United States Patent [19]

Schebalin

[11] **3,922,388**

[45] **Nov. 25, 1975**

[54] **METHOD OF MAKING AN ENCAPSULATED THICK FILM RESISTOR AND ASSOCIATED ENCAPSULATED CONDUCTORS FOR USE IN AN ELECTRICAL CIRCUIT**

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[73] Assignee: **Honeywell Inc.,** Minneapolis, Minn.

[22] Filed: **Nov. 20, 1974**

[21] Appl. No.: **525,587**

Related U.S. Application Data

[60] Continuation of Ser. No. 334,956, March 22, 1973, abandoned, which is a division of Ser. No. 120,199, March 2, 1971, Pat. No. 3,788,891.

[52] **U.S. Cl.** **427/103;** 427/102; 338/308

[51] **Int. Cl.²** **H01H 37/36;** H01B 1/02

[58] **Field of Search** 117/212, 215, 217, 227, 117/218; 338/309; 252/514, 518, 521

[56] **References Cited**

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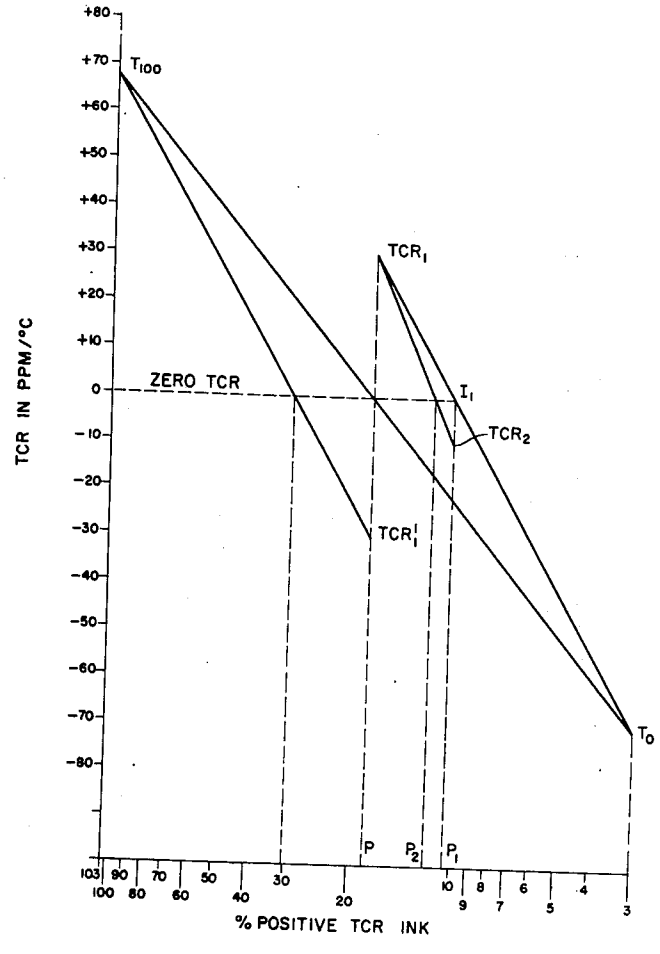
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Attorney, Agent, or Firm—Arthur H. Swanson; Lockwood D. Burton; J. Shaw Stevenson

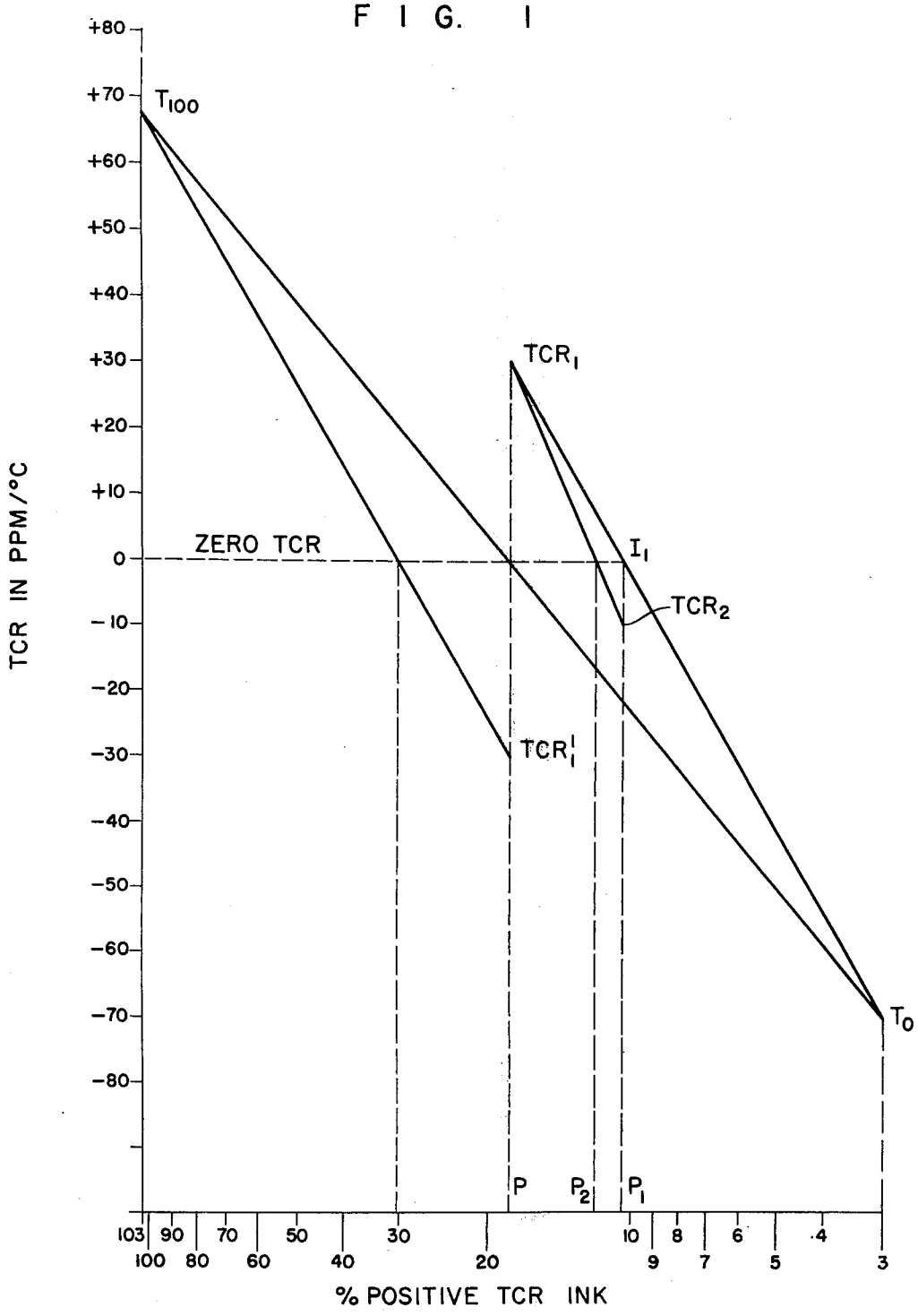
[57] **ABSTRACT**

A method of making an encapsulated thick film resistor and an associated encapsulated conductor so that the stability of the resistor will be maintained at a precise level over an abnormally long period of time by first firing selected mixtures of positive and negative thick film resistor ink materials on a non-electrically conductive substrate at a selected high temperature, jointly firing the resistor and conductor ink materials associated with this resistor at a temperature that is lower than the first mentioned temperature and which is at a level that will not allow any detrimental diffusion to occur between the conductor and the resistor materials, applying a resilient buffer material formed of a silicone polymer filled with magnesium oxide over the fired resistor and the fired conductor and then applying a hard outer glyptal coating over the resilient buffer.

1 Claim, 9 Drawing Figures



F I G. I


+80
+70
+60
+50
+40
+30
+20
+10
0
-10
-20
-30
-40
-50
-60
-70
-80
TCR IN PPM/°C
T100
TCR1
ZERO TCR
I1
TCR2
TCR1'
T0
P
P2
P1
103
100
90
80
70
60
50
40
30
20
10
9
8
7
6
5
4
3
% POSITIVE TCR INK

