Lecture 1 – Passive Components

Resistor characteristics. Resistor types. Choosing resistors. Capacitor characteristics. Types of dielectrics. Capacitor models. Film capacitors. Ceramic capacitors. Electrolytic capacitors. Mica capacitors. Glass capacitors. Choosing capacitors. Decoupling capacitors.

Introduction

A *resistor* is not a pure resistance of exact value. A real resistor has a series inductance and a parallel stray capacitance. These affect the behaviour of the resistor, particularly at high frequencies.

A resistor is not a pure resistance

A *capacitor* is not simply a capacitance, possibly with some losses. Both capacitance value and losses depend on frequency and temperature, sometimes quite significantly. A real capacitor has a series inductance, a series resistance and a parallel resistance. At higher frequencies capacitors behave as complex resonant systems. Above its series resonant frequency, a capacitor behaves like an inductance.

A capacitor is not a pure capacitance

The characteristics of capacitors are very different to one another since they depend on the dielectric and technology used to make them. It is extremely important to understand these material / technology specific characteristics, in order to choose the proper capacitor for a given application.

For the passive components we will:

- define the essential characteristics used to describe their performance;
- present the main types of devices, differentiated by the materials and technologies used in manufacturing them, as these determine the characteristics;
- compare the characteristics and recommend applications for different types of components.

1.2

Resistor Characteristics

Resistors are the most commonly used passive electronic component. The characteristics and the features to consider when choosing a resistor are: resistance value, tolerance on value, stability, temperature coefficient, voltage coefficient, humidity effects, power dissipation, frequency effects, noise, reliability, size and packaging, availability and cost. For insight into these factors, the materials and construction of the various resistor types must be considered.

Tolerance on value

Component tolerances are tolerances at time of purchase

Service variability of a resistor value is an *overall, long-term value tolerance* composed of factors such as purchase tolerance, ageing, stress and short-term excursions due to the local environment (temperature, humidity, etc). A resistor of, say, 10% *rated tolerance* can be selected to be within ±1% of the required value when installed in a circuit, but such a resistor might well drift within (and often even outside) the rated ±10% during its service. Hence, if either a *very accurate* or *stable* resistance value is required in a circuit, choose the right tolerance resistor when purchasing it, i.e. with a tolerance tighter than the required end-of-life tolerance.

Preferred Values and the Decade Progression

Fundamental standardization practices require the selection of *preferred* values within the ranges available. Standard values may at first sight seem to be strangely numbered. There is, however, a beautiful logic behind them, dictated by the tolerance ranges available.

Component values have been standardized by the IEC

The *decade progression* of preferred values is based on preferred numbers generated by a geometric progression, repeated in succeeding decades. In 1963, the International Electrotechnical Commission (IEC) standardized the preferred number series for resistors and capacitors (standard IEC 60063). It is based on the fact that we can linearly space values along a logarithmic scale so a percentage change of a value results in a linear change on the logarithmic scale.

Recall that for a geometric progression, each individual term is given by:

$$a_n = ar^{n-1} \tag{1.1}$$

where a_n is the *n*-th term, a is the scale factor, and r is the common ratio. If r is chosen to be the *k*-th root of 10, and the scale factor is set to 100, then:

$$a_n = 100\left(\sqrt[k]{10}\right)^{n-1} \tag{1.2}$$

Thus, the selection of k determines how many values of the geometric progression there are in one decade. For example, if 6 values per decade are desired, $k = 6$ and the common ratio is $\sqrt[6]{10} \approx 1.468$. The six rounded-off values become 100, 150, 220, 330, 470, 680.

Component values are spaced equidistantly on a logarithmic scale

To figure out what tolerance is allowable on resistors with these values, we can let the tolerance be $\pm\delta$. Then if we require successive values of resistors to increase with *almost certainty*, then:

$$\begin{aligned}
a_n(1+\delta) &= a_{n+1}(1-\delta) \\
\frac{a_{n+1}}{a_n} &= \frac{1+\delta}{1-\delta} \\
\sqrt[k]{10} &= \frac{1+\delta}{1-\delta} \\
\delta &= \frac{\sqrt[k]{10}-1}{\sqrt[k]{10}+1} \qquad (1.3)
\end{aligned}$$

For $k = 6$, we get $\delta = 18.95\%$. Thus, if we set the tolerance of resistors with 6 values per decade to $\delta = 20\%$, we get values that almost certainly increase, with minimal overlap:

100 ± 20% = 80 to 120	330 ± 20% = 264 to 396
150 ± 20% = 120 to 180	470 ± 20% = 376 to 564
220 ± 20% = 176 to 264	680 ± 20% = 544 to 816

The 'E' Series Values

The 'E' series values explained

The IEC set the number of values for resistors (and capacitors) per decade based on their tolerance. These tolerances are 0.5%, 1%, 2%, 5%, 10%, 20% and 40% and are respectively known as the E192, E96, E48, E24, E12, E6 and E3 series, the number indicating the quantity of values per decade in that series. For example, if resistors have a tolerance of 5%, a series of 24 values can be assigned to a single decade multiple (e.g. 100 to 999) knowing that the possible extreme values of each resistor overlap the extreme values of adjacent resistors in the same series.

Any of the numbers in a series can be applied to any decade multiple set. Thus, for instance, multiplying 220 by each decade multiple (0.1, 1, 10 100, 1000 etc.) produces values of 22, 220, 2 200, 22 000, 220 000 etc.

The 'E' series of preferred resistor and capacitor values according to IEC 60063 are reproduced in Table 1.1.

0.5% E192	1% E96	2% E48	0.5% E192	1% E96	2% E48	0.5% E192	1% E96	2% E48	0.5% E192	1% E96	2% E48	0.5% E192	1% E96	2% E48	
100	100	100	169	169	169	287	287	287	487	487	487	825	825	825	
101			172			291			493			835			
102	102		174	174		294	294		499	499		845	845		
104			176			298			505			856			
105	105	105	178	178	178	301	301	301	511	511	511	866	866	866	
106			180			305			517			876			
107	107		182	182		309	309		523	523		887	887		
109			184			312			530			898			
110	110	110	187	187	187	316	316	316	536	536	536	909	909	909	
111			189			320			542			920			
113	113		191	191		324	324		549	549		931	931		
114			196			328			556			942			
115	115	115	196	196	196	332	332	332	562	562	562	953	953	953	
117			198			336			569			965			
118	118		200	200		340	340		576	576		976	976		
120			203			344			583			988			
121	121	121	205	205	205	348	348	348	590	590	590				
123			208			352			597			5%	10%	20%	40%
124	124		210	210		357	357		604	604		E24	E12	E6	E3
126			213			361			612						
127	127	127	215	215	215	365	365	365	619	619	619	100	100	100	100
129			218			370			626			110			
130	130		221	221		374	374		634	634		120	120		
132			223			379			642			130			
133	133	133	226	226	226	383	383	383	649	649	649	150	150	150	
135			229			388			657			160			
137	137		232	232		392	392		665	665		180	180		
138			234			397			673			200			
140	140	140	237	237	237	402	402	402	681	681	681	220	220	220	220
142			240			407			690			240			
143	143		243	243		412	412		698	698		270	270		
145			246			417			706			300			
147	147	147	249	249	249	422	422	422	715	715	715	330	330	330	
149			252			427			723			360			
150	150		255	255		432	432		732	732		390	390		
152			259			437			741			430			
154	154	154	261	261	261	442	442	442	750	750	750	470	470	470	470
156			264			448			759			510			
158	158		267	267		453	453		768	768		560	560		
160			271			459			777			620			
162	162	162	274	274	274	464	464	464	787	787	787	680	680	680	
164			277			470			796			750			
165	165		280	280		475	475		806	806		820	820		
167			284			481			816			910			

Table 1.1 - IEC standard ‘E’ series of values in a decade

1.6

Marking Codes

IEC labelling for leaded resistors

The IEC also defines how manufacturers should mark the values of resistors and capacitors in the standard called IEC 60062. The colours used on fixed leaded resistors are shown below:

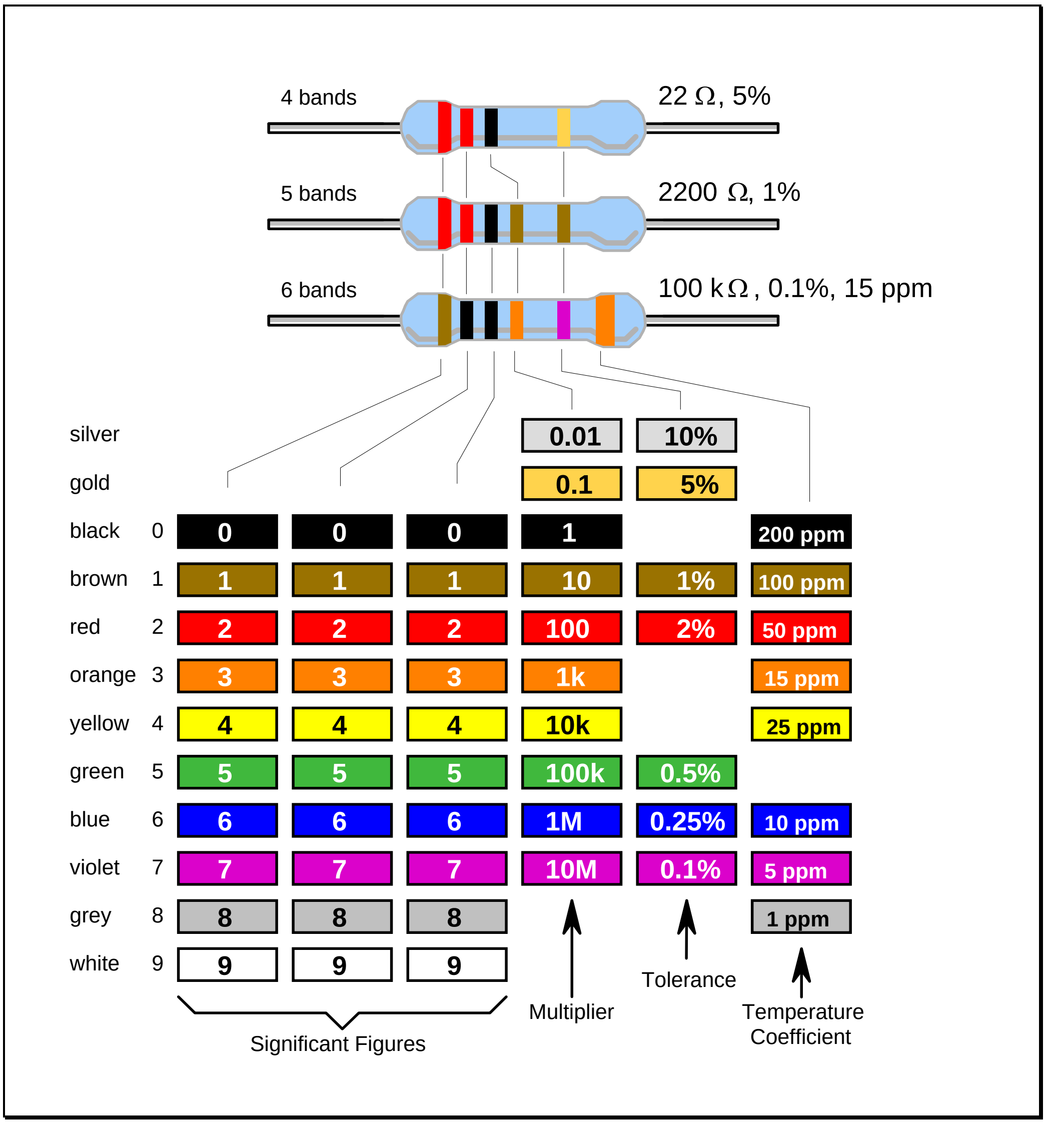


Figure 1.1 – Colour code marking of leaded resistors

The resistance *colour code* consists of three or four colour bands and is followed by a band representing the tolerance. The temperature coefficient band, if provided, is to the right of the tolerance band and is usually a wide band positioned on the end cap.

The resistance colour code includes the first two or three significant figures of the resistance value (in ohms), followed by a multiplier. This is a factor by which the significant-figure value must be multiplied to find the actual resistance value. (i.e. the number of zeros to be added after the significant figures).

Whether two or three significant figures are represented depends on the tolerance: ±5% and wider require two band; ±2% and tighter requires three bands. The significant figures refer to the first two or three digits of the resistance value of the standard series of values in a decade, in accordance with IEC 60063 as indicated in the relevant data sheets and shown in Table 1.1.

The colours used and their basic numerical meanings are recognized internationally for any colour coding used in electronics, not just resistors, but some capacitors, diodes, cabling and other items.

The resistor colour code explained

The colours are easy to remember: Black is the absence of any colour, and therefore represents the absence of any quantity, 0. White (light) is made up of all colours, and so represents the largest number, 9. In between, we have the colours of the rainbow: red, orange, yellow, green, blue and violet. These take up the numbers from 2 to 7. A colour in between black and red would be brown, which has the number 1. A colour intermediate to violet and white is grey, which represents the number 8.

Surface mount technology (SMT) chip resistors are frequently marked with a three-digit number, and some typical values are shown in the table below. The first two numbers are the significant digits of the value, and the last digit is the multiplier (the number of zeros to add to the first two digits). For example, a chip resistor labelled 102 has a value of $1\,\text{k}\Omega$.

Resistor marking for chip resistors

Resistor Value	Resistor Marking
0.1 Ω	0R1
1 Ω	1R0
22 Ω	220
3.3 kΩ	332
100 kΩ	104
1.5 MΩ	155

When resistors are labelled with numbers, an additional letter is appended to indicate the tolerance. The table below lists the letters used for the tolerance.

We use a letter to indicate tolerance

Resistor Tolerance	IEC Labelling
1 %	F
2 %	G
5 %	J
10 %	K
20 %	M

The figure below shows the markings on a single in-line package (SIP) of networked resistors (several resistors are in the one package) and the markings on a chip resistor (with just a three-digit number for space reasons):

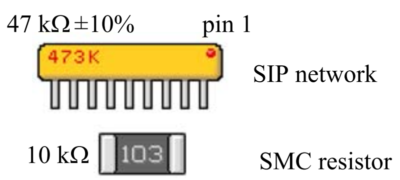


Figure 1.2 – Resistor markings

When resistors are labelled in diagrams, such as schematics, IEC 60062 calls for the significant figures to be printed as such, but replacing the decimal point with the SI prefix of the multiplier. Examples of such labelling are shown below:

IEC labelling for diagrams

Resistor Value	IEC Labelling
0.1 Ω	0R1
1 Ω	1R0
22 Ω	22R
3.3 kΩ	3K3
100 kΩ	100K
1.5 MΩ	4M5

Note how the decimal point is expressed, that the ohm symbol is shown as an R, and that 1000 is shown as a capital K. Note that although capital K is called for by the standard, a lower-case k is generally preferred because it aligns with the SI prefix and capital K has widely become used in computing to mean 1024 (as in KB – "kilobytes") . The use of a letter instead of a decimal point solves a printing problem! The decimal point in a number may not always be printed clearly, and the alternative display method is intended to help misinterpretation of component values in circuit diagrams and parts lists.

We use a letter in place of a decimal point for labelling component values

In circuit diagrams and constructional charts, a resistor's numerical identity is usually prefixed by 'R', e.g. R15 simply means resistor number 15.

Stability

Stability refers to the change in resistance value, expressed in % or parts per million (ppm, i.e. 10^{-6}), following exposure to a specified environmental condition or stress: high or low temperature, time (ageing), full rated power, moisture, soldering heat, short-time overload, radiation. Wire-wound resistors are the most stable ones, followed, in order, by metal film, chip and carbon film.

Stability defined

Temperature Coefficient (Tempco)

The *tempco* is defined as $\Delta R / (R \cdot \Delta T)$, and is expressed in % / ºC or ppm / ºC. It is poorest for carbon composition resistors; for carbon film resistors it is typically negative, -200 to -500 ppm / ºC. It is best for chip and metal film resistors (within ±20 to 100 ppm / ºC).

Temperature coefficient defined

Wire wound resistors can have nearly zero 'tempco'. They are wound from special alloys such as Constantan (55% copper, 45% nickel) which has a remarkably low tempco of 1-5 ppm / ºC.

