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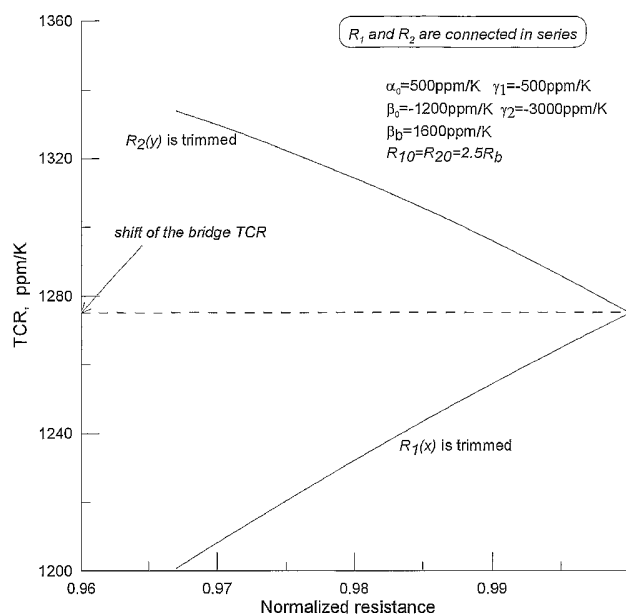
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(54) Title: COMPENSATING FOR TRIMMING-INDUCED SHIFT OF TEMPERATURE COEFFICIENT OF RESISTANCE



(57) Abstract: A compound resistor is used to compensate for trimming induced shift in temperature coefficient of resistance of a trimmable resistor. The compound resistor is composed of a first and second portion, at least one of the two portions being thermally trimmable, and the parameters for the first and second portion are selected such that the trimming induced shift can be minimized on an overall resistance and temperature coefficient of resistance of the compound resistors by trimming the trimmable resistor.



For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

**COMPENSATING FOR TRIMMING-INDUCED SHIFT OF TEMPERATURE
COEFFICIENT OF RESISTANCE**

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims priority of US Provisional Patent Application serial number 60/611,274 filed on September 21, 2004, the contents of which are hereby incorporated by reference.

TECHNICAL FIELD

The invention relates to resistors and resistor networks which are electro-thermally trimmable, and more specifically, to thermal trimming of these resistors to adjust resistance, temperature coefficient of resistance and relative temperature coefficient of resistance.

BACKGROUND OF THE INVENTION

In working with resistors referred to as "precision resistors", it is advantageous to have the capability to precisely adjust the resistance value. It is also advantageous to precisely adjust the temperature coefficient of resistance (TCR) of such a resistor.

It is known that joint and independent adjustment of resistance and TCR can be achieved for compound resistors containing a first portion with a first resistance value and a positive TCR and a second portion with a second resistance value and a negative TCR (US Patent 4079349, US Patent 4907341, US Patent 6097276). Independent trimming of these two portions of the compound resistor results in the adjustment of the total resistance and of the TCR of the compound resistor. The trimming technique is based on a process of cutting the resistive material such as by laser beam cutting or ultrasonic probe cutting or others. The material properties, namely the TCR, of

the bulk resistor material, remain substantially constant during this trimming process, since only the shapes of the resistor portions are being trimmed.

Another non-laser trimming technique is known to adjust the resistance of thin film resistors. This technique is based on thermal trimming of a resistor made from a thermally mutable material. Resistor trimming is achieved by heating using electric current pulses passed through the resistor itself or through an adjacent auxiliary heater (US Patents 4210996, 5635893, 5679275). Instead of direct physical removal of portions of the resistor material as is done in laser trimming, thermal trimming directly modifies the physical properties of the material such as resistivity and TCR.

It was reported that resistance trimming is accompanied by significant changes of TCR (K. Kato, T. Ono Changes in Thermal Coefficient of Resistance of Heavily Doped Polysilicon Resistors Caused by Electrical Trimming Jpn. J Appl. Phys. Vol. 35 (1996), pp.4209-4215; D. Feldbaumer, J. Babcock, C. Chen Pulse Current Trimming of Polysilicon Resistors Trans. On Electron Devices vol. 42 (1995), pp. 689-696; US Patent 6306718). As a measure of this effect, the term "Temperature Coefficient of Trimming" (TCT) is used hereinafter in this text and defines a change of TCR per fraction of trimming, which is a trimming-induced shift of TCR. For example, a TCT of -1000ppm/K/trim-fraction means that trimming resistance down by a trim fraction of 0.01 (1%) results in a shift of TCR equal to 10ppm/K in the opposite direction from the direction of the trim (in this case an increase of 10ppm/K). It is known experimentally that for polysilicon resistors, TCT is typically negative (increase in TCR with decrease of resistance), with its value dependent on type of dopant and doping level.

