

THIN FILM RESISTORS

HISTORICAL DEVELOPMENT

The earliest forms of thin film resistors were developed in Germany during World War II based on “cracked-carbon” which was deposited onto ceramic cores during a high-temperature chemical vapor deposition (CVD) process. The resistor was brought to value by removing material in a spiral pattern by grinding. A cap-and-lead termination was followed by polymeric encapsulation.

The performance characteristics of these carbon-film resistors were an order of magnitude improvement over prior resistors consisting of a carbon composition product. These exhibit sizable changes in value when subjected to fluctuations in temperature or humidity because of large dimensional changes in the resin matrix. By contrast, film resistors were far more stable and the in-line procedure for adjusting them to value enabled production in high yield of close-tolerance (1%) components.

The next evolutionary step was adopting the low-temperature-coefficient metal alloys which were used in wire-wound resistor construction. They were deposited as films using nickel-chromium carbonyl in a CVD process. Subsequent manufacturing steps were similar to the carbon film product. These “precision” metal film resistors had a much lower temperature coefficient of resistance (TCR) and greater overall endurance than the carbon film product. TCR is defined as the unit change of resistance per unit change in temperature, expressed as parts per million per degree centigrade (ppm/°C), and discussed later under “Performance Characteristics.”

During the 1960s the techniques for fabricating integrated circuits were also applied to manufacturing resistive components. At that time, the only substrate material which could be made with a sufficiently uniform surface was a very low-alkali-content borosilicate glass. Nichrome alloys were evaporated in high vacuum onto flat substrates. Patterns were produced by photolithography, resulting in very fine features. The techniques used for resistance adjustment by selective removal of the film, including chemical thinning and diamond grinding, were slow and clumsy. The development of laser trimming resolved those issues, but difficulty was encountered with microcracks in the glass substrate. Soon, however, an appropriate ceramic material in wafer form was developed. This had a flaw-free surface, chemical resistance, high thermal conductivity, and sufficient strength to survive the rigors of automatic equipment handling. This material, smooth, fine-grained, high-purity alumina, represented an important step in advancing thin film technology.

The problem of maintaining compositional consistency during evaporation of multicomponent alloys, such as nickel-chromium, was eventually resolved by adopting cathodic sputtering. However, it was soon discovered that nichrome in thin film form is subject to electromigration under high humidity. This corrosion resulted in occasional catastrophic failure. For this reason, another material, tantalum nitride, which had been developed during thin film capacitor research at Bell Labs, came into use.

Resistive materials in thin film form required greater attention to the nature of the termination than had bulk materials. For instance, the deposition of gold directly onto a thin

film of nichrome results in thinning of the resistor in the critical region adjacent to the termination by absorption of the nickel constituent by the gold. It was therefore necessary to interpose barrier layer materials between the resistive film and the overlaying termination to minimize adverse metallurgical interactions.

The adaptation of integrated circuit manufacturing techniques had enormous impact on passive component manufacture. As distinct from discrete resistors, it facilitated fabricating resistor *networks* within which all the elements were uniformly matched. Good tracking was an intrinsic property of integrated multielement networks. In addition, whereas the achievement of high precision had placed strict demands on the manufacture of discrete resistors for maximum *absolute* performance, integrated network construction allowed focusing the emphasis on unprecedented *relative* performance. In addition, the small size of single chip networks allowed economic packaging in hermetic enclosures using familiar chip and wire technology. Of course, the economy of simultaneously manufacturing hundreds or even thousands of resistors per wafer significantly reduced the unit cost.

DESIGN CONCEPTS

In choosing a resistor technology, consideration must be given to requirements for (1) the range of resistance values, (2) their precision and (3) the physical size in terms of power or voltage demands.

Different resistance values are obtained, in general, by selecting a material with appropriate specific resistivity, by arranging a given material in an appropriate geometrical configuration, and/or by a combination of both. For example, wire-wound resistors are composed of alloy compositions with exceptionally low TCRs. Differing values are obtained by using wires of different cross-sectional area and length. This is an exclusively geometric, mostly one-dimensional, approach.

By contrast, carbon composition resistors and thick film resistors are produced in a limited number of physical configurations in which the resistance value is varied by changing the resistivity of the material. In particular, thick film materials consist of a two-phase mixture of a conducting oxide particulate dispersed throughout a glass matrix. By varying the proportions of the two ingredients, the resistivity and, thereby, the resistance are adjusted controllably over a range of seven decades or so. The discontinuous nature of the conducting phase in composites, however, presents difficulties. It is not easy to obtain lower resistivities. Composites are also characterized by higher noise and greater voltage and temperature dependence. Nevertheless, composite materials attain resistivities far higher than those of any other technology. A comparison of thick and thin film resistor technologies is given in Table 1.

Thin film resistors are made from materials with a limited resistivity range, and different values are obtained primarily by geometric means. The most commonly used materials, nichrome and tantalum nitride, have a resistivity of about $500 \mu\Omega \cdot \text{cm}$ (this falls in the semimetallic category, characterized by a weak dependence of resistivity on temperature). The film thickness is varied in a practical manner only from a few hundred to a few thousand angstroms. The principal means

Table 1. A Comparison of Resistor Technologies

	Thick Film	Thin Film
Manufacturing process	Screen print	Vacuum deposit and photolithography
Film thickness	10 μm	0.1 μm
Line width	30 mils	0.3 mils
Material resistivity range	6+ decades	1 decade
Typical aspect ratio	20:1	2000:1
Resistance tolerance	1%	0.01%
TCR	250 ppm/ $^{\circ}\text{C}$	25 ppm/ $^{\circ}\text{C}$
TCR tracking	50 ppm/ $^{\circ}\text{C}$	5 ppm/ $^{\circ}\text{C}$
High-voltage capability	Yes	No
Current/Voltage linearity	Poor	Excellent
Current noise	-5 dB	-30 dB
Corrosion	Never	Sometimes
Custom tooling	Hard	Hard
Cost	Lower	Higher

of achieving different values is by varying the length and width of the conducting trace.

To facilitate design calculations, practitioners have rearranged the customary relationship describing the dependence of resistance R on resistivity ρ , length L and cross sectional area A into one which involves "sheet resistance" ρ_{sh} and "number of unit squares" n as shown in Fig. 1:

$$R = \frac{\rho L}{A} = \left(\frac{\rho}{t}\right) \left(\frac{L}{W}\right) = \rho_{\text{sh}} n \quad (1)$$

For example, a film of material with a resistivity of $500 \mu\Omega \cdot \text{cm}$ and 50 nm thick has a sheet resistance of $100 \Omega/\square$. The usefulness of this concept is based on the fact that the resistance across a square area is independent of its size, unlike one- and three-dimensional geometries. The sheet resistance must be multiplied by the number of unit squares in series which is given by the length/width ratio of the design trace, otherwise known as the aspect ratio.