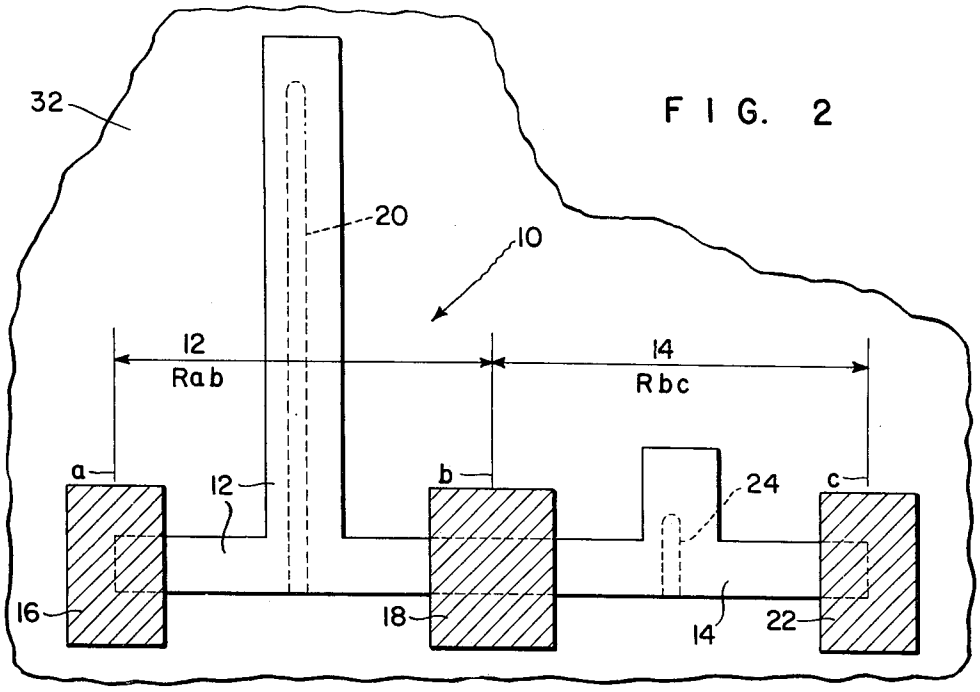


FIG. 2

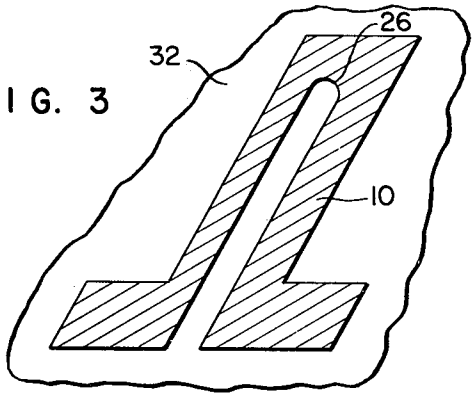


FIG. 3

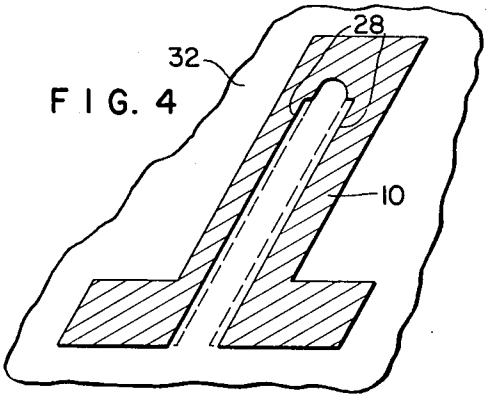


FIG. 4

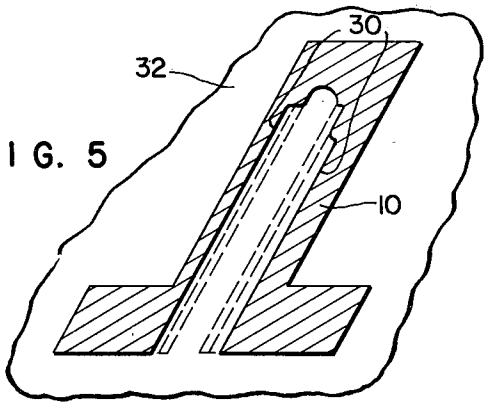


FIG. 5

FIG. 6

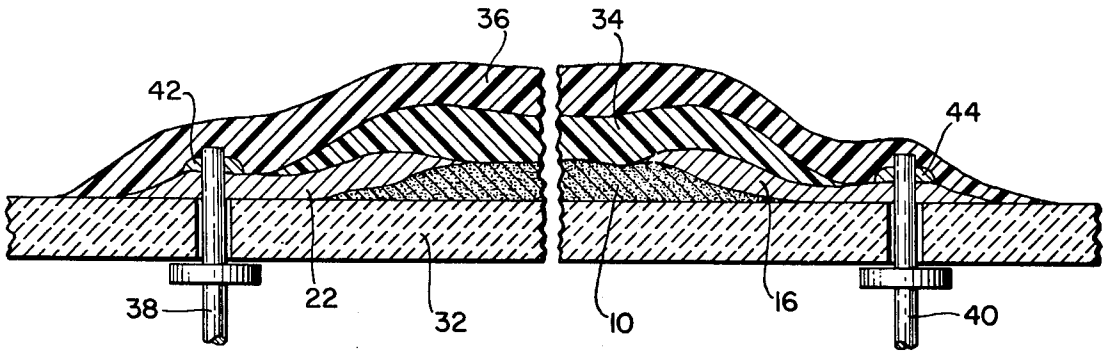

36
34
42
44
38
22
32
10
16
40

FIG. 7

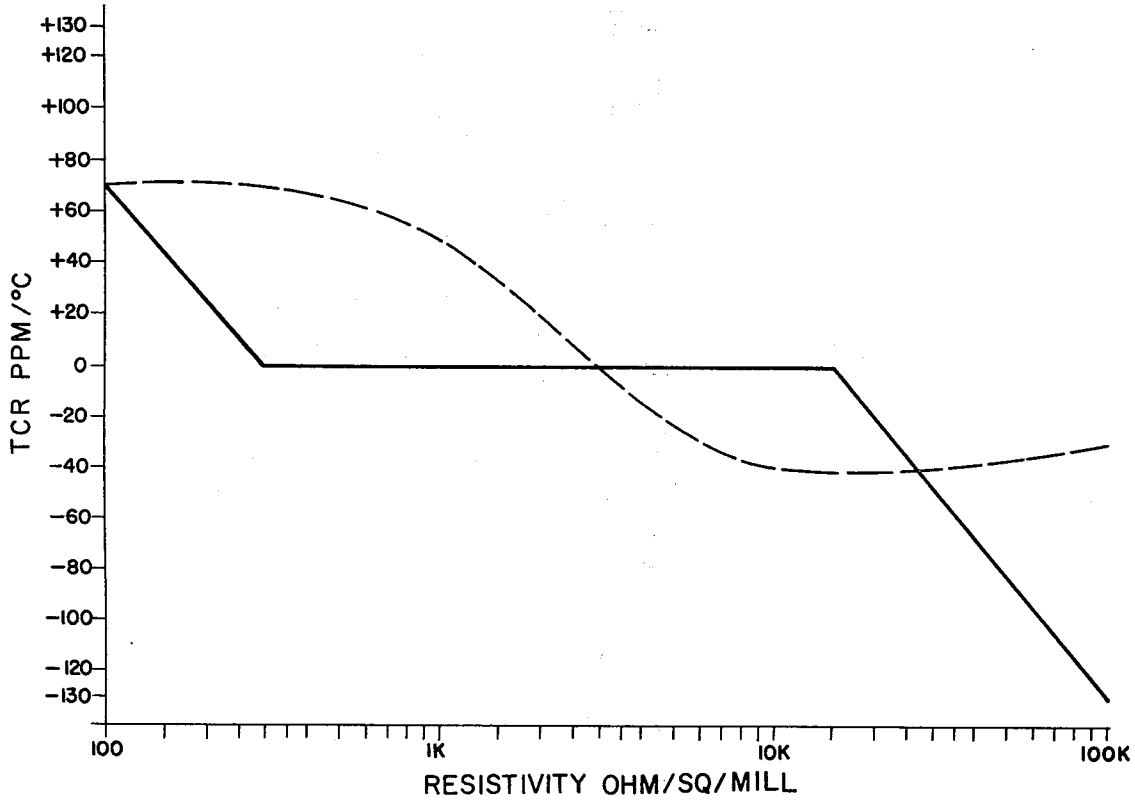

+130
+120
+100
+80
+60
+40
+20
0
-20
-40
-60
-80
-100
-120
-130
TCR PPM/°C
100
1K
10K
100K
RESISTIVITY OHM/SQ/MILL

FIG. 8

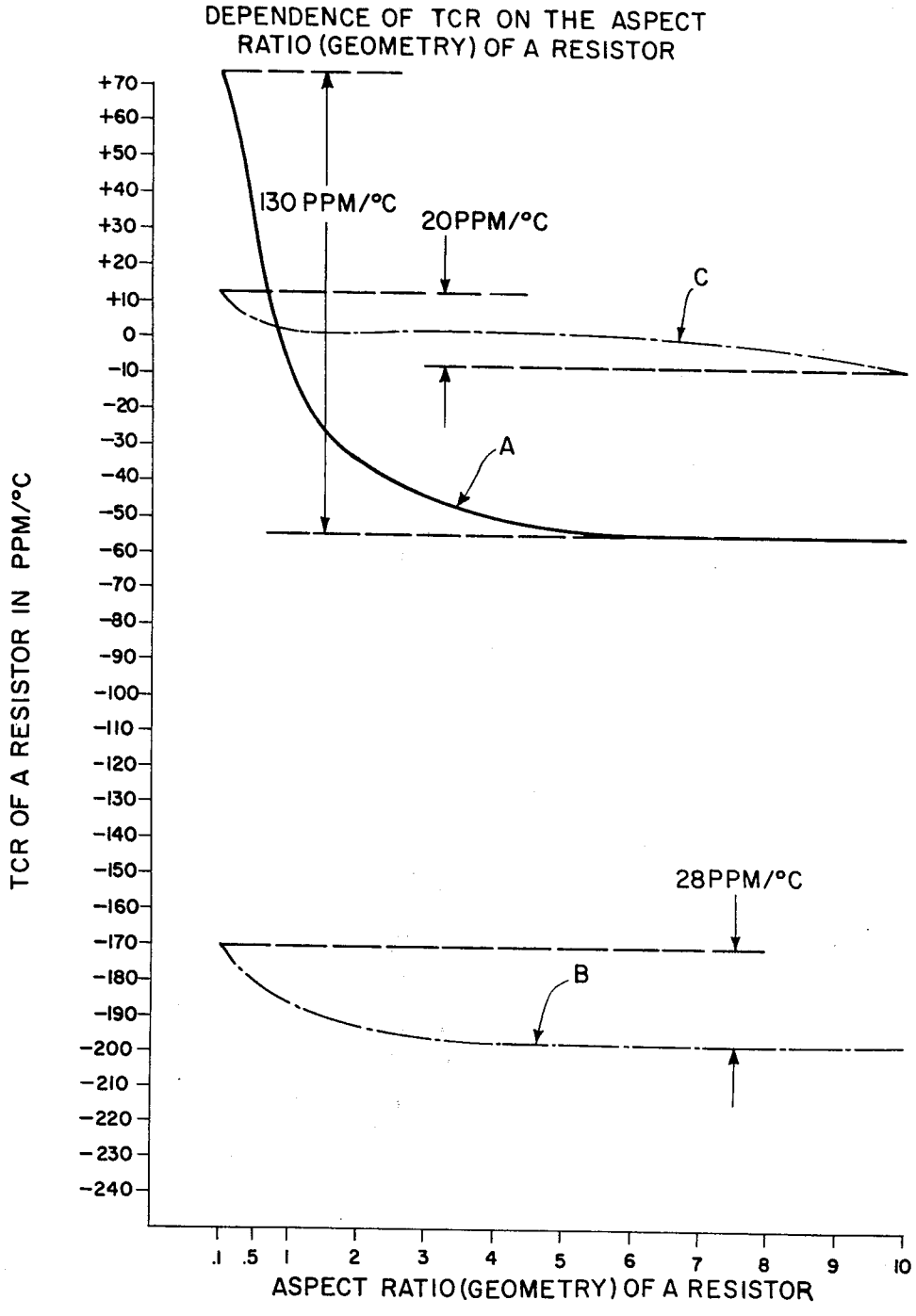
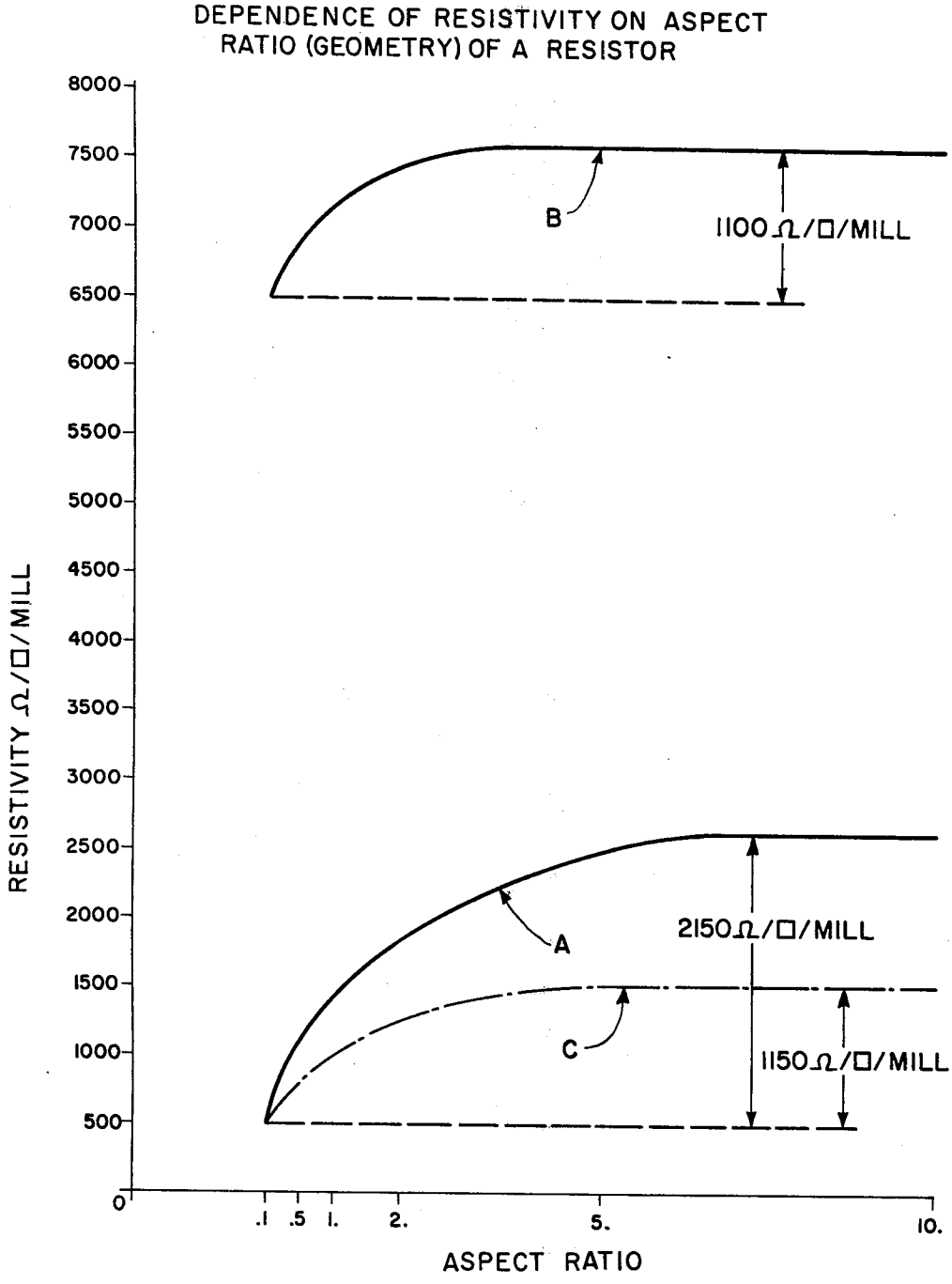

DEPENDENCE OF TCR ON THE ASPECT RATIO (GEOMETRY) OF A RESISTOR
TCR OF A RESISTOR IN PPM/°C
+70
+60
+50
+40
+30
+20
+10
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
-120
-130
-140
-150
-160
-170
-180
-190
-200
-210
-220
-230
-240
130 PPM/°C
20PPM/°C
C
A
28PPM/°C
B
.1
.5
1
2
3
4
5
6
7
8
9
10
ASPECT RATIO (GEOMETRY) OF A RESISTOR

FIG. 9


DEPENDENCE OF RESISTIVITY ON ASPECT RATIO (GEOMETRY) OF A RESISTOR
RESISTIVITY Ω/□/MILL
8000
7500
7000
6500
6000
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
B
1100Ω/□/MILL
A
2150Ω/□/MILL
C
1150Ω/□/MILL
.1
.5
1.
2.
5.
10.
ASPECT RATIO

METHOD OF MAKING AN ENCAPSULATED THICK FILM RESISTOR AND ASSOCIATED ENCAPSULATED CONDUCTORS FOR USE IN AN ELECTRICAL CIRCUIT

This application is a continuation of my prior application bearing Ser. No. 334,956, filed Mar. 22, 1973, now abandoned, which is a division of U.S. patent application Ser. No. 120,199, filed Mar. 2, 1971, now U.S. Pat. No. 3,788,891.

BACKGROUND OF THE INVENTION

Field of Invention

The invention relates to a method of making an encapsulated thick film resistor having encapsulated conductive end portions.

DESCRIPTION OF THE PRIOR ART

Prior to the present invention, coatings of glass, vinyl paint, acrylic paints, varnishes and different types of epoxy materials have been employed as hard coatings to cover thick film resistors. Such hard coatings are necessary to protect these resistors from scratches and from exposure to moisture and undesired corrosive gases in the atmosphere, such as chlorine gas, which have a tendency to corrode the resistor and alter its resistivity.

In the prior art, attempts to select a hard coating to cover thick film resistors that have exactly the same thermal expansion as the resistor that it covers so that stresses would not be introduced into the resistor and the coating during a change in ambient temperature have not been able to be achieved. Stresses were introduced into the resistor and its associated hard coating and transferred between the resistor and coating because slight differences were always present between the thermal expansion of the resistor and the thermal expansion of any one of the aforementioned hard coatings. Furthermore, as the magnitude of the ambient temperature change increases, the magnitude of the aforementioned stresses that are introduced into the resistor and coating also simultaneously increased. This change in stress of the resistor is also simultaneously accompanied by an undesired change in the resistance of the thick film resistor.

