°C) are normally used.

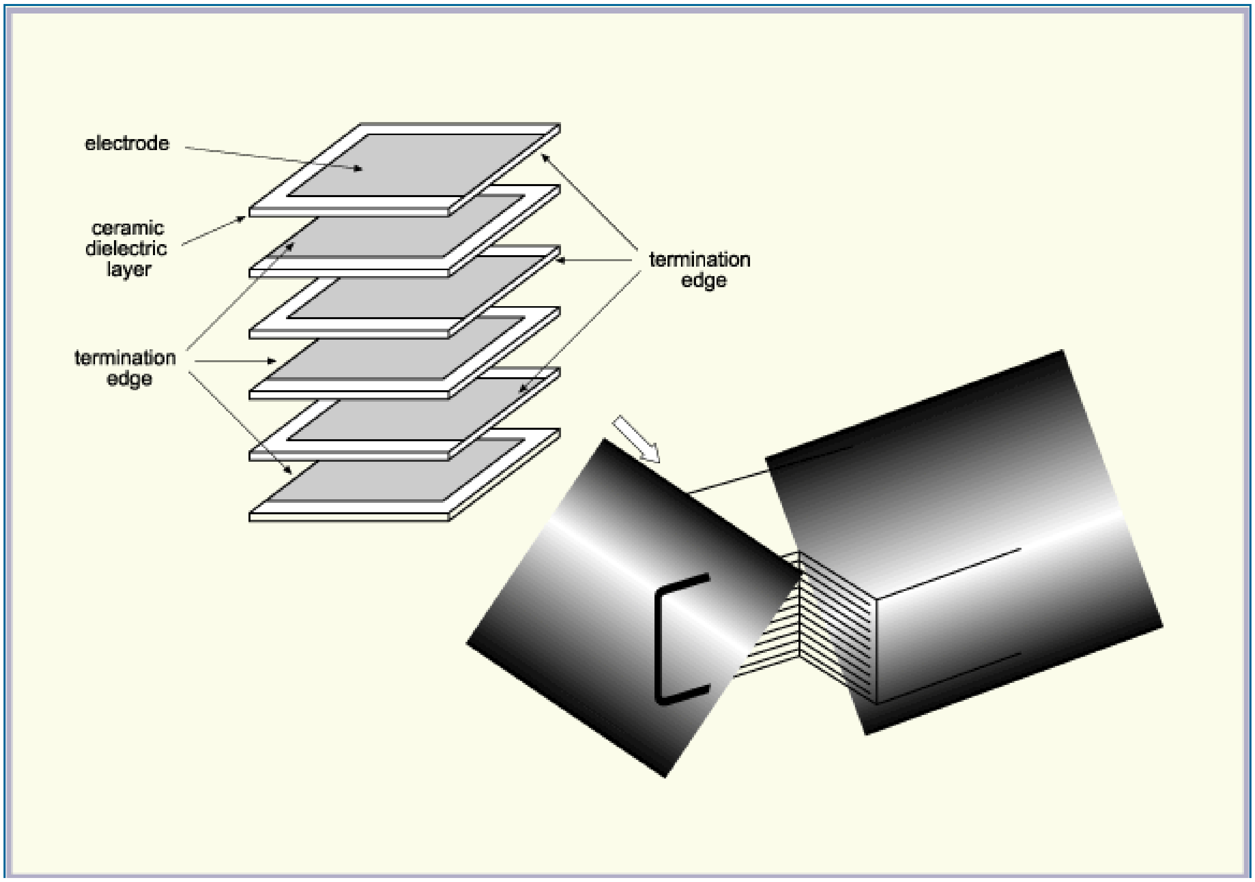
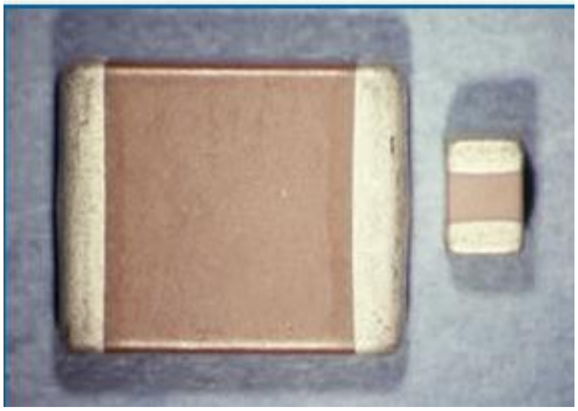


Figure 3: The structure of the multilayer ceramic chip capacitor



Different sizes of chip capacitor]

Contact is then made to the ends of the capacitative layers using metal terminations, commonly silver-palladium, which are applied by screening or dipping followed by firing, each making contact with one set of internal electrodes.

