HIGH-PRECISION THIN-FILM RESISTANCE NETWORKS
A USEFUL AND IMPORTANT TECHNOLOGY FOR THE CIRCUIT, INSTRUMENT, APPARATUS, AND SYSTEMS DESIGNER

by Lavar Clegg

High-precision thin-film resistor networks make it possible to design high-performance function circuits employing operational amplifiers and/or switches. Examples include sum-and-difference circuits, D/A converters, precision attenuators, and diode function-generators. At Analog Devices' Resistor Products Division*, the manufacture of standard and made-to-order networks at reasonable cost is a high art. In this article, we will discuss the nature of these networks, their properties, the materials and processes used in their manufacture, and the kind of design information that the circuit designer must consider to specify such networks for best results.

WHAT ARE THEY?

Resistance networks have come into increasing use as their cost comes down and their properties are better understood. There are two classes of resistor networks on the market:

a. The well-known low-cost networks that replace discrete resistors at savings in space, labor, and overall cost; they are now being sold in very large volume.

b. The less well-known thin-film high-precision networks that, besides providing savings in space and cost over assemblies of precision resistors, also provide the benefits of isothermal tracking, low capacitance and inductance, and improved reliability for critical applications.

The networks to be discussed here are of the latter class. They are characterized by high accuracy, high stability, low resistance-temperature coefficient (TCR), low noise, high reliability, low voltage-coefficient, and high speed.

THE NETWORK AS A COMPONENT

These important qualities of the network are most relevant when the precision resistance network is used as such, rather than as a group of independently-functioning resistors. In this sense, if the network is performing a function that depends on the location of all the resistors on a single substrate, with values that track, and with nearly-identical intrinsic properties, it can be considered as a circuit component, with properties specified in terms of its overall behavior. A general set of specifications that a typical network can be made to meet is listed in Table 1.

WHERE THEY ARE USED

Precision networks are likely to be found wherever attenuation, summing, division of voltage or current, setting of gains and ratios takes place. Perhaps the highest volume of usage of precision networks today is in ladder (or "bit weighting") networks for A/D and D/A converters. Examples of 12-bit ladder networks, which require tracking to better than 0.01%, include the AD850 modified-binary, and the AD855 R-2R.*

TABLE 1. Properties of typical thin-film precision resistance networks.

Substrate size	0.050 to 3.5in (1.27 to 89mm)
Resistance values	10Ω to 10MΩ
Resistivity	50 to 500Ω/square
Resistance tolerance (absolute)	±0.001% to ±20%
Temperature coefficient (TCR)	±20 to ±100ppm/°C
TCR tracking	1ppm/°C
Noise	−50dB per MIL-STD-202, Method 308
Voltage coefficient	Below measurable levels
Operating temperature range	−65°C to 150°C
Power dissipation	to 60W/in^2 (9.3W/cm^2)
Resistance density	10^{8}Ω/in^2 maximum (15.5MΩ/cm^2)
Long-term drift, absolute	0.02%/1000h @125°C
Long-term drift, ratio	0.001%/1000h @125°C

Feedback and summing networks for amplifier circuits are a popular application. Figure 1 shows an example of such a network. Notice that complete symmetry exists between the two sides of this differential network, in order to optimize balance and minimize common-mode errors. Other applications are in voltage regulators and voltage dividers. Precision function fitters,[1] employing op amps, diodes, and resistance networks, become more practical in this day of precision resistance networks and infra-low-cost op amps.