The maximum resistance value attainable with a given film is determined by the highest aspect ratio that can be generated in a given area, which, in turn, is determined by the lower limit of line and space width achievable via the patterning technique employed. The optimum pattern for this is serpentine, as shown in Fig. 2. Following are the relationships among the various parameters:

$$R = \rho_s n = \rho_s \left(\frac{L_1}{\ell}\right) \left(\frac{L_2}{\ell + s}\right) = \rho_s \left(\frac{A}{\ell(\ell + s)}\right) \quad (2)$$

For equal line/space width,

$$R = \frac{\rho_s A}{2\ell^2} \quad (3)$$

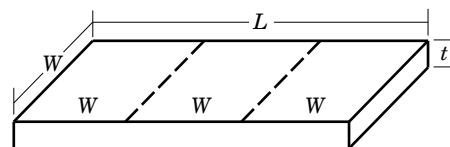


Figure 1. Simple rectangular resistor structure showing the basic concept.

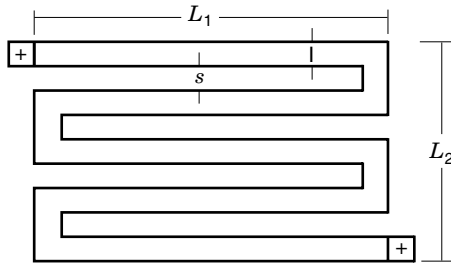


Figure 2. Typical serpentine resistor pattern to conserve space.

For example, with a film of sheet resistivity $100 \Omega/\square$ and minimum attainable line/space width of 0.5 mil, the maximum resistance value attainable in a 50×100 mil area is one megohm. To achieve higher values, a film of higher sheet resistivity would be necessary, or greater substrate area, or narrower line/space width, or a combination.

Very low resistance values are not easily obtained with thin films. The lowest sheet resistivity directly obtainable is about $10 \Omega/\square$. Low values are therefore often designed with fractional aspect ratios. This is done with interleaving termination traces, but the performance characteristics are compromised, because of the proportionately increasing roles of the conductor itself and the resistor-conductor interface.

The potential contribution of conductor traces within networks must be minimized even with midvalue resistors, where precision tolerances or ratios are required. This is done through appropriate design by keeping the aspect ratio of the conductor as small as possible and also by reducing its sheet resistance which is commonly done by electroplating to a thickness much greater than practical with vacuum deposition. The form of the external lead must also be taken into consideration, especially with chip-and-wire assembly, where the resistance of a typical wire lead is 0.1Ω . That amount adds significantly to the total resistance and affects the TCR, as shown in Table 2. The effect of lead resistance is minimized by utilizing alternative packaging techniques, such as direct soldering of lead wires in a single-in-line style. Fortunately, the circuit requirements for resistance networks are more often on voltage ratio output, in which case interconnection resistance is less important.

The design of thin film resistors must also allow for adjustment to a value. Modern laser systems are capable of adjusting resistors to very close tolerances at very high speed. However, the closer the required tolerance, the more carefully the resistor must be designed for both trimming efficiency and to minimize the amount of physical damage done to the remaining active area of the resistor by the laser beam. This is done by the use of special trim geometries, which allow for sequential steps from large to small increments of resistance

Table 2. Effect of 0.1 Ohm Lead Resistance on Resistance Value and TCR

	Total Resistance	Temperature Coefficient ^a
10 W	1.0%	40
100 W	0.1%	4.0
1000 W	0.01%	0.4

^a Assuming a TCR of gold of $+4000 \text{ ppm}/^\circ\text{C}$

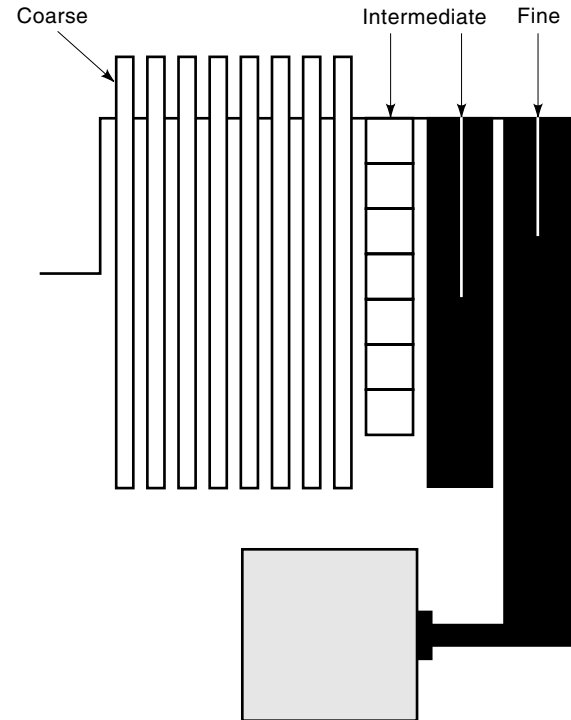


Figure 3. Special resistor design feature. A multitude of different designs are possible.

change. These special geometries occupy a significant amount of substrate area. An example of such a design is shown in Fig. 3.

WAFER-SCALE FABRICATION

The process of fabricating thin film resistors and networks is comparatively simple relative to that for active devices, but considerable variety is still possible along with much art. A typical sequence is described below.

The surface of the substrate is given some type of cleaning and/or conditioning to ensure good adhesion of the thin film. This is accomplished before deposition by chemical cleaning in ultrasonic baths followed by transport through a vapor-phase solvent system. Further conditioning is accomplished by plasma treatment during the initial stage of the vacuum deposition process. This is often done within a load-lock entry chamber, a system which allows maintaining the cathode within a controlled, nonreactive atmosphere. Film deposition is accomplished by dc sputtering in a controlled atmosphere across a gap of the order of one inch. The substrates are often periodically cycled under the cathode. The atmosphere employed is usually $10 \mu\text{m}$ of argon containing a partial pressure of either oxygen or nitrogen. Deposition is done at rates ranging from $1 \text{ nm}/\text{min}$ to $10 \text{ nm}/\text{min}$.

Most deposition systems accommodate multiple cathodes to deposit several different materials sequentially without breaking vacuum. This provides efficient operation, assures intimate contact between layers, and allows for the deposition of composite resistive films. The design and placement of physical shields, located in the cathodic dark-space region, govern the uniformity of deposition across a wafer. It is possi-

ble to attain uniformity of sheet resistance to within $\pm 10\%$ of a design value.

The general order of deposition is (1) resistive film, (2) barrier layer, and (3) conductive film. The barrier layer is included to minimize metallurgical interaction between the resistive and conductive layers, especially during subsequent high-temperature stabilization. It usually consists of nickel in the case of the nichrome/gold system and palladium in the case of the tantalum nitride/gold system.

Following film deposition, the appropriate resistor and conductor patterns are formed by photolithographic techniques, often in conjunction with an electroplating operation as noted earlier. An example of such a sequence is shown in Fig. 4 in idealized form. The first photoresist layer is applied, exposed in the termination pattern and developed. Then the wafer is electroplated, thickening the conductor traces within the openings in the photoresist layer. After stripping the photoresist, the remaining thin film conductor/barrier is etched away. Then the photolithographic patterning process is repeated with the resistive film.

It is common practice to employ a positive photoresist which stands up in electroplating solutions. The conductive layers are removed with cyanide solutions, and resistive materials are dissolved in potassium iodide or hydrogen fluoride solution.

