Lecture 4 – Resistors

Resistor characteristics. Resistor types. Choosing resistors.

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

For resistors 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.

4.2

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

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.

Component tolerances are tolerances at time of purchase

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:

$$a_n = ar^{n-1} \tag{4.1}$$

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:

$$a_n = 100\left(\sqrt[k]{10}\right)^{n-1} \tag{4.2}$$

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:

$$a_n(1+\delta) = a_{n+1}(1-\delta)$$
$$\frac{a_{n+1}}{a_n} = \frac{1+\delta}{1-\delta}$$
$$\sqrt[k]{10} = \frac{1+\delta}{1-\delta}$$
$$\delta = \frac{\sqrt[k]{10} - 1}{\sqrt[k]{10} + 1} \tag{4.3}$$

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:

$100 \pm 20\% = 80$ to 120	$330 \pm 20\% = 264$ to 396
$150 \pm 20\% = 120$ to 180	$470 \pm 20\% = 376$ to 564
$220 \pm 20\% = 176$ to 264	$680 \pm 20\% = 544$ 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 4.1.

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					
124	124		210	210		357	357		604	604				
126			213			361			612					
127	127	127	215	215	215	365	365	365	619	619	619			
129			218			370			626					
130	130		221	221		374	374		634	634				
132			223			379			642					
133	133	133	226	226	226	383	383	383	649	649	649			
135			229			388			657					
137	137		232	232		392	392		665	665				
138			234			397			673					
140	140	140	237	237	237	402	402	402	681	681	681			
142			240			407			690					
143	143		243	243		412	412		698	698				
145			246			417			706					
147	147	147	249	249	249	422	422	422	715	715	715			
149			252			427			723					
150	150		255	255		432	432		732	732				
152			259			437			741					
154	154	154	261	261	261	442	442	442	750	750	750			
156			264			448			759					
158	158		267	267		453	453		768	768				
160			271			459			777					
162	162	162	274	274	274	464	464	464	787	787	787			
164			277			470			796					
165	165		280	280		475	475		806	806				
167			284			481			816					

5% E24	10% E12	20% E6	40% E3
100	100	100	100
110			
120	120		
130			
150	150	150	
160			
180	180		
200			
220	220	220	220
240			
270	270		
300			
330	330	330	
360			
390	390		
430			
470	470	470	470
510			
560	560		
620			
680	680	680	
750			
820	820		
910			

Table 4.1 - IEC standard 'E' series of values in a decade

4.6

Marking Codes

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:
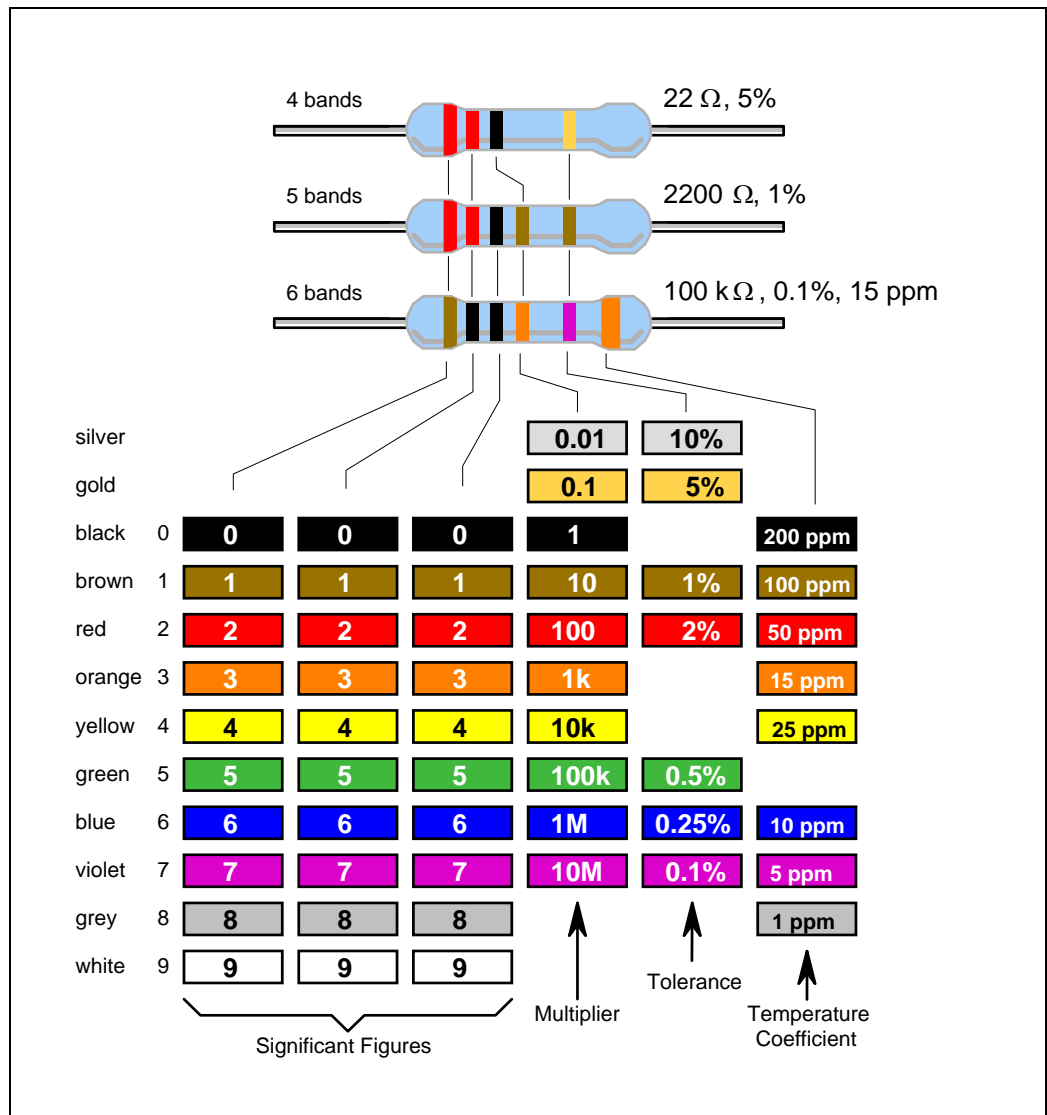
IEC labelling for leaded resistors