Several solderable termination options are available, for which there is a trade-off between cost and retention of solderability of the metallisation. The most usual final finish is a nickel barrier layer, followed by a solderable outer coating. The nickel prevents leaching of the silver into the molten solder during assembly.

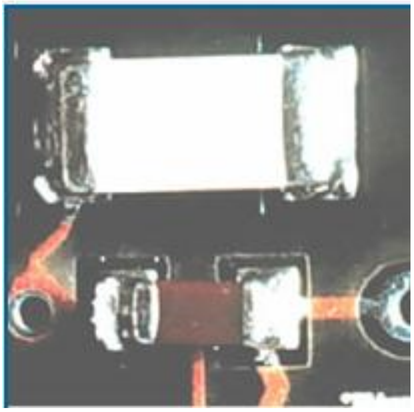
The resultant capacitor is very rugged and the electrode system is totally enclosed and protected from the influence of the ambient atmosphere. Standard versions are able to withstand immersion in 250°C molten solder as well as high humidity, without the need for further encapsulation.

The temperature coefficient of a multilayer chip capacitor is determined by the type of ceramic used. The temperature coefficient of NPO capacitors is close to zero over the relevant temperature range, but for others it can be either positive (capacitance increasing with rising temperature) or negative (capacitance decreasing with rising temperature). The considerable difference between different dielectric types is indicated in Figure 4. Generally, the more capacitance that is crammed into a given volume, the less stable the value will be.

The formulations of ceramic capacitor materials vary very significantly, depending on the dielectric constant and stability required. One can see colour differences – NP0 types are likely to be near-white, X7R often light brown, and Z5U may verge towards purple – but don't place any faith on this as a definitive indicator of likely value.

Different sizes and dielectrics which may have different

Characteristics



Different sizes and dielectrics which may have different characteristics

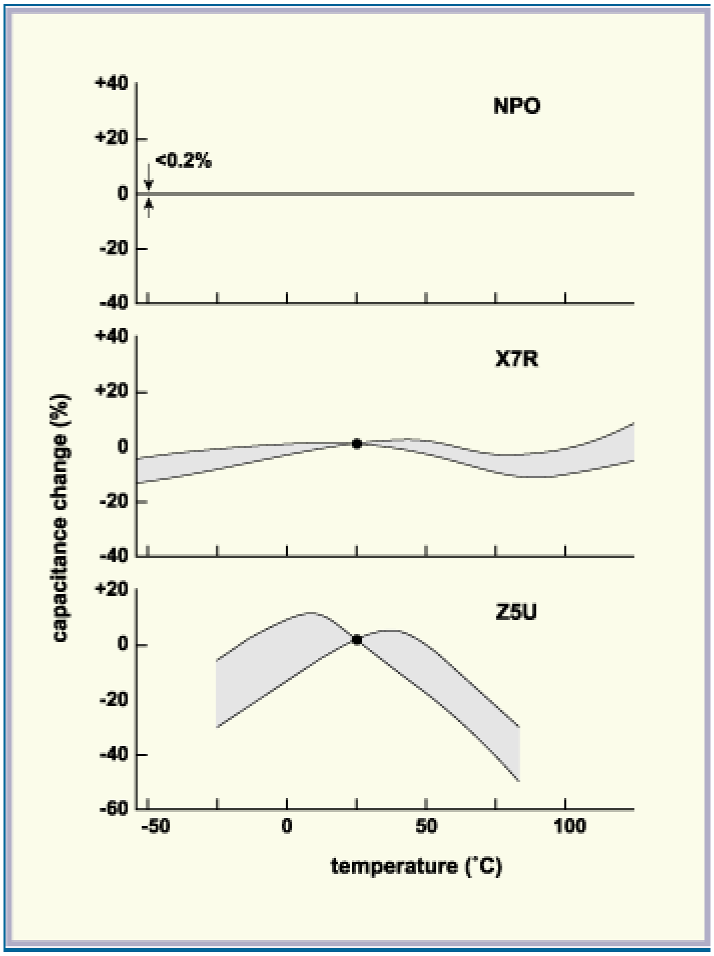
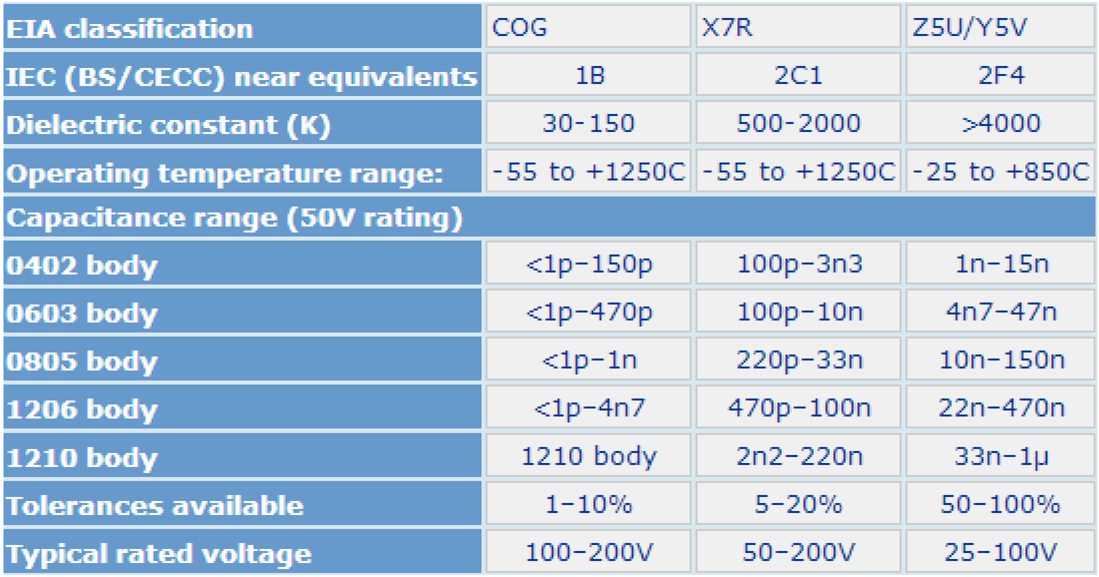