Non-zero TCT generates a new problem (not existing in typical cutting-based trimming techniques), which can be illustrated by the following example. Consider a resistor divider consisting of two trimmable resistors with

the same initial TCR, and $TCT = -2000\text{ppm/K/trim-fraction}$. If the resistance ratio is adjusted by trimming one of the resistors "down" by 10%, the accompanying change in relative TCR (RTCR) may reach 200ppm/K. While resistance matching can potentially be done very precisely using thermal
5 trimming (better than 0.01-0.1%), variation of ambient temperature in the range of $\pm 50^\circ\text{C}$ can make the divider voltage very unstable, with resistance ratio drift reaching $\pm 1\%$.

While near-zero TCR of the resistor is often desirable because it gives near-zero resistance drift with variation of ambient temperature, resistance
10 modulation due to self-heating in operation also should be minimized to avoid signal distortions in analog circuits. One of the problems of compound resistors consisting of two portions with positive and negative TCR is that near-zero TCR of the whole resistor does not mean zero resistance modulation due to self-heating. For example, a compound resistor with the
15 first portion having resistance of 10K ohm and TCR of 100ppm/K and the second portion (connected in series) having resistance of 1K ohm and TCR of -1000ppm/K, has zero net TCR. Electric current passing through the compound resistor results in power dissipated in the first portion 10 times higher than in the second portion. If the thermal isolation of the two portions is
20 the same, the first portion is heated to a temperature rise 10 times greater than the second. Assume that the overheating temperature of the first portion is 10°C and the overheating temperature of the second portion is 1°C . As a result, the first resistance increases by 0.1% or 10 Ohm while the second resistance decreases by 0.1% or 1 Ohm. Absolute resistance change of the
25 compound resistor equals 9 Ohm. The same relative resistance change of two portions gives a different absolute change of their resistance values. As a result, the total resistance will no longer be constant.

Therefore, it is clear that there are potentially negative effects stemming from non-zero TCT when doing thermal trimming.

SUMMARY OF THE INVENTION

An embodiment of the present invention compensates (or minimizes) RTCR (TCR mismatch) resulting from non-zero TCT of a thermally trimmable resistor network by constructing a compound resistor from at least two
5 resistive portions having different resistance and TCR values.

An embodiment of the present invention achieves independent adjustment of resistance ratio and RTCR of a thermally trimmable resistor network, the RTCR being adjusted to near-zero or intentionally to a non-zero value. A trimmable resistor network with adjustable non-zero RTCR can be
10 used in various different applications where temperature drift of circuit parameters (offset, gain, sensitivity and others) is needed.

An embodiment of the present invention reduces the influence of self-heating on resistance modulation of a compound resistor containing two portions with positive and negative TCR.

15 In accordance with a first broad aspect of the present invention, there is provided a method for providing a trimmable resistive component having a predetermined behavior of temperature coefficient of resistance (TCR) as a function of trimming, the method comprising: selecting materials to form a compound resistor having at least a first portion and a second portion, at least
20 said first portion including a first resistor that is thermally trimmable and has a first resistivity, a first temperature coefficient of resistance value α_0 , and a value of trimming-induced shift of temperature coefficient γ_1 , which defines a change in said α_0 per fraction of trimming x of said first resistivity, said second portion including at least a second resistor having a second resistivity value,
25 and a second temperature coefficient of resistance value β_0 ; determining how said TCR value of said resistive component changes as at least said first portion is trimmed, by generating a function of said TCR versus trim-fraction x , with R_1 and R_2 as variable parameters and α_0 , β_0 , and γ_1 as fixed parameters;

and selecting specific values for R_1 and R_2 or R_1/R_2 to provide said resistive component with said predetermined behavior of said TCR, thereby incorporating an effect of said γ_1 in said resistive component.