The value of a resistor must be maintained within plus or minus 0.1% in order to be classified as a precision thick film resistor. Since none of the aforementioned prior art encapsulated thick film resistors can be maintained within this ± 0.1% resistor value, none of these prior art hard coated encapsulated resistors have been found to be satisfactory for use as precision thick film resistors.

Another reason why a thick film resistor that is coated by any one of the aforementioned coatings is not satisfactory is that when the aforementioned stresses are introduced into these parts, due to their differences in thermal expansion, cracks formed in their coatings and this allowed the thick film resistor to become exposed to harmful atmospheric gases, such as previously mentioned chlorine gas.

Heretofore, it was a common practice, after the selection of the size and the aspect ratio of a resistor which would fall within a prescribed resistance range, to consult a table or a graph filled geometry correcting tables that predicts the resistivity and the T.C.R. as a function of the resistors geometry. This procedure is slow, tedious, and has circuit design limitations in that the resistor could only be made of a certain geometric shape and size. It is also well known that these resistors will have undesired different T.C.R. and resistivity values.

SUMMARY OF THE INVENTION

It is a major object of the present invention to disclose a unique method for making an encapsulated thick film resistor having encapsulated conductive end portions, which resistor is known in the art as a cermet resistor.

It is another object of the present invention to provide a method for manufacturing an encapsulated resistor of the aforementioned type that possesses electrical resistance characteristics, that are precise and whose performance is unaffected by the time it remains on the shelf, the time period over which it is employed in an electrical circuit or changes in ambient temperature.

More specifically, it is another object of the invention to provide a method of manufacturing a precision encapsulated resistor of the aforementioned type whose resistance will remain within an acceptable ± 0.1% level over long periods of use that extend beyond a two year period of time.

It is another object of the invention to provide a method of manufacturing an encapsulated cermet resistor for use in measuring circuits whose accuracy and overall stability is as good and reliable as those possessed by present day commercially available wire wound resistors.

One of the terms that is used to define a critical characteristic of a thick film resistor is its "sheet resistivity". This term sheet resistivity relates to the electrical resistance which a 1 milli-inch thick square of any size of resistive material offers to a steady current passing between any two opposite faces of this resistive material along which, for example, a conductive film is attached. This sheet resistivity is known to vary with ambient temperature between, e.g., +300 PPM/°C to −300 PPM/°C depending on the sheet resistivity of resistor material being used.

Another term that is used to define the characteristic of a thick film resistor is T.C.R. or temperature coefficient of resistivity whicch is the change in resistivity expressed in ohms per degree centigrade.

In achieving the aforementioned objectives, it has been discovered that an adverse change in resistivity and T.C.R. of a thick film cermet resistor is caused by diffusion of the conductive material in the conductor, which has an extremely low resistivity value, into resistive material of the resistor which has a much greater resistivity when the resistor and conductor are fired on a ceramic substrate. Heretofore it was a common belief that this adverse change was based upon the geometry, or the so-called aspect ratio factor which is a ratio of the length to width of the resistor.

It is another object of the invention to recognize for the first time that the aforementioned detrimental effect of diffusion is much greater between the ends of a rectangular strip of resistor and a conductor that extends away from the resistor when the longest opposite sides of the rectangular resistor strip are selected for connection to the conductor for jointly firing onto a substrate rather than the shorter opposite sides of the rectangular resistor strip.

Furthermore, experimentation has shown that firing temperature changes adversely affects T.C.R. and the resulting resistivity of thick film resistors because of the high degree of the aforementioned diffusion that takes place between the resistor and the associated conductors to which it is attached when they are jointly fired.

It is, therefore, another object of the invention to provide a unique method of firing resistor and conductor inks onto substrates so that no undesired diffusion will take place between the resistive and conductive materials that will adversely affect the T.C.R. and resistivity; and, therefore, the precise resistance offered by the resistor.

To accomplish the aforementioned feat it is another object of the invention to provide a means whereby the dried resistor ink is first fired for a preferred preselected period of time, e.g., 15 minutes at a high temperature of, e.g., 1000°C on a substrate to form an amorphic mass and thereafter the conductor extending from either side of the resistor is printed, dried and then fired for a similar period of time at a substantially lower temperature in the neighborhood of 550°C, onto the already fired resistor to eliminate substantially all of the undesired diffusion of the conductive material that would otherwise diffuse into or from the resistor material.

It is another object of the invention to provide a method of the aforementioned type which will allow an ink, such as a resistor ink having a high firing temperature, to be fired at a high temperature onto a substrate, and a conductor ink having a lower firing temperature than the resistor ink to be then fired jointly with portions of the already fired resistor ink onto the substrate so that undesired diffusion of the conductor ink material into the fired resistor ink will be negligible and an acceptable cermet resistor having a low T.C.R. to be produced.

It is, also, another object of the invention to eliminate the need for the previously mentioned geometry correcting tables.

It is also another object to provide a method of manufacturing a cermet resistor whose shape can be of any one of a number of different forms or configurations, and need not, therefore, be limited to a restricted shape as has heretofore been required.

It is another object of the invention to provide a method of blending one or more positive T.C.R. resistor inks with one or more negative T.C.R. resistor inks so that the resulting temperature coefficient of resistivity T.C.R. and the resistivity of the resulting resistor can be precisely predicted by changing the blending proportions of the negative T.C.R. resistor ink and the positive T.C.R. resistor ink before firing in the aforementioned unique manner so that a number of different shaped resistors can be formed which individually possess different precisely fixed resistance values.

It is another object to provide resistors of the aforementioned type that extend over a wide range and which will result in each of the resistors having a temperature coefficient of resistivity value, T.C.R., that is within a few parts per million per degrees centigrade from zero.

Since it is not possible to obtain a precise resistance value for the resistor from the aforementioned unique firing process nor from any other firing process, it is, therefore, another object of the present invention to provide a means of trimming such a resistor after it has been fired so that a more exact value of the resistance can be achieved for these resistors.

It is another object of the invention to provide a method of making an encapsulated cermet resistor and associated encapsulated conductor so that no undesired stresses will be introduced into the resistor and the resistance of the resistor to be altered thereby.

More specifically, it is a major object of the present invention to provide a method of the aforementioned type in which the resistor and associated conductors are first coated with a resilient buffer material, formed of silicone polymer filled with magnesium oxide, and then coated with a hard outer glyptal coating.

It is another object of the present invention to provide a method of the aforementioned type wherein the buffer coating is employed to eliminate any thermally induced stresses in the resistor and hard outer coating as thermal expansion of the resistor and thermal expansion of the hard outer coating takes place, thereby eliminating the possibility of cracks in the hard outer glyptal coating.

It is still another object of the present invention to employ the aforementioned encapsulating method as a way of preventing the resistivity and the T.C.R. value of the resistor produced by this method from being changed by exposure to the destructive oxidation of air, moisture, hydrogen sulfide or other similar ambient atmospheres.

It is another object of the invention to provide a method of blending one or more positive T.C.R. resistor inks with one or more negative T.C.R. resistor inks so that the resulting temperature coefficient of resistivity, T.C.R., and the resistivity of the resulting resistor can be precisely predicted by changing the blending proportions of the negative T.C.R. resistor ink and the positive T.C.R. resistor ink before firing in the aforementioned unique manner so that a number of different shaped resistors can be formed which individually possess different precisely fixed resistance values.

It is another object to provide encapsulated resistors of the aforementioned type that extend over a wide range and which will result in each of the resistors having a temperature coefficient of resistivity value, T.C.R., that is within a few parts per million per degrees centigrade from zero.

Since it is not possible to obtain a precise resistance value for the resistor from the aforementioned unique firing process nor from any other firing process, it is, therefore, another object of the present invention to provide a means of trimming such a resistor after it has been fired so that a more exact value of the resistance can be achieved for these resistors.

In accomplishing these and other objects, there has been provided in accordance with the present invention a method of making an encapsulated thick film resistor having conductive portions associated with opposite ends thereof that form portions of an electrically conductive circuit, comprising the first step of selecting an ink made from a mixture of positive and negative resistor inks, the second step of firing the resistor ink mix in amorphic form at 1000°C into a sintered state onto an electrically non-conductive substrate, the third step of selecting a conductive ink material that has a sintering temperature substantially lower than the sintering temperature of the resistor, the fourth step of firing said conductive ink at a sintering temperature of about 550°C in overlapping relationship with said opposite ends of said resistor on the substrate whereby the ten-

dency to diffusion between the conductive and resistive materials is minimized and whereby a resulting temperature coefficient of resistivity value of the resistor that is produced is within plus or minus twenty parts per million per degree centigrade from zero, the fifth step of applying a coating of resilient buffer material formed of a silicone polymer filled with magnesium oxide to cover said resistor and the said fired conductive ink and the sixth step of applying a layer of iron oxide with magnesium silicate suspended in xylene to cover the outer surface of said resilient material.