Figure 4.1 – 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 4.1.

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 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 4. A colour intermediate to violet and white is grey, which represents the number 8.

The resistor colour code explained

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 $1\,k\Omega$.

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
4.5 MΩ	155

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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):
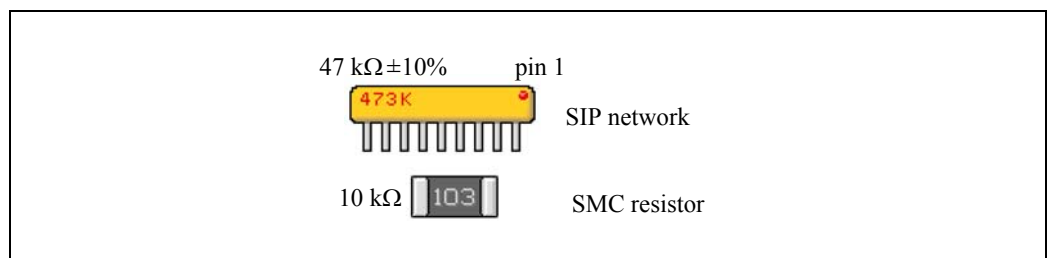
Figure 4.2 – Resistor markings

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
4.5 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 % / °C or ppm / °C. It is poorest for carbon composition resistors; for carbon film resistors it is typically negative, -200 to -500 ppm / °C. It is best for chip and metal film resistors (within ±20 to 100 ppm / °C).

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 / °C.

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Example

If the temperature coefficient of a resistor with $R_{rated} = 1\,\text{k}\Omega$ 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: $1000\,\Omega \pm \left(130 \times 200 \times 10^{-6}\right) \times 1000\,\Omega = 1026\,\Omega$ or $974\,\Omega$

at -55 ºC: $1000\,\Omega \pm \left(80 \times 200 \times 10^{-6}\right) \times 1000\,\Omega = 1016\,\Omega$ 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
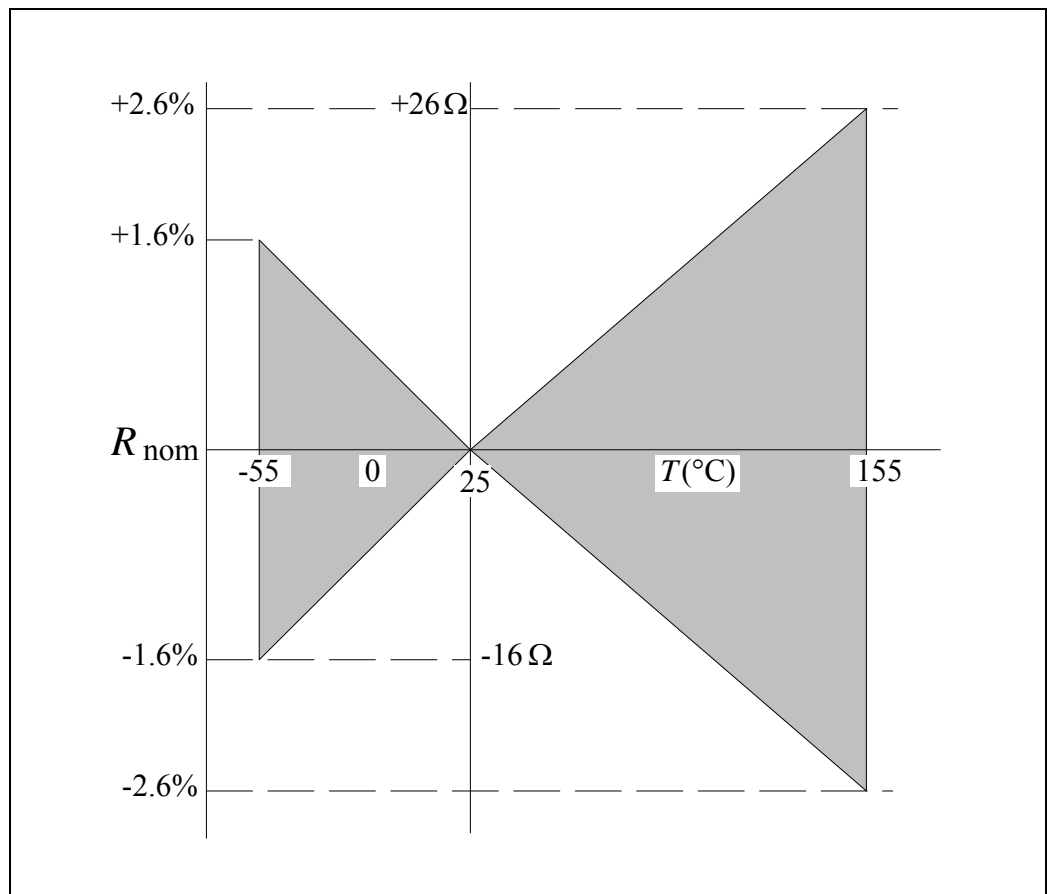
Figure 4.3 – Temperature coefficient