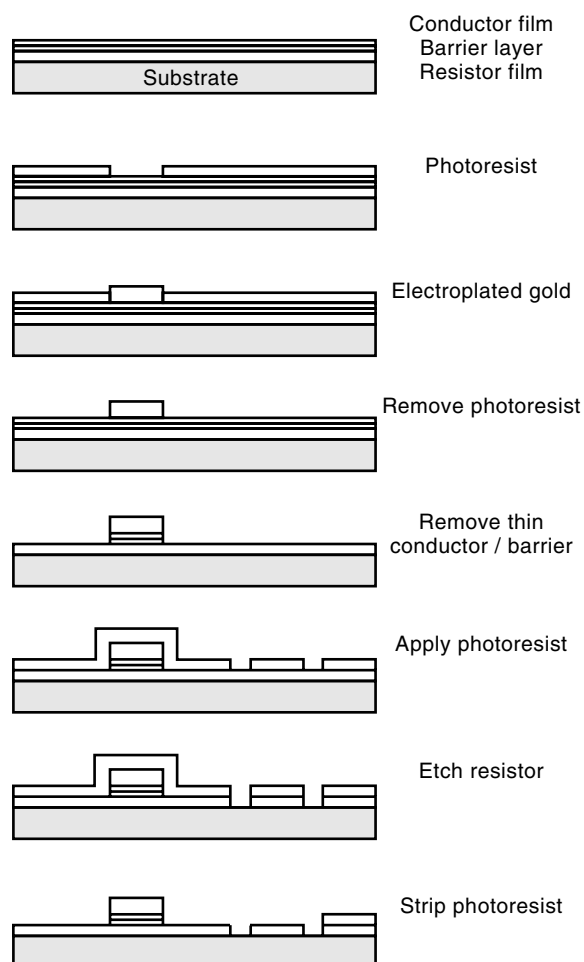


Figure 4. Typical resistor processing sequence. This is just one example of resistor fabrication.

Although there are many variants in the sequence of these steps, they always include stabilizing the resistive film by baking at high temperature in air, typically for several hours at temperatures in the 300–450°C range. This renders the material metallurgically stable and chemically inert. The precise conditions during stabilization are often adjusted slightly to bring the TCR within a required specification.

The resistors are adjusted to their required value by laser machining with automatic, especially designed high-speed operating systems. The choice of electrical probes for on-line measurement is critical, involving a balance between requirements for good electrical contact and optimum physical wear. Laser beam (YAG) parameters must be carefully chosen to provide clean, efficient removal of resistive film but with minimum disturbance of the remaining film and substrate. In the case of precision tolerances, a two-step trim procedure is frequently employed which includes an intermediate annealing step.

The final step in wafer-scale fabrication is dicing. This is done by laser scoring or diamond-wheel sawing. With a ceramic substrate, scoring is normally done with a CO₂ laser system and usually in the postage-stamp mode, followed by breakage. Alternatively, high-speed diamond-sawing is done with ceramic or silicon substrates.

Chip networks are usually assembled into one of many available types of package formats, including conformably coated single-in-line, hermetic dual-in-line, flatpack, or several molded small-outline package styles.

MATERIALS

Substrates

One of the most widely used substrate materials for thin film resistors is high-alumina ceramic. This is available from many suppliers in a variety of thicknesses ranging from 10 to 40 mils. It is manufactured by a green-tape process in sizes up to 6 inches. In finished form it consists of 99.6% alumina and has a surface finish generally better than 1 microinch/inch. It provides excellent adhesion of the deposited film. Its high strength is essential for withstanding the rigors of handling by manufacturing equipment. It is reasonable in cost and its comparatively high thermal conductivity is important for dissipating power and reducing thermal gradients within a chip network.

High-alumina does not saw easily, but, with the proper composite diamond blades and high-speed equipment, reasonable rates are achieved. Pulsed-laser scoring, and subsequent breaking is done much more rapidly but with attendant risk to higher precision network tolerances.

Ceramic substrate was not always available with consistent surface characteristics and, during its evolution, the use of oxide passivated silicon wafers became, and has remained, popular for fabricating film resistance networks. This material is readily available in large sizes with consistent surface characteristics. With it, much finer circuit features can be successfully imaged. It dissipates internally generated power very adequately.

Silicon substrates are favored in applications involving highly automated assembly equipment because of the superior pattern visibility in autoalignment systems and the relative ease and speed with which they can be singulated by dia-

mond-blade sawing. However, because of the inherent electrical conductivity of silicon and the relatively large capacitive reactance involved, it performs more poorly at higher signal frequencies than similar networks on ceramic. On the other hand, the combination of the conductive silicon base and its overlying dielectric layer provides the basis for fabricating integrated resistor-capacitor networks.

Experience with both high-alumina and silicon substrates indicates that better stability is generally obtained on ceramic, making it the preferred choice for precision network applications. Substrates of thin sapphire wafers (single crystal alumina) were used in high reliability applications when ceramic quality was still inconsistent. It is still employed occasionally in applications for which its superior thermal conductivity is critical.

Resistive Films

The use of nickel-chromium alloys (1) for fabricating thin-film resistor networks was a natural extension of their use in manufacturing wire-wound resistors. Nichrome wire was made in compositions with a very low TCR for instruments and the endurance of red heat for power applications. Compositional control of early film depositions by thermal evaporation of nichrome in high vacuum was difficult because of the different partial pressures of the constituents. This problem is resolved by high-voltage sputtering, which, after an initial break-in period, delivers a film whose composition is identical to that of the cathode itself. Sputtering provides excellent control of the film deposition process.

The composition of nickel-chromium alloys for thin films generally falls within the range 80/20 to 40/60. The as-deposited film is uniform in composition with varying degrees of microcrystallinity, depending on the temperature at which the substrate is maintained during deposition. During thermal annealing, however, stratification occurs, with chromium migrating to the surface where it is oxidized, leaving a nickel-rich underlayer. The chromium oxide layer is etch-resistant. The deposition is also done using a partial pressure of oxygen, which modifies the behavior during subsequent processing.

Nichrome is made in sheet resistance ranging from 25 to 1000 Ω/\square or so and in that range the TCR is maintained to within ± 50 ppm/ $^{\circ}\text{C}$. However, within the commonly employed narrower range of 100–200 Ω/\square , the TCR is held to a very low value, less than 10 ppm/ $^{\circ}\text{C}$, by exercising careful control of critical process steps. It remains the material of choice for high precision applications.

The TCR of the as-deposited film is generally negative and moves to a more (metallic) positive value during thermal stabilization. A near-zero TCR is attained by critical control of the process parameters. However, this is compromised by the significant nonlinearity of the resistance-temperature relationship, as shown in Fig. 5. Even with films with an incremental TCR of zero near room temperature, the slope of the curve at lower and higher temperatures may range between -5 and $+5$ ppm/ $^{\circ}\text{C}$.