5 In accordance with a second broad aspect of the present invention, there is provided a trimmable resistive component having a predetermined behavior of temperature coefficient of resistance (TCR) as a function of trimming comprising: a first portion composed of a first resistor that is thermally trimmable and has a first resistivity, a first temperature coefficient of resistance value α_0 , and a value of trimming-induced shift of temperature
10 coefficient γ_1 , which defines a change in said α_0 per fraction of trimming x of said first resistivity; and a second portion composed of at least a second resistor having a second resistivity value and a second temperature coefficient of resistance value β_0 , said first portion and said second portion having specific values for R_1 and R_2 or R_1/R_2 to provide said compound
15 resistor with said predetermined behavior of said TCR value; wherein said predetermined behavior of said TCR is defined by a function of said TCR versus trim-fraction x , with R_1 and R_2 as variable parameters and α_0 , β_0 , and γ_1 as fixed parameters, thereby incorporating an effect of said γ_1 in said resistive component.

20 In accordance with a third broad aspect of the present invention, there is provided an application specific circuit having an adjustable parameter of the circuit and an adjustable temperature coefficient of said parameter, the circuit comprising: at least one compound resistor including: a first portion composed of a first resistor that is thermally trimmable and has a first
25 resistivity, a first temperature coefficient of resistance (TCR) value α_0 , and a value of trimming-induced shift of temperature coefficient γ_1 , which defines a change in said α_0 per fraction of trimming x of said first resistivity; and a second portion composed of a second resistor having a second resistivity value and a second TCR value β_0 , said first portion and said second portion

having specific values for at least one of R_1 and R_2 and R_1/R_2 to provide said compound resistor with said predetermined behavior of said TCR value; control circuitry for thermally trimming said at least one compound resistor; and circuitry for said application connected to said at least one compound resistor; wherein said predetermined behavior of said TCR is defined by a function of said TCR versus trim-fraction x , with R_1 and R_2 as variable parameters and α_0 , β_0 , and γ_1 as fixed parameters, thereby incorporating an effect of said γ_1 in said compound resistor.

It should be understood that according to a separate aspect of the present invention, the circuit shown in figure 23a can be implemented with an R_{1_comp} and R_{2_comp} as per the prior art.

In a preferred embodiment, trimming algorithms such as those disclosed in PCT publications WO04/097859, WO04/097860, and WO04/083840 are used. In addition, control circuitry such as that described in PCT publications WO03/023794 and WO04/097859 to trim resistors is also preferred.

In accordance with a fourth broad aspect of the present invention, there is provided a method for providing a resistor having a predetermined resistance value and temperature coefficient of resistance value, the method comprising: providing a trimmable resistive component having a predetermined behavior of temperature coefficient of resistance (TCR) as a function of trimming, the method comprising: selecting materials to form a compound resistor having at least a first portion and a second portion, at least said first portion including a first resistor that is thermally trimmable and has a first resistivity, a first temperature coefficient of resistance value α_0 , and a value of trimming-induced shift of temperature coefficient γ_1 , which defines a change in said α_0 per fraction of trimming x of said first resistivity, said second portion including at least a second resistor having a second resistivity value,

and a second temperature coefficient of resistance value β_0 ; determining how said TCR value of said resistive component changes as at least said first portion is trimmed, by generating a function of said TCR versus trim-fraction x , with R_1 and R_2 as variable parameters and α_0 , β_0 , and γ_1 as fixed parameters;
5 and selecting specific values for R_1 and R_2 or R_1/R_2 to provide said resistive component with said predetermined behavior of said TCR, thereby incorporating an effect of said γ_1 in said resistive component; and thermally trimming said first resistor to obtain said predetermined resistance value and temperature coefficient of resistance value.

10 An embodiment of the present invention can be used for making precision adjustable resistors and resistor networks. Electro-thermal trimming used for the adjustment in general changes not only resistance value but also TCR of trimmable material. The proposed solutions allow the designer/user to achieve:

- 15 • resistance adjustment with reduced variation of the resistor's TCR;
- resistance ratio adjustment of at least two resistors, along with independent near-zero RTCR adjustment;
- resistance ratio adjustment of at least two resistors, along with intentional RTCR adjustment to a substantially non-zero value;
- 20 • reduced resistance modulation due to self-heating resultant from electric power dissipation in operation.

The term "compound resistor" is to be understood as a resistor composed of more than one identifiable resistor, which can have the same or different resistances, resistivity, sheet resistances, trim amounts, and other
25 physical properties.