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

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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.
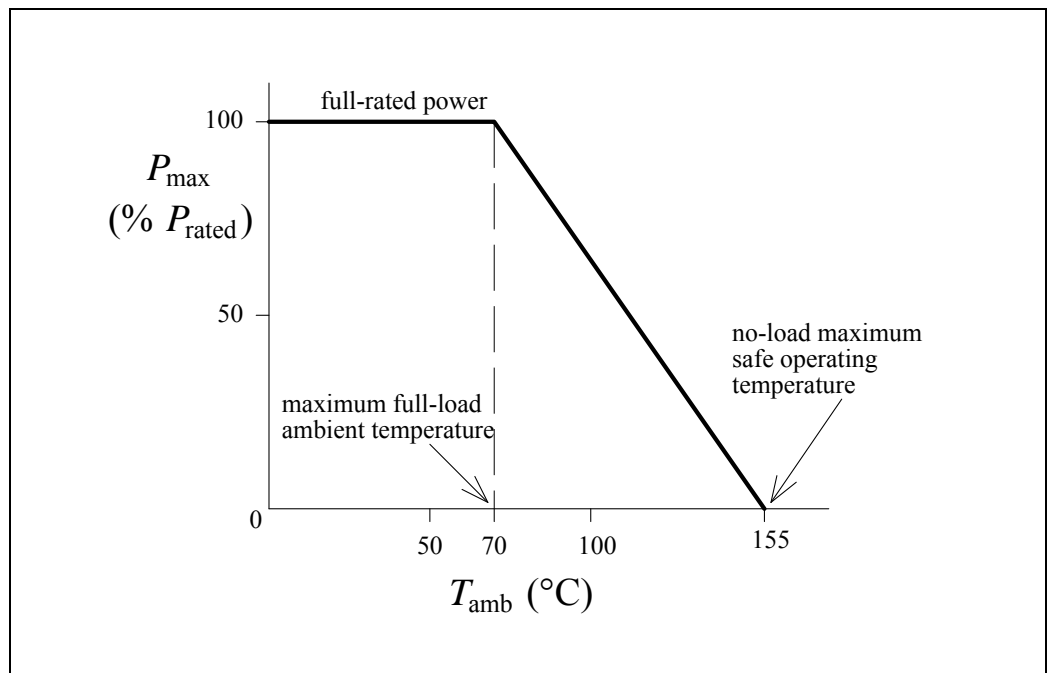
Figure 4.4 – Resistor derating curve

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 4.4, 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 $\theta_R = \left(155\,°C - 70°C\right)/P_{rated}$.