Properly manufactured nichrome thin films on ceramic substrates are exceptionally stable. The small resistance changes which occur in circuit operation are entirely a function of substrate temperature, induced by power loading or ambient. The rate of change of resistance measured at higher temperatures can be extrapolated to lower temperatures and

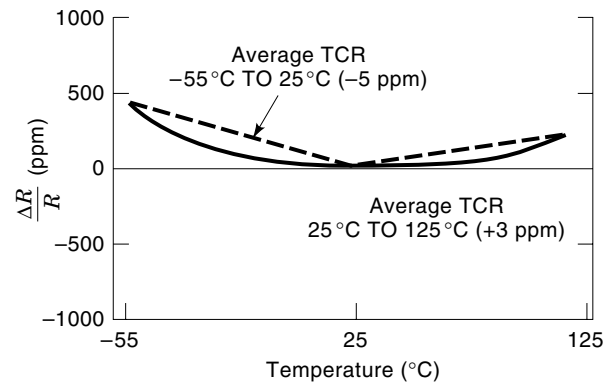


Figure 5. Example of nonlinear TCR. It is usually desired that TCR be linear.

longer times by classical kinetic equations, as in Fig. 6 and Table 3.

Nichrome thin films are often provided with deposited gold terminations for wire-bonding. If the gold is laid directly on the nichrome, however, it absorbs chromium from the nichrome nearby resulting in a region of high resistance and circuit vulnerability. This interaction is blocked by adding an intermediate nickel layer between the nichrome and gold.

Unlike its bulk forms, thin-film nichrome is subject to catastrophic failure by electromigration from dc voltage under high humidity which permits a condensed water layer to form. This phenomenon resulted in dramatic field failures before it was recognized and dealt with by hermetic packaging or by applying an insulating material to the nichrome surface.

To overcome moisture difficulties associated with nichrome, thin film resistors of tantalum nitride are employed. These are deposited on ceramic substrates by dc sputtering from a tantalum cathode at a pressure of about 10 μm with a partial pressure of nitrogen, appropriate for obtaining the

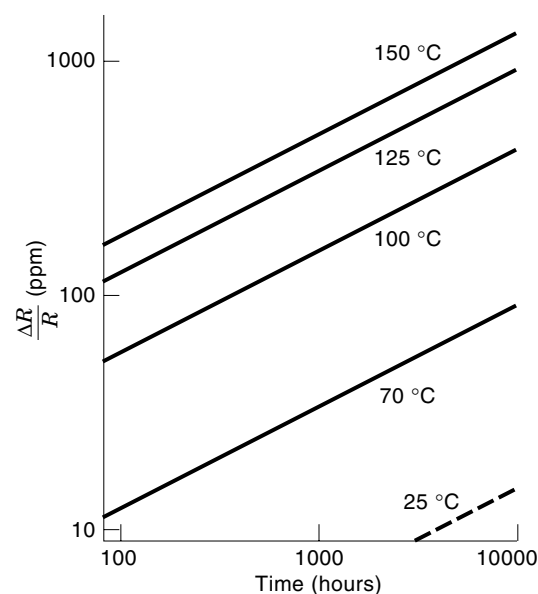


Figure 6. Change in TCR with time and temperature to show prediction of performance.

Table 3. Extrapolated Stability Data for Nichrome Films

Film Temp, °C	25		70		125	
	$\Delta R/R$, ppm		$\Delta R/R$, ppm		$\Delta R/R$, ppm	
	Absolute	Ratio	Absolute	Ratio	Absolute	Ratio
1000	–	–	50	10	500	100
2000	–	–	70	15	700	150
10000	15 ^a	3 ^a	150	30	1500	300
100000	50 ^a	10 ^a	500 ^a	100 ^a	5000 ^a	1000 ^a

^a Extrapolated data.

film in the form Ta₂N (2). These films usually have an interdiffusional barrier layer of palladium and gold termination. They are photolithographically imaged and thermally stabilized.

Tantalum nitride is made in a range of film thickness and sheet resistance similar to that of nichrome. It is regarded as having superior reliability. The disadvantage of tantalum nitride, compared with nichrome, is that it has an intrinsic TCR of -120 ppm/°C.

Efforts to combine the best features of nichrome and tantalum nitride in a single system have been made by way of a composite, two-layer film. A film of nichrome is covered with a thin film of tantalum which is subsequently converted by thermal treatment to an oxynitride. The resultant composite can be made with a very low and nearly linear TCR along with greatly increased resistance to electromigration.

Still another class of vacuum-deposited thin films utilized in resistor products are composites of mixed chromium and silicon oxides. Historically, these are obtained as vacuum evaporated mixtures, but serious process control was almost impossible. Now such films produced by sputtering from cathodes formed of chrome-silicon in an atmosphere with oxygen. High sheet resistance is obtained with these films, to values up to 10,000–20,000 Ω/\square . The TCR of these films is more suitable for general purpose applications, and the films exhibit higher levels of current noise and less stability than homogenous film materials. For situations requiring very high resistance and/or minimum size, these film materials fulfill a real need. A comparison of film materials is given in Table 4.

FINISHED FORMATS

Through-Hole Assembly

Regardless of the end product, all wafers in a given facility are processed in pretty much the same way. Following singulation, however, the chips are packaged in a variety of formats. For through-hole circuit-based assembly with 100 mil pin spacing, the choice is between dual-in-line and single-in-

Table 4. A Comparison of Resistive Film Materials

	NiCr	Ta ₂ N	Poly	
			Chrom.	Multilayer
Sheet resistivity range, Ω/\square	50–500	50–500	to 10,000	50–500
TCR ppm/°C	10–50	–120	<300	5–25
Thermal stability	Excellent	Excellent	Fair	Excellent
Reliability	Marginal	Excellent	?	Excellent

line and styles. The former may be hermetic or molded plastic. Both involve chip-and-wire assembly technology, which requires that a significant amount of additional electrical resistance must be taken into account in designing and trimming precision networks. This is more critical in networks with lower value resistors.

Dual-in-line construction imposes limits on chip size and thereby on the total amount of resistance which can be accommodated. However, a hermetic seal provides an added measure of reliability/stability.

An alternative format for through-hole assembly is single-in-line. These are nonhermetic, usually with a conformal resin encapsulation. Single-in-line format involves a much larger “chip” than dual-in-line but this added size allows much higher total resistance values. An advantage of single-in-line construction is that the external leads are connected directly to the chip, by soldering or thermocompression bonding.

The stability of thin film resistor networks is impacted by mechanical stress introduced within the chip during assembly, such as by mechanical contraction of a molding compound during curing or through the interaction of materials with a different coefficient of thermal expansion. Where the development of such stress is unavoidable, the effects are reversed or moderated by thermal annealing. It is also possible to allow for a final “tweak” of resistance value to close tolerances by laser matching just before the final assembly step.

Surface-Mount Format

In the case of surface-mount assembly, a greater number of formats are available, beginning with individual chip resistors. These are available on ceramic in a variety of standard sizes and standard values to tolerances of 0.1%. The solderable, wraparound end termination may be a thick film or thin film.

Another form of individual chip resistor is the square silicon chip, usually either 20 or 30 mil meant primarily for hybrid circuit application, with terminal pads for wire-bond connection. A major advantage of this product is that it is usually supplied as a two-element, three-terminal version, which allows adjustment to close ratio tolerance.