A "resistive component" can be a single resistance, a network of resistances, multiple resistances where some of the multiple resistances are

part of an application circuit, multiple resistances completely integrated into an application circuit, or multiple resistances external to an application circuit. It can also be a compound resistor as defined above.

5 The analysis done to generate the function can be numerical (when computer-based simulation tools are used), analytical (based on classic electricity laws), or experimental (when set of curves $TCR(x)$ is generated experimentally) and should not be limited to any one of these techniques. It can readily be understood by a person of ordinary skill in the art that basic electrical laws to be used in generating the function as described above can
10 be Ohm's Law (relating current, voltage and resistance in a resistor), Kirchoff's current law (for summing of currents at a node), Kirchoff's voltage law (regarding the sum of voltages around a closed electrical loop), and equations describing how the component values of electrical components (e.g. resistance) vary with temperature.

15 While the term "resistivity" (units: ohm-cm) is used, it should be understood that "sheet resistance" (units: ohms/square) could also be one of the properties of the materials instead of "resistivity". Starting from "resistivity", one can calculate resistance by multiplying by the length and dividing by the cross-sectional area ($R = \rho * L/A$). However, in practice thin films typical of
20 semiconductor devices may be used in the fabrication processes, and these are described in terms of "sheet resistance", in part because the resistivity may not be constant throughout the thickness of the film, because the layout designer typically may not have control over the vertical dimension (thickness) of the film, and because what can be most easily measured is the "sheet
25 resistance" (a property of the film). One calculates the resistance by multiplying "sheet resistance" by a number of "squares" that compose a resistor trace.

The terms "trim-fraction" and "fraction of trimming" are used interchangeably to mean the fraction of the as-manufactured resistance by which the trim reduces the resistance.

BRIEF DESCRIPTION OF THE DRAWINGS

5 Further features and advantages of the present invention will become apparent from the following detailed description, taken in combination with the appended drawings, in which:

Fig. 1 is a schematic of a compound resistor consisting of two parts connected in series, as per an embodiment of the present invention;

10 Fig. 2 is a comparative graph of the TCR of a single trimmable resistor R_1 and the TCR of a compound resistor as in fig 1;

Fig. 3 is a graph showing TCR of a compound resistor configured as shown in Fig. 1 vs. relative trimming of its resistance value, for several different ratios of R_{20}/R_{10} ;

15 Fig. 4 is a schematic of a compound resistor in a parallel configuration, as per another embodiment of the present invention;

Fig. 5 is a comparative graph of the TCR of a single trimmable resistor R_1 and the TCR of a compound resistor as in fig 4;

20 Fig. 6 is a graph which shows the dependence of the TCR of a compound resistor R_{comp} , composed of two trimmable portions in series, $R_1(x)$, $R_2(y)$, as a function of relative trimming of the compound resistor;

Fig. 7 shows a series connection of two compound resistors, each compound resistor consisting of two trimmable resistors;

Fig. 8 shows a series connection of a compound resistor as in Fig. 1, along with a third resistor which is trimmable;

Fig. 9 shows an alternative circuit configuration for a compound resistor, with two resistors forming the first portion and one resistor forming
5 the second portion;

Fig. 10 shows a full Wheatstone bridge, R_{b1} , R_{b2} , R_{b3} , R_{b4} , each with a trimmable compound resistor, R_{comp1} , R_{comp2} , R_{comp3} , R_{comp4} , connected in parallel, and a simplified representation where each bridge resistor and its associated compound resistor is combined and represented as R_{b_comp1} ,
10 R_{b_comp2} , R_{b_comp3} , R_{b_comp4} ;

Fig. 11 shows two different configurations of trimmable compound resistors, one where $R_1(x)$ and $R_2(y)$ are connected in series, and the other where $R_1(x)$ and $R_2(y)$ are connected in parallel;

Fig. 12 is a graph of overall TCR of an example of one R_{b_comp}
15 compound resistor having a series connection, as a function of its own normalized resistance, as one of the trimmable portions is trimmed down, where trimming $R_2(y)$ increases the TCR while trimming $R_1(x)$ decreases the TCR;

Fig. 13 is a graph of overall TCR of an example of one R_{b_comp}
20 compound resistor having a series connection, as a function of its own normalized resistance, as one of the trimmable portions is trimmed down, where trimming $R_2(y)$ changes the TCR by a much larger amount than does trimming $R_1(x)$;