BRIEF DESCRIPTION OF THE DRAWING

A better understanding of the present invention may be had from the following detailed description when read in connection with the accompanying drawings in which:

FIG. 1 shows a nomograph having a uniquely constructed semi-log scale for graphically determining the amount of additional positive or negative ink that should be added to an ink mixture of positive and negative inks to provide a thick film resistor ink of a desired zero T.C.R.;

FIG. 2 shows the steps required in a first method of trimming the aforementioned thick film resistor;

FIG. 3 shows the first step required in a second method of trimming the aforementioned thick film resistor;

FIG. 4 shows the second step required in the second method of trimming a thick film resistor;

FIG. 5 shows the third step required in the second method of trimming the aforementioned thick film resistor;

FIG. 6 shows how the aforementioned trimmed thick film resistor can be encapsulated to prevent the destructive oxidating effect of the ambient atmosphere from affecting its resistivity and T.C.R. value; and

FIG. 7 shows a chart having a solid line thereon to indicate the wide resistivity range of values over which a zero T.C.R. prevails for many different positive and negative cermet resistor ink blends when they are produced by the unique method to be hereinafter described in which no diffusion is allowed to occur between the conductor and the resistor as contrasted by the line shown in dash line thereon which indicates that zero T.C.R. can be achieved for only a single resistivity value of many psoitive and negative cermet resistor inks when they are produced by the well known profile firing method as a result of undesired diffusion occurring between the conductor and its associated resistor.

FIG. 8 is a graph to vividly illustrate the desirable independent relationship that can be achieved, as shown by curve B, between the temperature coefficient of resistivity and the aspect ratio (geometry) values of thick film resistors by firing them in the previously referred to unique non-diffused manner with their associated conductors onto a substrate. FIG. 8 also shows a curve A which represents the undesired dependent, restricted, temperature coefficient of resistivity versus aspect ratio (geometry) relationship that must be adhered to when thick film resistors and their associated conductors are fired jointly at a high temperature which causes diffusion to occur between the last mentioned conductors and their associated resistors.

FIG. 9 is a graph to vividly illustrate the desirable independent relationship that can be achieved as shown by curve B between the resistivity and the aspect ratio (geometry) values of thick film resistors by firing them in the previously referred to unique non-diffused manner with their associated conductors onto a substrate. FIG. 9 also shows a curve A which represents the undesirable dependent restricted resistivity versus aspect ratio (geometry) relationship that must be adhered to when thick film resistors and the associated conductors are fired jointly at a high temperature which causes diffusion to occur between the last mentioned conductors and their associated resistors.

DESCRIPTION OF THE PREFERRED EMBODIMENT

Method of Blending Cermet Inks to Fabricate Encapsulated Thick Film Resistors Having Encapsulated End Portions Which Are Not Sensitive to Temperature Charges

The temperature coefficient of resistivity, T.C.R., for thick film cermet resistors has heretofore been changed by altering the firing temperature profile and/or by changing the geometry, or in other words, the previously referred to aspect ratio of these resistors.

Since the changes in T.C.R. obtained by these methods are several parts per million per degree centigrade, PPM/°C, usually in the vicinity of 1 to 10 PPM/°C for 1° C change in firing temperature, they are, therefore, not sufficiently exact to obtain the desired T.C.R. value.

A unique method of ink blending to obtain a desired T.C.R. value which does not have to rely on the selection of a desired firing temperature profile will now be described.

The magnitude of change of T.C.R. obtained by this unique method is at least 10 times larger than the previously mentioned method which was based upon a change in firing profile and a change in the geometry of the resistor.

Experimentation has shown that an addition of a metal in powder form such as a gold powder with the particle size of three to twenty microns or a metal powder mixed with lead-boro-silicate glass powder of the same particle size when mixed with a liquid agent such as "decanol" provide a suspension that will decrease the sheet resisitivity of a resistor and cause a change in its T.C.R. in a positive direction. The addition of metal oxide powder, for example, ruthenium oxide powder, or a metal oxide powder mixed with boro-lead-silicate glass powder and a liquid agent such as "decanol" causes a change in T.C.R. in a negative direction. It can, therefore, be concluded that by adding metal or metal oxide to a cermet ink the T.C.R. is changed in either a desired positive or a negative direction; and, therefore, if two or more resistor inks are available and if one of them has a positive T.C.R. and the other a negative T.C.R. or vice versa, they may be blended to obtain a desired T.C.R., and the blending proportion can be calculated by the method to be hereinafter described:

Measure the T.C.R. of resistors made from the ink which is to be modified to obtain a zero T.C.R. resistor. This measurement of T.C.R. is accomplished by firing the resistor ink on an electrically non-conductive substrate and then taking measurements of its electrical resistance at room temperature such as 73°F and at a higher temperature such as 173°F and calculating the T.C.R. from these values of the following formula:

$$TCR \frac{\Delta R}{R \Delta t^{\circ}} \times 10^{6} \text{ in PPM/°C}$$

where Δ R equals the resistance of the resistor at the aforementioned high temperature minus its resistance at the aforementioned room temperature.

R is the resistance value at room temperature and Δ $t°$ equals the difference between the aforementioned high temperature and room temperature.

If the T.C.R. value of the resistor is zero, no further modification of the ink is needed. If it is not zero and it is negative, then a metal such as gold is added to the ink. It is then blended and a measurement of its T.C.R. value is again made in a manner similar to that already described.

The amount of metal added to the ink, such as gold must be large enough to provide a positive T.C.R. value of not less than 20 parts per million per degrees centigrade. If the T.C.R. of the ink under modification is found to be positive then metal oxide, e.g., powder 325 mesh, ruthenium oxide, is added until the ink provides a negative T.C.R. resistor material of 20 parts per million per degrees centigrade of a higher negative number. The purpose of the above modification of the available commercial inks is to make a pair of inks so that one of the pair will have a negative T.C.R. resistor value and the other of the same pair will have positive T.C.R. value. These two inks are then blended by mixing them together in a proportion that will provide a blend of zero T.C.R. ink.

The amount of positive T.C.R. ink and the negative T.C.R. ink forming the blended proportion is calculated from the following equation and is done as explained below:

$$P = \text{Exp}\left[A - \frac{T_{100}}{T_{100}-T_0}(A-B)\right] - S$$

Where:

P = % of positive T.C.R. ink in blend for manufacture of zero T.C.R. resistors

Exp = base of natural log

$A = 1n^{\epsilon}$ (100+s)

$B = 1n^{\epsilon}$ S

S = a constant, based on statistical data derived from experimentation for ruthenium system inks which is equal to 3

T_{100} = T.C.R. of positive T.C.R. ink

T_0 = T.C.R. of negative T.C.R. ink

Both T_0 and T_{100} are in PPM/°C. S is dimensionless.

The percentage of positive ink in a blend which will provide zero T.C.R. resistors is found through the use of the aforementioned equation. This same percentage can also be found graphically by first plotting the T.C.R. of the positive ink on the semi-log paper chart as shown in FIG. 1. The point T_{100} plotted on the semi-log chart shown in FIG. 1 is the T.C.R. of a positive ink or in other words is the T.C.R. of a blend which consists of 100% positive ink. The abscissa of this point does not correspond with the 100% point on the abscissa axis but instead purposefully corresponds with the 103% point. This offset of 3% is the variable S in the aforementioned equation. In this particular example where ruthenium system ink is used it has been found by experimentation that the value of $S = 3$.

The T.C.R. of a negative T.C.R. ink is then plotted as an ordinate on a linear scale on the semi-log chart of FIG. 1 as the point To. This represents the value of a blend which has zero percent of positive ink in it. The abscissa, or log scale value, of this point does not correspond with the zero percent point on the abscissa axis, but rather corresponds with the 3% point selected as a result of statistical data derived from experimentation. This offset of 3% is variable S in the equation. After the positive and negative T.C.R's of a pair of inks are plotted as described above the percentage of positive ink P which should be in the blend to provide zero T.C.R. resistors is found as follows:

A straight line is drawn between T_{100} and T_0. This line represents a change in T.C.R. of resistors versus percentage of positive T.C.R. ink in the blend and crosses the zero T.C.R. line. Looking at the base of the graph immediately below the point at which the aforementioned line crosses the zero T.C.R. line we find that its value as read on the abscissa is the percentage of positive ink in the blend which will provide desired zero T.C.R. resistor value. It should be noted that the value of this point along the abscissa is the value of the P shown in the previously mentioned equation.

Knowing the percentage P of the positive ink in the blend the zero T.C.R. blend can then be prepared. However, the T.C.R. of the resistors made from this blend will not necessarily be zero; it may not even be within the zero plus or minus 20 parts per million per degree centigrade limits. This is so because the previously mentioned equation represents the best fit or linearized condition that can be derived from the T.C.R. versus log percentage of blend that exists for several different blending proportions. The degree of misfit depends on the number of test blends and on the ink composition. If the T.C.R. of resistors prepared from this blend is not zero as claculated from the previously mentioned equation

$$TCR = \frac{\Delta R}{R\,\Delta t^{\circ}} \times 10^6 \text{ in PPM/°C}$$

or is not within the desired limits, the blend must be corrected. It is evident that the process parameters relating to the preparation of resistors must be constant. For example, the firing profile, absolute humidity in the furnace, atmosphere in the furnace, and the dried thickness of the resistors must be kept constant.