Example

If the temperature coefficient of a resistor with $R_{\text{rated}} = 1\,\text{k}\Omega$ between -55 ºC and +155 ºC is $\pm 200 \times 10^{-6}\,/°\text{C}$, its resistance value will be:

at +25 ºC: $1000\,\Omega$ (nominal = rated value)

at +155 ºC: $1000\,\Omega \pm \left(130 \times 200 \times 10^{-6}\right) \times 1000\,\Omega = 1026\,\Omega \text{ or } 974\,\Omega$

at -55 ºC: $1000\,\Omega \pm \left(80 \times 200 \times 10^{-6}\right) \times 1000\,\Omega = 1016\,\Omega \text{ or } 984\,\Omega$

If the temperature coefficient is specified as within $\pm 200 \times 10^{-6}\,/°\text{C}$, depending on temperature, the resistance will be within the shaded area shown below:

Tempco of resistors: effect of temperature changes

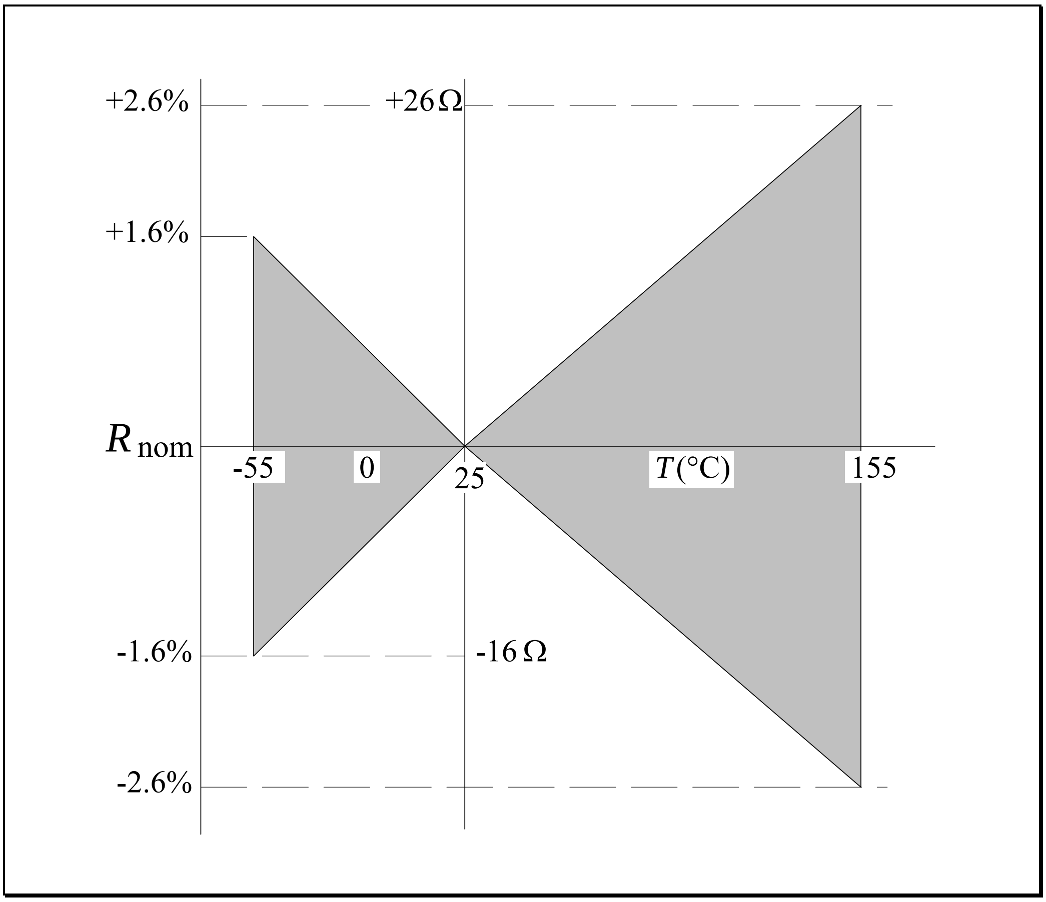


Figure 1.3 – Temperature coefficient

Voltage Coefficient (Voltco)

When a voltage is applied to a resistor there might be a slight decrease in resistance value (apart from temperature induced changes). The voltage coefficient is expressed in % / V or ppm / V. It can be large (-500 ppm / V) for carbon composition. The 'voltco' is about 5 to 30 ppm / V for carbon film, and 0.05 to 10 ppm / V for metal film or chip resistors.

Voltage coefficient defined

Humidity Effects

On the surface of a high resistance value resistor, moisture can provide a low resistance leakage path. If moisture penetrates the coating, it can react chemically with the resistive film and alter it. The danger is mainly when the resistors are stored or the equipment is not used, because then the resistors are cold. The effect of prolonged humidity is also expressed in % or ppm change.

Humidity effects

Power Dissipation

Resistors must be operated within specified temperature limits to avoid permanent damage to the materials. The temperature limit is defined in terms of the maximum power, called the power rating, and a derating curve. The power rating of a resistor is the maximum power in watts which the resistor can dissipate. The maximum power rating is a function of resistor material, maximum voltage rating, resistor dimensions, and maximum allowable hot-spot temperature. The maximum hot-spot temperature is the temperature of the hottest part on the resistor when dissipating full-rated power at rated ambient temperature.

Power dissipation depends on the resistor construction, and depends on the ambient temperature

The maximum allowable power rating as a function of the ambient temperature is given by the derating curve. The figure below shows a typical power derating curve for a resistor.

Power derating curve for a resistor

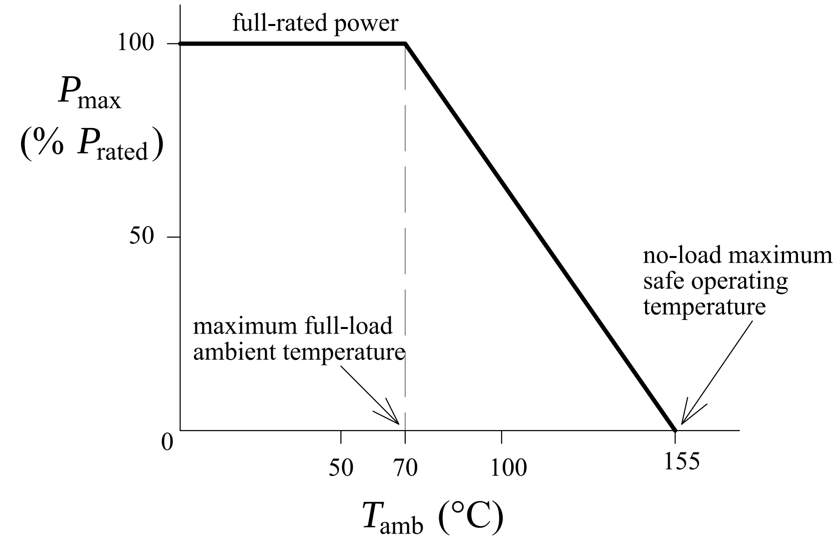


Figure 1.4 – Resistor derating curve

The derating curve is usually linearly drawn from the full-rated load temperature to the maximum allowable no-load temperature. A resistor may be operated at ambient temperatures above the maximum full-load ambient temperature if operating at lower than full-rated power capacity. The maximum allowable no-load temperature is also the maximum storage temperature for the resistor.

Example

According to Figure 1.4, a resistor rated 1 W can dissipate 1 W only if it is mounted so that air can circulate freely around it, and if $T_{amb} \leq 70\,°C$. If the ambient temperature (i.e. *the temperature inside the equipment's enclosure*) is above $70\,°C$, the power dissipation must be reduced to avoid the resistor temperature reaching a maximum temperature of $155\,°C$. The thermal resistance can also be calculated from the derating curve as $\theta_R = (155\,°C - 70°C)/P_{rated}$.

Voltage Rating

Discrete resistors are available in power dissipation ratings from 1/20 W to 2 W or more. However, for high values of resistance, *voltage*, rather than *power* is the limiting factor, ranging from 150 V for smaller packages to about 750 V for 2 W resistors. The critical resistance value, which is the boundary between the two limitations is $R = V^2 / P$, where V and P are the rated voltage and power dissipation respectively.

For a given value of voltage and power rating, a critical value of resistance can be calculated. For values of resistance below the critical value, the maximum voltage is never reached; for values of resistance above the critical value, the power dissipated is lower than the rated power.

Sometimes voltage rating, rather than power rating, is a limiting factor of a resistor's operation

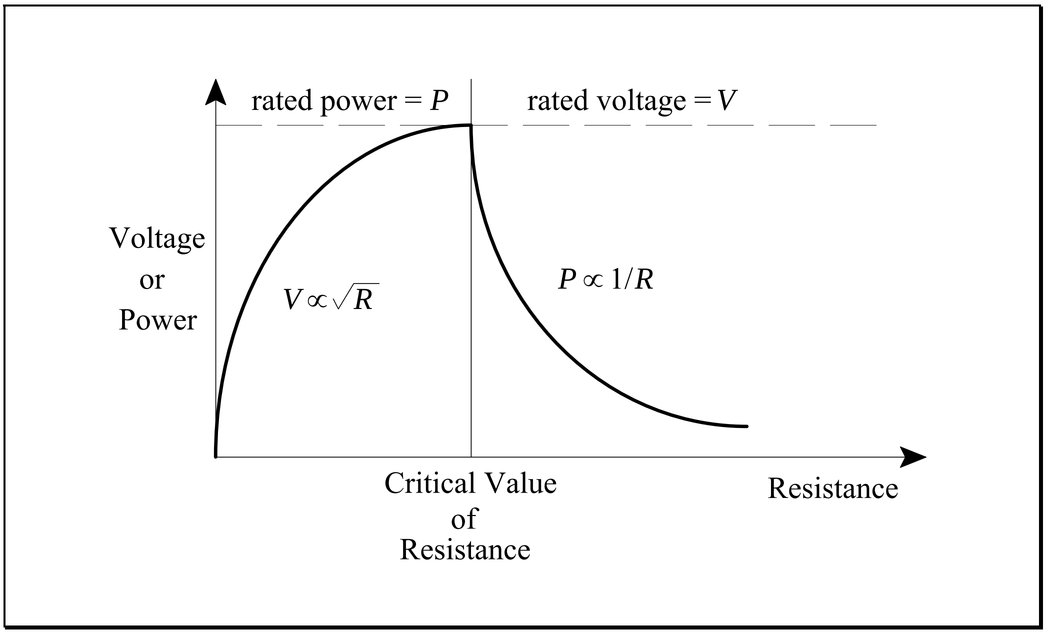


Figure 1.5 – Relationship of applied voltage and power above and below the critical value of resistance

Frequency Effects

The resistance of a resistor remains constant only at low frequencies. Frequency response is affected by distributed capacitance and inductance in the resistive path, lead inductance, capacitance from case to ground, skin effect, dielectric losses. The simplest approximate *equivalent circuit* of a resistor at high frequencies is a parallel resonant circuit, as shown in Figure 1.6, with capacitance and inductance figures shown for chip resistors of standard sizes.

Typical values of inductance and capacitance…

QUANTITY	**CHIP PROPERTIES**			
	THIN FILM	**THICK FILM**		
	1206 $R < 1\,\text{k}\Omega$	**1206**	**0805**	**0603**
Capacitance	0.05 pF	0.05 pF	0.09 pF	0.05 pF
Inductance	2 nH	2 nH	1 nH	0.4 nH

… for a resistor's equivalent circuit

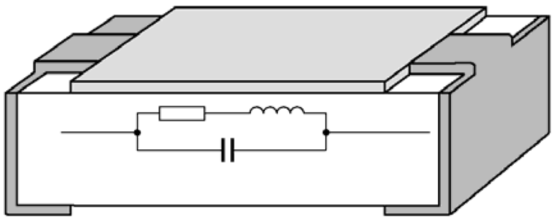
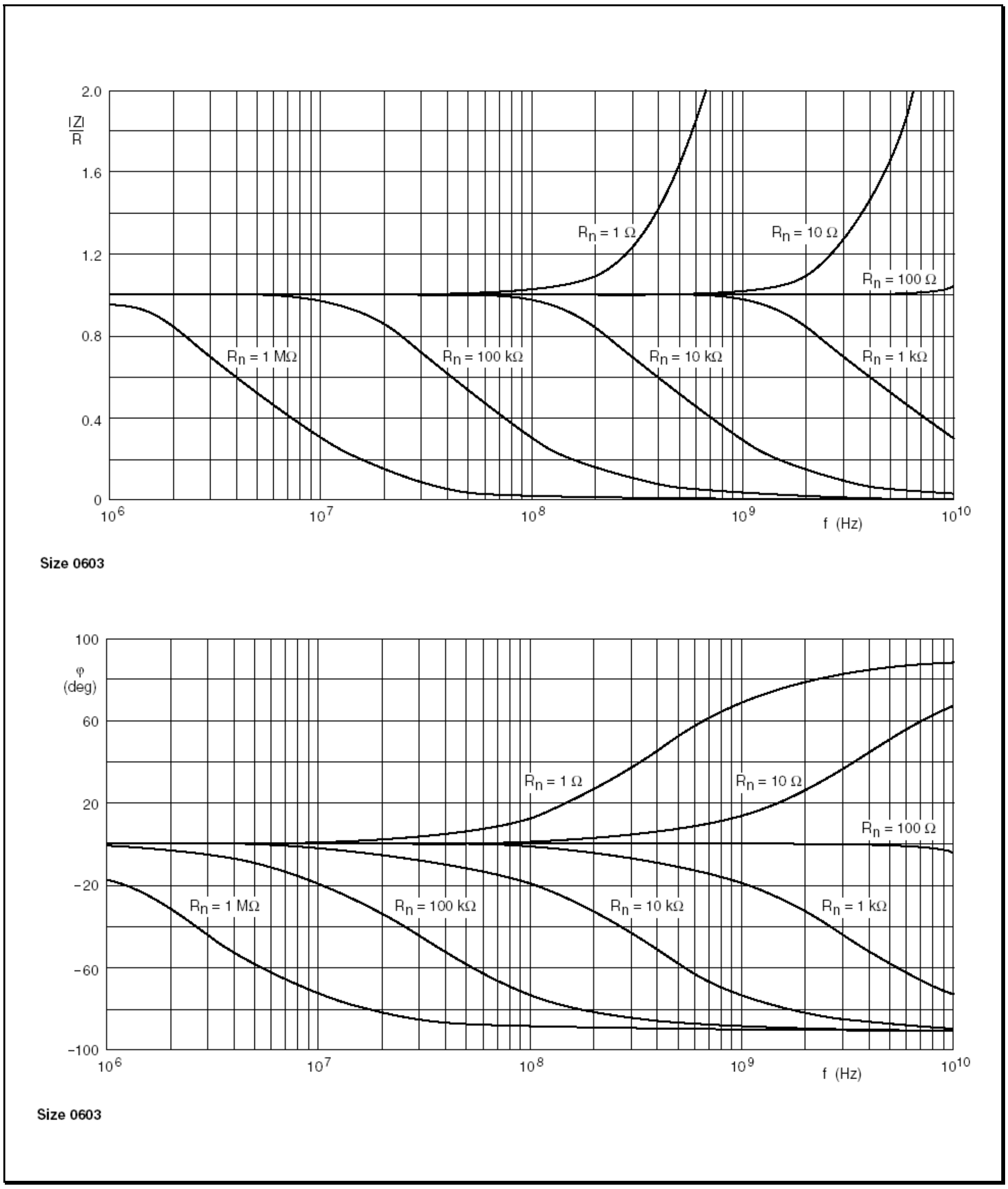


Figure 1.6 – Resistor equivalent circuit

The equivalent circuit parameters are not always supplied by the manufacturers. Instead, impedance versus frequency behaviour is given in plots of $|Z|/R$ versus frequency, and phase shift versus frequency as in the figure below:



Impedance as a function of frequency for a resistor

Figure 1.7 – Impedance as a function of frequency for a resistor

Generally the frequency response is best for low value, small size, not spiralled resistors (e.g. chip resistors). In Figure 1.7 one can see that a $10\,\text{k}\Omega$ chip resistor of size 0603 maintains its R value to about 70 MHz (a very high frequency). The response is poorest for high value, spiralled resistors. Wire-wound resistors are inductive even at audio frequencies.

Noise

All resistors generate a *thermal (Johnson) noise* voltage, caused by the random motion of the electrons. Since this source of noise is caused by the random motion of electrons, we expect that it is related to absolute temperature T. In fact thermal noise is *directly proportional* to T and, as T approaches zero, thermal noise also approaches zero. Since the noise is essentially random and follows a Gaussian distribution about 0 V, we are interested in the *RMS noise voltage*:

RMS thermal noise voltage

$$V_n = \sqrt{4kTRB} \tag{1.4}$$

where:

V_n = RMS thermal noise voltage

k = Boltzmann's constant (1.38×10^{-23} J/K)

T = absolute temperature, in Kelvin (e.g. 298K = 25°C)

R = resistance value, Ω

B = noise bandwidth, Hz

It is useful to remember for thermal noise that a $1\,\text{k}\Omega$ resistor has a thermal noise power spectral density of $V_n^2/B = 16\times10^{-18}\ \text{V}^2/\text{Hz}$. This can be written in RMS form as $V = 4\,\text{nV}/\sqrt{\text{Hz}}$ where the form $\text{nV}/\sqrt{\text{Hz}}$ is used to emphasize that the *RMS noise voltage* varies as the *square root* of the bandwidth. This noise is bothersome when the circuit handles low-level signals, e.g. at the input of a high-gain amplifier.

In addition to thermal noise, most resistors generate noise *due to the passage of current* through the resistor. This additional noise is dependent on the amount of current, the resistive material and the physical construction of the resistor. Laser trimming, which cuts a groove in the resistive material, affects the additional noise.

Typical noise levels due to current are shown below:

Typical noise levels in a resistor due to current

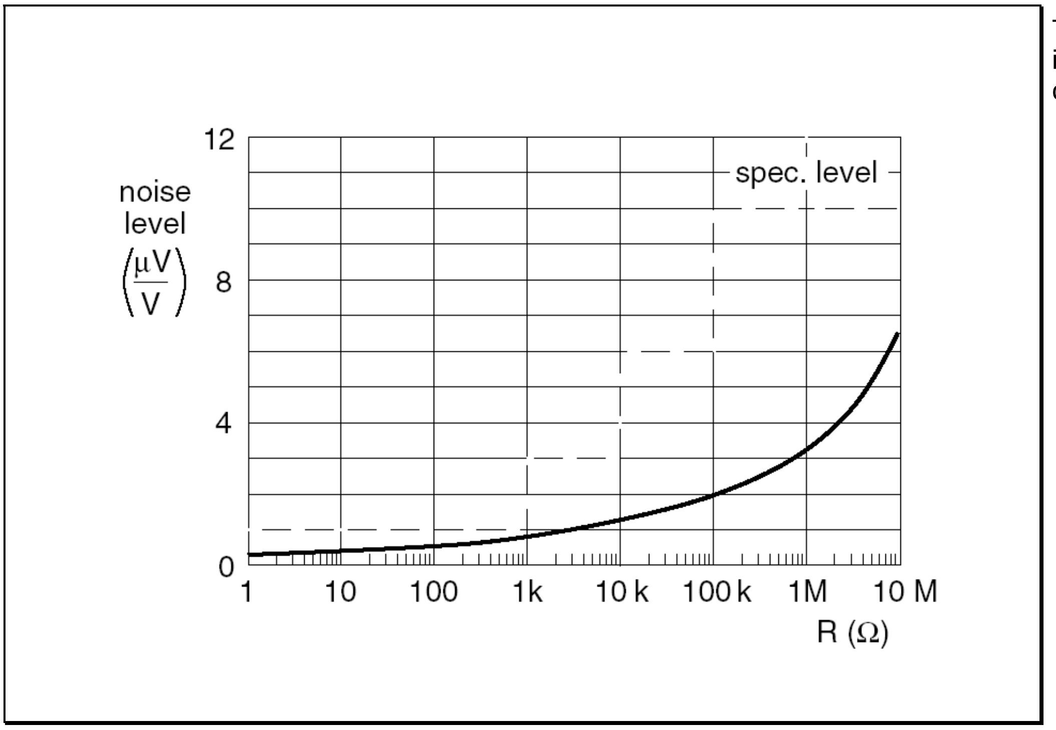


Figure 1.8 – Typical noise levels as a function of rated resistance

Reliability

Reliability of resistors is excellent, and is mostly affected by the environment

Reliability refers to the probability that a resistor will still be within specifications after a given time under certain specified conditions. Reliability is expressed in terms of failure rate in percent per thousand hours of operation, or in units of Failure-In-Time (FIT) – a FIT being 1 failure in 1 billion device-hours of operation. A typical value, for good quality film resistors, operating at an ambient temperature of 25 °C, is 2 FITs. Resistors may fail catastrophically (open or short circuit) or may drift out of specification.