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 then *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
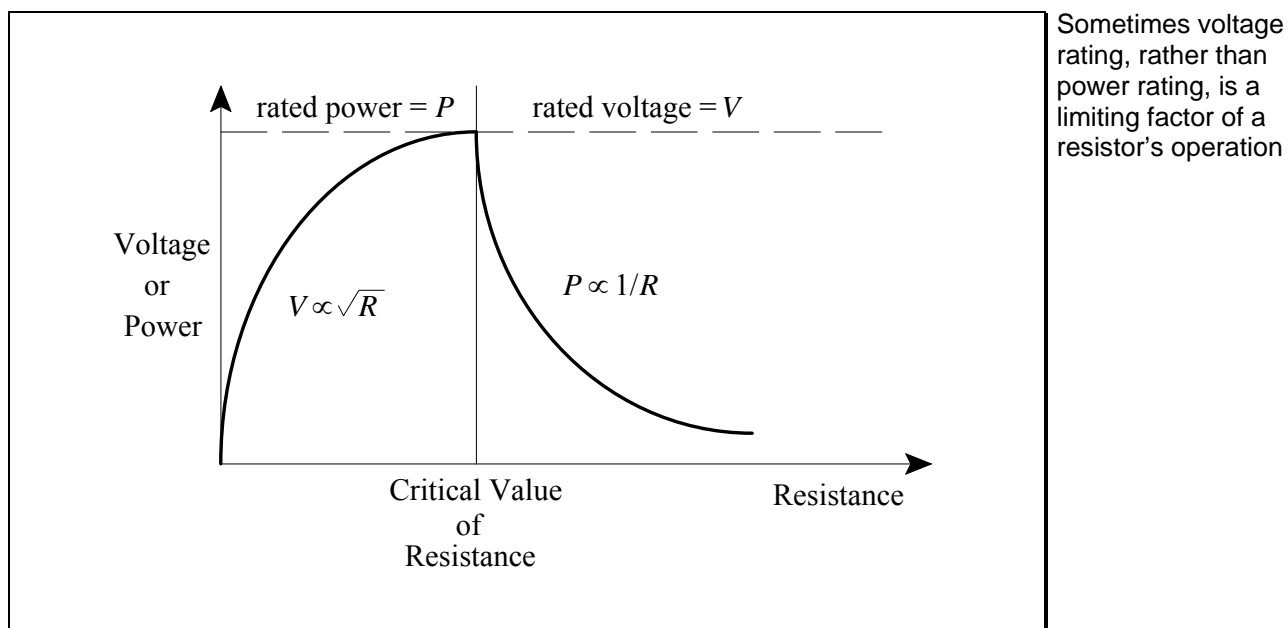
Figure 4.5 – Relationship of applied voltage and power above and below the critical value of resistance

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 4.6, 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
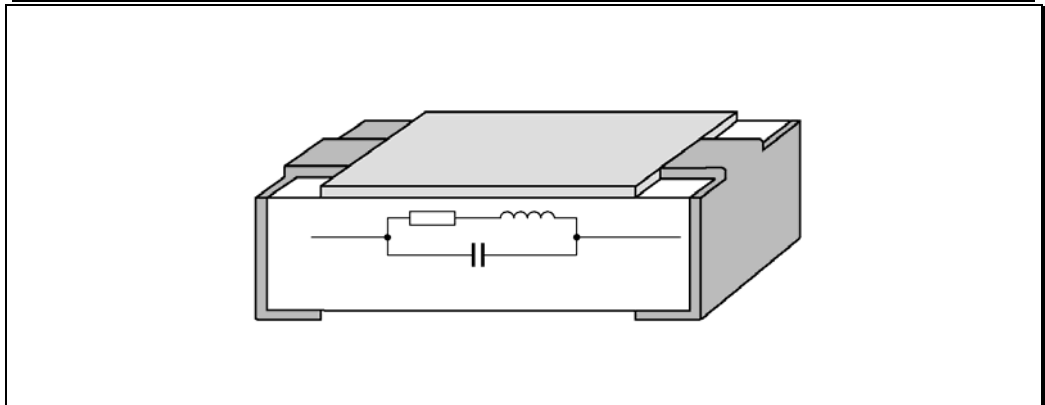
Figure 4.6 – Resistor equivalent circuit

