RESISTORS

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INTRODUCTION

Electrical resistance is a fundamental property of a normal electrically conductive material or conductor by which it impedes the flow of electric current in a circuit, resulting in a voltage drop across the conductor and the generation of heat energy. The electrical resistance in a circuit, measured in ohms, is equal to the ratio of the voltage drop across the resistor measured in volts divided by the current measured in amperes. *Resistors* are a class of electrical components whose primary function is to introduce resistance in an electrical circuit for purposes of operation, protection, or control. They are used for voltage measurements, current measurements, setting voltage biases, controlling amplifier gains, setting time constants, matching and loading circuits, heat generation, temperature and humidity measurements, strain gauges, and other related functions.

The first resistors used by experimenters were constructed of iron, copper, or other pure-metal wires of arbitrary lengths and sizes. It soon became evident that a "standard" of resistance was needed to permit the intercomparison of results by different experimenters. In 1861 the British Association for the Advancement of Science appointed a committee to establish resistance standards (British Association for the Advancement of Science, 1913). The first resistance standard consisted of a coil of platinum–silver alloy wire sealed in a container filled with paraffin. It was known as the British Association unit and served as a standard for nearly two decades. Its disuse was a consequence of its large temperature coefficient of resistance (TCR). By 1900 wirewound resistance standards were constructed from manganin (Pe-

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terson, 1956), a copper–manganese–nickel alloy having substantially a zero TCR near room temperature. The next major development in wire-drawn resistance alloys occurred around 1948 with the discovery of Evanohm® (Peterson, 1956) by the Wilbur B. Driver Co., an alloy of nickel, chromium, aluminum, and copper. Like manganin it also has a small TCR; however, its resistivity is 2.3 times that of manganin. Today manganin and Evanohm® are still the alloys of choice for the construction of wirewound resistors—manganin for low-value resistors (<100 Ω) and Evanohm® for high-value resistors up to 100 MΩ.

The origin of non-wirewound resistors dates back to the time of World War I with their use in communication equipment (Coursey, 1949). Frequency errors of wirewound resistors resulting from series inductance and shunt capacitance made them unsuitable for use in high-frequency amplifiers. A need also arose for multi-megohm resistors that were not available as wirewound resistors for use in radio receivers. Carbon composition resistors were developed to satisfy these needs. Mixtures of carbon and resin are altered to produce resistance materials having a wide variety of resistivities. For the construction of resistors, either the mixture is extruded as a solid rod or it can be deposited on a glass substrate. These resistors can be produced in various physical sizes, resistance values, and power ratings.

Later, film-type resistors supplanted carbon composition resistors for general-purpose use because of better accuracies, stability, lower noise, and high-frequency performance. Film-type resistors are available with thin-film or thick-film resistive elements. The materials of choice for the construction of film-type resistors are pure metals, metal alloys, conductive oxides, and semiconductors. Film-type resistors have really come into their own in integrated-circuit and surface-mount technologies.

Around 1964 the metal-foil resistor was developed (Kaufman *et al.*, 1988). This new technology resulted in the production of resistors having smaller TCRs and better long-term stability than film-type resistors. The TCR, accuracy, and stability of these metal-foil resistors are approaching those of the best precision wirewound resistors.

The first section of this article defines resistance and the unit of resistance. It also describes the use of resistors in the measurement of other physical parameters. The following sections describe resistor fabrication, types of resistors, resistor characteristics, and classification of resistors according to use.

1. ELECTRICAL RESISTANCE

1.1 Definition of Resistance

The concept of electrical resistance is based on the experimental work of Georg S. Ohm, who in 1826 formulated the quantitative relationship between voltage and current in a dc electrical circuit. This relationship or "Ohm's law" expresses the fact that the magnitude of the current flowing in an electrical circuit depends directly on the electrical potential difference (voltage) and is inversely proportional to the property of the circuit known as the resistance (Wellard, 1960). In modern terminology his experimental equation for bulk metallic conductors can be expressed as

$$R = E/I,$$

where R is the resistance and E is the potential difference across the conductor when a current I flows. Resistance is a fundamental property of any conductor and can be expressed by the following integral expression:

$$R = \int \rho dl/A,$$

where l is the length, A the cross-sectional area, and ρ the resistivity of the conductor. For thin-film resistors it is convenient to define a quantity ρ_s, called the sheet resistance, which is equal to ρ divided by the film thickness d. A thin-film resistor consisting of a simple rectangle of length l (in the direction of current) and width w has a resistance of

$$R = (\rho/d)(l/w) = \rho_s(l/w).$$

The ratio l/w is usually equated to the number of squares of side w. Then ρ_s has the units ohms per square (Ω/□), since "squares" is a pure number. Thus, the value of a thin-film resistor is equal to ρ_s multiplied by the number of squares.

The power P (measured in watts) dissipated in a resistor may be expressed by any one of the following expressions:

$$P = EI = I^2R = E^2/R,$$

where electrical energy is irreversibly converted into heat.