Open circuits can be caused by cracked substrates, open welds, broken resistive elements and chemical corrosion. Make sure to *never stress* a resistor *mechanically*.

Short circuits may be caused by electrical breakdown (over-voltage), foreign objects and silver migration. Excessive drift is due to moisture penetration, corrosion, electrostatic discharge and transient overloading.

Derating

A policy of derating components leads to increased reliability and stability

Derating is a policy of *deliberately under-stressing components* so as to provide increased reliability and stability, e.g. using a $1/2\ \mathrm{W}$ resistor in circuit conditions demanding a $1/4\ \mathrm{W}$ dissipation is an effective and well established method of achieving a very reliable design. In most cases a component's reliability and stability improve when operating stresses like temperature, voltage and power dissipation are reduced. Unfortunately, this will usually require a larger size component.

Designers of military, medical and high-reliability equipment always derate component specifications. They account for extremes of power-supply fluctuation, ambient temperature, loss of active cooling systems, material variation, memory errors (in a digital system) due to high-energy particle radiation and the expected degree of "specsmanship" on the part of their component suppliers. Then, if they really want the product to work, designers test all components before putting them into the system.

Not every project deserves such scrutiny, but it is standard practice to allocate a healthy margin of safety in an electronic design.

Resistor Types

This section briefly examines the construction method and materials used in the manufacture of different types of resistors, and therefore shows why the different types of resistors have such different characteristics.

Carbon Composition Resistors

Carbon composition resistors are made from a mixture of powdered carbon and a resin binder, and are pressed to form a rod. The resistor is then coated with epoxy. It is the oldest type of resistor, but is still used in some applications.

Carbon composition resistors…

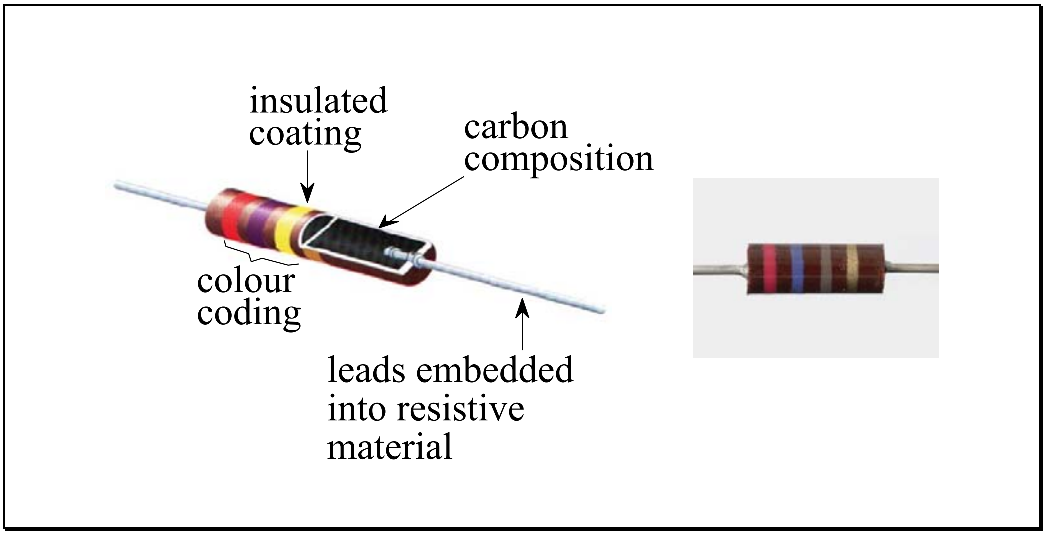


Figure 1.9 – Carbon composition resistor

The main advantage of carbon composition resistors is their pulse handling capability. They are used as surge protection resistors in medical monitoring equipment and as output resistors in defibrillators. For example, in an emergency situation where monitoring equipment is attached to a patient (e.g. ECG), it may be necessary to apply a defibrillator pulse in the case of a cardiac arrest. In such circumstances there would not be time to disconnect all of the sensitive monitoring equipment and therefore this equipment must be protected.

…have the advantage of a high pulse handling capability

Carbon composition resistors, either mounted inside the equipment or moulded into the leads of the monitoring equipment, provide protection. These resistors are required to withstand all of the pulse energy – typically around 30 J.

Advantages: Low price, wide range, low inductance, good surge capability.

Disadvantages: Poor tolerance (5% at best), poor stability, moisture sensitivity, high noise figure. Seldom used except in special applications.

Carbon Film Resistors

A film (2 μm to 100 μm thick) of pure carbon is deposited (by pyrolytic decomposition at 1000 °C) on a small ceramic rod. The two ends are covered with metal caps and wire terminals soldered. To adjust the resistance value to within the required tolerance, a process called *spiralling* is used: a helical groove is cut in the resistive layer with an automatic grinding machine or a laser, under computer control, to trim (increase) the resistance to the rated value.

Carbon film resistors are general purpose resistors that are not used often anymore due to surface mount technology

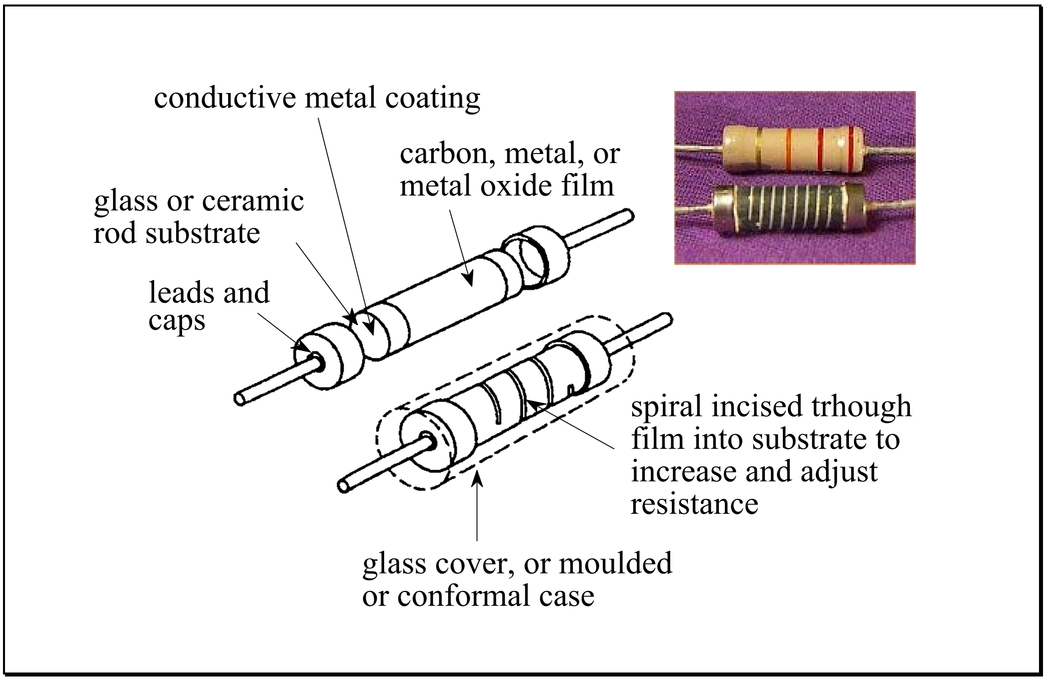


Figure 1.10 – Film resistor construction, spiralling and carbon film resistors

Unfortunately, spiralling also adds inductance to the resistor. Finally the resistor is coated with lacquer and marked. Carbon film resistors have replaced carbon composition resistors as general purpose, low cost resistors.

Advantages: Tighter tolerances (down to 0.5%), better stability, good high-frequency performance, lower noise. Power ratings 1/10 to 2 W. Distinctive feature: negative temperature coefficient of typically -200 to -300 ppm / °C.

Disadvantages: Large stray inductance, especially for high value resistance; poor surge capability. Carbon film resistors are *general purpose resistors*, used for less critical applications.

Metal Film Resistors

A film of low 'tempco' metal alloy (Ni, Cr, Au, Al) or of metal oxide is deposited on a ceramic body, then metal caps are added; a helical groove is cut to trim the value (spiralling, as in Figure 1.10), then the body is lacquered and marked.

Metal film resistors are used in precision applications that demand higher power ratings than surface mount components

Figure 1.11 – Metal film resistors

Advantages: Compared to carbon film: tolerances can be much tighter (typically 1% to 2% and can be accurate to 0.05% to 0.1%); can be of smaller size and lower power dissipation (down to 1/20 W). The 'tempco' is smaller: from ±100 ppm / °C down to ±25 ppm / °C. Stability, high frequency performance is superior.

Metal film are the resistors used in *precision* and *high precision applications*, such as gain setting in op-amp feedback networks and frequency setting in *RC* filters and oscillators.

Wire Wound Resistors

Wire wound resistors are the most accurate and stable and can handle high powers, but they are bulky and expensive

Resistive wire is wound on a ceramic rod or a glass core. Metal caps are pressed over the ends of the rod. The resistor is coated with cement or enamel (high power resistors).

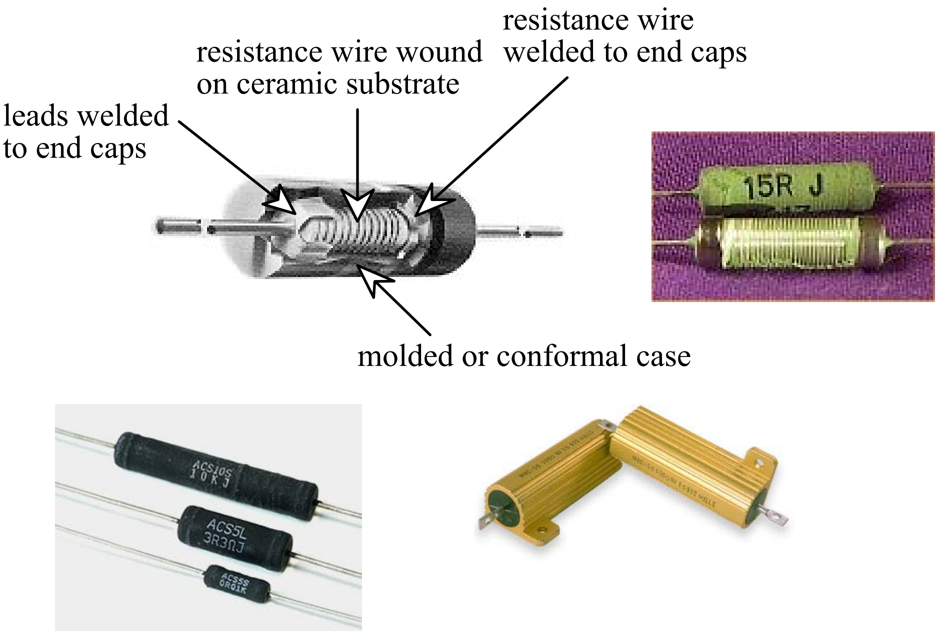


Figure 1.12 – Wire wound resistors

Advantages: High power, less than 20 W; highest precision: 0.01%; 'tempco' 0.2 to 2 ppm / °C.

Disadvantages: Large, expensive, very poor frequency response.

Chip Resistors

Chip resistors are surface mount components (SMC) and are made in either thick-film or thin-film.

In thick-film technology, a paste with metal oxides is screen-printed on a ceramic body, dried, then fired (this technology is also designated '*cermet*'). The composition of the metal oxides determines the approximate value of the resistor. Metallic end terminals are attached. The resistor is then laser trimmed to the final value and coated.

Thin-film resistors are made by sputtering (a method of vacuum deposition) the resistive material onto an insulating substrate, and then a pattern is etched into the metal layer.

Chip resistors are small and come with wide ranging characteristics

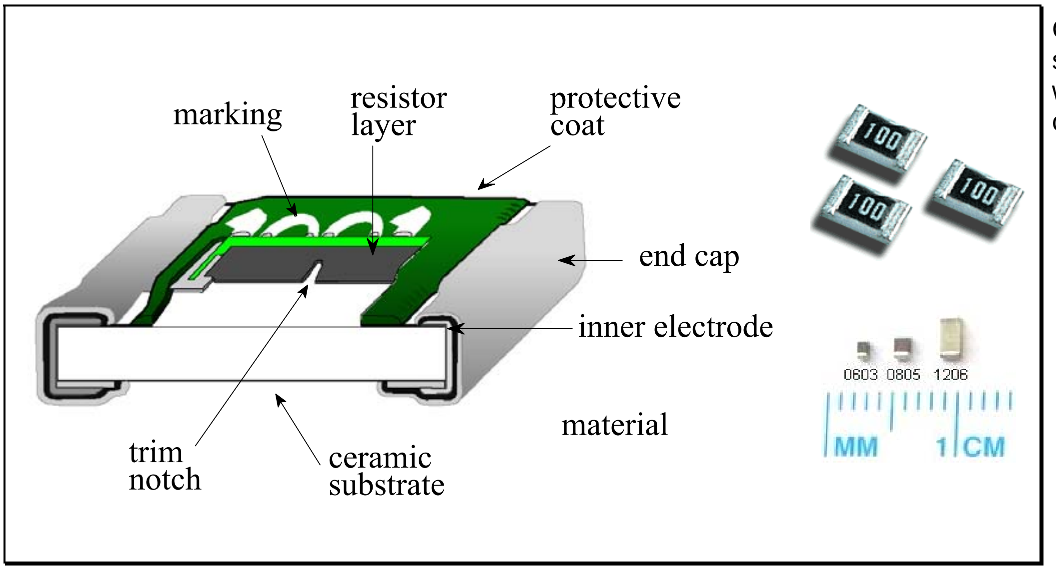


Figure 1.13 – Construction and sizes of chip resistors

Standard sizes and code designations are also shown in the table below.

Sizes of chip resistors – note how light they are too!

SIZE CODE	Length (mm)	Length (inches)	Width (mm)	Width (inches)	Mass (mg)
1206	3.2	0.12	1.6	0.06	10
0805	2.0	0.08	1.2	0.05	4
0603	1.6	0.06	0.8	0.03	2
0402	1.0	0.04	0.5	0.02	0.8
0201	0.6	0.02	0.3	0.01	0.15

Advantages: Very small size; range of values, tolerances, tempco and stability nearly as good as of metal film resistors.

Chip resistors are made both as general purpose and for precision applications. Usage has increased rapidly due to extensive adoption of surface mount assembly (SMA), where they are mandatory.

Chip resistors are by far the most common type of resistor in a modern circuit

All *modern circuits* now make use of chip resistors, with leaded resistors reserved for special applications. They are by far the most common type of resistor, and were a necessary development in achieving the miniaturization of everyday electronic devices, such as the mobile phone and MP3 player.

Thick film has the advantages of lower cost, of being able to handle more power, and of being able to service a higher range of ohmic values.

Thin film has the advantages of tighter absolute and ratio tolerances and more environmentally stable components with lower noise and tighter tempco than thick film. Thin film technology is used wherever precision resistors are needed.

Parameter	**Thick-Film**	**Thin-Film**
Resistance	3 Ω to 20 MΩ	10 Ω to 100 kΩ
Resistance Tolerance	0.5%, 1%, 2%, 5%	0.01% to 5%
Tempco	±100ppm/°C	±25ppm/°C
Tempco Tracking	100ppm/°C	5ppm/°C
Operating Temperature	-55°C to +125°C	-55°C to +125°C
Max. Operating Voltage	100 V	50 V
Power	0.125W to 0.5W	0.1W to 0.2W

Table 1.1 – Thick-Film vs. Thin-Film Resistors

Resistor Networks

Resistor networks can be discrete components in a single package, but typically are thick- or thin-film networks. Most leaded networks are in a Dual In-line Package (DIP) or a Single In-Line Package (SIP). Resistor networks for SMA are also readily available. Tolerances can be very tight, like for any metal-film or chip resistor. Particularly, the *tolerance on resistance ratios are extremely tight*, a few ppm / °C, which makes them extremely useful as accurate voltage dividers, attenuators, feedback networks for accurate gain op-amps and instrumentation amps, ladder networks for DACs and ADCs etc. other applications are digital pull-up / pull-down terminations in logic circuits.

Resistors networks save space but also provide matching component values

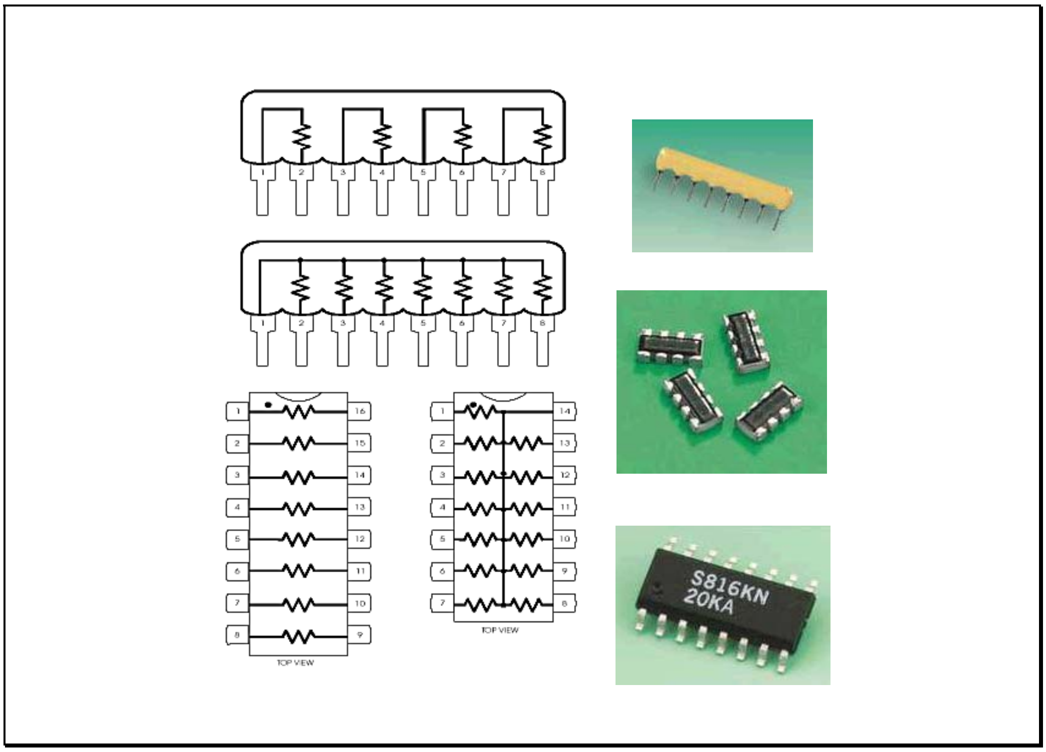


Figure 1.14 – Resistor networks

Choosing Resistors

The table below provides comparative data for different types of resistors.