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:
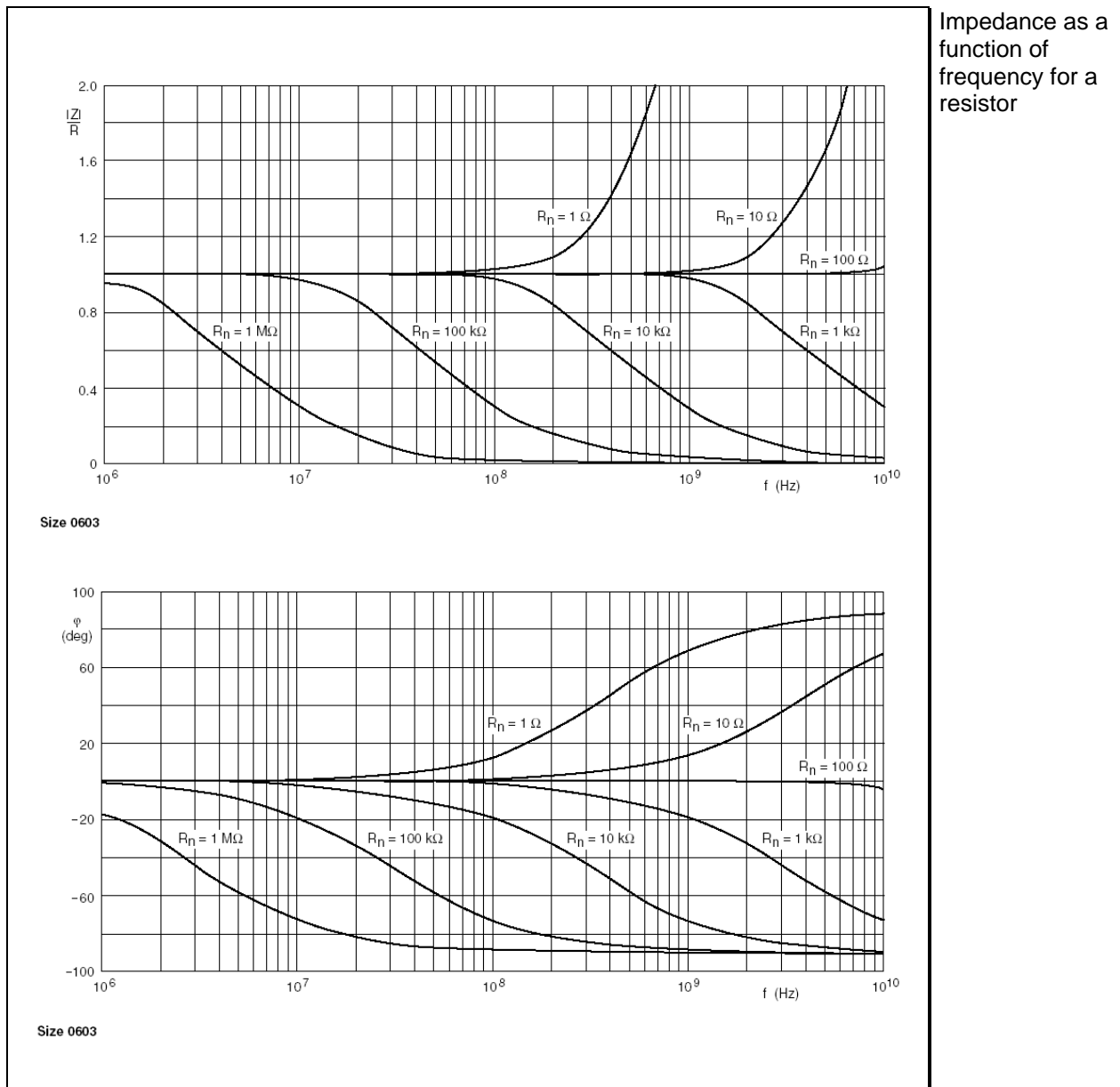

Impedance as a function of frequency for a resistor

Figure 4.7 – 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 4.7 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.

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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

$$V_n = \sqrt{4kTRB} \tag{4.4}$$

where:

V_n = RMS thermal noise voltage

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

T = absolute temperature, in Kelvin (e.g. $298\text{K} = 25°\text{C}$)

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 $V_n^2/B = 16 \times 10^{-18}$ V^2/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:
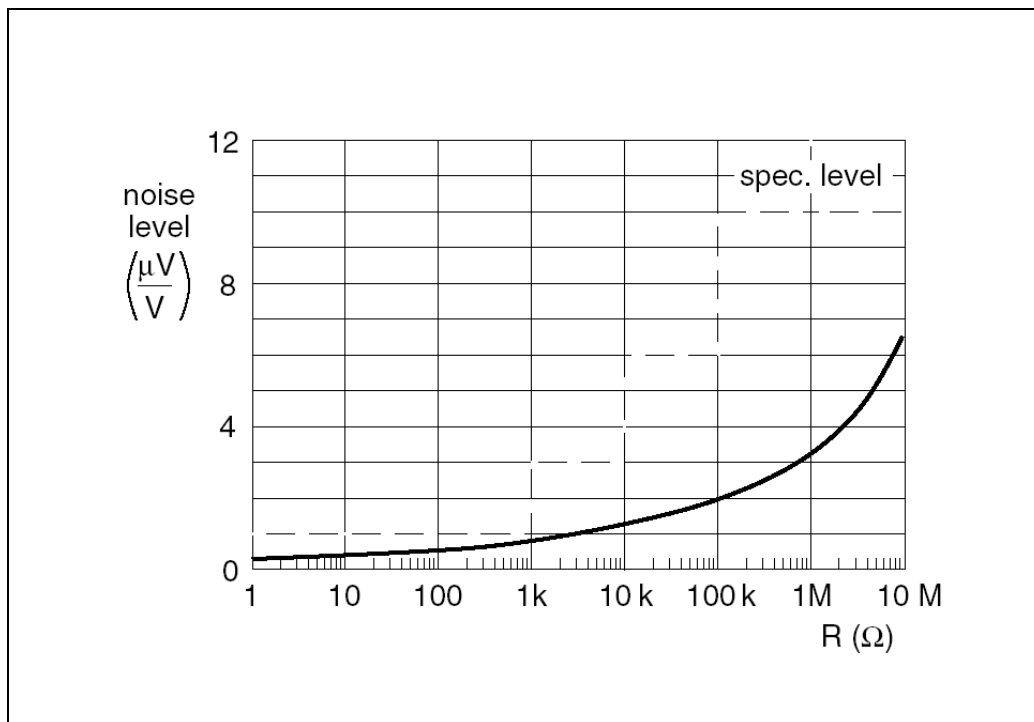
Figure 4.8 – Typical noise levels as a function of rated resistance

Reliability

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.