The following blending proportion correction is performed in order to bring T.C.R. of the resistor closer to a zero value.

The actual value of the T.C.R. of the resistor, $T.C.R._1$, as derived from the equations

$$TCR_1 = \frac{\Delta R}{R\,\Delta t^{\circ}} \times 10^6$$

is determined from representative samples of the blend and is plotted in FIG. 1. If this $T.C.R._1$ is positive as indicated by its plotted position in FIG. 1, this point $T.C.R._1$ is connected with the already plotted point T_0 or in other words, the point which is the T.C.R. value of the negative T.C.R. ink. This line between the points $T.C.R._1$ and T_0 represents a corrected change in T.C.R. of resistors versus percentage of positive T.C.R. ink in the blend or, in other words, the change T.C.R. of resistors versus percentage of positive T.C.R. ink in the blend which was previously determined in FIG. 1 was incorrect due to imperfect linearization when parame-

ters were chosen as previously described for the first previously mentioned equation that was used to figure out the value of P.

If this TCR_1 were negative, e.g., TCR_1' this TCR_1 ' point would be connected by a straight line to the point T_{100}. The line connecting point TCR_1 with point T_0 or TCR_1' with point T_{100} must in each instance cross the zero T.C.R. line. In one example, the T.C.R. of the resistors made from a blend prepared by the previously mentioned graphical method is positive and plotted at its point TCR_1 in FIG. 1. The abscissa of the point of intersection or point I_1 on FIG. 1 between the TCR_1–T_0 line and the zero T.C.R. line is a corrected percentage of positive ink in the blend which shall provide zero T.C.R. resistors and is marked on FIG. 1 as P_1.

Knowing P_1 which is the corrected and more accurate percentage of positive T.C.R. ink in the blend, the blend can be either corrected by adding corresponding amounts of negative T.C.R. ink to the blend or a new second blend can be prepared based the information derived in the aformentioned manner.

Even now, the second corrected blend may still not provide zero T.C.R. resistors. If this is the case, a second correction is needed and the T.C.R. of the resistors made from No. 2 blend as determined from the equation

$$TCR_2 = \frac{\Delta R}{R \Delta t^{\circ}} \times 10^6$$

in FIG. 1 as point TCR_2 is then determined. In this example, TCR_2 turned out to be negative. This is accomplished by drawing a line through this point TCR_2 and the previously obtained point TCR_1. This line represents the second corrected change of T.C.R. versus percentage of positive ink in the blend. The abscissa of the point of intersection between the line TCR_1–TCR_2 and the zero T.C.R. line is a corrected percentage of positive inks in the blend which will provide zero T.C.R. resistors and is marked P_2 in FIG. 1.

Knowing P_2 which is the second corrected percentage of positive T.C.R. ink in the blend, this blend can then be either corrected by adding corresponding amounts of positive T.C.R. ink, for example, ink with $TCR = T_{100}$ or a new third blend can be prepared based on the aforementioned information.

In the above example, the T.C.R. of the second blend TCR_2 was negative. If it were positive then the TCR_2 point would be connected by a straight line with point T_0 and the abscissa of the point of intersection between line TCR_2–T_0 and the zero T.C.R. line would be the percentage of positive T.C.R. ink in the third blend. When an additional correction of the blend is needed, such as in the case where the T.C.R. of the resistors made from the blend are outside of the desired limits, the last obtained and plotted T.C.R. point, e.g., TCR_2 is then connected with the nearest T.C.R. point of opposite sign as measured along the abscissa. The abscissa of the intersection point of this last mentioned line which connects the two nearest T.C.R. points of opposite signs with the zero T.C.R. line represents the percentage P_2 of positive T.C.R. ink which should be in the corrected blend.

Experimentation has shown that in the majority of blending operations only two such corrections are sufficient to bring the T.C.R. within the ± 20 parts per million per degree C limits.

It should also be further understood that a method has been described that can be used for obtaining any desired T.C.R. for resistors other than zero by observing where the interconnecting line between T_0 and T_{100} passes a horizontal line on the chart that passes through the desired positive or negative value of the blend that is desired rather than through the zero T.C.R. line. This T.C.R. of the blend cannot, of course, be made more negative or more positive than the T.C.R. value of the two basic inks that were used to make this blend.

The change in T.C.R. resistors causes the change in the sheet resistivity of the resistors and the more negative that the T.C.R. is the higher will be the sheet resistivity. This is so because the addition of metallic oxide to the ink causes the T.C.R. to change in the negative direction and increases the sheet resistivity.

Knowing the sheet resistivity of the two inks which are used for blending and knowing their percentage in the final blend the sheet resistivity of resistors made from this blend can be easily predicted by using known methods of calculation.

METHODS OF TRIMMING OF HIGH ACCURACY RESISTORS (CERMET) WITH LOW ACCURACY TRIMMING MACHINE

Present day accuracy of cermet resistors after they are printed and fired is about ± 20% of the value desired. Therefore, if a better accuracy is desired, they must be corrected. Usually, the correction consists of removing a portion of the resistor until the resistance reaches the desired value. A partial removal of resistor material causes an increase in the resistance. In other words, the value of resistance can be corrected only in the direction of increase of the resistance.

Usually the resistance of the resistor under trimming is constantly measured by using a high precision resistance measuring bridge, for example, a Kelvin bridge.

The accuracy of resistance measuring bridges is usually of ± 0.05%. However, the accuracy of trimmed resistors is seldom better than ± 1%. This is caused by the unpredictable time lag between the electrical signal from the bridge, indicating that the resistor has reached its desired value and the execution of the signal (i.e., stopping the trimming) by conventional electromechanical and pneumatic links between the bridge and the cutting device. The degree of overtrim or, in other words, overcuts, depends on the speed of the cutting device which is usually a nozzle which directs the stream of abrasive particles on the resistor and also on the resistivity of the resistor's material. The higher the nozzle speed and the resistivity, the larger will be overtrim or error. Usually, the degree of overtrim does not exceed 1% of nominal desired resistance. In other words, even if the trimming machine, which includes resistance measuring bridge and the cutting devices, has a high precision bridge, its total accuracy, i.e., the accuracy of trim, usually is in a low precision range.

Described below are two methods of trimming a high precision resistor **10** with low precision trimming machines, which have a high precision resistance measuring bridge. The first method is as follows:

The resistor **10** is laid out so that it consists of two parts **12** and **14** as shown in FIG. **2.** Part **12** measured between points a and b of conductive parts **16, 18** must be of sufficient size and length to provide at least 98% of the nominal desired total resistance after trimming along trimming path **20.** Part **14** resistor measured between the points b and c of conductors **18, 22** must

have not more than 1% of the nominal total resistance before it is trimmed along the trimming path **24.**

Measuring across the entire resistor, i.e., between the points a and c of conductors **16, 22,** the resistor part **12** is trimmed to 98% of the total nominal resistance because the accuracy of trimming machine is ± 1%. The resistance of the entire resistor measured between a and c will be 98% ± 1% of the total nominal resistance and the resistance of just trimmed resistor alone measured between a and b of conductors **16** and **22** can be 98% of nominal ± 1% of nominal $-R_{bc}$, where R_{bc} is the resistance of the untrimmed part **14** measured between **18** and **22.**

As it was mentioned before, the maximum resistance of untrimmed R_{bc} resistor **14** does not exceed 1% of total nominal resistance, therefore, in the worst case, the minimum resistance of just trimmed R_{ab} resistor is 98% − 1% = 97% of the total nominal resistance.

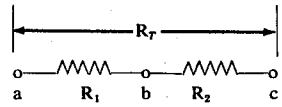
To correct the error after the first trim along trim path **20** the actual value of the trimmed R_{ab} resistor part **12** must be measured. Since the resistance measuring bridge only is involved in this measurement, the measured value of R_{ab} resistor **12** will be within the accuracy of the bridge, i.e., usually within ± 0.05%. This uncertainty in the trimmed R_{ab} value can obviously not be corrected, and it depends on the accuracy of measuring bridge alone.

Assuming that R_{ab} resistance of resistor part **12** after trim was 97% of total nominal resistance, the untrimmed resistor **14** must be trimmed along trimming path **24** until it reaches 100% − 97% = 3% of the total nominal value.

Because of ± 1% accuracy of the trimming machine, the resulting value of trimmed resistor **14,** measured between points b and c during the trimming, and trimmed along trim path **24** will be 3% of total nominal resistance ± 1% of 3% of nominal or 3% ± 0.03% of total nominal value versus desired **3%** of nominal. Assuming one of the worst possible cases, the resistance of trimmed resistor part **14** can be 3% − 0.03% = 2.97% of the total nominal value; and the total value will be R_{ab} (part **12**) + R_{bc} (part **14**) = 97% + 2.97% = 99.97% of the total nominal value, i.e., the error after two trims will be − **0.03%**. Adding the uncertainty or the resistance measuring bridge (± 0.05%) the maximum error after two trims will be (in this example) ± **0.05 − 0.02 = −0.08%.**

The above example shows that, dividing the resistor **10** into two parts **12, 14** and performing two trims **20, 24,** the final accuracy obtained is more than ten times better thann the accuracy of conventional trimming machine and that it approached the accuracy of a precision resistance measuring bridge.