Other forms of surface mount packaging for chip networks include:

1. hermetic flatpack, with chip and wire internal connection and 50 mil pin spacing;
2. leadless chip carrier, with solderable, wraparound terminals on two or four edges in 50 mil pin spacing;
3. small-outline (50) formats, primarily of molded construction with chip-and-wire assembly, in 50 and 25 mil gull-wing lead spacing on two edges. The popular RC networks are supplied in this format;
4. lead-frame-bonded directly to a ceramic chip in gull-wing style.

Most surface-mount networks are designed for general purpose (1% tolerance) networks to attain maximum component on-board density.

PERFORMANCE CHARACTERISTICS

Integrated Construction

An important aspect of integrated, thin-film resistor construction is that all the resistors on a given wafer close to one another are exposed to nearly identical conditions during manufacturing which results in matching their electrical characteristics very closely. This ensures that the relative values of resistance remain virtually unchanged throughout a variety of operational conditions. During the lifetime of the circuit, the resistors within a given network are said to track one another closely.

The difference in TCR between a seemingly matched pair of *discrete* resistors may be as great as twice the specified absolute TCR. For example, for a TCR of 0 ± 2.5 ppm/°C, the tracking between a pair may be as much as 5 ppm/°C. With integrated film networks, the tracking is independent of the absolute TCR and usually an order-of-magnitude better. For instance, even with an absolute TCR of ± 25 ppm/°C the internal tracking is generally less than 2 ppm/°C.

An additional advantage of integrated construction is that serpentine patterns are essentially noninductive compared with discrete, spiraled resistors. Further, the interconnections between resistors in a network at the chip level are inherently more reliable than those made with external lead connections, greatly improving the overall reliability of the network.

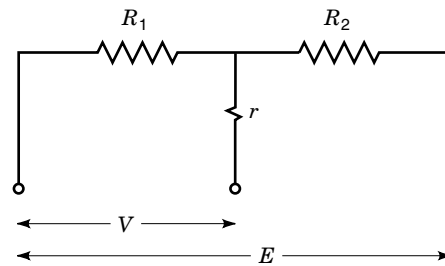
Thermoelectric voltages are generated if the terminations of a resistor are at different temperatures. This is a real problem with discrete precision resistors where measurable thermal gradients easily exist over the relatively large dimensions of conventional circuit boards. In thin-film integrated networks, all resistors are at nearly the same temperature as a result of the small chip size, proximity and the heat-spreading effect of the thermally conducting substrate. It is not surprising, therefore, that there are no reported thermoelectric effects in thin-film networks.

Temperature Coefficient of Resistance

The temperature coefficient of resistance is the measure of resistance change with a change in ambient temperature. It is defined as the unit change of resistance per unit change in temperature, and is commonly expressed as parts per million per degree centigrade (ppm/°C). It is the property by which different types of resistors are most often characterized or differentiated. In practice, the TCR is usually determined experimentally by measuring the resistance value at several temperatures and calculating the rate of change over the specific temperature interval, as indicated later. If the resistance changes linearly with temperature, the TCR is constant, regardless of the temperature interval. However, when it is not linear, the TCR varies according to the exact temperature interval over which the measurement is made. For this reason, it is critical that the interval is specified:

$$\text{TCR} = \left[\frac{R_2 - R_1}{R_1(T_2 - T_1)} \right] \times 10^6 \quad (4)$$

where TCR = temperature coefficient of resistance (ppm/°C), R_1 = resistance at room temperature (Ω), R_2 = resistance at



$$\frac{V}{E} = \frac{R_1}{R_1 + R_2} \neq \frac{R_1}{(R_1 + r) + (R_2 + r)}$$

Figure 7. Voltage ratio versus apparent resistance ratio.

operating temperature (Ω), T_1 = room temperature (°C), and T_2 = operating temperature (°C).

By adjusting processing conditions, it is possible to tailor the resistance versus temperature curve to produce a TCR with a negative slope below 25°C and a positive slope above it, with an incremental TCR of zero in the vicinity of room temperature, as shown in Fig. 5.

A zero absolute TCR is especially advantageous in circuit operation whereby current is switched on and off in one resistor which is matched to a reference resistor carrying a constant current. In this case, even though the two resistors are perfectly matched, they may differ in value because of differential self-heating, depending on the absolute TCR of the pair. In these situations, the absolute TCR should be as low as possible in the operating temperature region.

TCR Tracking

TCR tracking is defined as the difference between the TCR of a pair of resistors over a given temperature interval. Close tracking is difficult to achieve among discrete components, but is intrinsic to integrated construction. TCR tracking among neighboring resistors on the same wafer is usually no more than a few tenths of a ppm/°C. However, an “apparent” TCR tracking is sometimes found which is higher than the “true” TCR tracking because of the contribution of terminations with a small but measurable resistance r and a large metallic TCR. The contribution of the common lead disappears when critical ratios are specified and measured according to voltage division rather than resistance ratio.

Voltage Ratios

Frequently when resistors are employed as voltage dividers, it is more appropriate to deal with voltage ratio specifications than with resistance ratios. Ideally, the voltage drop across a pair of resistors is determined by the ratio of resistance values: $R_1/(R_1 + R_2)$ as shown in Fig. 7. When the resistance values are not equal, however, the voltage ratio differs from that calculated from the apparent (measured) resistance values by an amount governed by the resistance of the common lead. This deviation can be quite significant, especially with low value resistors. For a 10 kilohm resistor in series with a 1 k Ω resistor with a common “tap” lead of 100 m Ω resistance,

the two ratios differ by 75 ppm:

Voltage Ratio Calculated Using Apparent Resistance:

$$\frac{1000.1}{1000.1 + 10,000.1} = 0.0909165$$

Voltage Ratio Measured Directly: $\frac{1000}{1000 + 10,000} = 0.0909090$

Voltage ratio tracking over temperature is always less (better) than TCR tracking.

Thermal Stability

The effects described in the previous sections are reversible. The changes are not permanent and disappear when the temperature reverts to its initial point. Irreversible changes, however, are brought about by holding the components at an elevated temperature for extended intervals. The advantage of integrated construction again becomes evident. All resistors in a given film network exhibit very similar absolute changes during life testing, and the changes in resistance ratio or voltage ratio are an order-of-magnitude smaller.

Power Rating

Because thin film networks are not generally used in high-power applications, methods for establishing maximum power ratings are not as formalized as for discrete resistors. However, because chip size is quite small, internally generated power *density* may reach significant levels.

Rated power is generally accepted as that power which is sustained without raising the surface temperature of a part above a specified maximum operating temperature, commonly 150°C. The designer must, therefore, consider the power density developed at the chip surface. For more precise tolerances, a limit of 25 W/in² is appropriate. More general tolerances sustain power density levels up to 200 W/in² without jeopardizing their integrity. Allowance must be made for the fact that different packaging formats vary greatly in their ability to dissipate heat and thereby lower the chip surface temperature.