1.2 Unit of Resistance

In 1862 the BA Committee adopted the name "ohm" for the unit of resistance (British Association for the Advancement of Science, 1913). The following year the committee adopted the "absolute" system of units, which provided compatibility between the mechanical units and electrical units. Throughout the years many different systems of units have been in use, which culminated in 1960 with the adoption of the International System of Units (SI), which since then has been accepted internationally (Harris, 1962). In SI units the ohm is defined in terms of the mechanical units of length, mass, and time—the meter (m), kilogram (kg), and second (s), respectively—and the unit of electric current, the ampere (A). The ohm (Ω) is given by the definition

$$1\ \Omega = 1\ \mathrm{m^2\ kg\ s^{-3}\ A^{-2}}.$$

The ohm can be realized by means of a calculable capacitor whereby its impedance, determined from length measurements and the velocity of light, is compared with a resistance through a complex chain of ac and dc bridges.

Commercial, industrial, and scientific requirements for the long-term repeatability and worldwide consistency of measurements of resistance often exceed the accuracy with which the SI unit of the ohm can be readily realized. To meet these severe demands, it has become necessary to establish a "representation" of the ohm that has superior long-term reproducibility and constancy as compared with the present direct realization of the ohm.

1.2.1 Quantized Hall Resistance By international agreement, the representation of the ohm has been based on the quantum Hall effect (QHE) since 1 January 1990 (Hartland, 1992). The QHE occurs at the interface between two semiconducting layers in suitable MOSFET or heterostructure devices when placed in a large applied magnetic field greater than 1 T and cooled to a temperature of 4.2 K or below. Under these conditions, if a constant current of less than 100 μA flows between the source and drain electrodes, plateau regions of constant Hall voltage and hence Hall resistance occur as a function of magnetic field or gate voltage depending upon the type of semiconductor device. These plateaus as shown in Fig. 1 occur at values of the Hall resistance R_{H} given by

$$R_{\mathrm{H}}(I) = V_{\mathrm{H}}/I = R_{\mathrm{K}}/I,$$

where V_{H} is the Hall voltage, I the current through the device, I refers to the ith plateau, and R_{K} is the von Klitzing constant and is believed to be equal to h/e^2, h being the Planck constant and e the elementary charge. The voltage V_x along the channel is essentially zero at a plateau site, as shown in Fig. 1. The value of the von Klitzing constant adopted internationally beginning 1 January 1990 is equal to

$$R_{\mathrm{K-90}} = 25\,812.807\ \Omega.$$

This conventional value is believed to be consistent with the SI ohm to within 0.005 Ω, corresponding to a relative uncertainty of 0.2 ppm. It is based on direct determinations of R_{K} using calculable capacitors and indirect measurements involving combinations of fundamental constants that yield h/e^2 independently of R_{K}. Still there is some small doubt concerning the equality of $R_{\mathrm{K}} \equiv h/e^2$, which can only be resolved with more precise direct measurements of R_{K}. However, the ohm can be reproduced by means of the QHE to about 0.001 ppm.

1.3 Importance of Resistors

Resistors are important in the measurement of other electrical quantities. A large number of physical and chemical phenomena are investigated by means of measurements of voltages, and the measurement of voltage is customarily carried out by the measurement of resistance ratios. Electric