Characteristic	Carbon Composition	Carbon Film	Metal Film	Wire Wound	Chip (thick- and thin-film)
Resistance	1 Ω to 100 MΩ	1 Ω to 10 MΩ	1 Ω to 10 MΩ	0.1 Ω to 10 MΩ	0.1 Ω to 10 MΩ
Tolerance at purchasing	5% to 20%	0.5% to 10%	0.1% to 10%	0.01% to 1%	0.5% to 10% Th F 0.01% to 10% Tn F
Power dissipation	1/8 W to 2W	1/10 W to 2 W	1/20 W to 2 W	0.1 W to 20 W	50 mW to 500 mW
Effect of soldering	2%	0.5%	0.05%	0.01%	0.25% Th F 0.05% Tn F
Frequency limit	1 MHz	100 MHz	400 MHz	50 kHz	100 MHz to 500 MHz
Tempco (ppm / °C)	-800 to +1600	-200 to -1000	±20 to ±200	±20 to ±200	±25 to ±100
Reliability	Good	Good	Good	Poor	Good
Stability	Poor	Good	Good	Very good	Good
Approx. cost	0.2 c	0.05c to 1c	1c to 4 c	50 c to $1	0.1 c to $10
Advantages	Low cost High reliability Surge capacity	Lowest cost	Good accuracy Good stability Small size	Highest accuracy and stability	Smallest size Typical for SMA
Disadvantages	Poor accuracy and stability	Relatively large tempco	Poor surge capacity	Very expensive Poor frequency response	

Table 1.2 – Features of Common Resistors

Summary of Resistor Characteristics According to Type

Carbon composition resistors have good pulse and surge response, but poor accuracy and stability. They tend to be replaced in most applications by carbon film resistors.

Carbon film resistors are used for general purpose applications, (e.g. consumer electronics or non-critical applications) where very high stability in time and small change with temperature are *not* required (the tempco is rather large, over -300 ppm / °C).

Metal film resistors are very accurate (readily available with 0.1% tolerance) and stable, with a very low temperature coefficient (from ± 10 to ±100 ppm / °C). They are used as precision resistors in professional applications.

Chip resistors are either metal film or of the 'cermet' type, and have accuracy and stability specifications close to those of other film resistors. Chip resistors are very small in size and are surface mount components (SMC), intended for surface mount assembly (SMA). Usage of chip resistors is now almost universal in all large volume electronic products. The main limitation is the low power dissipation (to about 1/2 W).

Wire wound resistors are the most accurate and stable resistors, but are also the largest and most expensive. They also have a very poor frequency response. Usage is limited to very high precision or high power applications at power (50Hz) and low frequencies.

Resistor networks are used to replace sets of chip resistors in large-volume produced electronic products. Handling and mounting components on a PCB is often more expensive than the components themselves. The use of the smallest SMC is sometimes limited by the difficulty of picking and placing them correctly. The amount of handling and mounting of small SMC resistors can be reduced by combining a number of resistors in a network, produced in thick- or thin-film, on a single substrate, and mounted as a single multi-pin component. They are also used in circuit demanding extremely accurate and stable resistance ratios (op-amp gain settings, ADCs, DACs etc).

Capacitor Definitions and Basic Relations

Capacitors are the second-most-used passive component in electronic circuits (after the resistor). There is a wide variety of capacitor types, with substantial differences between their characteristics, depending on the dielectric and technology used. Each type has its own combination of features and drawbacks. We will examine, from a design engineer's viewpoint, the available choices among the most used types:

- *Film capacitors* with a number of different dielectric films
- *Ceramic capacitors* of *type I* (low ε_r) or *type II* (high ε_r) ceramic
- *Electrolytic capacitors* with aluminium or tantalum

Each type of capacitor is recommended for some applications and can be quite inadequate for some other applications. It is essential for any electrical engineer to be aware of:

- how the characteristics of capacitors are expressed
- the basic characteristics of various types of capacitors
- the main areas of application of each type of capacitor

Capacitance is defined as the *ratio of charge to voltage* between two conductors:

$$C = \frac{q}{v} \tag{1.5}$$

Of course:

$$v = \frac{q}{C} = \frac{1}{C}\int i\,dt \tag{1.6}$$

where *i* is the current charging or discharging the capacitor.

The instantaneous energy stored in a capacitor is:

$$E = \frac{1}{2} C v^2 \qquad \text{or} \qquad E = \frac{q^2}{2C} \tag{1.7}$$

The *reactance* of a capacitor is given by:

$$X_C = -\frac{1}{2\pi f C} \tag{1.8}$$

The capacitance of a parallel plate capacitor (neglecting fringing effects) is:

$$C = \frac{\varepsilon_r \varepsilon_0 A}{d} \tag{1.9}$$

where:

ε_r is the relative permittivity of the dielectric

ε_0 is the permittivity of vacuum: $\varepsilon_0 = 8.85419 \times 10^{-12}$ $[\mathrm{Fm^{-1}}]$

A is the area of overlap of the plates $[\mathrm{m^2}]$;

d is the thickness of the dielectric [m]

Capacitors should be as small as possible. Since most needs are for low-voltage devices, much of the emphasis in capacitor manufacture is on thin and uniform dielectric, and on methods for obtaining a large overlap-area to volume ratio.

Film capacitors use flat-plate electrodes and dielectric films with a rather small relative permittivity, $\varepsilon_r = 2 \ldots 5$. They have excellent electrical characteristics, but are rather bulky and expensive at capacitance values above 0.1 to 1 μF.

Ceramic capacitors attain much larger capacitance / volume ratios by using dielectrics with a large relative permittivity, ε_r from about 100 to over 100,000.

Electrolytic capacitors have the highest capacitance / volume ratios, achieved by using chemically etched electrodes, with very large effective surface areas, and very thin dielectric films.

Ceramic class II capacitors and electrolytic capacitors show higher losses and generally poorer electrical characteristics then film capacitors. Their use is recommended for applications where large capacitance values are required, such as decoupling and rectifier filtering, because they are much smaller in size and their cost is lower.

Capacitor Characteristics

The characteristics and the features to consider when choosing a capacitor are: capacitor value, tolerance on value, rated voltage, surge voltage, leakage current, insulation (leakage) resistance, maximum current, rated pulse rise-time and ripple current. For insight into these factors, the materials and construction of the various capacitor types must be considered.

Rated Capacitance and Tolerance on Value

Component tolerances are tolerances at time of purchase

Like resistors, each capacitor has a rated (nominal) capacitance value and % tolerance on this value. The *preferred capacitance values*, depending on tolerance, are chosen based on the same IEC E-Series as used for the resistors. As with resistors, a precision capacitor with a tighter tolerance on value will also be more *stable in time* and will change less with temperature, i.e. will have a smaller *temperature coefficient of capacitance*.

Rated Voltage

The maximum working voltage of a capacitor is the sum of the DC voltage plus the AC peak voltage which may be applied continuously to its terminals. Operating a capacitor at a voltage lower than its maximum working value extends its life.

Surge Voltage

There is a maximum safe voltage to which a capacitor can be subjected under any combination of circumstances over a short period of time. This is the DC surge voltage rating. Above the surge voltage, the dielectric of the capacitor will break down. Normally, testing for surge voltage involves applying a signal several volts above the rated working voltage. It is applied via a 1 kΩ series resistor in repeated cycles of 0.5 minutes on and 5 minutes off.

Leakage Current

A relatively small direct current flows through a capacitor when a voltage is impressed across it. Electrolytic capacitors have the largest leakage currents.

Insulation (Leakage) Resistance

This is a measure of the ability of the charged capacitor to withstand leakage of DC current. For capacitors of less than 10 nF the insulation resistance should normally exceed 100 GΩ.

The leakage resistance, R_l depends on the resistivity ρ, area *A*, and thickness *d* of the capacitor's dielectric:

$$R_l = \frac{\rho d}{A} \tag{1.10}$$

Of course, *d* and *A* are the same as those used to calculate the capacitance. Hence, a capacitor (of a given type, construction and rated voltage) which has a larger capacitance, will have a lower value of leakage resistance, and vice-versa. Therefore, to provide a general specification for the leakage of capacitors of a given type and construction, usually the leakage time constant $\tau_l = R_l C$ is specified. The value of the leakage resistance for a particular capacitance value can then be calculated easily.

Maximum Current

Exceeding the maximum specified current through a capacitor can lead to fusing of the internal or external terminals, or of the capacitor's electrodes (sometimes very thin metal films).

Under *steady-state AC conditions* the values of current and voltage in an ideal capacitor are related by:

$$|\mathbf{I}| = 2\pi f C |\mathbf{V}| \tag{1.11}$$

where $|\mathbf{I}|$ and $|\mathbf{V}|$ are the RMS (or peak) values of current and voltage, respectively, and f is the frequency in Hz.

One can see that, besides a maximum allowed surge voltage across a capacitor, (set to avoid breakdown of the dielectric), in some cases there might be a *frequency dependent maximum allowed AC voltage across a capacitor, to avoid an excessive current*.

Rated Pulse Rise-Time

Since the current through a capacitor is the time derivative of charge, one can write:

$$i = \frac{dq}{dt} = C\frac{dv}{dt} \tag{1.12}$$

This equation points to a *limitation in maximum allowed rate of change of the voltage* (*pulse rise-time* or *voltage pulse slope*) across the capacitor, $dv/dt|_{\max}$. If the rate of change dv/dt exceeds the specified limit, the large resulting current might damage the terminals or the electrodes. The rated voltage pulse slope multiplied by the capacitance gives the peak allowed current through the capacitor.

Ripple Current

Electrolytic capacitors are frequently used in rectifier filters, where they are subjected to an AC voltage superposed on a DC voltage. Because of the ohmic and dielectric losses, the resulting AC current increases the temperature of the capacitor. The maximum value of the AC RMS current that may be applied to an electrolytic capacitor is termed *maximum ripple current*. The capacitor should be able to withstand this ripple current at 100 Hz up to 85 °C. The higher the ripple current the shorter the capacitor's life.

Types of Dielectrics

A real capacitor dissipates energy as well as stores it. This energy loss, which appears as heat, is a result of several effects: the *finite conductivity of the lead wires, electrode contacts and electrodes*; the *finite resistivity of the dielectric*, which results in the DC *leakage current*; and *AC dielectric losses*, which are determined by the polarisation mechanism within the dielectric and are frequency dependent.

Dielectric materials can be classified as *non-polar*, in which there are no dipoles before the electric field is applied; and *polar*, in which dipoles pre-exist the electric field.

Non-Polar Dielectrics

When an electric field is applied to a *non-polar dielectric*, its atoms or molecules are deformed, and an induced dipole moment appears. In non-polar dielectrics losses are very small up to very high frequencies. The two varieties of polarisation are:

- **electronic (optical)**: the cloud of electrons is displaced relative to the nucleus in the presence of an electric field. This mechanism shows no losses to $f = 10^{15}\text{ Hz}$ and is typical for air, rare gases and polystyrene.

- **ionic**: in molecules having ionic bonds, the positive ions are displaced relative to the negative ions in the presence of an electric field. The upper frequency of ionic motion is about 10^{14} Hz. An example of an ionically bonded dielectric is polytetrafluoroethylene (PTFE), also known by DuPont's brand name as Teflon.

Polar Dielectrics

Polar dielectric materials contain permanent dipoles whose orientation, in the absence of a field, is random. An electric field aligns the dipoles, and electric charges are attracted to the surface of the material. When an AC electric field is applied, the dipoles are reoriented at each cycle. The internal friction of the dipoles inside the material leads to energy losses. Polar dielectrics produce generally the highest AC losses, that increase significantly with frequency. The upper frequency of this dipole motion is within 10 kHz to 1 GHz, depending on the material. There are three main types of polar dielectrics:

- **molecular**: a permanent dipole moment exists as a result of the molecular structure.

- **orientational**: the dipoles are larger than a single molecule. Examples: Transformer oils, certain ceramics and electrolytic dielectrics.

- **interfacial (dielectric absorption)**: In some dielectrics, defects such as missing atoms, dislocations and impurity centres, can trap free electrons moving in the field near the electrodes of the capacitor. A local accumulation of charge in the dielectric (*dielectric absorption*) induces an image charge in the electrode. This charge is not released instantly when the field disappears. The mechanism operates from DC to about 100 Hz. It can cause the re-appearance of a charge on a capacitor immediately after it has been discharged, due to release of the trapped charge. Among capacitors showing dielectric absorption: aluminium electrolytic, paper, polyester film, mica.

Capacitor Models

The simplest model to account for capacitor AC losses is an *Equivalent Series Resistor* (ESR) R_s in series with an ideal capacitor C_s as shown in Figure 1.15a below:

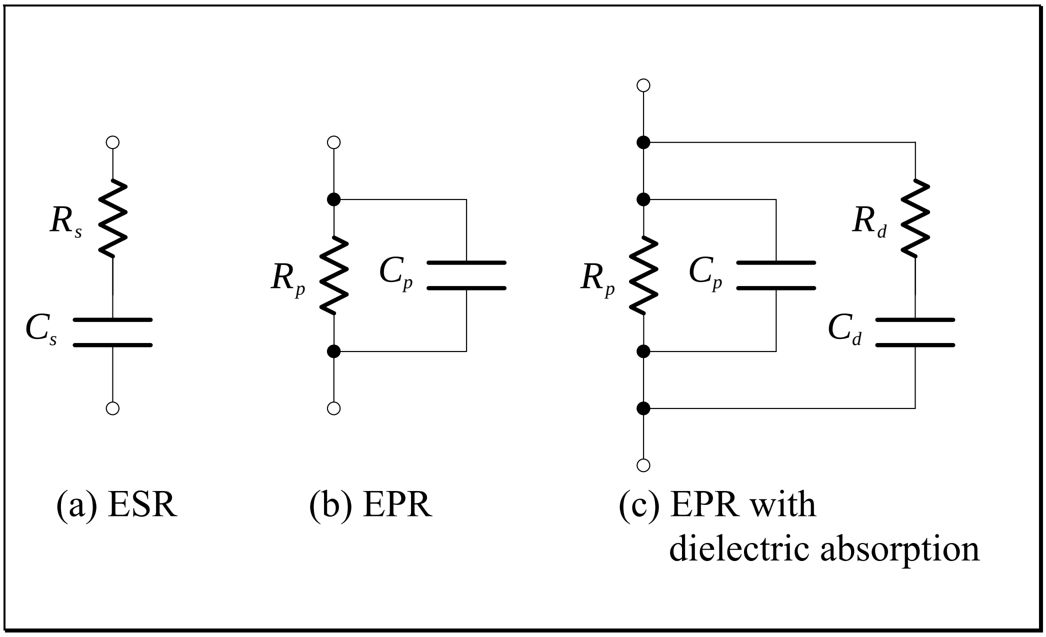


Figure 1.15 – Simplified Models of a Capacitor

In this model, all internal series resistors of a capacitor are lumped into the ESR to represent the losses in the terminals and dissipation in the dielectric.

Another model, useful to represent both AC dielectric losses and DC leakage, is the *Equivalent Parallel Resistor* (EPR) equivalent circuit, with R_p parallel to an ideal capacitor C_p (Figure 1.15b).

Note that C_s is not equal to C_p, and the components in the model generally are frequency dependent.

The model of Figure 1.15c represents *a capacitor with dielectric absorption*. The [C_d in series with R_d] combination, in parallel to [C_p and R_p], models this effect. C_d is the capacitance corresponding to the charge absorbed in the dielectric; R_d in series with C_d accounts for the (relatively long – a few seconds) time constant of the charge release from the dielectric.

The conversion from parallel to series and from series to parallel model parameters can be made using the following relations:

$$R_s = \frac{R_p}{1 + R_p^2\omega^2 C_p^2} \qquad C_s = \frac{1 + R_p^2\omega^2 C_p^2}{R_p^2\omega^2 C_p} \tag{1.13}$$

and:

$$R_p = R_s + \frac{1}{R_s\omega^2 C_s^2} \qquad C_p = \frac{C_s}{1 + R_s^2\omega^2 C_s^2} \tag{1.14}$$

Quality of a Capacitor

There are different ways to express the quality of a capacitor, i.e. to show how small its energy losses are relative to the energy stored. These can be understood by referring to Figure 1.16:

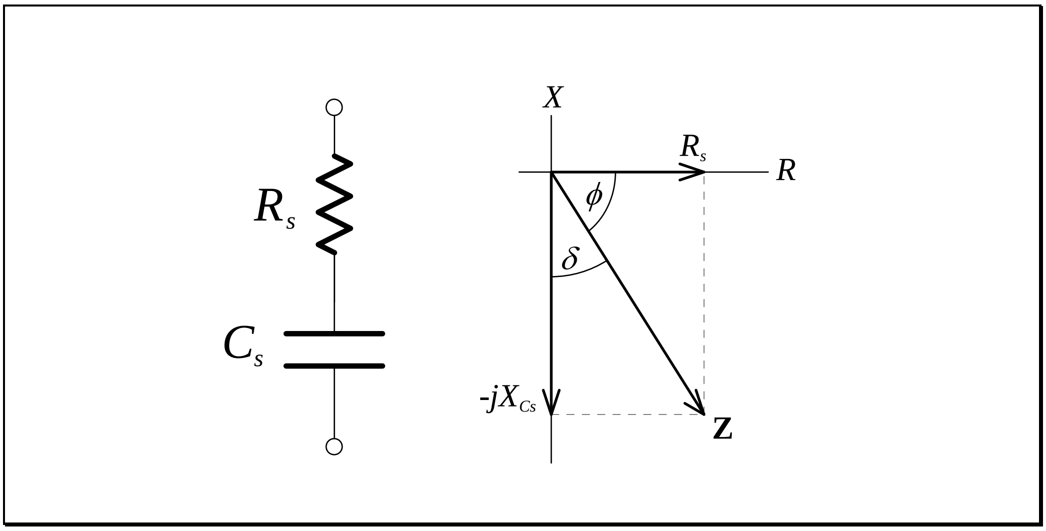


Figure 1.16 – Losses of a Capacitor

The *quality factor*, or Q, of a network is defined as 2π times the ratio of the maximum stored energy to the energy dissipated per period at a given frequency. The higher the value of Q, the closer to ideal a capacitor is.