Voltage Coefficient of Resistance and Current Noise

These two characteristics, which can be a serious drawback in resistors made from composite materials, such as cermets or polymers, are inconsequential in thin-film networks. Voltage coefficient of resistance is the unit change in resistance per unit change in voltage expressed as ppm/V. It is a measure of the nonohmic behavior and, in thin films, reaches identifiable levels only in the megohm range, where it has been measured at about 0.1 ppm/V. Current noise is characterized and measured by an industry-standard instrument. Typical values for thin film elements are less than -35 dB.

SUMMARY OF THE ADVANTAGES OF THIN FILM, INTEGRATED RESISTOR CONSTRUCTION

- Very small, high-density, multielement networks.
- Extremely close matching of all elements in a network, insuring close tracking over temperature and throughout life.

- The small chip size enables hermetic construction in a variety of standard, contemporary formats.
- Repeatable and consistent characteristics part-to-part and lot-to-lot.
- Very low inductance.
- Outstanding reliability—fewer man-made interconnections.
- No discernible thermoelectric effects on voltage coefficient.
- Very low current noise.
- Installed costs are usually less than for discrete resistors.

NiCr THIN FILM RESISTORS

Background

Studies of NiCr TFRs have utilized resistance variation with annealing of different elemental ratios of Ni and Cr to achieve low values of the TCR (3). Nucleation and growth of microcrystalline particles occur with annealing in air or vacuum (4,5). Vacuum annealing may positively increase the TCR because of grain growth whereas air annealing forms surface oxides of Cr with a negative TCR which compensates for the effect of grain growth. Grain growth and intermetallic phases were observed (6) for SiO_x protected films, and selective oxidation of Cr on the top of unprotected films led to the development of an in-depth concentration gradient.

NiCr TFRs may be optimally developed (7) by annealing to minimize the TCR, by stability testing for various annealing conditions, and by identifying the annealing mechanism by secondary ion mass spectrometry (SIMS), electron spectroscopy for chemical analysis (ESCA), scanning electron microscopy (SEM), energy dispersive X-ray (EDAX), and transmission electron microscopy (TEM).

Fabrication Techniques

A thorough study of the NiCr TFR was conducted in a joint project by SUNY at Buffalo and Ohmtek, Inc. (8). NiCr thin film resistors used RF sputter deposition from a 40/60 NiCr:Si target on alumina substrates to a thickness of 300–700 Å. Sheet resistivities ρ_s of 10, 100, 150, 191, 212, 280, 500, and 1000 Ω/\square were studied. The TCR was determined for both air and vacuum annealing, as in Table 5, in the range -180°C to +100°C. The TCR of 10, 500, and 1000 Ω/\square samples was not improved satisfactorily by annealing. Films within the range of 100–200 Ω/\square were successfully annealed, except for the vacuum annealing of the 191 Ω/\square case. Vacuum annealing for 100 Ω/\square samples required higher temperature to achieve the same TCR improvement as air annealing. The 150 Ω/\square sample attained the lowest TCR with less range span. For the 191 Ω/\square case, only air annealing improved the TCR. As shown in Fig. 8, air annealing flattens the TCR versus T increases but an opposite effect was observed for vacuum annealing.

Samples were tested for stability after one month using repeated temperature cycling between 40 and 150°C for 8 h; elevated temperature at 150°C for 4 h; humidity >90% for 4 h and then 8 h. During a one month storage period, before stability tests, air annealed 100 Ω/\square samples retained the

Table 5. Result of TCR Measurements on NiCr TFRs

Sheet Resistivity, ohm/sq	Annealing Environment	Temperature, °C	Typical As-Deposited TCR, ppm/°C	Typical Annealed TCR, ppm/°C
10	Air	300	+70 ± 20	+90 ± 50
100	Air	337	-40 ± 20	+5 ± 5
100	Vacuum	400	-40 ± 20	+5 ± 5
150	Air	360	-45 ± 10	+3 ± 1
191	Air	350	-45 ± 8	+5 ± 4
191	Vacuum	340	-45 ± 8	-40 ± 10
500	Vacuum	300	-55 ± 10	-50 ± 8
1000	Air	200	-70 ± 27	-110 ± 20
1000	Vacuum	400	-70 ± 27	-50 ± 15
1000	Vacuum	500	-70 ± 27	-80 ± 20

low TCR whereas the vacuum annealed 100 Ω/□ and air annealed 191 Ω/□ samples had a TCR change from 5 to 17 ppm/°C. In 100 Ω/□ and 191 Ω/□ samples, the TCR was undisturbed by the previously described stability tests.

Mechanisms of Stabilization

SIMS analysis reveals that annealing enhances the Cr oxide to the same level as Si oxide. ESCA and TEM analyses confirm this in that an elemental Cr peak for the as-deposited film is replaced by a Cr oxide peak. The absence of Ni in the ESCA spectrum for annealed samples indicates segregation of Cr to the surface. SIMS reveals that the oxide ratio of Cr to Si in the bulk is lower for the samples with improved TCR. The lack of a Cr–Si structure in the unimproved samples, evidenced from the electron diffraction patterns, and also the limited range of sheet resistivity showing a TCR improvement, suggests that the bulk Cr oxides, then coordinated with Si, are important in achieving a low TCR, that is, Si is the medium for CrO and Ni interaction. After optimal annealing of samples consisting of enough Si–Cr structure in the 100–200 Ω/□ range, the amount of bulk oxide with a negative TCR balances the positive TCR contributed by the nucleation of segregated Ni. Thus, NiCr TFRs have a low and stable TCR after annealing because new compounds form and a balance between negative and positive TCR components in the film.

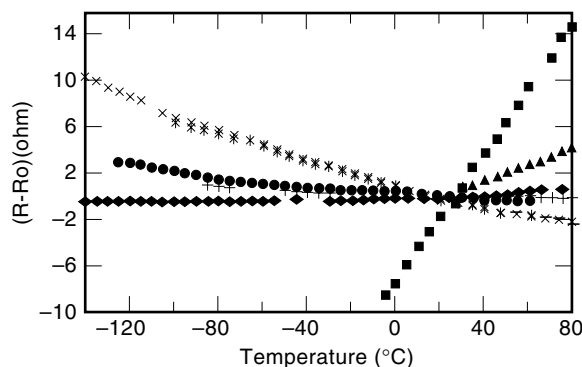


Figure 8. Resistance variation versus ambient temperature for 191 Ω/□ films of NiCr. The change in resistance decreases as air annealing temperature increases from 250°C to 350°C (7). * = 250°C in air, 1 h; ● = 330°C in air, 1 h; + = 340°C in air, 1 h; ◆ = 350°C in air, 1 h; ■ = 380°C in air, 1 h; ▲ = 340°C in air, 2 h; × = 340°C in vac, 1 h.

However, NiCr is not easily tuned to a TCR of ±5 ppm/°C and degrades in a harsh environment.

TANTALUM NITRIDE THIN FILM RESISTORS

Fabrication Techniques

The linear TCR and physiochemical inertness make Ta–N superior to the more popular NiCr for thin film resistors. The mass production of Ta₂N TFRs, deposited at 450°C by magnetron sputtering, with sheet resistivity of 50 to 100 Ω/sq and TCR of about -80 ppm/°C, was announced in 1982 (9). A slow annealing process under vacuum (10) might produce a near-zero TCR.