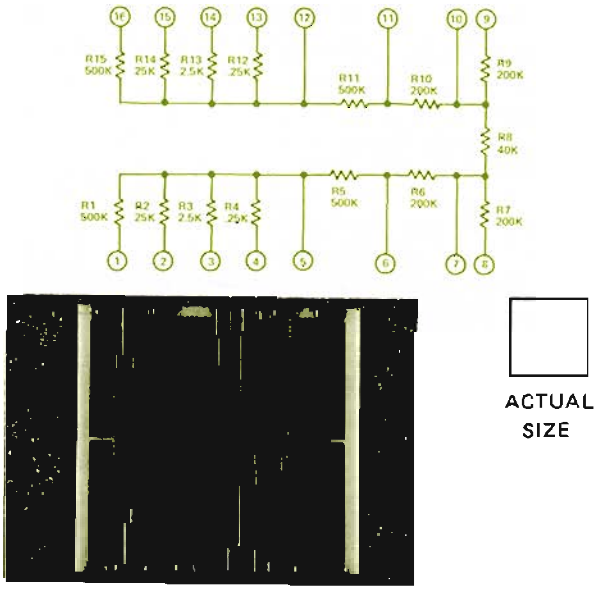

Figure 1. Differential-amplifier feedback and summing network. Actual size .4 x .4 inch. (10.2 x 10.2mm)

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*For further information on the capabilities of ADI/RPD, use the reply card. Request **L4**.

*For data on the AD850 and the AD855, request **L5**.

[1] See for example pp. 52-55 and 94-97 in *Nonlinear Circuits Handbook*, edited by D. H. Sheingold, published by Analog Devices, Inc., 1974, 534pp., $5.95. To order a copy on approval, initial the reply card and request

Applications for these networks occur in every conceivable discipline, including space, military, industrial, consumer, communications, instrumentation, biomedical electronics, and computer technology. The networks are of especial interest for systems exposed to the rigors of man and nature, such as the extremes of temperature, pressure, moisture, corrosion, vibration, and acceleration.

HOW THEY ARE MADE

1. MATERIALS

A thin-film circuit consists of a substrate, a layer of resistive material, and a layer of a conductive material, suitably etched into a pattern of resistors and interconnections. Its cross-section (not to scale) is shown in Figure 2.

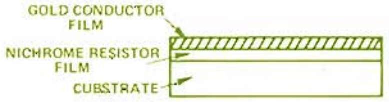

Figure 2. Cross section (not to scale)

Substrate. The most widely-used substrate material is alumina ceramic. It is the best compromise, given the choice among glass, silicon, and alumina. The ideal substrate would be perfectly smooth, flat, hard, non-porous, high in thermal conductivity, low in dielectric constant, durable, stable, and easy to "dice." No material rates high in all these conflicting properties. Glass is flat and smooth, with surface roughness of about 1μin (254Å); it is easily diced and has generally good electrical properties. However, it is susceptible to scratching, is generally fragile, and has very low thermal conductivity, a shortcoming serious enough to eliminate glass as an acceptable substrate for most precision networks. The passivated silicon wafer, while having excellent surface properties and high thermal conductivity, has excessive capacitive coupling because of the thin oxide layer and conductive bulk.

Alumina is durable, hard, reasonably flat, and is almost as thermally-conductive as silicon. Its major disadvantage, surface roughness (about 10μin, or 2500Å) can be overcome by glazing the top surface with about 2 mils (50μm) of glass. Alumina is also available in "fine-finish" form, with about 1/3 the surface roughness of ordinary alumina; not being polished, its cost is reasonable. Though other types of substrate exist, they are not usually used, either because of high cost or for technical reasons.

The most-commonly-used substrates are, therefore, glazed alumina, fine-finish alumina, or regular alumina (depending on the application), in thicknesses from 10-25 mils (0.25-0.64mm).

Thin-film resistors. The most widely-used materials are nichrome, tantalum, and various cermets. Our choice for precision networks is nichrome. It has a convenient range of sheet resistivities, does not require anodization, has a well-behaved TCR, and is inherently stable.

Conductor. Gold is used as the conducting film. Nearly ideal, it has low resistivity, low contact resistance, and good adhesion to the underlayer; it does not corrode or oxidize. It is suitable for all commonly-used interconnecting techniques: gold thermocompression bonding, aluminum- or gold-ultrasonic wire-bonding, and soldering. Aluminum is a viable alternative; it may be used more widely in the future if gold is priced out of the market.