Quality factor for a capacitor is therefore defined as:

$$\boxed{Q = \frac{X_{C_s}}{R_s} = \frac{1}{2\pi f R_s C_s} = 2\pi f R_p C_p} \tag{1.15}$$

Quality factor defined

Bridges often measure the *Dissipation Factor DF* of a capacitor, which is the reciprocal of *Q*, and is often expressed in %. We can write:

$$\boxed{DF = \frac{1}{Q} = \tan\delta = \cot\phi = 2\pi f R_s C_s} \tag{1.16}$$

Dissipation factor defined

The *loss angle* δ is the deviation of the capacitor's impedance phasor angle from 90°, i.e., from the phase of an ideal capacitance (see Figure 1.16).

The *Power Factor PF* can also be used to specify the losses. The Power Factor is defined as the cosine of the phase angle between the voltage and current vector:

$$\boxed{PF = \cos\phi = \sin\delta = \frac{R_s}{|\mathbf{Z}|}} \tag{1.17}$$

Power factor defined

For low-loss dielectrics, $\tan\delta$ and $\cos\phi$ are approximately equal, and can be used to express dielectric loss. In a "low-loss" capacitor, the dissipation factor is small, typically less than 0.1%.

Equivalent Series Resistance (ESR)

The Equivalent Series Resistance is an important parameter when the capacitor is used for decoupling purposes. The ESR can be obtained from:

$$\mathrm{ESR} = \frac{\tan\delta}{2\pi f C_s} \tag{1.18}$$

Series Resonant Frequency (SRF)

The simplified models shown in Figure 1.15 describe well the capacitor's behaviour at relatively low (at most audio) frequencies. A very accurate model over a wide frequency range is difficult to produce, because capacitor parameters are distributed. A reasonably accurate high frequency model is shown below:

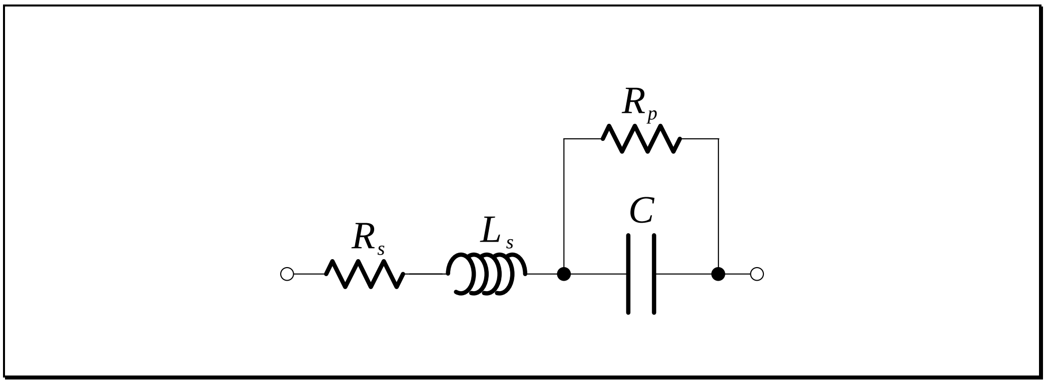


Figure 1.17 – High-Frequency Model of a Capacitor

The dielectric losses are represented by R_p and the conductor (series) losses by R_s. The series inductance L_s models the *inductance of the leads and of the capacitor structure itself*. Leadless chip capacitors and ceramic capacitors generally show smaller inductance.

If R_p is neglected, the capacitor behaves as a typical *series RLC resonant circuit*, whose impedance versus frequency curve is shown below:

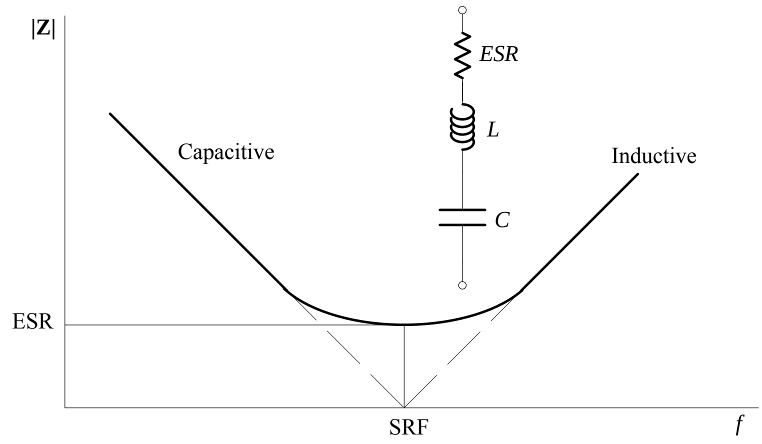


Figure 1.18 – Simplified High-Frequency Model of a Capacitor

The minimum impedance of the capacitor, reached at the Series Resonant Frequency (SRF), is the Equivalent Series Resistance (ESR). Above the SRF, $|\mathbf{Z}|$ increases with f, i.e. *the capacitor behaves as an inductor*!

For a particular family of ceramic capacitors, the impedance curves vary:

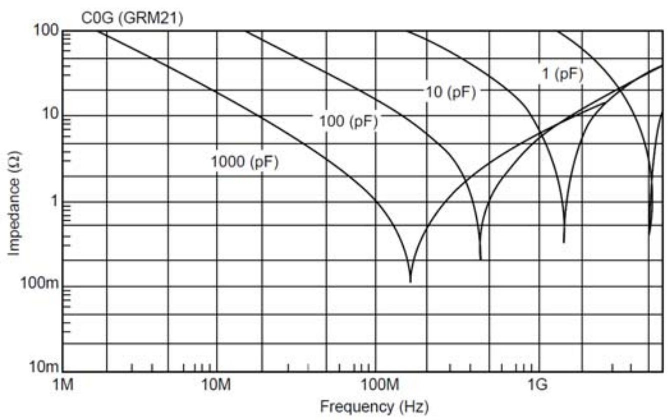


Figure 1.19 – Impedance versus Frequency Variation

Figure 1.19 shows that in a capacitor family (same type and construction), *the larger the capacitance, the smaller the Series Resonant Frequency* (SRF).

Film Capacitors

Film capacitors are very widely used. The availability of extremely thin films and the wide variety of materials provides the versatility for a variety of applications including filtering, coupling, bypassing, timing, and noise suppression.

Film capacitors can operate at relatively high temperature, have high insulation resistance, have good stability and are available in tolerances as tight as 0.5%. The self-healing property of metallised films is useful in some applications, where surge voltages might happen occasionally. Three main construction techniques are used: wound foil, meta1lised film, stacked film.

Wound Foil Capacitors

A wound foil capacitor is made of two aluminium foils separated by sheets of dielectric and rolled into a compact cylinder. Contacts to foil are made by welding or inserting tabs during winding (Figure 1.20a) or, in the extended foil type, by allowing the foils to extend beyond the dielectric on opposite sides (Figure 1.20b). After winding, leads are attached to the tabs or exposed foil edges. After the leads are attached the assembly is moulded, potted, dipped in a protective resin coating or sealed in a metal can.

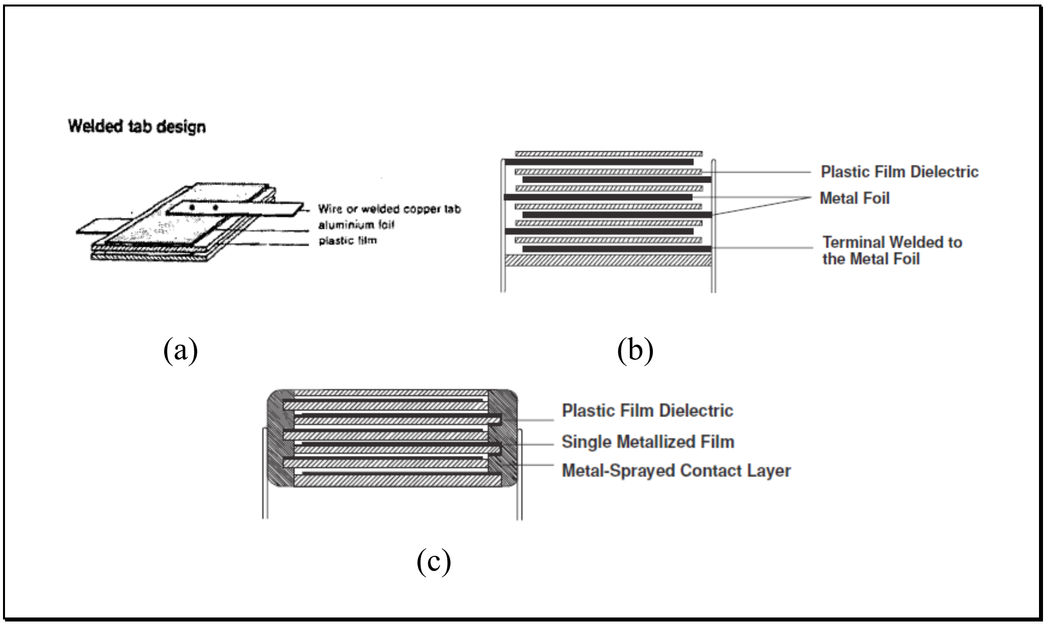


Figure 1.20 – Film Capacitors

Metallised Film Capacitors

Metallised film capacitors are made by vacuum deposition of aluminium 0.1 µm thick directly onto the dielectric film. The pattern is basically that of an extended foil configuration.

After winding, contact to each end of the roll is made with a fine spray of molten metal, to which leads are finally soldered (Figure 1.20c). This construction reduces the volume of low-voltage large-value capacitors and provides a voltage breakdown property known as 'self-healing' or 'self-clearing'. During the 'healing stage' of the manufacturing process, the rated voltage is applied to the capacitor. If a defect should occur in the dielectric, the discharge current through the defect generates enough heat to vaporise the thin metal electrodes. This isolates the defect site and permits restoration of insulation. Self-healing also happens under moderate surge conditions in normal operation of metallised film capacitors (in the wound foil construction, the electrodes are much thicker, and a breakdown results in a permanent short). Self-clearing requires a minimum energy of 10 to 50 pJ. Low values of metallised film capacitors used in low-voltage high impedance applications may be shorted, and fail instead of clearing.

Stacked Film Capacitors

Stacked film capacitors are of a newer construction. Metallised films are wound onto a large cylinder, then cut into rectangular sections. Connections are made to alternate electrodes on opposite ends, resulting in a stack of metallised film connected in parallel. The structure is similar to that of multilayer ceramic capacitors, except the dielectric is much thinner. This compensates for the low permittivity of film dielectrics and produces a much better capacitance/volume ratio. Stacked film chip capacitors are an alternative to multilayer ceramic capacitors in some applications.

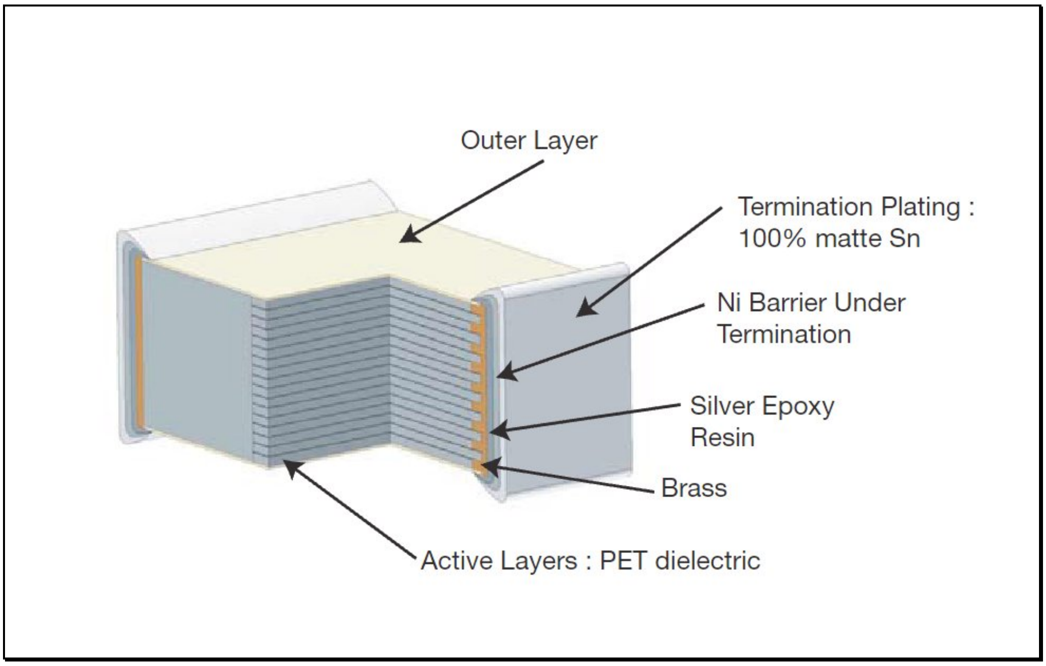


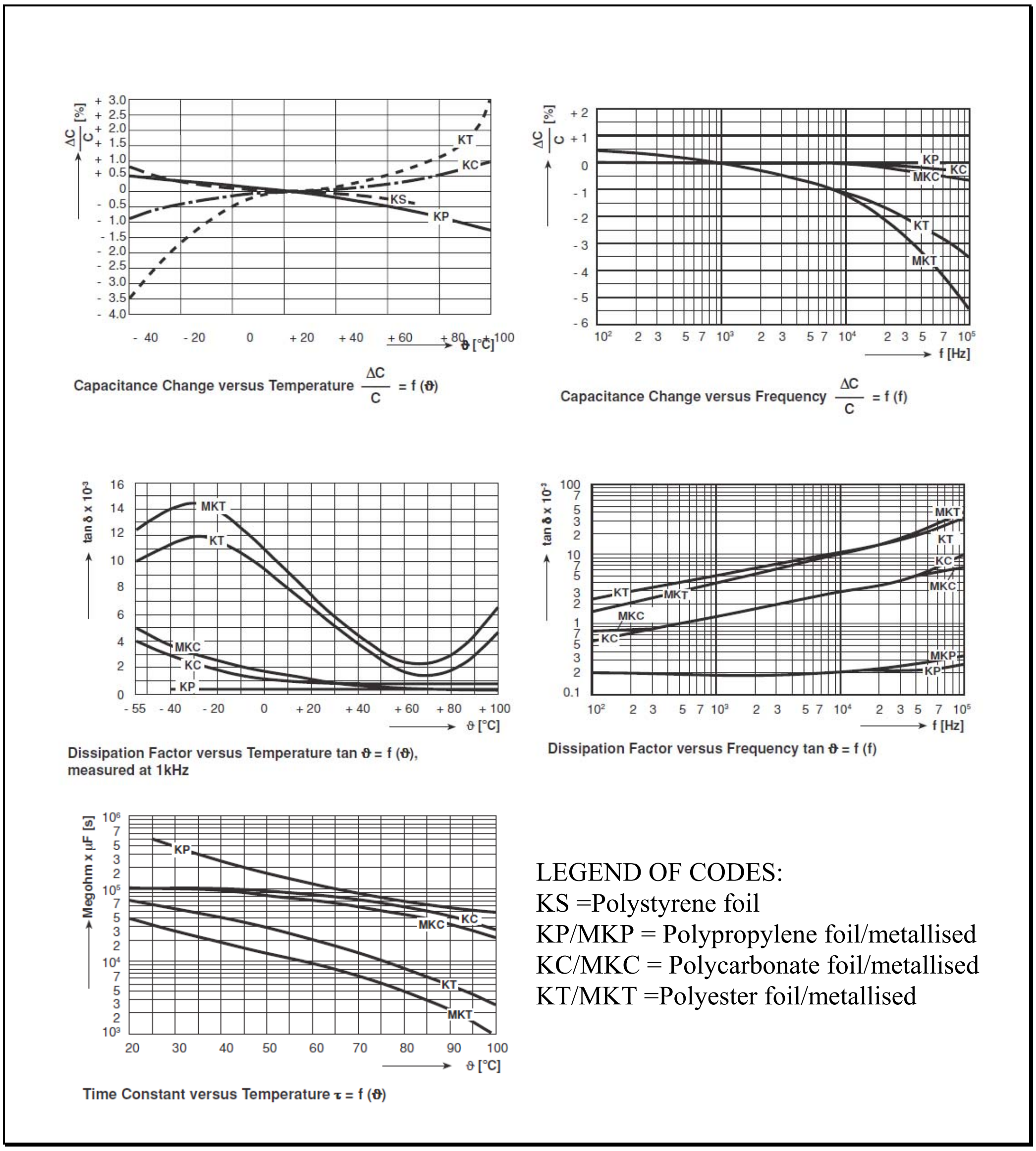
Figure 1.21 – A Stacked Film Chip Capacitor

Basic Properties of Film Capacitor Dielectrics

Film capacitors are available in values of 100 pF to 1 μF (seldom to 10 μF) and in voltage ratings from 50 V to several thousand volts. Tolerances are 20% down to 0.5% for some types. Dissipation Factors (DF) are less than 1% at 25 °C. Films with low DF at room temperature have generally low DFs over the entire temperature range. Insulation resistance generally decreases with temperature, sometimes by up to two or three orders of magnitude at 125 °C. Film capacitors can be used at high frequencies, depending on the size and length of the leads. The basic properties of film dielectric materials are listed in Table 1.3 and Figure 1.22 below.