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

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.

4.18

Derating

Derating is a policy of *deliberately under-stressing components* so as to provide increased reliability and stability, e.g. using a 1/2 W resistor in circuit conditions demanding a 1/4 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.
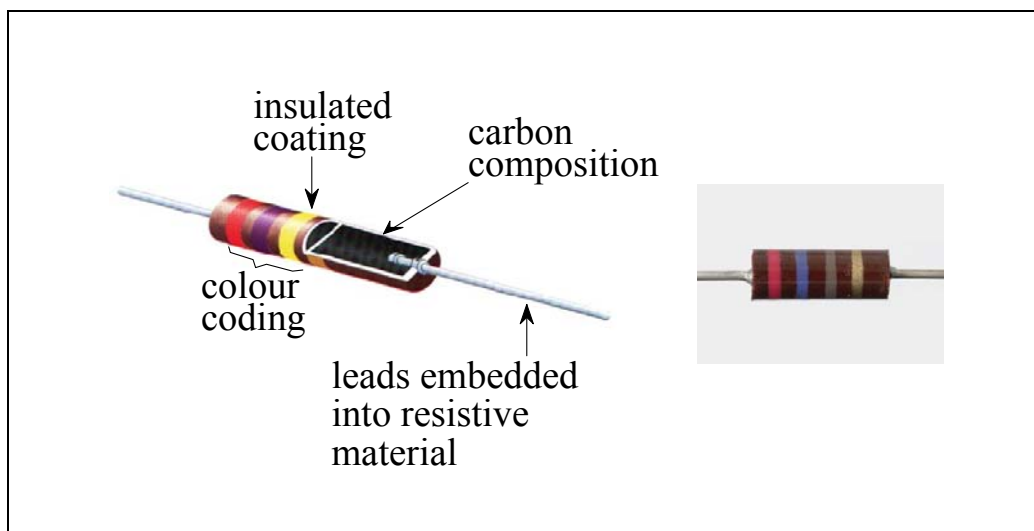
Carbon composition resistors…

Figure 4.9 – 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.

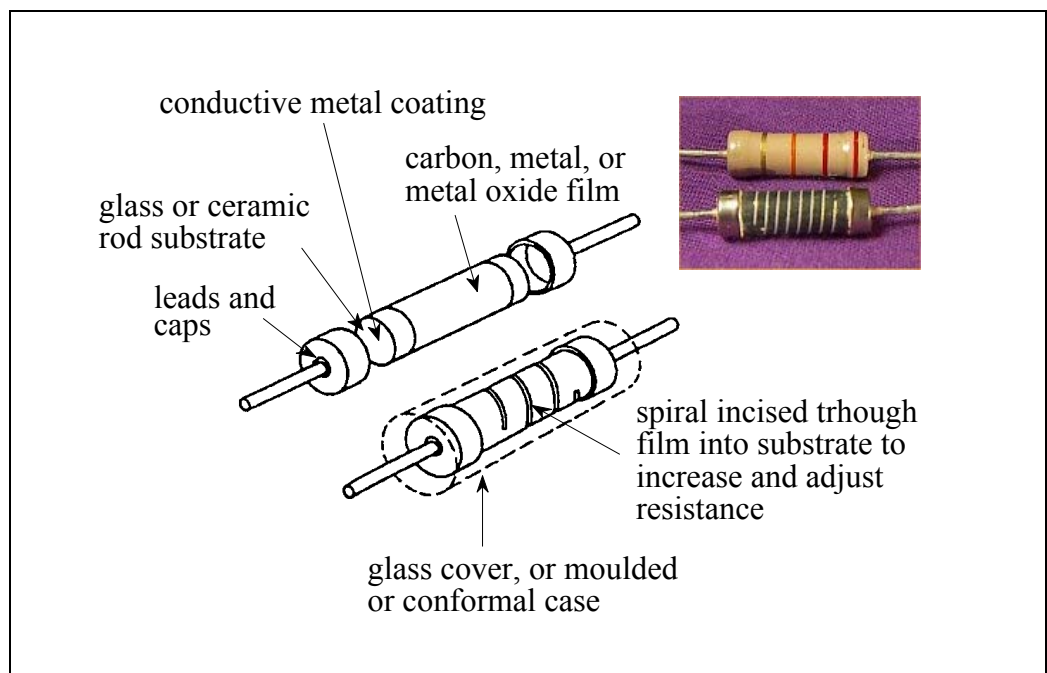Carbon film resistors are general purpose resistors that are not used often anymore due to surface mount technology