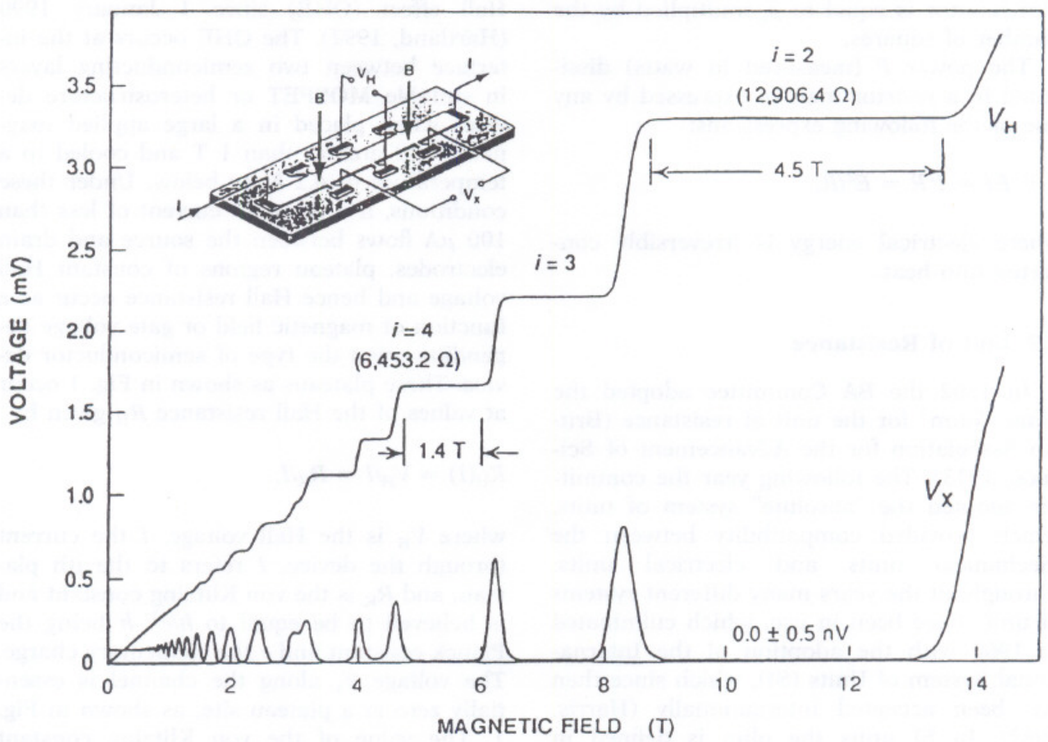

FIG. 1. The quantum Hall effect showing plateaus of constant Hall resistance with values $R_H(i)$.

current is readily most conveniently measured in terms of a voltage across a known resistor. Multimegohm resistors are used in the measurement of low currents extending downward to the picoampere range. Special low-valued resistors, called shunts, are used to measure high currents extending upward to the kiloampere range.

Resistors constructed out of pure metals such as copper or platinum have a high positive TCR and are used in the measurement of temperature. Thermistors are a special type of resistor with a very high negative or positive TCR and are also widely used to measure temperature. Changes in resistance with dimensions are utilized for measuring small displacements, and change in resistance with stress is utilized for the measurement of liquid pressures and force.

2. RESISTOR FABRICATION

The main factors involved in the selection of a resistor for a particular application are cost, resistance value, accuracy, power rating, time stability, frequency dependence, TCR, voltage coefficient of resistance (VCR), and the influence of other environmental factors such as humidity and pressure. Many of these factors can be minimized or optimized during the resistor fabrication process. The constructional features of a resistor can be separated into four general categories: base material, resistive element, terminations, and protective enclosure (Wellard, 1960).

2.1 Base Material

The base material for the resistive element must be a good insulator and have good mechanical stability over the range of ambient conditions to which the resistor is subjected. Common base materials for precision wirewound resistors are usually in the form of insulated metal cylinders, thin mica cards, or ceramic spools. For film-type resistors it is more important to consider matching the thermal-expansion coefficient of the base or "substrate" material with that of the closely adhering resistive element. Fused-sil-

Table 1. Typical electrical properties of some resistance materials.

Material	Composition (%)	ρ (20 °C) ($\mu\Omega$ cm)	TCR (20 °C) (ppm/K)
Carbon	C	3500	−500
Constantan	Cu 60, Ni 40	49	0 ± 20
Copper	Cu	1.7	+3900
Evanohm®[a]	Ni 75, Cr 20, Al 2.5, Cu 2.5	110	0 ± 5
Gold	Au	2.4	+3400
Manganin	Cu 84, Mn 12, Ni 4	48	0 ± 15
Nichrome®[b]	Ni 80, Cr 20	110	+140
Palladium–silver	Pd 60, Ag 40	42	+20
Platinum	Pt	10	+3000
Silver	Ag	1.6	+3800
Tantalum	Ta	13.5	+3100
Zeranin®[c]	Cu 92, Mn 7, Ge 1	43	0 ± 10

[a]Registered trademark, Wilbur B. Driver Company.
[b]Registered trademark, Driver Harris Company.
[c]Registered trademark, Isabellenhütte.

ica glass or alumina ceramic materials are generally used as the substrate material for thin-film, thick-film, and metal-foil resistors because of their excellent electrical and thermal properties.

2.2 Resistive Element

The main considerations in the design and construction of the resistive element are

1. the type of resistance material, and
2. the geometry of the resistance material as applied to the base material.

The material chosen for the resistive element depends on the type of resistor and its application. The main requirements are that the material have suitable resistivity and be sufficiently stable so that any changes in resistance value that occur during its operating life may be expected to fall below some prespecified value. Finally, the process used to construct the resistive element with the chosen material must be such that the final resistor can be made to meet its specifications at a reasonable cost. Tables 1 and 2 list electrical properties of some resistance materials used in the construction of wirewound and film-type resistors. Section 3 describes in more detail considerations of the geometry of the resistance material as applied to the base material.

2.3 Resistor Terminations and Terminals

Terminations are applied to the resistive element to define the exact value of resistance, while terminals provide the mechanical means by which the resistive element is connected into the electrical circuit. Termination is usually accomplished by soldering or welding lead wires to the ends of the resistive element. This is easily accomplished for wirewound elements but is more complicated for film-type elements. Termination for resistive films is commonly made by depos-

Table 2. Typical electrical properties of thin-film and thick-film resistance materials.