Dielectric	Code	Permit-tivity ε_r	DF 1 kHz 25 °C %	DF 1 MHz 25 °C %	Max. Temp °C	$\Delta C/C$ @ -40 °C %	$\Delta C/C$ @ 100 °C %	Leakage Time Const. (25 °C) MΩ x μF
Paper	P	3	0.5	3	100	-8	4	40,000
Polyester	KT	3.3	0.5	2	125	-4	3	100,000
Polycarbonate	KC	2.9	0.12	1.1	125	-0.7	1	300,000
Polystyrene	KS	2.4	0.02	0.04	85	0.8	-0.4 (70 °C)	500,000
Polypropylene	KP	2.2	0.02	0.04	100	1	-1.5	100,000
Polysulfone (Polyphenylene sulfide)	KPS	3	0.1	0.18	150	0.6	-0.7	100,000
PTFE or Teflon (polytetra-fluoroethylene)		2.1	0.02		150	1	-2	5,000,000

Table 1.3 – Basic Properties of Film Capacitor Dielectrics



LEGEND OF CODES:
KS =Polystyrene foil
KP/MKP = Polypropylene foil/metallised
KC/MKC = Polycarbonate foil/metallised
KT/MKT =Polyester foil/metallised

Figure 1.22 – Changes in Capacitance and Loss angle with Temperature and Frequency of Film Capacitors

Tolerance

The tolerance of film capacitors is given by a letter – some of the more common are shown in the table below:

	Code	B	C	D	F	G	J	K	M	Z
Tolerance	*C* < 10 pF ±pF	0.1	0.25	0.5	1	2				
	C > 10 pF ±%			0.5	1	2	5	10	20	+80 -20

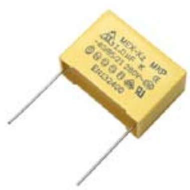
Table 1.4 – Common Tolerance Codes of Film Capacitors

Recommended Applications for Film Capacitors

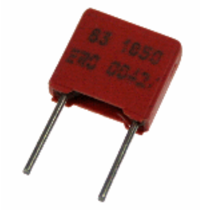
From Table 1.3 and Figure 1.22 one can see that the films showing the lowest losses at high frequencies and the best temperature stability are polystyrene, polypropylene, polycarbonate and PTFE (Teflon).

Polystyrene film (KS) has excellent electrical characteristics. The loss angle of polystyrene film capacitors is low over a wide frequency range but the electrodes degrade performance with higher capacitance values as frequency increases. A device under 1 nF will typically rise from $\tan\delta < 1\times10^{-4}$ at 1 kHz to less than 1×10^{-3} at 1 MHz. For values between 10 and 100 nF, in a typical example, the power factor ($\tan\delta$) will be as low as 1×10^{-4} at 1 kHz, but at l MHz, the power factor might increase to 5×10^{-3}. As a major drawback, the maximum ambient temperature of KS capacitors is only 85 °C. Also, capacitors over 10 nF tend to be rather bulky. Solvents affect the film, so sealed encapsulation is sometimes needed.

Polypropylene film (KP) is another excellent choice for precision and HF applications. The dissipation factor can stay below 1×10^{-3} to over 10 MHz. Polypropylene has a higher operating temperature (125 °C) and capacitors can be made smaller.



Polystyrene and polypropylene films are the first choice for high frequency, high precision, or high voltage applications due to their very low dissipation factor, low temperature coefficient and high dielectric strength. KS and KP capacitors are recommended for circuits where capacitance stability and low losses are critical, e.g. frequency dependent applications such as accurately tuned filters, oscillators, timers, integrators, ADCs and VFCs. For circuits of the same category, operating at higher frequencies of, say, above 1 to 10 MHz, ceramic class 1 capacitors would probably be preferable.



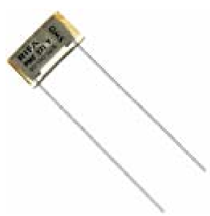
Polycarbonate (KC) film has a relatively low loss angle, but the loss angle increases slightly more with frequency than the films mentioned above. Polycarbonate shows a small change of capacitance with temperature and can be made as a thinner film, so devices are generally smaller.

PTFE (Teflon) film has an extremely high insulation resistance, up to a high temperature, and is therefore excellent when very low leakage is required. PTFE also maintains low dielectric losses up to microwave frequencies. PTFE capacitors are of higher cost than the other film capacitors. They are used mainly in dedicated applications, e.g. microwave, high temperature, or where extremely low leakage is required, where the other films cannot compete.

Polyester film (KT) capacitors have higher losses and are less stable then the other film capacitors, but they are of lower cost and smaller size, because of a slightly higher relative permittivity.

Polyester and polycarbonate dielectrics are used in general purpose applications where a small DC bias voltage and small AC voltages at low frequencies are usual. Polyester film capacitors (so-called 'green caps') are recommended mainly for audio- or video-frequency coupling, bypassing or simple lowpass or highpass filtering, where tolerance and stability are not critical. The most important advantages are the high capacitance per volume for polyester and the capacitance stability over a wide temperature range for polycarbonate.

Polyphenylenesulfide (PPS) (or Polysulfone) is a newer dielectric. Its high melting point allows it to be used in non-encapsulated SMD capacitors, because it can withstand the soldering heat unprotected by a case. PPS is about as stable, and has losses as low as, polycarbonate.



Paper capacitors (P) have the disadvantages of a lager variation in capacitance with temperature change and a shorter service life relative to most other types. Paper capacitors are still used for medium capacitance values of approximately 1 nF to 1 μF, mainly at power line frequency, as for example in interference suppression capacitors.

Ceramic Capacitors

Ceramic dielectrics and ceramic capacitors using these dielectrics are divided into three classes.

Class 1 ceramic dielectrics are materials with relatively low permittivity ($\varepsilon_r = 6\ldots600$), good control of tolerances, excellent stability and ageing characteristics, low dissipation and very good Q up to very high frequencies. The capacitance versus temperature characteristics are well-controlled and basically linear, with *specified temperature coefficients*. They are used in such applications as oscillators and filters where low losses, capacitance drift compensation and high stability are required.

Class 2 ceramic dielectrics are materials of higher permittivity ($\varepsilon_r = 250\ldots100{,}000$), which allow much higher capacitance/volume efficiencies, but show higher losses and have non-linear capacitance-temperature characteristics; the capacitance is also voltage dependent and subject to ageing. They are used for coupling and decoupling, notably in pulse and high-frequency circuits where their small series inductance is valuable.

Class 3 ceramic dielectrics offer a still higher volumetric efficiency, but again this is at the expense of poor accuracy and stability and a low dissipation factor. They are also not normally able to withstand high voltages. The dielectric used is often barium titanate that has a dielectric constant of up to about 1250. A typical class 3 capacitor will change its capacitance by -22% to +50% over a temperature range of +10°C to +55°C. It may also have a dissipation factor of around 3 to 5%. It will have a fairly poor accuracy (commonly 20%, or -20%/+80%). As a result, class 3 ceramic capacitors are typically used for decoupling or in other power supply applications where accuracy is not an issue. However they must not be used in applications where spikes are present as these may damage the capacitor if they exceed the rated voltage.

EIA temperature coefficient codes

In order that the performance of ceramic capacitors can be standardized and easily defined, a set of codes has been defined by the Electronic Components Industry Association (ECIA) which are called the Electrical Industries Association (EIA) standards. These codes enable ceramic capacitor performance to be defined in an easily managed way. The codes are different though for class 1 and class 2 ceramic capacitors.

Class 1 capacitor codes

Class 1 capacitors are comprised of a three character EIA code:

1. The first character is a letter which gives the significant figure of the change in capacitance over temperature in ppm/°C.
2. The second character is numeric and gives the multiplier.
3. The third character is a letter and gives the maximum error in ppm/°C.

The table below details what each of the EIA codes means.

FIRST CHARACTER (LETTER) SIGNIFICANT FIGURES		SECOND CHARACTER (DIGIT) MULTIPLIER		THIRD CHARACTER (LETTER) TOLERANCE	
C	0.0	0	-1	G	±30
B	0.3	1	-10	H	±60
L	0.8	2	-100	J	±120
A	0.9	3	-1000	K	±250
M	1.0	4	+1	L	±500
P	1.5	6	+10	M	±1000
R	2.2	7	+100	N	±2500
S	3.3	8	+1000		
T	1.7				
V	5.6				
U	7.5				

Table 1.5 – EIA Temperature Codes for Class 1 Ceramic Capacitors

As an example, one common type of class 1 capacitor is a C0G and this will have 0 drift, with an error of ±30 ppm/°C.

Industry commonly uses an "N/P" designation system that is obsolete, but is more intuitive, and more reflective of what is actually in production. The "N" is used for capacitors with a negative temperature coefficient, and a "P" for those with a positive coefficient. Manufacturers usually use both in their catalogs, while distributors' catalogs often use only the N/P codes.

Industry:	P100	NP0	N030	N075	N150	N220	N330	N470	N750	N1500	N2200
EIA:	M7G	C0G	B2G	U1G	P2G	R2G	S2H	T2H	U2J	P3K	R3L

Table 1.6 – Some Commonly Available Class 1 EIA and Industry Codes

For example, a P100 class 1 capacitor has a temperature coefficient of +100 ppm/°C, whilst an N470 has -470 ppm/°C.

Class 2 capacitor codes

Class 2 capacitors are comprised of a three character EIA code:

1. The first character is a letter. This gives the low-end operating temperature.
2. The second is numeric and this provides the high-end operating temperature.
3. The third character is a letter which gives capacitance change over that temperature range.

The table below details what each of the EIA codes means.

FIRST CHARACTER (LETTER) LOW TEMPERATURE		SECOND CHARACTER (DIGIT) HIGH TEMPERATURE		THIRD CHARACTER (LETTER) CHANGE	
X	-55 °C	2	+45 °C	D	±3.3%
Y	-30 °C	4	+65 °C	E	±1.7%
Z	+10 °C	5	+85 °C	F	±7.5%
		6	+105 °C	P	±10%
		7	+125 °C	R	±15%
				S	±22%
				T	+22% / -33%
				U	+22% / -56%
				V	+22% / -82%

Table 1.7 – EIA Temperature Codes for Class 2 Ceramic Capacitors

Two very common examples of class 2 ceramic capacitors are the X7R capacitor which will operate from -55 °C to +125 °C with a capacitance change of up to ±15%, and the Z5U capacitor which will operate from +10 °C to +85 °C with a capacitance change of up to +22% to -56%.

Construction of Ceramic Capacitors

Ceramic capacitors are manufactured in disk or square plate form, in tubular form, or as multilayer or 'monolithic' capacitors. The dielectric material is mainly barium titanate, calcium titanate or titanium dioxide with small amounts of other additives for specific characteristics.

Disk capacitors are made from carefully formulated powders, milled to produce a small particle size. The powder is compressed into a thin disk or square plate which is then fired at a high temperature (1200…1400 °C) to fuse the material. Electrodes are screen printed on each side of the disk and fired (at about 800 °C). Leads are soldered with a high melting temperature solder, then the capacitors are lacquered or immersed in epoxy resin to provide a protective coating. The capacitance value is marked on the body in clear text or in colour code. The temperature coefficient or temperature dependence are also indicated by colour coding. Disk capacitors have a limited range of electrode area and thickness. The dielectric formulation is varied to achieve a wide range of capacitance values.

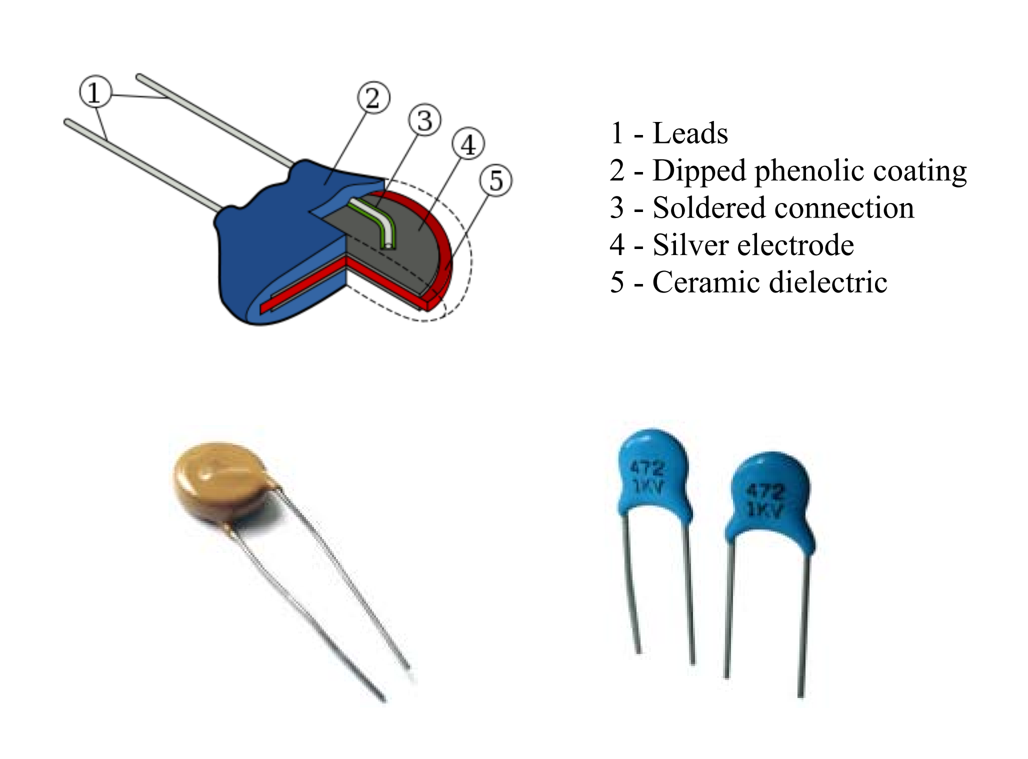


Figure 1.23 – Ceramic Disk Capacitors

Multi-layer ceramic capacitors (*MLCC*) First, a slurry consisting of dielectric powder, a binder and a solvent is cast into a thin sheet on a stainless-steel or plastic belt. After drying, the electrodes are printed on the sheets, which are then stacked and compressed. The stacks are cut into individual capacitors, heat treated and fired at a high temperature. Finally terminals are attached on both ends and the device is encapsulated. The range of capacitance values, for a given dielectric, is realized by changes in electrode area and the number of layers in the stack.

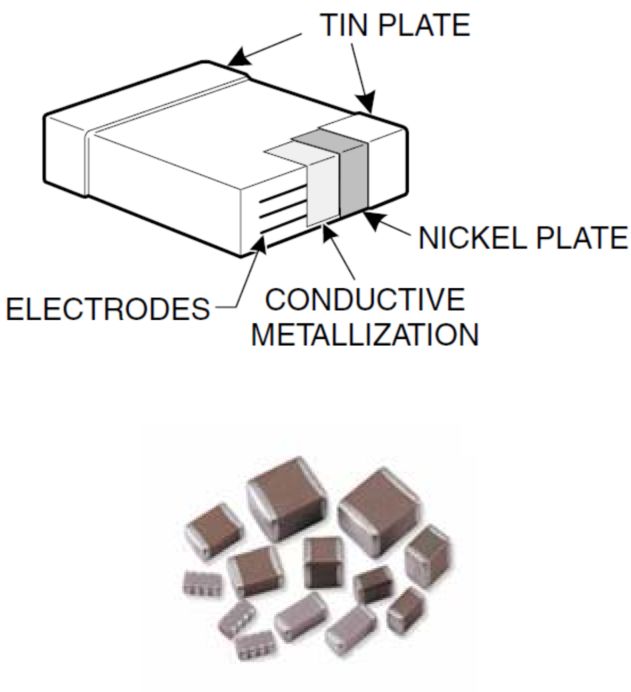


Figure 1.24 – Multi-layer Ceramic Capacitors

Characteristics of Ceramic Capacitors

The characteristics and applications of ceramic capacitors are quite different for class 1 and class 2 dielectrics.

Class 1 dielectrics can be used for capacitance values of 1 pF to 10 nF (in chip form, to 100 nF) with tolerances of ± 20% to ± 1 % (or ± 0.1 pF for C < 10 pF), and voltage ratings to kilovolts. The specified temperature coefficient of capacitance extends from P100 (+100 ppm/°C) to N470 (-470 ppm/°C), with additional ranges from N750 to N4700 (see Figure 1.25). The most frequently used dielectric is C0G of nominally 0 ppm/°C, but actually guaranteed to be within ±30 ppm/°C. The capacitance of class 1 ceramic capacitors is very stable in storage or in operation. The dissipation factor for C0G, for example, is less than 0.1 % over the full temperature and frequency range, up to several tens of MHz. The voltage coefficient is essentially zero.

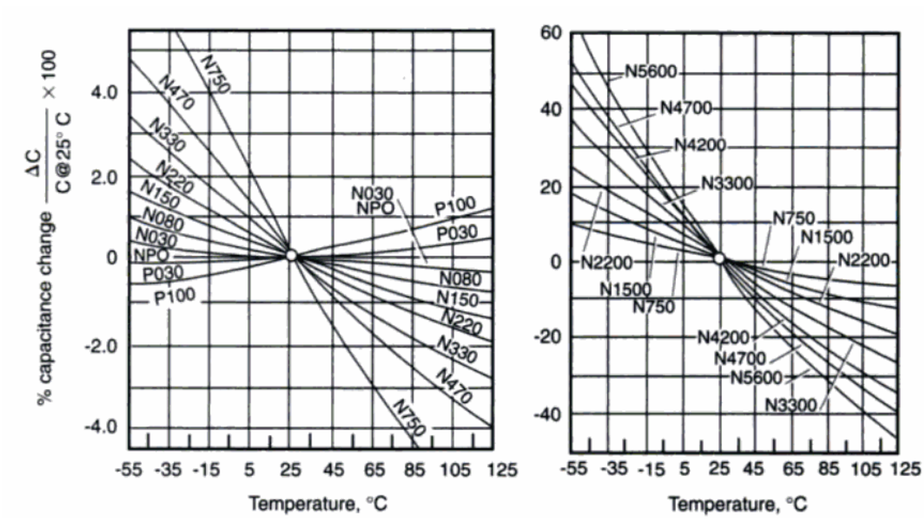


Figure 1.25 – Capacitance Variation with Temperature for Class 1 Ceramic Dielectrics

Class 2 ceramic dielectrics are used for general purpose applications, where small size is important, and stability and tolerance are less important (the designation of the most frequently used material for Class 2 are X7R and Z5U). Capacitance values range from 1 pF to 1 μF in disk capacitors, and to 10 μF in multi-layer capacitors. Typical voltage ratings are up to 1000 V in disk, and up to 200 V in MLCC. Temperature, frequency and voltage dependence of capacitance (up to -50% for some types), as well as variations due to ageing are large in class 2 capacitors. The dissipation factor is typically 1% to 10% and is very dependent on temperature (decreases at higher temperatures) and on frequency (increases to over 30% at 1 MHz).