The accuracy obtainable by this two trim method is determined as follows:



$E = \pm (2A^2 + AB + A^3 + C)$

R = Nominal (desired) value of R_T (Ohms)

C = Accuracy of resistance measuring bridge (%)

A = Accuracy of trimming machine (including % bridge accuracy)

B = Value of R_2 untrimmed (in % of nominal)

R_1 = Part 1 of total resistor R_T (or R_{ab} resistor) (Ω)

R_2 = Part 2 of total resistor R_T (or R_{bc} resistor) (Ω)

R_T = Total resistance ($R_T = R_1 + R_2$) (Ω)

E = Total maximum error in R_T after trimming (in % of nominal)

After first trim described above:
$R_T = (1-A)\ R \pm (1-A)\ RA$

NOTE: The resistor is trimmed to (1−A) % of nominal value. A is expressed in decimals.

R_1 trimmed = $R_T - R_2$ untrimmed = $(1-A)\ R \pm (1-A)\ RA - BR = R\ [1 - (A+B) \pm A\ (1-A)]$

Note: B is expressed in decimals

Error in R_1 trimmed $- R = R - (A+B) \pm A\ (1-A) = -R\ (A+B) \pm A\ (1-A) \pm CR$

Note: C is expressed in decimals. The error in R_1 trimmed is measured with res. bridge of ± C % accuracy.

After the second trim, i.e., after R_2 is trimmed to [R_1 trimmed − R] value:

R_2 trimmed = $R\ [(A+B) \mp A\ (1-A)] \pm CR \pm AR\ [(A+B) \mp A\ (1-A)] = R\ \{(A+B) \mp A\ (1-A) \pm CR \pm A\ [(A+B) \mp A\ (1-A)\ ]\} = R\ \{(A+B) \mp A\ (1-A) \pm C \pm [A^2 + AB \pm A^2\ (1-A)]\}$

$R_T = R_1$ trimmed + R_2 trimmed = $R\ \{[1 - (A+B) \pm A\ (1-A)] + [(A+B) \mp A\ (1-A)] \pm C \pm [A^2 + AB \pm A^2\ (1-A)]\} = R\ \{1 - (A+B) \pm A\ (1-A) + (A+B) + A\ (1-A) \pm C \pm [A^2 + AB \pm A^2\ (1-A)]\}$

Error in $R_T = R_T - R = R\ \{-(A+B) \pm A\ (1-A) + (A+B) \mp A\ (1-A) \pm C \pm [A^2 + AB \pm A^2\ (1-A)]\} = R\ \{\pm C \pm [A^2 + AB \pm A^2\ (1-A)]\} = \pm R\ \{A^2 + AB \pm A^2 \mp A^3 \pm C\}$

Max error in $R_T = \pm R\ \{2A^2 + AB + A^3 + C\}$

$$\%\ \text{max error in } R_T = \frac{\text{max error in } R_T}{R} = \pm (2A^2 + AB = A^3 + C)$$

Note: A, B, C, expressed in %

A numerical example where $A = \pm 1\%$, $B = 1\%$, $C = .05\%$, as it was described before will yield the following accuracy in the resistor trimmed by described method:

Max. error = ± (2 (0.01%) + 0.01% + 0.0001% + 0.05%) = ± 0.0801%. A second method of trimming high precision resistors with low precision trimming machine which employs a high precision bridge is described below, and shown on FIGS. **2, 3** and **4.**

The resistor **10** is trimmed along a trimming path as shown at 26 to 98% of its desired value. The maximum error after this trim is usually ± 1%.

Without changing the resistor position in the trimming machine, the resistor **10** is trimmed again to 99.5% of the desired value along trimming path **28.** In other words, the cutting device (which usually is a nozzle which provides a jet of abrasive particles suspended in air) repeats the same cutting pattern. Experiments have shown that the amount of resistor's material removed by this second trimming is about 0.5% of that removed in the first trimming. This is equivalent to slowing down the trimming speed by the factor of 1/200.

The same trimming pattern is repeated for a third time along trimming path **30** and the resistor is trimmed to its desired value. The amount of resistor material removed by this third trim is about 0.05% of that removed by the first trim, which is equivalent to slowing down the trimming speed by the factor of 1/2000 as compared with the first trimming period.

The accuracy of the trimmed resistors (assuming the accuracy of resistance measuring bridge as ±0.05%) is usually in the order of 0.08–0.09%, which is comparable with the first described method.

The accuracy of trimmed resistors can be improved further if four trims are used instead of three, approaching the accuracy of the resistance measuring bridge.

Both of the methods described herein allow a single thick film resistor to be trimmed to any one of a number of desired values.

The aforementioned precise trimming method enables a reduction to be made in the cost of manufacturing resistors having different resistor values because the same common blend of positive and negative resistor ink having a zero T.C.R. can be fired onto each one of a number of substrates before different individual selective trimming of each of these resistors occurs.

It should be noted that trimming of the cermet resistor by either of the aforementioned methods is done after the previously described selected zero T.C.R. blend of positive and negative cermet resistor ink that was used to form resistor **10** has been fired onto the aluminum oxide substrate **32.**

When a thick film cermet resistor **10** of the aforementioned type is left exposed to its surrounding atmosphere its precisely manufactured resistance and T.C.R. value will be altered with time because of the destructive oxidation and other similar detrimental effects which air, moisture, hydrogen sulfide or other similar destructive delequescent materials have on the resistor **10.**

More particularly, the stability of cermet resistors that are not protected from the ambient atmosphere, whether under a load or no load condition, is usually in the order of 0.3–0.5% per year. In other words, the resistance of these resistors have heretofore changed by 0.3–0.5% a year after they are manufactured.

Such a poor stability precludes the possibility of the manufacture of high precision resistors which have a tolerance of ± 0.1% or better.

Manufacturing a thick film resistor in the manner to be hereinafter described provides a resistor which will retain a stability of 0.1% for at least 2 years.

In other words, the resistance of these resistors will change no more than 0.1% of their nominal value after two years of active use in a circuit or during the period in which they are stored on the shelf for this length of time.

Experimental tests showed that the main reason for the instability of thick film resistors or, in other words, drift in resistivity with time was caused by oxidation of the metals in the resistor and by absorption of water, contained in the atmosphere.

Therefore, the resistors must be insulated from the ambient atmosphere.

To solve this problem, an insulator layer must be provided which has the same temperature coefficient of expansion as the ceramic substrate **32** and the resistor **10** and conductor **16** and **22.** Otherwise, thermal stresses will develop with an accompanying change in resistance. Another way is to make the insulating layer flexible enough to prevent stresses from occurring in the resistor which would change its resistance by more than ± 0.05% for the desired specified temperature range, e.g., a 100° change in ambient temperature. Also, the layer which physically contacts the resistor must be chemically inert with respect to resistor material, for example, it should not cause oxidation or reduction of the resistor material to occur and at the same time it must be able to adhere to the resistor **10.** Another factor that had to be considered was that since the flexible insulation layer must possess a soft flexible characteristic it needs additional protection from mechanical damage such as scratches, etc. The encapsulating structure on the substrate as described below provides a system of layers to protect the cermet resistor from ambient air, water vapors, water, and hydrogen sulfide (H_2S). Furthermore, the layers to be described have been found satisfactory in protecting the resistor from being affected when continuous changes in ambient temperature that may vary from the standard reference level of 25°C ± 50°C so that no more than ± 0.1% change in value of the resistor can occur.

The ceramic substrate **32** which is preferably at least 96% pure aluminum oxide material is exposed to 1000°C for 15 to 20 minutes. It is assumed that the substrate **32** is clean prior to this operation; if it is not, it is cleaned ultrasonically in ethyl or methyl alcohol for 3 minutes. Next, the previously mentioned resistor **10** and conductor inks **16, 22** are printed, dried and fired in the manner previously described as shown in FIG. **6** of the drawing.

A silicone polymer filled with magnesium oxide **34** such as dimethylpolyxilaxane which is commercially available from the EMCA Company as plastic coat **1139B** is then printed or brushed over the resistor **10** and conductor areas **16, 22** except for the conductor areas that are reserved for the terminals **38** and **40.** The substrate **32** is then heat cured at 108°C for **24** hours to provide polymerization and the resistor **10** is trimmed through the plastic coat **34** to 99 ± 1% of its desired value as previously described and the terminals **38, 40** are then soldered with suitable soldering material **42, 44** as shown in FIG. **6.**

Next, the substrate **32** is heat cycled twice between 25°C to 125°C at the temperature-time slope of 20°C per minute and kept for 2 hours at 125°C then cooled down on the same rate to 25°C. The same heat cycle is repeated for a second time, and then for a third time for a period of 15 hours instead of 2 hours and at the same temperatures.

The resistor is then finally trimmed as previously described under the description of FIGS. **2–5** to minus 0.03% of the desired value. The resistor is then cleaned with a jet spray of nitrogen. A mixture of iron oxide with magnesium silicate suspended in xylene 36 such as

glyptal 1201B paint that is commercially available is sprayed over the entire substrate including the resistor conductors and portions which form the solder joint and terminals. The substrate is then exposed to 100°C for 4 hours.