Figure 4: MLCs: different dielectrics

Figure 4 and Table 3 give information on the three most commonly used materials. Note that there are differences in detail between the EIA classifications developed in the USA, and the IEC designations, although the specifications are similar.

In using Table 3, also bear in mind that the maximum capacitance value in a given package depends on the voltage rating and on the materials and technology, so that capacitance value ranges will vary between manufacturers. Some makers also truncate the bottom end of general purpose capacitor ranges, preferring to supply the more stable material where there is an overlap between dielectric types.

Table 3: Electrical characteristics of representative chip capacitor dielectrics



EIA classification	COG	X7R	Z5U/Y5V
IEC (BS/CECC) near equivalents	1B	2C1	2F4
Dielectric constant (K)	30-150	500-2000	>4000
Operating temperature range:	-55 to +1250C	-55 to +1250C	-25 to +850C
Capacitance range (50V rating)			
0402 body	<1p-150p	100p-3n3	1n-15n
0603 body	<1p-470p	100p-10n	4n7-47n
0805 body	<1p-1n	220p-33n	10n-150n
1206 body	<1p-4n7	470p-100n	22n-470n
1210 body	1210 body	2n2-220n	33n-1μ
Tolerances available	1-10%	5-20%	50-100%
Typical rated voltage	100-200V	50-200V	25-100V

The capacitance value of a multilayer chip capacitor is a function of the number of layers, the area of each electrode, and the permittivity and thickness of the dielectric. All but the first of these are variables which depend on the manufacturing process, and inevitably are not constant. There is therefore a spread of values in any batch, the range depending on the nature of the manufacturing technology and the quality of its process control.

Close tolerance parts are generally selected from the 'as-fired' batch, and reflect this in their higher price. It is possible to reduce the value of a capacitor by drilling into the structure whilst measuring its value, and then filling the pit produced with a protective glass, but this is both expensive and of uncertain reliability.

Which 'selection tolerances' are appropriate will depend on the dielectric type and its inherent stability: NPO parts are available down to ±1% and X7R types to ±5%. Note however that, for low value capacitors, measurement uncertainties generally restrict the best available accuracy to ±0.25pF.

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Source: http://www.ami.ac.uk/courses/topics/0135_cc/index.html