Applications of Ceramic Capacitors

The main advantages of *class 1 ceramic* capacitors over film type capacitors are:

- generally lower cost
- better control and wide range of temperature coefficients
- lower inductance and good high-frequency characteristics

The main disadvantages over film capacitors:

- higher losses than polystyrene, polypropylene or polycarbonate film
- lower leakage resistance than most film capacitors

Class 1 capacitors are used in circuits requiring stability and low loss (high Q), particularly at high frequencies, say over 0.1 to 1 MHz, over the full temperature range.

The main advantages of *class 2 ceramic* capacitors for general purpose applications are:

- lower cost for values to 10 nF
- comparable in cost between 10 nF and 1 μF
- lower inductance and better high-frequency performance, especially compared to electrolytic capacitors.

Applications of class 2 capacitors are filtering ripple, DC blockage, coupling and decoupling components in circuitry where stability is not an important criterion but low inductance and a high self-resonant frequency are important.

Electrolytic Capacitors

Electrolytic capacitors fall into two main categories – aluminium and tantalum.

Aluminium Electrolytic Capacitors

Aluminium electrolytics are of the foil type, with an electrolyte that can be aqueous, paste or dry. The anode is made of high purity aluminium foil, 25 to 100 μm thick. The foil is usually electrochemically etched to increase its surface by a factor of 8 to 30 or more. The foil is then "anodised" to produce electrochemically a layer of aluminium oxide ($\mathrm{Al_2O_3}$ with $\varepsilon_r = 8.4$) which is the dielectric. The voltage used for the final stage of anodising (the "forming voltage") determines the oxide thickness and voltage rating (about 2/3 of the forming voltage, which can be as high as 600 V).

Non-solid polarised electrolytics. In this, the most common structure, (Figure 1.26) a second, non-oxidised aluminium foil is the cathode connection. The *cathode* aluminium foil serves only as an electrical contact to the *electrolyte*, (e.g. glycol-borate) which is the actual cathode. (In nonpolarised electrolytics, the cathode is also anodised, but the capacitance is halved). The anode and cathode foils are welded to lead wires and then wound into a tight capacitor. In newer constructions, the foils are arranged in stacks, with a tab extension on each foil, to reduce ESR and inductance.

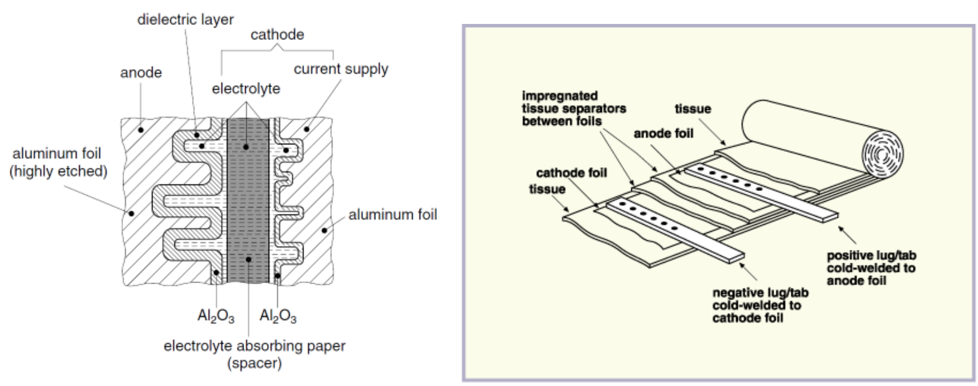


Figure 1.26 – Structure of a Non-Solid Electrolytic Capacitor

Solid Electrolyte Aluminium is a newer type of aluminium electrolytic, using technologies similar to solid electrolyte tantalum capacitors. Solid electrolyte capacitors have better frequency characteristics, (to > 100 kHz) and lower leakage than non-solid aluminium electrolytics. SMD implementations of solid electrolyte capacitors are increasingly being used.

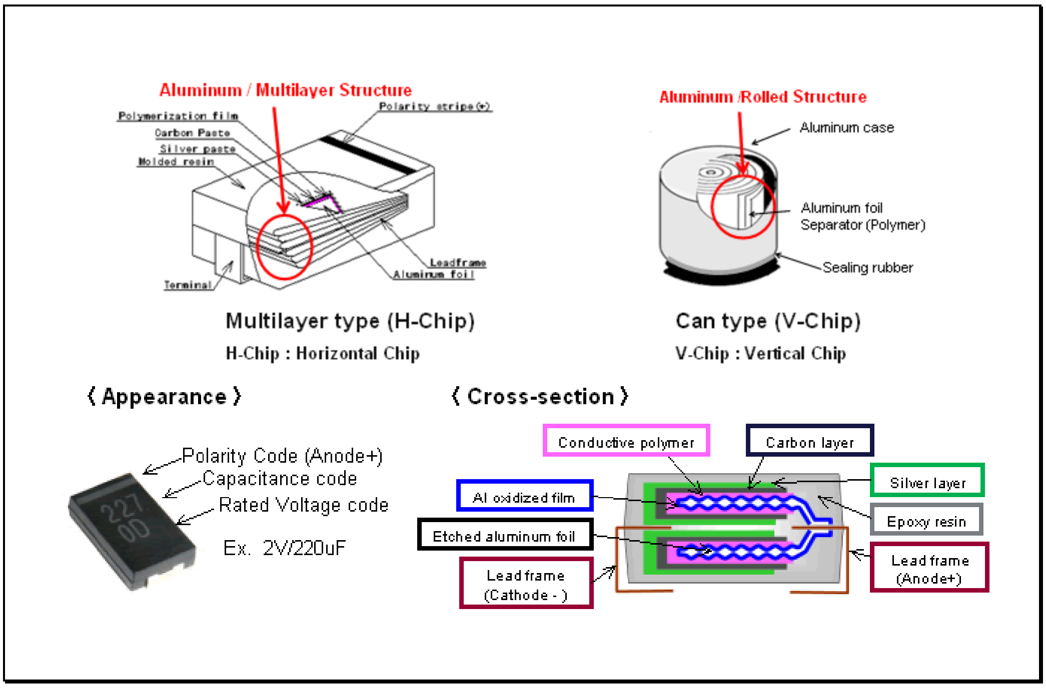


Figure 1.27 – Structure of a Non-Solid Electrolytic Capacitor

Very recently, new types of Sintered Aluminium Solid Electrolytic Capacitors, e.g. "Alsicon" and "OS-CON" (the latter one, using an organic solid electrolyte) have been developed, which compete favourably in characteristics with solid tantalum electrolytics, especially in high-frequency applications, up to 1 MHz.

Aluminium electrolytics are available in capacitor values of 1 μF to 1 F, with voltage ratings of 3 to 475 V. Higher voltages imply lower capacitance per unit volume, because the aluminium oxide film must be thicker. Tolerances are typically -20% to +150% (for applications in coupling or decoupling, a minimum capacitance value must be guaranteed, but a larger capacitance is usually not harmful).

Polarised aluminium electrolytic capacitors can withstand a reverse voltage of up to 1.5 V without noticeable effect on their operating characteristics. Excess voltage applied for short periods will cause some change in capacitance but will not lead to failure. On the other hand, exposure to reverse or excess forward voltage for a longer time leads to rapid heating of the capacitor and to breakdown. The specified maximum *AC ripple current* (when filtering AC rectifier based power supplies) must also not be exceeded to avoid overheating.

Newer aluminium electrolytic capacitors are made with a built-in pressure relief mechanism. This is designed to open and slowly release gas pressure that may build up if the device overheats during operation.

The *capacitance* of electrolytics *is very dependent on temperature*, (Figure 1.28). It decreases significantly at lower temperatures. Over extended periods of time (years) aluminium electrolytics show a gradual decrease in capacitance, due to loss of electrolyte (drying) through the seals.

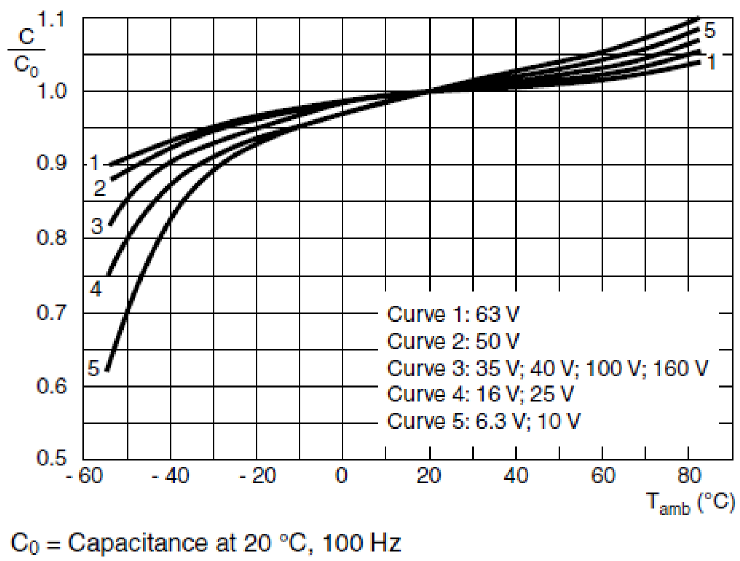


Figure 1.28 – Dependence on Temperature of an Electrolytic Capacitor

The capacitance also decreases quite significantly with increasing frequency, from about 1...10 kHz (Figure 1.29). On the other hand, the dissipation factor increases rapidly with frequency above 10 kHz. All these frequency effects limit the use of these capacitors, e.g. as coupling capacitors to ≤ 20 kHz. The losses, expressed by the ESR, increase at low temperatures.

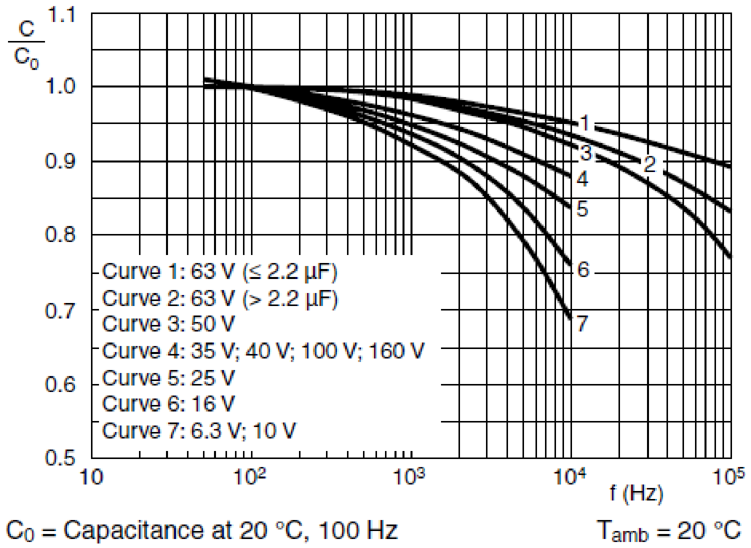


Figure 1.29 – Dependence on Frequency of an Electrolytic Capacitor

The leakage current is quite large (caused by the oxide film not being a perfect insulator), at 25°C, typically one to a few µA, and depends on time from application of a DC voltage. The leakage current increases significantly with applied voltage and with temperature. After long periods of storage, the oxide layer may partially dissolve in the electrolyte, and leakage may be catastrophic. To restore the oxide, the capacitor must be "reformed", by increasing very gradually the applied DC voltage, until the rated values are reached.

Applications of Aluminium Electrolytic Capacitors

These devices provide high capacitance in a small space at a low cost.

Electrolytic capacitors are polarised. If connected incorrectly, the insulating oxide film is not formed and there is no capacitance. Reverse connection eventually causes overheating and then failure.

Main advantages

- low cost
- large capacitance per unit volume
- very large capacitance values are available – to 1 F
- impedance and ESR can be small up to a few MHz for capacitances < 100μF

Main disadvantages

- poor tolerance on values (typically -20% ,+50%)
- capacitance very dependent on temperature, frequency, storage/usage time
- high losses, especially at frequencies ≥ 20 kHz
- large leakage current (μA), strongly dependent on temperature, voltage, time
- electrolytics are basically polarised capacitors (the peak of the AC voltage component must be less than the DC bias voltage to *make sure that the anode is at any instant positive relative to the cathode*), although nonpolarised versions (with half the volume efficiency), are produced

Main applications

- filtering in power supplies
- coupling, effective to about 20kHz
- decoupling, bypass, effective to a few MHz for C < 100μF

Tantalum Electrolytic Capacitors

Tantalum capacitors offer a form of capacitor that provides a very high capacity density – as much as three times better capacitance / volume efficiency than aluminium electrolytic capacitors. Tantalum capacitors are widely used in many mass produced items of electronics equipment where there is a need for a small size and a high level of capacitance.

There are three types of tantalum electrolytic capacitors: foil, liquid electrolyte and solid electrolyte.

Tantalum foil capacitors are made the same way as aluminium electrolytic capacitors. The dielectric is tantalum pentoxide ($\mathrm{Ta_2O_5}$ with $\varepsilon_r = 26$). They are available in sizes of 0.1 to 3000 μF, at voltages up to 450 V. The capacitance is less dependent on temperature than in Al electrolytics, but losses and leakage current, although smaller by one to two orders of magnitude than in Al electrolytics, are similarly temperature dependent. This type of tantalum capacitor is used only in the higher voltage ranges, as a better quality, but more expensive alternative to Al electrolytics. For lower voltage applications it compares unfavourably with the other two types of tantalum electrolytics, which use sintered anodes. As high voltage (above 100V) usage in electronics has decreased since the advent of transistors, this type of tantalum capacitor is seldom used.

Liquid electrolyte (wet slug) tantalum capacitors have the highest volumetric efficiency of any capacitor. This is due to the very large surface area possible in the porous tantalum pellet anode. The anode pellet is produced by sintering powdered tantalum around a tantalum lead wire with a technology ensuring a light, porous assembly. The anode pellet is then anodised to produce the thin Ta oxide layer. The anode is enclosed in a case, plated with silver and platinum and filled with electrolyte, which serves as a cathode. Due to the low reactivity of the tantalum oxide, electrolytes of high conductivity can be used, and the ESR is low.

The main application of liquid electrolyte tantalum capacitors is in power supply filters. The maximum voltage is typically 125 V and the capacitance ranges from 1 to 2000 μF. Although much more volume efficient, the liquid electrolyte tantalum capacitor has two main disadvantages over solid tantalum capacitors: possibility of leakage of the corrosive electrolyte; and the necessity to prevent the application of even short duration reverse voltage (it might lead to a catastrophic short-circuit, and sometimes explosion).

Solid tantalum capacitors are the variety that are most commonly used. The anode is produced the same way as that of the liquid electrolyte capacitor. After the pellet is anodised, several films of solid cathode material are produced by pyrolytic conversion of manganous nitrate solution into manganese dioxide. MnO_2, which is a reasonably good conductor, serves as the first layer of the cathode, which is extended with colloidal graphite, then silver paint, to provide a good connection to the metal cathode.

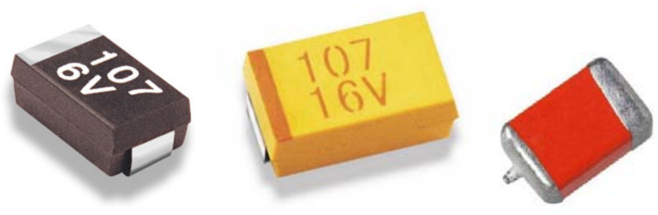


Figure 1.30 – Solid Tantalum Capacitors

Applications of Tantalum Capacitors

Tantalum capacitors offer many advantages over other types of capacitor. This has meant that their use has risen considerably over the years, and now they are widely used in all forms of electronics equipment. The advantages are:

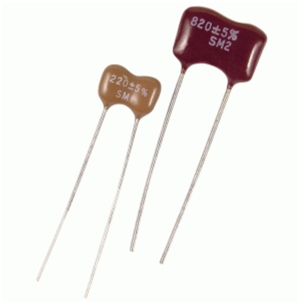
- ***Volumetric efficiency:*** Tantalum capacitors offer a very high level of volumetric efficiency – much greater than many other types. In particular they are better than Al electrolytic capacitors which are their main rival.
- ***Good characteristics:*** The frequency response of tantalum capacitors is superior to that of Al electrolytic capacitors. They also have a lower series resistance and lower leakage current. This means that they are more suitable for use in a number of applications where Al electrolytics could not be used.
- ***High reliability:*** Tantalum capacitors are more reliable than many other forms of capacitor. Provided they are operated within their ratings they are able to provide an almost unlimited life. Their use is not time limited as in the case of Al electrolytic capacitors.
- ***Wide operating temperature range:*** Tantalum capacitors are able to operate over a very wide temperature range. They are often specified for operating over the range -55°C to +125°C, with a variation as little as 10%. This makes them an ideal choice for use in equipment used in harsh environmental conditions.
- ***Compatibility with modern production methods:*** Modern production techniques often expose components to high temperatures during soldering as the whole assembly is heated by infra-red heat. Using conventional leaded components only the board surface was heated and the amount of heat conducted by the leads was usually insufficient to damage the components. Tantalum capacitors are able to withstand the temperatures of SMT production and are therefore ideal for use in many new electronics designs.

Tantalum capacitors have a number of disadvantages, and these need to be considered when using them in new designs.