Type	Resistance range	TCR (ppm/K)	VCR (ppm/V)	ρ_s ($\Omega/\square$)
Carbon film	4 Ω to 20 MΩ	−250 to −400	<500	50 to 5 × 10^6
Cermet	10 Ω to 5 MΩ	−550 to +150	<100	10 to 10^5
Tin oxide	10 Ω to 100 kΩ	−280 to +140	<25	20 to 400
Nickel–chromium	15 Ω to 150 kΩ	−300 to +350	<1	25 to 300
Tantalum	15 Ω to 150 kΩ	−100 to +100	<1	25 to 300
Tantalum–nitride	15 Ω to 150 kΩ	−25 to +25	<1	25 to 300
Palladium, silver glaze	10 Ω to 1 MΩ	−250 to +250	<1	10 to 10^4

iting noble-metal (gold or silver) contact pads or using noble-metal conducting paint at the ends of the element. Leads then can be attached by compression, welding, or soldering. For carbon composition resistors, the leads are embedded within the resistive material.

2.4 Protective Enclosure

A resistor enclosure provides mechanical and environmental protection to the resistive element. The protective means usually takes one of three forms:

1. an enclosure usually of metal with insulating feedthroughs, ceramic, or glass,
2. a coating applied in liquid form and then cured, or
3. a molding in a suitable encapsulating material.

3. TYPES OF RESISTORS

3.1 Carbon Composition Resistors

The carbon composition resistor is perhaps the most widely used resistor in discrete circuits because of its low cost, high reliability, and small size. Basically, the resistive element is a mixture of carbon and a suitable binder. It is molded under high temperature and pressure into a cylinder with embedded solder-coated wire leads and an insulating plastic or ceramic jacket. Different resistance values are obtained by varying the carbon and filler content. Table 3 lists the standard color code (Wellard, 1960) for composition and some axial-type resistors. Different color bands are used to designate the resistance value and accuracy.

3.2 Wirewound Resistors

The base materials for precision wirewound resistors are usually in the form of insulated metal cylinders, thin mica cards, or ceramic spools. The metal cylinders are coated with an insulating enamel or varnish, and the resistance wire is wound in close thermal contact with the metal cylinder in order to dissipate readily any heat generated by the wire. These metal cylinders are ordinarily of brass, which has a coefficient of thermal expansion nearly the same as that of the wire resistance alloys. This is important to avoid small stresses in the wire introduced by temperature changes. Such stresses can change both the resistance value and its stability.

The mica-card winding form also provides a coefficient of thermal expansion compatible with the resistance wire to minimize temperature effects. The thin profile of these cards produces resistors with very thin cross section, thereby reducing inductance effects of wire loops and making the most efficient use of space. Most ceramic spools have poor heat conductivity and their temperature coefficients of thermal expansion are considerably smaller than for the resistance wires. If ceramic spools are used in the construction of precision resistors, the resistance wire is loosely wound on the spool and the structure sealed in close contact with a thermally con-

Table 3. Resistor color code.

Color of band	1st band, 1st significant figure	2nd band, 2nd significant figure	3rd band, multiplier	4th band, tolerance
Black	0	0	1	···
Brown	1	1	10	±1%
Red	2	2	10^2	±2%
Orange	3	3	10^3	···
Yellow	4	4	10^4	···
Green	5	5	10^5	···
Blue	6	6	10^6	···
Violet	7	7	10^7	···
Gray	8	8	10^8	···
White	9	9	10^9	···
Silver	···	···	10^{-2}	±10%
Gold	···	···	10^{-1}	±5%
None	···	···	···	±20%

ducting insulating fluid such as mineral oil or silicone fluid. The spools for general-purpose wirewound resistors are usually made out of ceramic, epoxy, steatite, or a vitreous material.

Almost all resistance alloys used for constructing wirewound resistors have either a copper or a nickel base (see Table 1). Manganin alloy, whose composition is approximately 84% Cu, 12% Mn, and 4% Ni, has a resistivity of about 48 $\mu\Omega$-cm and a thermal emf to copper of <3 μV/K, and is widely used to construct low-value resistors of nominal values below 100 Ω. Thermal emf refers to the Seebeck thermoelectric effect whereby a voltage is developed when the junctions of a circuit of two dissimilar metals are maintained at different temperatures (Harris, 1962). The TCR of manganin can be reduced to zero at a temperature near room temperature by proper heat treatment; however, the curvature of its resistance–temperature curve at room temperature is approximately -0.5 ppm/K^2. It is subject to surface oxidation and has a pressure coefficient of resistance (PCR) of approximately $+2.3$ ppb/hPa, where ppb refers to parts per billion (10^9).

For the construction of wirewound resistors of nominal values of 100 Ω or higher, Evanohm® is the usual alloy of choice. Its nominal composition is 75% Ni, 20% Cr, 2.5% Al, and 2.5% Cu. It has a resistivity of 110 $\mu\Omega$-cm and a thermal emf to copper of <1 μV/K. The resistance–temperature curve for Evanohm® is much flatter than that for manganin; its curvature at room temperature is approximately -0.05 ppm/K^2. Heat treatment of Evanohm® changes its temperature and time stability. A prolonged heat-treatment process of temperature cycling and soaking time is necessary in order to condition the alloy for zero TCR at a selected temperature and long-term stability. Its PCR is approximately -1.1 ppb/hPa and opposite in sign of the PCR for manganin.