A thorough study of Ta₂N–TFRs was jointly conducted by SUNY at Buffalo and Ohmtek, Inc. (11,12). The Ta–N films were deposited on SiO₂/Si or alumina from a pure Ta target by either dc diode or magnetron reactive sputtering, without substrate heating, on stationary or rotating substrates for better uniformity. The end contact materials consisted of Au on an interlayer of NiCr, TiW, or Tamelox (the trade name for the Ta/NiCr), for adhesion and a diffusion barrier.

Optimal air annealing was at 425°C for 15 min followed by 375°C for 1 h. The result in Fig. 9, shows a linear TCR, better than -20 ppm/°C for the temperature range of -150 to +100°C. Air annealing effectiveness was a strong function of sheet resistance and the initial TCR. As for vacuum annealing, both high and low sheet resistivity films (25–140 ohm/sq) were effectively improved in TCR. Ten 140 Ω/sq resistors

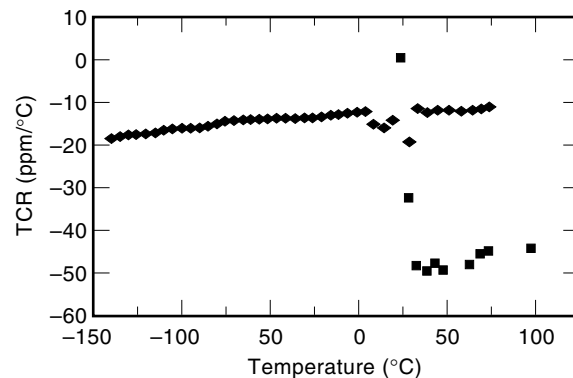


Figure 9. Typical TCR behavior after air annealing Ta–N TFRs, >70 Ω/□ (12), ■ as deposited; ◆ annealed at 400°C in air, 1 h.

Table 6. Result of TCR Measurements on Ta₂N TFRs

Sheet Resistivity, ohm/sq	As-Deposited TCR, ppm/°C	Annealing Condition	After annealing TCR, ppm/°C	Comments
30–90	<–60	Air	–20	–
80	<–60	Air	–120	Not improved
25	–140	Vacuum	±30	Extremely sensitive to condition
140	–140	Vacuum	±5	Highly reproducible results

with an initial TCR = –140 ppm/°C were improved to close to zero TCR (±5 ppm/°C) by annealing at 700°C for 2 min. Fig. 10 shows a linear and very low TCR resulting from vacuum annealing. Air annealing would not be successful for such high sheet resistivity films. A summary of annealing effects is listed in Table 6. The 25 Ω/sq films are extremely temperature sensitive, resulting in a wider TCR range after vacuum annealing.

An aging test (or burn-in) may be conducted at 250°C and an accelerated lifetime test at 150°C. Because the Ta₂N material possesses a very high free energy of formation (–457 kcal/mol) (13), no aging would occur at a lower temperature. It is desired to maintain the change in resistance, for resistors held at 150°C, to less than 0.02% after 1000 h.

Annealing at 680–700°C in vacuum followed by 250°C in air for 100 h is effective in stabilizing TFRs with a wide range of initial values of *R*. Contacts of TiW or Tamelex are superior to Au/NiCr contacts. Data in Table 7 indicate results of a stability study at 150°C after air annealing at 250°C. Degradation is seen after 600 h but this is attributed to the contacts and not to the resistor itself.

Mechanisms of Stabilization

TEM reveals little crystallinity in as-deposited Ta–N. Elevated temperature annealing produces Ta–N interaction and grain growth. Vacuum annealing produces Ta₂N regardless of the initial resistivity whereas air annealing is effective for high resistivity films. Stabilized grain size is about 150 nm. Analysis by ESCA indicates a competing mechanism between oxide or nitride formation. Vacuum annealing promotes nitride formation and reduces the oxygen signal. The gradually aggregated Ta₂N crystallites follow the predicted activated

tunneling conduction mechanism. As the amorphous Ta–N matrix is consumed, the exposed substrate participates in the conduction mechanism. This phenomenon happens only when the films are excessively annealed. The Ta₂N structure remains intact after overannealing, and the TCR remains around +80 ppm/°C in the vacuum annealing temperature range from 750 to 850°C. In high-frequency applications, substrate selection is the most important factor. It has been shown that Al₂O₃ is five orders of magnitude better than the SiO₂/Si substrate.

Ta₂N thin film resistors are electrically and physically superior to NiCr. The linearity of the TCR behavior, the low TCR, high recrystallization temperature, and resistance to strong acidic medium are positive attributes. Ta–N is prepared with a TCR ranging from –150 ppm/°C to almost zero. Convenient and inexpensive air annealing is used with TCR stabilized from as low as –150 ppm/°C. For high precision applications, a vacuum annealing process is used, with a resulting TCR within ±5 ppm/°C. After 400 h at 150°C, the Ta₂N resistors are stable within 0.02%. Aging at 250°C is by a bulk diffusion mechanism. With confident extrapolation, the resistors would be stable at 150°C within 0.05% for 1000 h if a stable contact like TiW is used.

RUTHENIUM OXIDE THIN FILM RESISTORS

Background

RuO₂ TFRs represent a further improvement over presently available materials (14). Transition-metal oxides with rutile structures, such as RuO₂, may be a very attractive metallization option in a variety of very large scale integrated circuit applications. RuO₂ is a good diffusion barrier in silicon contact metallizations with an aluminum overlayer (15–18). RuO₂ thick film resistors find wide application in hybrid circuits (19–22).

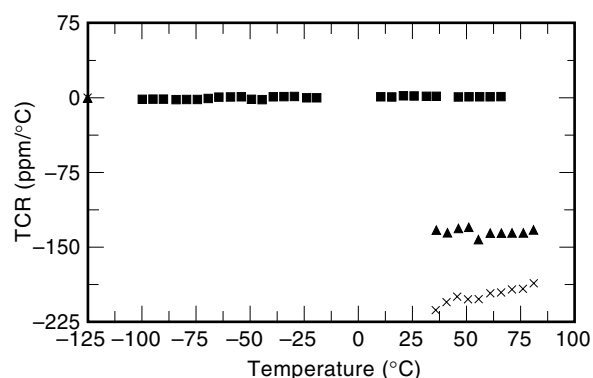


Figure 10. Typical TCR behavior after vacuum annealing Ta–N TFRs (12). ▲ as deposited; × annealed at 400°C in air, 1 h. ■; annealed at 650°C in vacuum plus 250°C in air.