2. PROCESSING

Table 2 is a flow diagram, outlining the major processing steps in simplified form. The actual process has many more steps with more-detailed designations and specialized purposes.

TABLE 2. Major Processing steps – Flow Diagram

Deposition
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Electroplating
↓
Photolithography
↓
Heat Stabilization
↓
Resistor Trimming
↓
Dicing
↓
Encapsulation
↓
Test

Deposition. The thin films are deposited on the substrates in a specially-designed vacuum chamber by electron-beam evaporation. The evaporation parameters are carefully controlled for consistent and uniform films. Because dirt is the #1 enemy of thin-film processing, all deposition processes (including pre-deposition cleaning and preparation of raw substrates) are performed in clean-room areas, an important key to success. The capacity of this system is quite large: the 32ft^3 (0.91m^3) chamber can process 20 3½" x 3½" (89 x 89mm) substrates, each of which may be fabricated into as many as 300 conventional-size resistor networks.

Electroplating. Only about 15μin (0.38μm) of gold are deposited in the vacuum chamber; greater thickness is built up by electroplating. To achieve good bonding properties and a conductor resistivity of less than 10mΩ/square, a nominal gold thickness of 150μin (3.8μm) is commonly used. The plating bath and plating processes are of course carefully controlled to provide a plating of the highest purity and uniformity.

Photolithography. The resistor-conductor pattern is created by selectively etching away portions of the originally-continuous films. Two complete photographic processes are required, one for the conductor pattern and one for the resistor pattern. In each, the surface is coated with light-sensitive photoresist, then exposed to light through a photomask, developed, and etched. To obtain acceptable and repeatable work from these processes with line-widths down to 1 mil (25μm) or less requires a highly-perfected and controlled process. Keys to success include control of the photoresist purity and thickness of application, precise exposure time, and controlled etching time.

Of course, no pattern can be of better quality than the photomask used; similar quality is required to those used in the semiconductor industry. Mylar is used instead of glass; while it has the same high-resolution emulsion as glass and adequate dimensional stability, it has sufficient flexibility to conform to the ceramic substrate surface. (With glass masks, there would be areas of poor contact between surfaces, resulting in poor line definition in those areas.)

Heat stabilization. After photolithography and cleaning, the substrate is exposed to temperatures of 350° to 400°C in air for 1-2 hours. This bake serves two functions: it oxidizes the surface of the resistor film, providing a passivated layer of sorts, making the resistors less susceptible to mechanical and chemical attack than they would be without protection; and it renders the resistance stable in any heat-aging condition that may be imposed on the film at temperatures below the stabilization temperature. Because metal is used up by the oxidation, the process causes an increase in sheet resistivity of the film, typically about 75%. The exact duration and temperature of the bake is determined by the stability required, the initial and final resistivities, and certain properties of the film. Naturally, cleanliness and uniformity of temperature are essential to success, Figure 3 shows a typical substrate at this stage of the process.

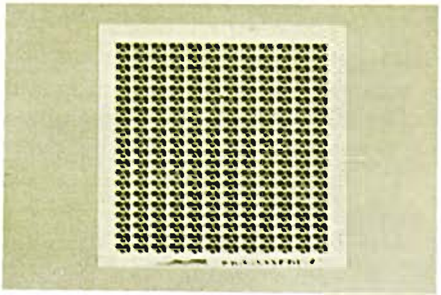

Figure 3. 3½" x 3½" (89 x 89mm) substrate with 240 resistor networks ready for trimming and/or dicing.

Trimming. Though trimming may occur either before or after dicing, the trend towards more automation and batch processing results in more trimming at the whole-substrate level. Since the resistance value of a resistor is determined by its shape, not its size, trimming involves changing the geometry of the resistor by cutting part of it away, under control. Cutting increases its resistance value. The method that is evolving towards universal application is laser-trimming, a clean, convenient operation that is compatible with (and conducive towards) automation, hence lower cost. Besides being fast, the laser is effective on all types of substrates.