The limitation of wirewound resistors at high-frequency operation is their inherent reactance that is developed as a result of the "coil" type of construction. A number of winding techniques have been developed to reduce the residual inductance and capacitance of wirewound resistors. The most common are the bifilar, thin-card, Ayrton–Perry, and reverse-pi winding methods (Wellard, 1960). The bifilar winding is accomplished by bending the wire back onto itself at its midpoint to form a long loop or "hairpin" with the two sides as close together as the wire insulation will permit. This technique reduces the inductance; however, it may result in a large capacitive effect if the loop is long. Consequently, this technique is used for short loops or low-valued resistors. Winding the resistance wire on a thin card made of mica or other insulating material produces low residual inductance due to the presence of currents in opposite direction separated only by the thickness of the card. Capacitive effects are small since the starting and finishing ends of the winding are at opposite ends of the card. The card form of construction is sometimes used with two windings in parallel, wound in opposite directions around the card, with one winding spaced between the turns of the other. This method, called the Ayrton–Perry winding, gives better cancellation of magnetic fields than the single winding. The reverse-pi method consists of windings in an even number of sections or "pi's" on a bobbin resistor form. As each section is filled, the direction of winding is reversed in the next section, so as to help cancel the inductive effects.

3.3 Metal-Foil Resistors

In the construction of this type of resistor, a layer of thin bulk metal (foil) several microns thick is cemented to a glass or ceramic substrate (Kaufman *et al.*, 1988). The foil is etched using a pattern designed for low residual reactance. The foil is compressed slightly by the substrate as a result of their unequal coefficients of expansion. The compressed foil has a negative TCR that cancels out the inherent positive TCR of the foil. As a result, the metal-foil resistor has a TCR close to zero. Since the foil has a thickness of several microns instead of the extremely thin film of a film resistor, the natural stability of the alloy is preserved, resulting in a resistor having better long-term stability.

3.4 Thin-Film Resistors

3.4.1 Metal Film Materials in thin-film form have higher resistivities than the bulk material because of the additional resistivity due to scattering of the conduction electrons at the boundary of the film (Maissel, 1970). The films are deposited on the substrate by either vacuum evaporation or cathode sputtering.

Nickel–chromium alloy is generally used in the manufacture of thin-film resistors, following logically from its use in bulk form for wirewound resistors. The properties of these films greatly depend on the film composition, which can vary over wide limits depending on deposition parameters such as substrate temperature, source temperature, vacuum, or rate of deposition. Good stable films with TCRs ranging from 5 to 100 ppm/K are obtained by selection. The films have poor stability under conditions of high humidity and therefore must be fully sealed against the entry of moisture.

Single-metal films are often used as resistive elements to avoid problems of composition control such as those occurring in the deposition of alloys such as nickel–chromium. Tantalum films are widely used because of their relatively high resistivities and low TCRs as compared with other pure-metal films and the tough, self-protective oxide that tantalum forms during heat treatment in oxygen. This oxide has excellent dielectric properties; this has led to the development of tantalum capacitors.

3.4.2 Metal-Oxide Film The most popular metal-oxide or cermet film (Maissel, 1970) used in the manufacture of resistors is chromium–silicon monoxide (Cr–SiO). This film is produced by the coevaporation of Cr and SiO and features high resistivity and stability with a TCR on the order of 100 ppm/K. The electrical resistivity can be varied over several orders of magnitude by varying the Cr content.

Tin-oxide (SnO_2) films (Maissel, 1970) used as resistive elements are formed by spraying the material in vapor form onto a heated glass or ceramic substrate. The reaction results in an extremely adherent, fully oxidized film. SnO_2 films have high resistivity and are very stable and rugged. They can withstand temperatures as high as 450 °C without deterioration. One interesting feature of SnO_2 films is that they possess a high degree of transparency. They have therefore found wide application in areas such as the manufacture of so-called "conducting glass" and as heating elements.

3.4.3 Carbon Film Carbon-film resistors (Grisdale *et al.*, 1951) have supplanted carbon composition resistors for general-purpose use because of lower cost, better tolerances, increased stability, lower noise, and better high-frequency performance. They are fabricated by pyrolytic decomposition of carbon on the surface of a cylindrical ceramic substrate. The characteristics of the resistors are sensitive to the deposition conditions, especially film thickness. During fabrication the resistance value of a carbon-film resistor is adjusted by a procedure known as spiraling, i.e., a thin grinding wheel is used to cut a groove through the film along a helical path to increase the resistance.