**Figure 4.10 – 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 4.10), then the body is lacquered and marked.
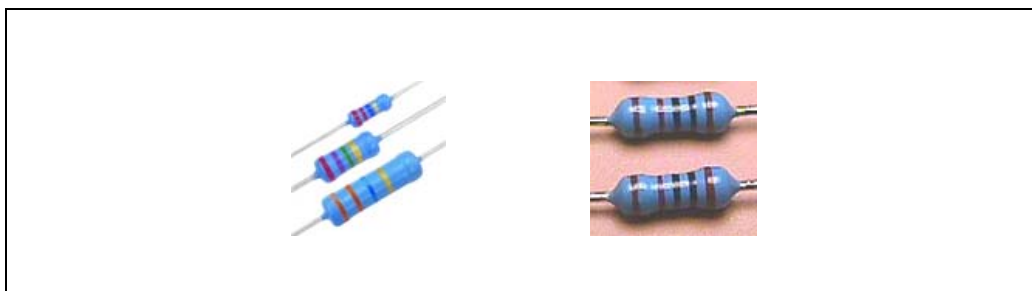
Metal film resistors are used in precision applications that demand higher power ratings than surface mount components

Figure 4.11 – 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

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).

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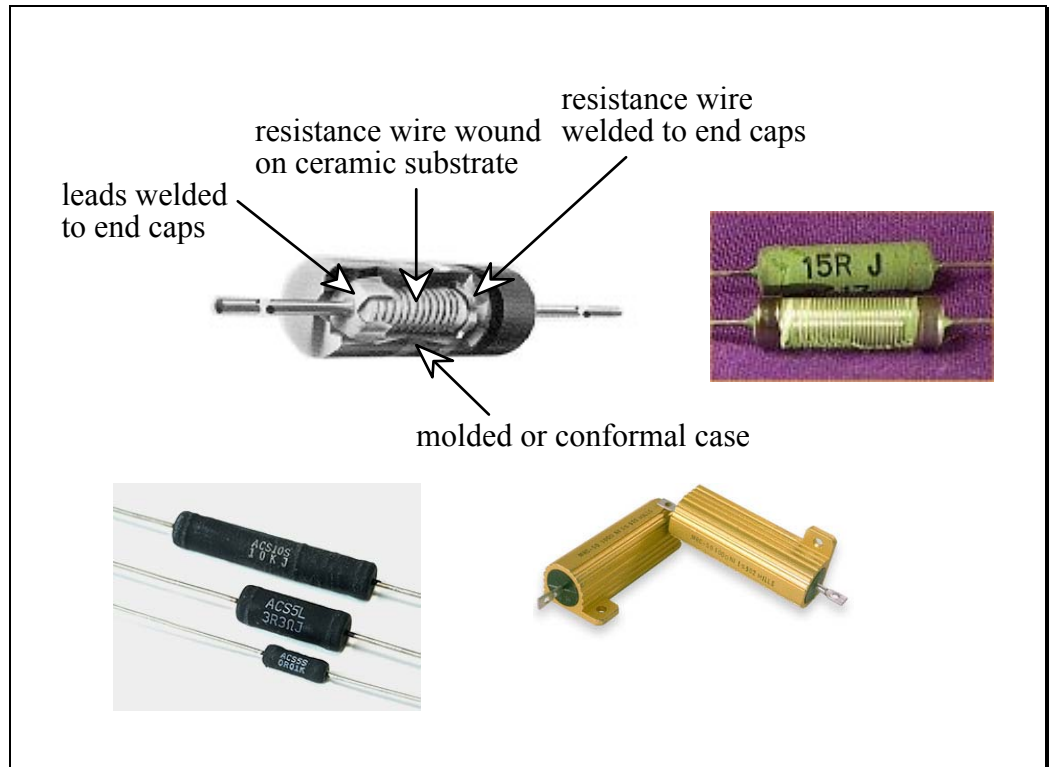