The thickness of the flexible silicone polymer layer **34** that is selected is never less than 12 microns and the thickness of the hard glyptal layer **36** is not less than 50 microns. A cross-sectional view of the projected resistor **10** is as shown in FIG. **6.**

Experimentation has also shown that cermet resistors that are prepared in the above-described manner will remain stable within ± 0.1% for at least two years or more.

The plotted dotted line shown in FIG. **7** indicates that it is possible through the use of a conventional diffusion introducing profile firing method to obtain only a single resistor blend of ink that has a zero T.C.R. value from a series of different blends of inks which possess different sheet resistivity values.

FIG. **7** also shows a second plotted solid line to indicate that a series of resistors having different resistivity values over a wide resistivity range can be obtained which each has a zero T.C.R. value when the resistor is first fired by the unique non-diffusing method previously described in which the resistor is first fired to the substrate at one temperature and the conductor and resistor are thereafter jointly fired at a second temperature that is approximately 500°C lower than the first mentioned temperature.

The unique steps employed in the preparation of a zero T.C.R. thick film resistor are:

1. Ultrasonically clean substrate **32** in methanol for 30 seconds.
2. Prefire substrate **32** at 1000°C.
3. Clean substrate **32** with N_2, print resistor.
4. Dry resistor at 107°C for 45 minutes.
5. Ascertain the correct firing temperature of the furnace.
6. Fire resistor at a plateau temperature of 1000°C on a 2-inch per minute moving belt.
7. Clean substrate **32** with N_2 and print conductors **16, 22.**
8. Dry conductors **16, 22** at 107°C for 45 minutes.
9. Ascertain the correct firing temperature of the furnace.
10. Fire the conductors **16, 22** at a plateau temperature of 550°C on a two-inch per minute moving belt.
11. Anneal by heat cycling at 177°C for 15 hours.
12. Clean resistor **10** and conductors **16, 22** with N_2 and screen on flexible layer **34.**
13. Dry flexible layer **34** at 126°C for 12 hours.
14. Stake pins **38** and **40** and solder at **42, 44.**
15. Trim resistor **10–98%** of its normal resistance value and clean with N_2.
16. Heat cycle at 121°C two times for 2 hours and then overnight to eliminate stresses induced by trimming.
17. Trim to desired value and clean with N_2.
18. Spray on hard layer **36.**
19. Dry hard layer **36** at 93°C for 4 hours.

The significance of eliminating the harmful effects the diffusion has on T.C.R. and resistivity which has heretofore been brought about by firing the resistor and conductor at substantially the same high temperature is clearly illustrated in FIGS. **8** and **9.**

FIGS. **8** and **9** show, for example, how T.C.R. and the resistivity of thick film resistors are dependent on the previously referred to geometry, or aspect ratio of the resistor when they are fired with associated conductors at the same high temperature and how this dependence was practically eliminated when the unique process heretofore described was employed.

Curve A in FIG. **8** shows the dependence of T.C.R. on the aspect ratio when a thick film precision resistor is manufactured by using conventional methods in which the resistor and conductor is fired at the same high temperature. It can be seen in this conventional method that the T.C.R. value changed from +74 PPM/°C at the aspect ratio of 0.1 to −56 PPM/°C at the aspect ratio of **10.** In other words, curve A shows that a total change in T.C.R. of 130 PPM/°C occurred when the previously mentioned ruthenium system ink is used as the resistor material, platinum gold ink is used as the conductor material and after the resistor ink and conductor were fired at the high temperature of 1000°C.

FIG. **8** curve B shows how the dependence of T.C.R. on the aspect ratio is for all practical purposes eliminated when the thick film resistor is manufactured by the previously described unique method of manufacturing.

The dependence of T.C.R. on the aspect ratio decreases from 130 PPM/°C for conventional methods that have heretofore been used as shown in FIG. **8** curve A to 28 PPM/°C for the unique method of manufacturing that has for the first time been disclosed herein.

Furthermore, in addition to the decrease in the T.C.R. dependence on the aspect ratio it can be seen that the T.C.R. versus aspect ratio curve shifts in a negative direction after the unique manufacturing method was used.

More specifically, both curves A and B represented the relationship between the T.C.R. and the aspect ratio for the same ruthenium system ink resistor material. The only difference in the manufacturing process depicted in the curves A and B shown in FIG. **8** is that in curve A the resistors and their associated conductors were fired at approximately the same temperature such as about 1000°C and for curve B the resistors were first fired at 1000°C and thereafter the resistors and their associated conductors were jointly fired at about 550°C.

It should also be noted that the conductor which is connected to the resistor represented by curve B contains silver combined with glass instead of the conventional platinum-gold (PtAu) combined with glass type conductor as represented by curve A. The only reason for the change in conductor material from PtAu to silver was that it was not possible to fire a PtAu type conductor at 550°C whereas a silver type conductor can be fired at this temperature.

A shift of curve B in a negative direction shows that the degree of diffusion of conductor material into the resistor material has decreased and that the true T.C.R. of the resistor ink is in reality that shown on curve B rather than the generally heretofore assumed value that is shown on curve A.

Curve C, FIG. **8,** depicts the dependence of T.C.R. on the aspect ratio after the resistive ink was blended with ink having positive T.C.R., such as PtAu type conductor ink or pure gold powder. After blending, the resulting ink lies approximately between +13 PPM/°C

and −8 PPM/°C T.C.R. and its dependence on the geometry (aspect ratio) for all practical purposes is nil.

FIG. **9**, curve A shows the dependence of resistivity on the aspect ratio when the thick film resistors are manufactured by conventional methods.

2150 ohm per square per mil was the change in resistivity that occurred when a change in aspect ratio went from 0.1 to 10.

Curve B of FIG. **9** provides a way of showing the independence of resistivity on the aspect ratio when the resistor is manufactured by the unique method previously described for FIG. **8**, curve B.

The dependence of resistivity on the aspect ratio (geometry) decreases from 2150 ohm per square per mil on curve A to 1100 ohm per square per mil on curve B.

FIG. **9**, curve C shows the resistivity versus aspect ratio after blending as previously described under FIG. **8**.

It has been determined by experimentation that substantially 20% by weight of RuO_2, 40% by weight of Ru and 40% by weight of glass frit is one type of positive temperature coefficient of resistivity resistor ink that can be employed to advantage in the aforementioned described ink mixtures that are formed from positive and negative temperature coefficient of resistors ink. It has also been determined by experiment that substantially 40% by weight of RuO_2, 20% by weight of Ru and 40% by weight of glass frit is one type of negative temperature coefficient resistivity resistor ink that can be advantageously used in the aforementioned ink mixture to make the resistor **10**.

It can, therefore, be seen that the unique apparatus and method of first firing the resistor **10** onto a substrate **32** at 1000°C and the later joint firing of the resistor **10** and its associated conductors **16, 22** onto the substrate **32** at a lower temperature, namely 550°C, will substantially eliminate diffusion that has heretofore occurred between the conductor material and the resistor material.

By procuring a resistor and its associated conductors after firing in the substantially same undiffused state that they were in before firing, it is for the first time possible to eliminate the T.C.R. and resistivity dependency on the geometry of the resistor commonly referred to as aspect ratio that has heretofore existed when other firing means have been employed for this purpose.

Because of the aforementioned advantages derived from the unique firing technique, it is now possible for the first time to manufacture precision thick film resistors without concerning oneself with the heretofore existing problem of:

1. Selecting the right aspect ratio or, in other words, the length-width ratio, or the geometry, of the resistor that is to be fired onto a substrate,
2. Spending time in consulting geometry correcting tables to predict resistivity and the T.C.R. of the resistor as a function of the resistors geometry, and
3. Requiring the creative ability of the designer who is designing an electrical, thick film circuit from being able to present the most desired economical compact circuit because the resistors that have heretofore been used were required to be of a prescribed geometric shape and size.

The embodiments of the invention in which an exclusive property or privilege is claimed is defined as follows:

1. A method of making an encapsulated thick film resistor having conductive portions associated with opposite ends thereof that form portions of an electrically conductive circuit, comprising the first step of selecting an ink from a mixture of positive and negative resistor inks, the second step of firing the resistor ink mix in amorphic form at 1000°C into a sintered state onto an electrically non-conductive substrate, the third step of selecting a conductive ink material that has a sintering temperature substantially lower than the sintering temperature of the resistor, the fourth step of firing said conductive ink at a sintering temperature of about 550°C in overlapping relationship with said opposite ends of said resistor on the substrate whereby the tendency to diffusion between the conductive and resistive materials is minimized and whereby a resulting temperature coefficient of resistivity value of the resistor that is produced is within plus or minus 20 parts per million per degree centigrade from zero, the fifth step of applying a coating of resilient buffer material formed of a silicone polymer filled with magnesium oxide to cover said resistor and the said fired conductive ink and the sixth step of applying a layer of iron oxide with magnesium silicate suspended in xylene to cover the outer surface of said resilient material.

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