3.5 Thick-Film Resistors

Mixtures of metal, metal compounds, glass, and solvents are commonly used for the manufacture of resistive elements (Dummer, 1970). The usual method of applying these thick films on a flat or cylindrical alumina substrate is by dipping or rolling. The substrate with the liquid glaze (e.g., tantalum, tantalum nitride, glass, and a carrier) is fired at approximately 1000 °C to fuse the glass particles and bind the film to the substrate. This technology provides a resistive element that is impervious to environmental conditions without the need for an air-tight encapsulation. The inherent ruggedness of this glaze allows it to absorb higher voltage surges and overloads than a thin-film counterpart.

4. RESISTOR CHARACTERISTICS

A summary of key characteristics of different resistor types is listed in Table 4.

4.1 Accuracy

All resistors have a specified initial accuracy or tolerance. It expresses the maximum deviation in resistance from its nominal value in either percent or ppm. Carbon composition and some other film-type resistors use a color code to denote tolerances as listed in Table 3. Tolerances are typically 5% to 20% for carbon composition resistors, 0.5% to 10% for carbon-film resistors, 0.1%

Table 4. Typical resistor characteristics.

Characteristic	Wirewound (precision)	Metal foil	Metal film	Carbon film	Carbon composition
Resistance range	0.1 mΩ to 100 MΩ	0.5 Ω to 1 MΩ	1 Ω to 10 MΩ	1 Ω to 10 TΩ	1 Ω to 100 MΩ
Power dissipation	10 mW to 100 W	0.5 to 2 W	50 mW to 2 W	0.1 to 2 W	$\frac{1}{8}$ to 2 W
Tolerance	2 ppm to 1%	50 ppm to 1%	0.05% to 1%	0.5% to 10%	5%, 10%, 20%
Frequency limit	50 kHz	100 MHz	400 MHz	100 MHz	1 MHz
TCR (ppm/K)	± 1 to ± 20	0 ± 2.5	± 20 to ± 200	-200 to -1000	-800 to $+1600$
VCR (ppm/V)	0	<0.1	<1	-10	-50
Stability	Best	Good	Good	Moderate	Poorest
Advantages	Highest accuracy and stability	Low TCR, low VCR, high speed	Best frequency response	High resistance and low cost	Low cost and small size

to 1% for metal-film resistors, 0.01% to 1% for precision wirewounds, and 0.0001% (1 ppm) to 0.01% (100 ppm) for ultraprecision or standard resistors (Wellard, 1960).

4.2 Stability

Stability refers to the change in resistance value with time or environmental stress. Stresses include high- or low-temperature exposure, application of full rated power, short-time overload, moisture, soldering heat, or radiation exposure. Carbon composition resistors generally have the poorest stability; wirewounds are the most stable, followed by metal-foil, metal-film, and carbon-film resistors.

4.3 Power Rating

The power rating of a resistor is defined as the maximum specified wattage that can be continuously dissipated at a maximum specified temperature without damage to the resistor. The choice of materials in the construction of the resistor along with its physical size determines its power rating. An important consideration is the temperature rise of the resistor. If the resistor is mounted so that it is close to other heat-producing components or has restricted ventilation, the power dissipation of the resistor may have to be reduced to avoid reaching the maximum allowable temperature.

4.4 Temperature Coefficient of Resistance

All resistance materials exhibit some change in resistance with temperature, and the magnitude of this change is usually expressed in %/°C or ppm/°C. For general-purpose resistors over a limited temperature range, this change in resistance with temperature is treated as a linear function given by the relationship

$$R = R'[1 + \alpha_0(t - t')],$$

where R and R' are the resistance values at temperature t and reference temperature t', respectively, and α_0 is the mean TCR expressed in proportional parts per °C over the temperature range of operation (Harris, 1962). For most materials the resistance–temperature curve is not linear; therefore, for precision resistors, especially wirewounds, this relationship is more accurately expressed as

$$R = R'[1 + \alpha(t - t') + \beta(t - t')^2],$$

where α is the slope of the resistance–temperature curve at t' and β is the curvature at any temperature over the range of operation.

The TCRs of film-type resistors (Maissel, 1970) can span a wide range, as shown in Table 2. The main factors that cause this effect are the type of substrate, film thickness, film composition, film structure, and important parameters during deposition such as substrate temperature. Resistance in bulk materials results from electron scattering by phonons, impurities, and defects. In thin-film materials, surface boundaries cause additional scattering effects that influence the resistivities and TCRs of these films. Typically, thin films have lower TCRs compared with bulk materials primarily because of the high resistivity of thin films.

4.5 Load Coefficient

The load coefficient of a resistor is defined as the change in resistance caused by the production of joule heating (I^2R) in the resistor at the rate of one watt and is usually expressed in ppm/W. This change, however, is a function of time. When a current starts flowing in a resistor the resistance material (wire or film) very quickly takes up a temperature above that of the base material in which it is mounted. The amount of this change depends on the thermal contact between the resistance and base materials, thermal time constant of the resistance and base materials, and TCR of the resistance material, and also upon the changes in stress in the resistance material and its support. The load coefficient of a resistor is a rather indefinite quantity, varying with time of flow of current and with the environment of the resistor.