Mechanical scribing, using a diamond stylus, is effective only on glass- or glazed-substrates. Though it has a number of limitations, including low speed, it can be quite accurately controlled and has a removal path width of about 0.2 mils (5μm), about 20% of that for a laser.

Dicing. The individual circuits are separated by sawing with a diamond wheel while the substrate is mounted on a holder with a temporary adhesive. The dice are then demounted and cleaned. A die resulting from this process is shown in Figure 4. An alternate process is to scribe the substrate with a diamond, then break, as is done with glass and silicon substrates. But alumina is quite hard, and tends to limit the diamond's life to just a few passes.

More practical is laser-score-and-break, using a laser with considerably more power than that used for trimming. After the substrate is scored to approximately 1/3 of its thickness, it is a simple matter to break it along the score lines. With quality close to that produced by sawing, but potentially lower cost (because the method is easily automated), this technique is growing in popularity.

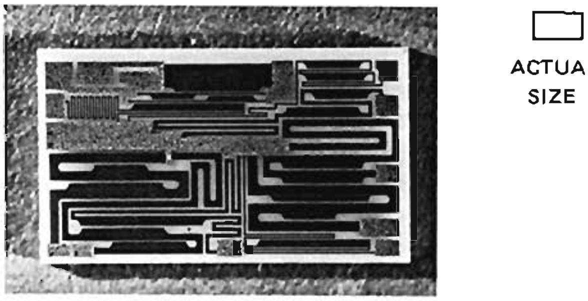

Figure 4. Single network after dicing. Actual size is .140 x .240 inches (3.6 x 6.1mm).

Packaging. The simplest package is no-package-at-all. The networks are shipped to the user after dicing and incorporated directly into hybrid circuits. Users do not require a great deal of micro-circuit equipment to benefit by the use of dice; as a result, this form of use is gaining in popularity.

However, for most uses, means of protection and interconnection are necessary. This requirement is satisfied by the same techniques and materials that are used throughout the integrated-circuit industry. Typical packages are multi-lead flatpacks, dual in-line, or round can with ceramic or glass seals. The resistor-network die is mounted and secured into the cavity of the package with epoxy, which is strong, stable, and thermally conductive. If an all-metal system is required, the back of the substrate will have been metallized, allowing the die to be soldered into the cavity.

Connections from the die to the package leads are made by aluminum ultrasonic wire-bonding, or by gold-wire thermo-

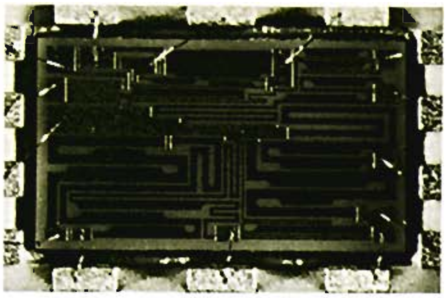

Figure 5. Cavity of TO116 header with resistor network mounted and wire-bonded.

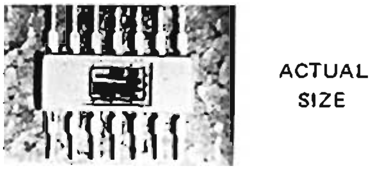

Figure 6. Network ready to be sealed.

compression bonding, using wire of 1 or 2-mil (25–50μm) diameter. Both allowable resistance and assembly considerations affect the choice of wire. Figure 5 and 6 show the die of Figure 4 mounted and wired. Figure 7 shows gold and aluminum wires on a single network.

The interconnections completed, the package is then hermetically sealed, either by welding or by soldering. The same machine is used to perform either operation, with the package relatively cold (i.e., below solder-melting temperature), while the seal frame and cover are heated sufficiently to flow-solder or weld the two surfaces. If hermeticity is not required, it is practical to pot the cavity with high-grade silicone resin. This method has been demonstrated to perform, over the extremes of temperature, as reliably as hermetic sealing. Hermetically sealed or otherwise, packages ranging in size from ¼" to 2" (6.4mm to 51mm) are available.