Table 7. Stability after Optimized Air Treatment for Ta₂N TFRs

Annealing Condition	Avg. Δ <i>R/R</i> Environment	Avg. TCR, ppm/°C
After vacuum annealing	–	–4.5
After air annealing (0 h)	–	–1.3
After air annealing (160 h)	0.014	0.4
After air annealing (390 h)	0.016	–
After air annealing (610 h)	0.111	–
After air annealing (1400 h)	0.363	+0.8

Fabrication Techniques

Thin RuO₂ films with thicknesses of 20–200 nm are reactively sputtered by a dc magnetron. Using a target of Ru with a purity of 99.9% and diameter 5 cm, RuO₂ thin-film resistors are deposited onto SiO₂/Si substrates, directly patterned with a shadow mask during sputtering to be 1 mm wide and 10 mm long (23). Sputtering is done with the substrate temperature ranging from 25 to 500°C, O₂ pressure from 5×10^{-5} – 1×10^{-3} Torr, total pressure (Ar + O₂) of 10 mTorr, distance between substrate and target of 7.5 cm, and sputtering rate of approximately 50 nm min⁻¹.

The TCR is controlled by a combination of substrate temperature and oxygen pressure. Films deposited at relatively low temperature give a negative TCR. A positive TCR is obtained with films deposited at relatively high temperature. Clearly, the films undergo a change in microstructure and/or chemical composition as the TCR changes from semiconductor-like to metal-like. A critical substrate temperature T_{cs} during sputtering exists, at which the TCR changes signs from negative to positive, as shown in Fig. 11, where the O₂ pressure was 5×10^{-4} Torr. The critical temperature from a simple curve fitting of experimental data is about 85°C. A TCR as low as -30 ppm °C⁻¹ to -80 ppm °C⁻¹ may result for thin film resistors deposited at a substrate temperature of 80°C and oxygen pressure of 5×10^{-4} Torr. The TCR is further improved to 0 ± 3 ppm °C⁻¹ by heating the sample at 150°C in air for several hours.

Figure 12 shows that the positive or negative TCR of the film is controlled by changing the oxygen pressure during sputtering. However, the resistance becomes unstable for oxygen pressure lower than 1×10^{-4} Torr. From a practical viewpoint, the substrate temperature during sputtering rather than oxygen pressure should be used to control the TCR.

Mechanism of Stabilization

Using SEM and XRD, the films are amorphous or have a very fine grain size when deposited at lower substrate temperatures. The grain size of the film becomes much larger with increasing substrate temperature during sputtering. XRD patterns show that the films undergo a structure change when the substrate temperature changes from room temperature to 500°C during sputtering. From the viewpoint of material structure, amorphous RuO₂ gives a negative TCR

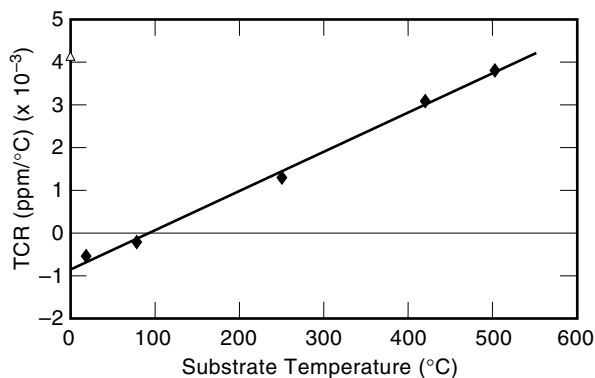


Figure 11. Dependence of TCR on the substrate temperature during sputtering for RuO₂ thin films with oxygen pressure of 5×10^{-4} Torr (14). Symbols represent data points.

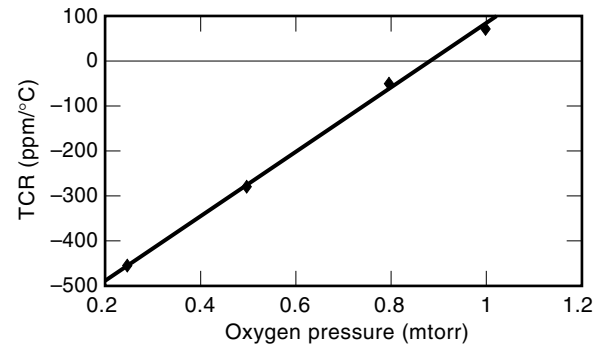


Figure 12. Dependence of TCR on the oxygen pressure during sputtering for RuO₂ thin films with the substrate temperature of 80°C (14). Symbols represent data points.

whereas polycrystalline thin films have a positive TCR (22–25).

Using in situ annealing, it is possible to routinely fabricate near-zero-TCR resistors. Resistors annealed in such a way have a layer-like structure, automatically formed during the in situ annealing in oxygen. The TCR of the resistors is mainly controlled by the oxygen content in the film. The top layer, which contains more stoichiometric RuO₂, has a positive TCR, but the bottom layer, which shows oxygen deficiency, has a negative TCR. This can be clearly seen from the AES depth profiling shown in Fig. 13. The in situ technique is very controllable and reproducible.

DOUBLE-LAYER RuO₂/Ta₂N THIN FILM RESISTORS

A resistor design which overcomes potentially weak areas of the single-layer structure of NiCr, Ta₂N, or RuO₂ uses a layered structure of RuO₂/Ta₂N. This design combines the best characteristics of the two different materials Ta₂N and RuO₂ in one system. Thin film Ta₂N has a negative TCR, whereas RuO₂ has a positive TCR. Near-zero-TCR resistors are fabricated by layering Ta₂N and RuO₂. Because the resistance of RuO₂ decreases with time and that of Ta₂N increases with time, the layered design is expected to be unchanged with time. The high thermal stability and acidic or environmental hardness of RuO₂ make it a perfect capping layer in this sys-

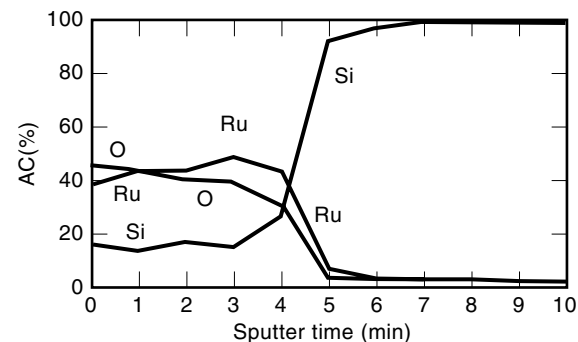


Figure 13. AES depth profiling of a resistor with a near-zero TCR deposited at room temperature followed by annealing in situ at 250°C in oxygen for 60 min (oxygen pressure of 0.5 m Torr during film deposition). AC = atomic concentration (23).

tem. The use of highly conductive RuO₂ as a capping layer also provides a very easy way to form an ohmic contact in the resistor termination. More versatile techniques and materials for packaging and assembly become possible because of the unique barrier properties of RuO₂ and its resistance to acids (27–29).

CONCLUSION

In order of use today, TFRs are made from NiCr, Ta₂N, RuO₂, or multilayers. Performance quality is improved in the same order. Fabrication consists of reactive sputtering, annealing in situ or ex situ, patterning, contact formation, long-term burn-in to establish *R* and TCR and, finally, stability testing. A near-zero TCR (<±5 ppm/°C) is achieved with long-term stability. Each material system has a different mechanism of stabilization which include oxidation, nitridation, grain growth, and layering. As applications become more demanding, RuO₂ or RuO₂/Ta₂N TFRs may become materials of choice.

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