- ***Low ripple current ratings:*** It is hardly surprising in view of their size that tantalum capacitors do not have a high ripple current rating. They should not normally be used in areas that require high levels of current to be passed.
- ***Not tolerant to reverse or excess voltage:*** Tantalum capacitors do not like reverse or excess voltage. Even spikes can destroy them. If they are exposed to excess or reverse voltages, then they can explode.
- ***More expensive than other types:*** Tantalum capacitors are more expensive than many other forms of capacitor. As a result their cost should be considered during the design phase as the other benefits may outweigh any increased costs.

Mica Capacitors

Silver mica capacitors are made by plating silver electrodes directly on to a mica dielectric. Several layers are used to achieve the required capacitance. Wires for the connections are added and then the whole silver mica capacitor assembly is encapsulated to provide protection.



Silver mica capacitors are able to provide very high levels of accuracy, stability and low loss. As a result, silver mica capacitors have found many uses in radio frequency applications, particularly for oscillator and filter circuits where their stability, accuracy and low loss (leading to high Q) were needed. Although not as widely used these days, they can still be obtained and are used where stability of value is of the utmost importance and where low loss is required.

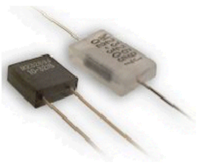
The reason for the continued use of silver mica capacitors is the fact that they can offer very high levels of performance, better in many areas than any other type of capacitor. However in many applications, other more modern technologies provide levels of performance that meet the requirements.

The particular properties of the silver mica capacitor are summarised below:

- ***High accuracy:*** Silver mica capacitors can be obtained with tolerance figures of ±1%. This is much better than virtually every other form of capacitor available today.
- ***Temperature co-efficient:*** The temperature co-efficient of silver mica capacitors is much better than most other types of capacitor. The temperature coefficient is positive and is normally in the region 35 to 75 ppm / °C, with +50 ppm / °C being an average value.
- ***Value range:*** Values for silver mica capacitors are normally in the range between a few picofarads up to two or possibly three nanofarads.
- ***Low capacitance variation with voltage :*** Silver mica capacitors exhibit very little voltage dependence.
- ***High Q :*** Silver mica capacitors have very high levels of Q that are almost independent of frequency.

Glass Capacitors

Glass capacitors are made from potash lead glass, drawn into a thin ribbon which is then stacked with alternate layers of aluminium foil. Alternate foils are then welded to lead wires, cover glass is added and the assembly sealed at high temperature.



Glass dielectric capacitors offer very high levels of performance, although their cost is high when compared to many other forms of capacitor. Typically a glass capacitor will have a relatively low capacitance value. The values of glass capacitors may range between a fraction of a picofarad up to two to three nanofarads. As such these capacitors are used mainly in radio frequency (RF) circuit design. The supply of glass capacitors is limited to a small number of manufacturers and suppliers. Glass capacitors offer several advantages over other types of capacitor:

- ***Low temperature coefficient:*** Glass capacitors have a low temperature coefficient. Figures of just over 100 ppm / °C are often obtained for these capacitors.
- ***No hysteresis:*** Some forms of capacitor exhibit hysteresis in their temperature characteristic. This is not the case for glass capacitors which follow the same temperature / capacitance curve when the temperature is rising and falling.
- ***Zero ageing rate:*** Many electronics components change their value with age as chemical reactions take place within the component. Glass capacitors do not exhibit this effect and retain their original value over long periods of time.
- ***No piezoelectric noise:*** Some capacitors exhibit the piezoelectric effect to a small degree. This can result in effects such as microphony (voltages caused by vibration) on oscillators. Where this could be a problem, the use of glass capacitors could help solve the problem.
- ***Extremely low loss / high Q:*** Glass capacitors are very low loss as there is virtually no dielectric loss. This enables very high *Q* circuits to be built using them provided the other components (e.g. inductors) are not lossy.
- ***Large RF current capability:*** Some capacitors are not able to withstand large values of current. This is not the case for glass capacitors which are suitable for use in RF high power amplifiers, etc.
- ***High operating temperature capability:*** Glass dielectric capacitors are able to operate at very high temperatures. Many are able to operate at temperatures up to about 200 °C without fear of damage or performance shortfall.

Choosing Capacitors

The following diagrams facilitate selection of capacitor types for specific applications. These diagrams should point to the types of capacitors that could be used for a given capacitance range, tolerance on value and frequency range. Of course, price and availability must also be considered. There is a wide overlap in specifications among the various families of capacitors.

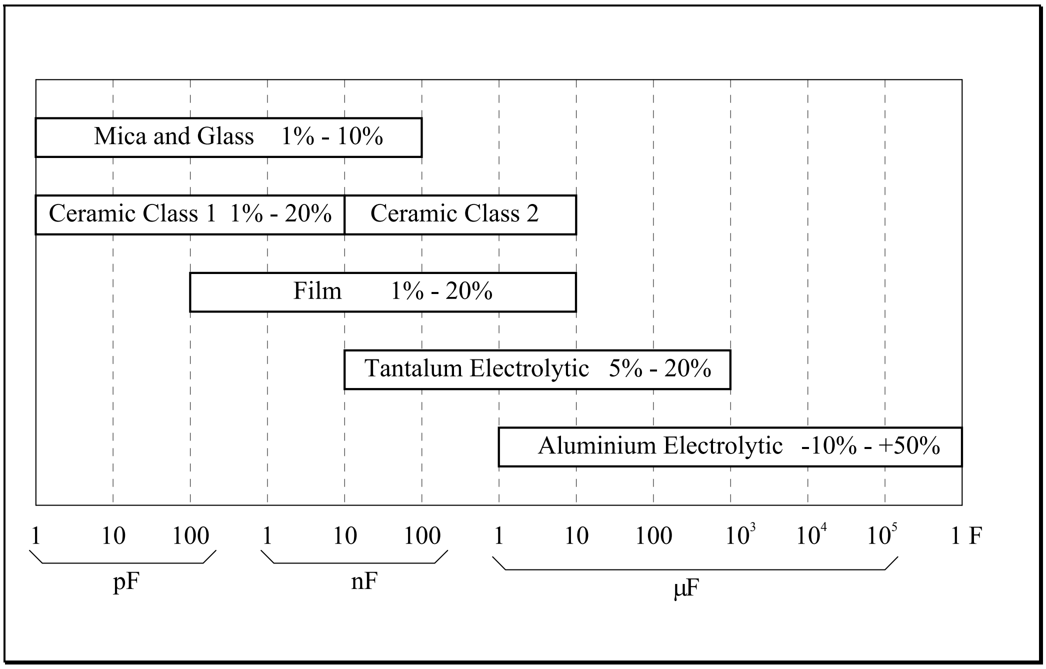


Figure 1.31 – Range of Capacitance Values and Tolerances for Different Capacitor Types

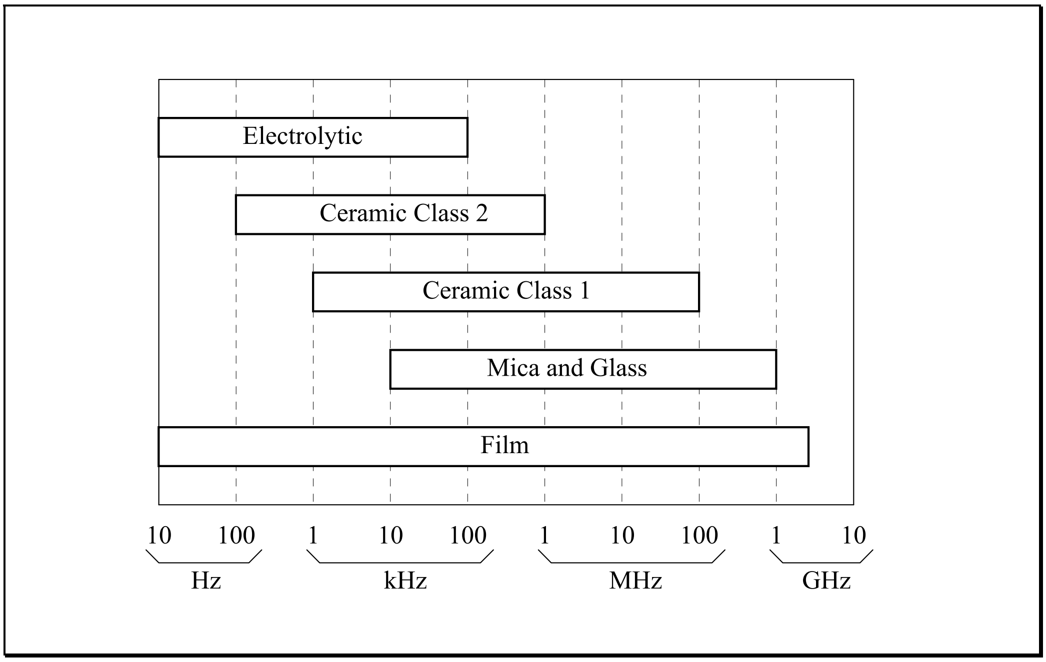


Figure 1.32 – Useful Frequency Ranges for Different Capacitor Types

Type	Advantages	Disadvantages
Polystyrene	Low cost Low DF Wide range of values Good stability Tolerance to 0.5%	Temperature < +85 °C Large case size for C > 10 nF Relatively high inductance
Polypropylene	Low cost Low DF Wide range of values Good stability Tolerance to 1%	Temperature < +105 °C Relatively large Relatively high inductance
Polycarbonate	Low cost Good stability Wide temp. range	Large High inductance
Polysulfone (Polyphenylene-sulfide)	Low cost Good stability Wide temp. range	Large High inductance
Polyethylene-terephtalate (Teflon)	Good stability Temperature > +125 °C Wide range of values Tolerance to 1%	Large High inductance High cost
Polyester	Low cost Small size	Moderate stability Temp. and frequency dependent Largest DF of film capacitors
Ceramic Class 1	Small size Low cost Good stability Wide range of values Tolerance to 1% Low inductance	DF larger than film capacitors at frequencies < 10 kHz
Ceramic Class 2	Wide range of values Low inductance	Poor stability Poor DF
Mica	Low loss at HF Low inductance Very stable Tolerance to 1%	Quite large Low values (< 10 nF) High cost
Aluminium Electrolytic	Large values Small size High voltages	High leakage Usually polarised Poor accuracy Poor stability Inductive
Tantalum Electrolytic	Large values Very small size Medium inductance Reliable	Quite high leakage Usually polarised High cost Poor stability Poor accuracy

Table 1.8 – Features of Common Capacitors

Decoupling Capacitors

One of the wider uses of capacitors, in both analog and digital circuits, is for '*decoupling*' or '*bypassing*' a power supply, an IC, or a resistor, by *shunting them with a negligibly small impedance at AC or pulse signal frequencies*.

High-speed or high-level circuits can inadvertently interact with low-level circuits on the same printed circuit board (PCB) by way of an impedance common to both circuits. Such a common impedance might be:

- the internal AC impedance of the DC power supply
- the impedance of the leads from the power supply to the positive supply or negative supply connecting pads on the PCB
- the ground connection from the PCB to the power supply
- the 'invisible resistance' of the ground track on the PCB, if it is common to high-level and low-level signals, or to digital and analog sub-circuits
- a voltage dropping resistor or divider, common to both sub-circuits
- the 'invisible resistance' of a common track on the PCB

To avoid as much as possible this type of parasitic coupling, one must take care to:

- carefully layout the PCB
- properly bypass the likely offending common impedances

A most likely offending impedance, that usually is common to many different subcircuits on a PCB, is the AC internal resistance of the DC power supply.

Voltage regulator IC's ensure that the power supply has a very small internal resistance, typically a few milliohms, but only to about 100 to 1000 Hz. Above this frequency, the AC internal impedance of the voltage regulator IC increases rapidly, because the inner control loop gain drops at higher frequencies. A small AC impedance of a power supply can be ensured above 1 kHz only by using suitable bypass capacitors.

For the decoupling to be effective, the bypass impedance must be maintained at a small value over a much wider frequency range than the actual useful signal frequency range. Parasitic coupling may happen not only at signal frequencies, but also at a very low or a very high frequency, well outside the useful signal band. And, as long as *there still is sufficient parasitic loop gain available in the circuit*, parasitic oscillations may occur. This can happen at a very low frequency (so called 'motor-boating') or at a high frequency (say MHz), where only an oscilloscope might help in detecting them.

The capacitors most used for decoupling are electrolytic capacitors, which, depending on value, can ensure a small impedance from very low frequencies, say a few Hz or tens of Hz up to, say, 0.1 MHz...10 MHz.

The minimum value of bypass impedance that a capacitor can provide is set by its equivalent series resistance, ESR. To assess the suitability of a capacitor for decoupling, particularly for decoupling switching power supplies, the ESR is as important as the capacitance value.

Of course, if the impedance of the capacitor, due to series resonance, instead of decreasing continuously with frequency ($X_C = 1/2\pi fC$) starts increasing above the *Series Resonant Frequency* (*SRF*), the decoupling effect gradually disappears.

Of the different capacitor types, ceramic capacitors have usually the smallest inductances, and the highest *SRF* (typically to well over 10 MHz). Modern film capacitors are now also manufactured in low-inductance versions. Lead-less capacitors, e.g. SMC chip capacitors, have generally higher *SRF*s than the equivalent wire terminal capacitors. Electrolytic capacitors on the other hand, because of large capacitance values, have generally lower *SRF*.

The best practice, especially for decoupling the supply terminals of fast pulse circuits or high-frequency circuits, is to place a large capacitor – say an electrolytic of 10 μF or 100 μF in parallel with a smaller capacitor, say a 10 nF or 100 nF ceramic capacitor, across the positive supply to common and negative supply to common power supply input pads of the printed circuit board, as shown below:

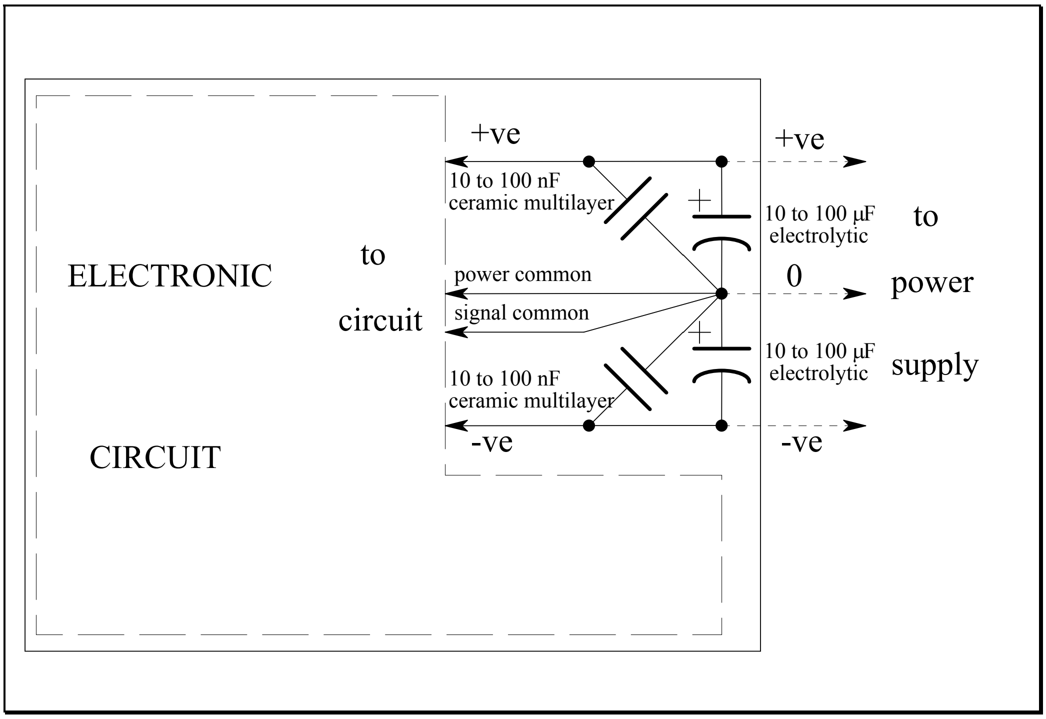


Figure 1.33 – Decoupling Power Supply Entry to a Printed Circuit Board

Note the single point star connection to the ‘0 V’ of the power supply, the power common, and the signal common.

The two different capacitor types used in the decoupling would normally have quite different Series Resonant Frequencies, and would make sure that a small bypass impedance is maintained over a wider range of frequencies.

The large electrolytic capacitor will take care of decoupling, i.e. ensure a small impedance of a few mΩ to a few Ω , from about, say, 10 Hz, to about a few tens or hundreds of kHz. The ceramic capacitor will continue maintaining a small bypass impedance into the tens of MHz.

Besides decoupling the supply rails, for fast pulse/digital ICs it is strongly recommended that a small 10 nF to 100 nF ceramic capacitor should be placed directly across the supply and common pads of each IC on the PCB.

In any IC decoupling circuit, the capacitor is essentially a local energy source that supplies current to the chip during switching. Without bypassing, the impedance of the PCB tracks causes a voltage drop on the supply line. Depending on the frequency, the typical unbypassed dynamic impedance of the positive supply track can be about 50 to 100 Ω. This is enough to produce a considerable drop during short current pulses unless a bypass capacitor is used.

As an example, assume that a current swing of 300 mA with a duration of 3 ns is produced by a digital IC, i.e. it requires briefly a charge:

$$\Delta Q = I\Delta t = 0.3\times 3\times 10^{-9} = 0.9\times 10^{-9}\ \mathrm{C}$$

If the voltage drop is to be limited to $\Delta V = 0.1\,\mathrm{V}$, the bypass capacitor required is:

$$C = \Delta Q/\Delta V \approx 10\,\mathrm{nF}$$

The recommended capacitor type would be a multilayer ceramic (typically class 2) capacitor.

Of course, if the pulse duration were to be longer, say about 30 ns in the pulse conditions of our example, the required capacitor would be about 100 nF, again multilayer ceramic.

To ensure bypassing as far as possible towards higher frequencies, as required for fast pulse circuits, the capacitor should be a leadless ceramic mult-ilayer (chip) capacitor, and the tracks on the PCB to the nodes to be bypassed should be as short as feasible. This bypass capacitor will also ensure that there is no electromagnetic radiation caused by large pulse currents through the PCB tracks.

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