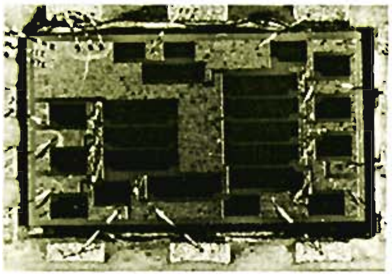

Figure 7. Example of large multiple wire bonds used in critical lead connection to decrease lead resistance. TO116 cavity.

CONTROLS

Because of the critical nature of the work and the large number of military applications in the early days of the industry, quality control is thorough and pervasive. A typical production flow chart will show that almost every single operation is followed by an inspection (mostly on a 100% basis) by a Q.C. function that is independent of Manufacturing. Visual inspections are performed with high-quality metallurgical microscopes at 50x to 100x. Additional inspections, performed on every lot of material, include: film-adhesion test, TCR check, gold-thickness measurement, wire-bond-strength test, hermeticity (leak) tests, dimensional inspections. All incoming raw materials are subjected to inspection and lot control. Manufacturing records are kept by lot, and these documents are subject to quality review before completed resistor networks are shipped to the customer.

SPECIFYING RESISTANCE NETWORKS

The most important thing to remember when specifying a network is that it is itself a component and should be specified in terms of the *overall performance of its function*, rather than the properties of its individual resistors. For example, a resistance-ladder network for a 12-bit D/A converter may be specified for accuracy, linearity, and monotonicity of its voltage (current) output in a particular conversion circuit. Its input and output impedance might also be specified. But none of these parameters requires direct specification (or measurement) of the tolerance of each resistor in the network.

This rule applies even to simple networks. For example, in a simple voltage divider with 2 resistors, depending on the interpretation, a specification of 0.01% can mean 3 different things (with a range of 5.3:1): resistance-ratio error, voltage-ratio error (% of ratio), voltage-ratio error (% of full-scale).

For high-accuracy applications, the method of application affects the means of specifying and testing, especially if low resistance values (usually less than 1kΩ) are involved, since their tolerance might be comparable to the resistance of the internal wire bond and the I.C. package lead. It is important to provide complete information on the use of the network and to define accuracy.

It is also important to specify which leads carry current, and which are to be connected to high-impedance amplifier inputs. The effects of temperature on accuracy may be specified either in terms of a range of resistance variation corresponding to a range of temperature variation, or by specifying 25°C accuracy plus TCR tracking (ppm/°C).

Power and voltage ratings are often written improperly. Power rating is meaningful only as it relates to temperature, life, drift, and the operating environment, in terms of the *function* of the resistor network. The meaningful rating for a simple voltage divider, for example, is the maximum operating level of V_{IN}, and any short-term overvoltage requirements. It would not be meaningful to rate the resistors equally in power or voltage, since the only common parameter is current. If a constraint of equal power ratings for the resistors were imposed, it might well create a sacrifice in tracking accuracy, Here are some rules for obtaining good power ratings:

1. Specify the network as a functional component, rather than as individual resistors.
2. Do not use separate (conflicting) power and voltage ratings.
3. Define the ambient operating conditions.
4. Do not be constrained to round numbers. Film resistors may be designed for any rating from zero on up.

Other electrical specs that are often important (if relevant) include settling time, capacitance, stability, noise.

Also specify mechanical and packaging requirements. The package and lead configurations normally specified are those common in the I.C. industry, including TO-5, TO-8, TO-116 configurations, and metal, plastic, glass, and ceramic materials.

Environmental requirements must be specified as called for. Those characterized by MIL-STD-883 are commonly used and understood.

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EXAMPLE OF A NOVEL APPLICATION

Two resistors, equal in value, are designed for simultaneous active trim with a single trim pass. Each resistor increases by precise 5% increments to as high as 4.5x the initial value when all 31 steps are used. In addition, each resistor is trimmable linearly and separately up to 50% of initial value. This unencapsulated resistor network, which is used as a hybrid component, is completely compatible with automatic trimming techniques. Actual length of the resistors is 0.3" (7.6mm).