Figure 4.12 – Wire wound resistors

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 'c*ermet*'). 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.
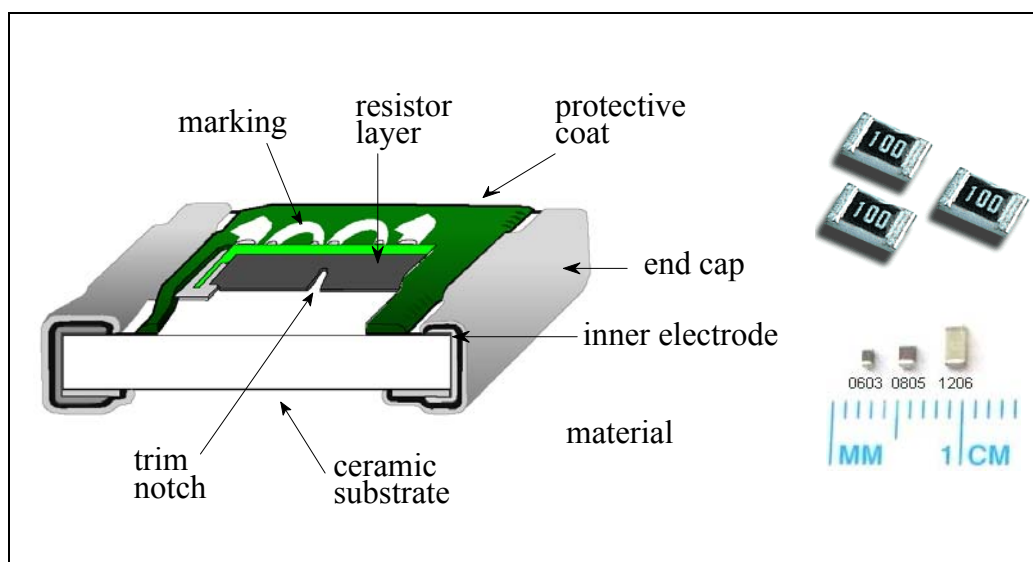
Chip resistors are small and come with wide ranging characteristics

Figure 4.13 – Construction and sizes of chip resistors

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

SIZE CODE	Length (mm)	Length (inches)	Width (mm)	Width (inches)	Mass (mg)
1206	3.2	0.12	4.6	0.06	10
0805	2.0	0.08	4.2	0.05	4
0603	4.6	0.06	0.8	0.03	2
0402	4.0	0.04	0.5	0.02	0.8
0201	0.6	0.02	0.3	0.01	0.15

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

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%	0.1%, 0.2%, 0.5%
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 4.1 – 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.
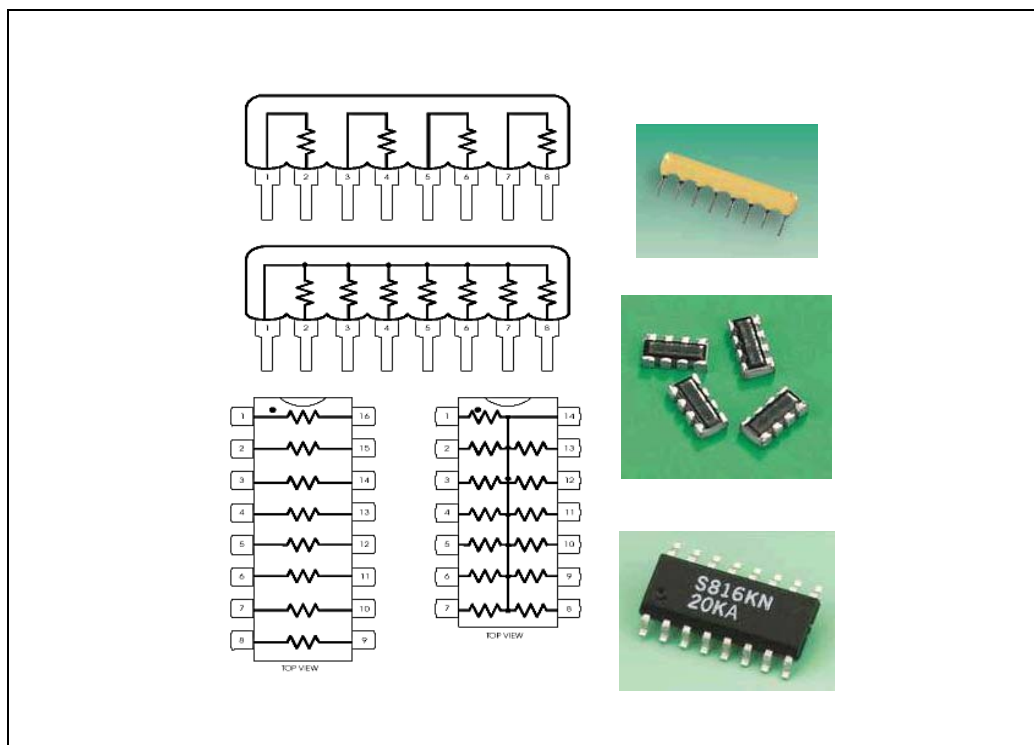
Resistors networks save space but also provide matching component values

Figure 4.14 – Resistor networks

4.26

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	$1\,\Omega$ to $100\,M\Omega$	$1\,\Omega$ to $10\,M\Omega$	$1\,\Omega$ to $10\,M\Omega$	$0.1\,\Omega$ to $10\,M\Omega$	$0.1\,\Omega$ to $10\,M\Omega$
Tolerance at purchasing	5% to 20%	0.5% to 10%	0.1% to 10%	0.01% to 1%	0.5% to 10% Th F 0.1% 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 1 c
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 4.2 – 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).

4.28

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