Fig. 14 is a graph of overall TCR of an example of one R_{b_comp}
25 compound resistor having a series connection, as a function of its own normalized resistance, as one of the trimmable portions is trimmed down,

where trimming $R_1(x)$ decreases the TCR by a larger amount than the increase caused by trimming $R_2(y)$;

Fig. 15 is a graph of overall TCR of an example of one R_{b_comp} compound resistor having a parallel connection, as a function of its own
5 normalized resistance, as one of the trimmable portions is trimmed down, where trimming $R_2(y)$ increases the TCR by a larger amount than the decrease caused by trimming $R_1(x)$;

Fig. 16 is a graph of overall TCR of an example of one R_{b_comp} compound resistor having a parallel connection, as a function of its own
10 normalized resistance, as one of the trimmable portions is trimmed down, where the magnitudes of the changes in TCR are smaller than those in figure 15;

Fig. 17 is a graph of overall TCR of an example of one R_{b_comp} compound resistor having a parallel connection, as a function of its own
15 normalized resistance, as one of the trimmable portions is trimmed down, where trimming $R_2(y)$ causes a larger increase in TCR than the decrease in TCR caused by trimming $R_1(x)$;

Fig. 18 shows the trimming behavior of one compound resistor R_{b_comp} having several different values of the nominal TCR (β_b) of the bridge resistor
20 (R_b), where the changes in TCR and relative resistance remain almost the same, for the three different values of β_b ;

Fig. 19 shows a scheme of TCR compensation of the bridge as a whole, where the trimmable compound resistor R_5 is connected in parallel with the whole bridge, such that it experiences the entire voltage applied to the
25 bridge, U_b ;

Fig. 20 shows an example of trimming the TCR of the overall bridge using resistor R_5 , connected in parallel with the entire bridge;

Fig. 21 shows another scheme of TCR compensation of the bridge as a whole, where the trimmable compound resistor R_6 is connected in series with the whole bridge, such that it experiences the same current as that applied to the bridge;

5 Fig. 22 shows the temperature coefficient of bridge voltage (upper graph), and the ratio U_b/U (lower graph, where U is the excitation voltage of the circuit shown in Fig. 21), as functions of normalized resistance of the trimmable resistor $R_6(x)$ from Fig. 21;

10 Fig. 23a shows a schematic of a single module containing a resistor bridge with two trimmable compound resistors R_{1_comp} and R_{2_comp} on one side of the bridge, and an amplifier having gain K_1 ; and

Fig. 23b shows a schematic demonstrating how several modules from Fig. 23a could be cascaded such that $N=3$, to obtain a third-order polynomial function of temperature.

15 It will be noted that throughout the appended drawings, like features are identified by like reference numerals.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

Fig. 1 shows a schematic of the compound resistor consisting of two parts connected in series, a trimmable resistor R_1 with TCR α_0 , negative TCT γ_1 and ballast resistor R_{20} (non-trimmable) with TCR β_0 . Suppose that resistor R_1 is trimmable in the range of $\pm 15\%$ from its middle resistance value R_{10} :

$$R_1(x) = R_{10}(1+x) \quad (1)$$

where x is the trim fraction and $-0.15 < x < 0.15$. The TCR of the resistor R_1 varies as:

25 $\alpha(x) = \alpha_0 + \gamma_1 x \quad (2)$

The resistance and TCR of the compound resistor can be expressed as:

$$R_{comp}(x) = R_1(x) + R_{20} \quad (3a)$$

$$\alpha_{comp} = \frac{R_{10}(1+x)(\alpha_0 + \gamma_1 x) + R_{20}\beta_0}{R_{10}(1+x) + R_{20}} \quad (3b)$$

5 It can be shown that the variation with trim-fraction of the compound resistor, $\frac{d\alpha_{comp}(x)}{dx}$ equals to zero at $x=0$ when the resistance ratio $k = R_{20}/R_{10}$ equals:

$$k = \frac{\gamma_1}{\beta_0 - \alpha_0 - \gamma_1} \quad (4)$$

Note that this condition (valid for series connection), can be moved to a
10 different value of x by changing the value of the ratio k . Fig 2 depicts the TCR of a single trimmable resistor R_1 and the TCR of a compound resistor (such as shown in Fig. 1), as a function of resistance trimming relative to its middle value R_{10} . The parameters of the resistors used in this example are: $\alpha_0=500\text{ppm/K}$, $\beta_0=-1200\text{ppm/K}$, $\gamma_1=-500\text{ppm/K/trim-fraction}$. The resistance
15 value of the resistor R_2 used for TCT compensation was calculated from eq. (4): $R_{20} = 0.417R_{10}$.