4.6 Voltage Coefficient

When voltage is applied to a carbon or film-type resistor there may be a decrease in resistance apart from changes caused by loading of the resistor (Wellard, 1960). This decrease in resistance with increase in voltage results from the breakdown of contact resistances between carbon particles in carbon composition resistors or the breakdown of boundary resistances between islands of material on substrates of film-type resistors. This change in resistance per applied volt is called the voltage coefficient of resistance. In carbon composition resistors, the change in resistance value due to applied voltage is usually -200 ppm/V or less. For carbon-film resistors, the VCR can vary from -10 to -50 ppm/V. Metal-film resistors have VCRs from -1 to -30 ppm/V depending on their wattage, whereas metal-oxide–film resistors have VCRs from -1 to -5 ppm/V. Wire-wound resistors do not exhibit a VCR.

4.7 Humidity Effects

Unless the resistive element is hermetically sealed in a glass or metal container with glass-to-metal seals, moisture can permeate a resistor and change its resistance value. Moisture can produce two reversible effects:

1. On the surface of a high-value resistor or its housing it can provide a path for leakage currents and thus lower the apparent resistance.
2. If moisture is absorbed through the insulator protecting the resistive element, such as the enamel coating of resistance wire, or the jacket of a carbon composition resistor, or the overglaze film of film-type resistors, the insulator will swell, resulting in pressure being exerted on the resistive element. This effect usually causes the resistance to increase and is directly proportional to the insulator thickness and inversely proportional to the thickness of the resistive element (Starr *et al.*, 1970). The increase can vary from 0.1% to 10% for a 50% change in relative humidity depending on the type of resistor.

4.8 Pressure Effects

Resistance materials are affected by changes in pressure (Meaden, 1965). These changes of resistance as a function of pressure are not well understood, and, depending on the material, resistors may have either a positive or negative pressure coefficient of resistance. Fortunately, for well-constructed resistors these changes of resistance with pressure are only significant for those of the highest quality. For pressure changes of 500 hPa, the change in resistance would be within 1 ppm.

4.9 Frequency Effects

A resistor may be represented to a first approximation by the circuit of Fig. 2, which shows a pure dc resistance R in series with

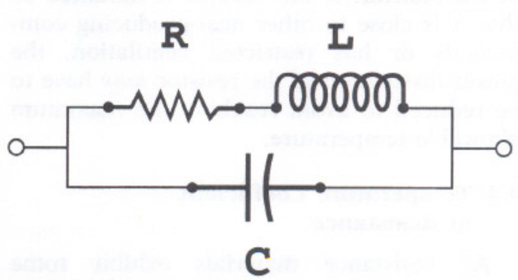

FIG. 2. Simplified model of a resistor.

an inductance L and this combination shunted by a capacitance C (Harris, 1962). The net equivalent inductance is given by

$$L' = L - CR^2.$$

The overall inductive effect of a resistor is reduced by its shunt capacitance. The time constant of a resistor is defined as

$$\tau = L'/R = L/R - CR.$$

The time constant of a resistor may be either positive or negative, depending on which of the terms, L/R or CR, predominates. For a well-designed ac resistor, the value of the time constant should be 10^{-7} or less. Low-valued resistors generally have a positive time constant, which means a net inductive effect, while high-valued resistors have a negative time constant or a net capacitive effect. The crossover point for wirewound resistors is around 100 Ω. Film-type resistors have the best high-frequency performance. The effective dc resistance of these resistors for most resistance values remains fairly constant up to 100 MHz and then decreases at higher frequencies (Hierholzer *et al.*, 1977).

For high-accuracy requirements other frequency effects need to be considered. These include dielectric losses, losses arising from eddy currents induced in nearby conductors, and losses due to skin effect. The skin effect (Harris, 1962) results from a decrease in the current density in the interior of the resistive element and an increase toward its surface as the frequency increases. The effective resistance increases and is a function of the resistivity of the material and the geometry of the resistive element.

5. CLASSIFICATION OF RESISTORS

The most common classification of resistors is according to their intended use and inherent performance.

5.1 Standard Resistors

Standard resistors (Harris, 1962) are used for calibration purposes in resistance measurements. They are usually commercially available only in decimal multiples from 0.01 mΩ to 10 TΩ. Standard resistors of nominal values to 100 MΩ are constructed of wire or strip resistance material. Manganin is the material of choice for resistors up to 10 Ω, and Evanohm® material is usually used in the construction of resistors above 10 Ω to 100 MΩ. Above 100 MΩ, the best available resistors are of the thin–metal-film construction. Standard resistors 100 Ω and below are constructed as four-terminal types to eliminate the problems of lead and contact resistances and to define the resistance more precisely. The important requirements of standard resistors are stability with time, low TCR, small thermal emfs against copper, well-defined terminations, and ruggedness. Standard resistors are adjusted to 0.01% or better from nominal value for wirewound resistors, and from 1% to 10% from nominal value for metal-film resistors.

5.2 Resistors for Electronic Circuits

The majority of resistors manufactured are intended for use in electronic circuits. These include resistors of all types of construction as listed in Sec. 3. For critical low-frequency circuits wirewounds are still in use; otherwise, metal-film resistors are used because of their excellent high-frequency performance. The other important requirements include small size, high reliability, and low cost. Resistor tolerances vary from 0.01% to 20% depending on their use. These resistors are intended for use in circuits involving potentials up to several hundred volts, but currents seldom over 10 to 100 mA.

A variety of thin- and thick-film resistor chips are available for hybrid microelectronic circuits (Hierholzer *et al.*, 1977). They measure as little as 1 mm by 1 mm, and have resistance values from a few ohms to 1 GΩ. A typical power rating is 0.25 W or less, with TCRs in the order of 20 to 200 ppm/K.

5.3 Integrated-Circuit Resistors

Integrated-circuit resistors (Fogiel, 1972) that lie in the range 20 Ω to 30 kΩ are generally formed by the diffusion of p-type material in an n-type epitaxy layer. Their tolerances, however, are poor, being in the order of ±25%. The tolerance of the ratio of two diffused resistors can be as low as ±2%. Diffused resistors are not desirable for higher values, since large chip areas are required. Above 30 kΩ, resistors can be formed from ion-implanted layers. These are quite reproducible, have a large dynamic range, and are linear.

5.4 High-Current Resistors

High-current resistors or shunts (Harris, 1962) are used for the measurement of direct current in the range from 10 A to 10 kA or higher. They are four-terminal resistors made from sheets or rods of manganin, using several elements in parallel for the lower-resistance, high-current values. They are designed for operation either in an air environment or mounted in an oil-filled container equipped with a stirring mechanism. The range of resistance is from about 10 μΩ to 10 mΩ. Because of the high power dissipation and the less well-defined thermal conditions, the accuracy obtainable is limited to 0.01% at the low-current values, and degrades to about 0.1% for high-current values.

5.5 High-Voltage Resistors

High-voltage resistors (Wellard, 1960) are designed to fulfill the special requirement for high-voltage, high-resistance units capable of dissipating moderate power. These resistors are rated from 5 to 20 kV, have a resistance range from 2 kΩ to 1 GΩ, and are rated from 5 to 20 W. These resistors are noninductive and are used primarily in high-voltage bleeder circuits, high-voltage dividers, and high-voltage networks.

GLOSSARY

Ayrton–Perry Winding: A resistor winding method where alternate winding layers are wound in opposite directions to reduce inductance by causing electrical fields to cancel.

Bifilar Winding: A resistor winding method in which a wire is folded in half into a long loop or "hairpin" with the two sides as close together as possible and then wound side by side.

Cermet: A resistance alloy consisting of a metal oxide, usually chromium–silicon monoxide (Cr–SiO).

Evanohm®: A resistance alloy of nickel, chromium, aluminum, and copper, developed by the Wilbur B. Driver Co. in 1948, having a low TCR and a resistivity 77.5 times that of copper.

Load Coefficient: The change in resistance caused by the production of joule heating in a resistor at the rate of one watt and usually expressed in ppm/W.

Manganin: A resistance alloy of copper, manganese, and nickel, developed around 1890, having a low TCR and a resistivity 27.8 times that of copper.

Ohm: The unit of resistance required to cause a voltage drop of 1 V with a flow of 1 A of current.

ppm: Parts per million (10^6), which is also 0.0001%.

Quantized Hall Resistance (QHR): A reference based on the QHE that defines a base resistance believed to be equal to the ratio of the fundamental constants h/e^2 and other quantized resistances equal to submultiples of h/e^2.

Quantum Hall Effect (QHE): An observed property at low temperatures in special microelectronic samples in which a two-dimensional electron gas exists and energy states are quantized when subjected to a strong magnetic field.

Resistance: The property of a conductor that causes it to impede the flow of electrons.

Resistance Alloy: A material, with properties of moderate to high resistivity, low temperature coefficient of resistance, and long-term stability, used in the construction of resistors.

Resistivity: The resistance per unit length of a material with uniform cross section.

Shunts: Special class of resistors of nominal values from about 10 μΩ to 10 mΩ designed to carry large currents in the range from 10 A to kA or higher.

Stability: The degree to which the resistance changes with time or environmental stress.

Standard Resistors: The highest quality of resistors used for calibration purposes in resistance measurements.

Temperature Coefficient of Resistance (TCR): The change in resistance per a degree change in temperature expressed in ppm/K or ppm/°C.

Thermal emf: The voltage generated when the junctions of a circuit of two dissimilar metals are maintained at different temperatures.

Voltage Coefficient of Resistance (VCR): The change in resistance as a function of voltage expressed as ppm/V.

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