Only positive values of resistance ratio k (eq. (4)) have physical meaning. Therefore TCT compensation is possible only if:

$$\alpha_0 - \beta_0 > -\gamma_1 \quad (5)$$

20 Consider the result from the derived equation (4). TCT compensation for a resistor having negative TCT is possible only in the case when the ballast resistor R_{20} has a more negative TCR than the trimmable resistor. For example, compensation for a trimmable resistor having $\alpha_0=1000\text{ppm/K}$ and $\gamma_1=-500\text{ppm/K/trim-fraction}$ is possible when the ballast resistor R_{20} has TCR

$\beta_0 < 500 \text{ ppm/K}$. Another example of possible compensation is $\alpha_0 = -1200 \text{ ppm/K}$, $\gamma_1 = -3000 \text{ ppm/K/trim-fraction}$ and $\beta_0 < -4200 \text{ ppm/K}$. (Note that we do not consider here the practical realization of a resistor or resistor network with a particular TCR such as -4200 ppm/K).

5 It also should be understood that the compound resistor has a trimming range narrower than that of a single trimmable resistor by a factor of $1/(1+k)$. That is why the trimming range of the compound resistor in Fig. 2 is $1/(1+0.417) = 0.706$ narrower than the trimming range of a single resistor R_1 . To maintain a substantial trimming range for the compound resistor, it is
10 preferable to choose materials for its two portions so that the parameter k is minimized. A simple guideline for this is to use resistor materials with low TCT γ_1 and high TCR difference $\alpha_0 - \beta_0$. Application-specific cases where an intentionally narrow trimming range of the compound resistor is needed also may exist. Equations (4,5) can be used to make a proper choice of the
15 resistor materials.

Fig. 3 is a graph which shows the TCR of the compound resistor vs. relative trimming of its resistance value. The resistor is analogous to those shown in Fig. 1 and has the following as-manufactured parameters for the two resistive portions: resistance R_{10} , TCR $\alpha_0 = 500 \text{ ppm/K}$, TCT $\gamma_1 =$
20 $500 \text{ ppm/K/trim-fraction}$, for the first portion, and correspondingly R_{20} and $\beta_0 = -1000 \text{ ppm/K}$, for the second portion. TCT compensation is reached at $k = R_{20}/R_{10} = \gamma_1/(\beta_0 - \alpha_0 - \gamma_1) = 0.5$.

In practice, thermal trimming usually results in reduction of resistance from its as-manufactured value to a certain target value, and the resistance
25 seldom subsequently reaches above the as-manufactured value. It may be preferable to have minimal variation of TCR of the compound resistor in a given trimming range. It can also be seen from Fig. 3 that the compound resistor with ratio $R_{20}/R_{10} = 0.26$ has better TCR uniformity in a 30% trimming

range than the compound resistor with ratio $R_{20}/R_{10}=0.5$ ($\pm 8.5\text{ppm/K}$ vs. $\pm 50\text{ppm/K}$). Analogously, compound resistors with ratios $R_{20}/R_{10}=0.4$ and $R_{20}/R_{10}=0.323$ have optimal TCR uniformity in their trimming ranges of 10% and 20%, respectively, (corresponding to $\pm 1\text{ppm/K}$ and $\pm 3.5\text{ppm/K}$, respectively). Note that the trim-fractions at which the compound resistor becomes ideally TCT-compensated are located approximately at the middle of the trimming range. These points are designated by triangles in the figure. Specifically at these points, the resistance ratio of the two portions is defined

by a modified version of equation (4): $\frac{R_{20}}{R_1(x)} = \frac{\gamma_1}{\beta_0 - \alpha(x) - \gamma_1}$. These specific trim-fractions at which the compound resistor becomes ideally TCT-compensated, can be pre-determined (designed by the user), by proper selection of the resistor values and properties. It should be understood that $R_1(x)$, $\alpha(x)$ are not as-manufactured resistance and TCR of the first portion but its actual values reached at a certain trimming level (at these "predetermined trim-fractions").

A procedure for implementing an embodiment of the method of the present invention is as follows (for a circuit as shown in Fig. 1):

1. The materials are chosen for the two portions of the resistor (with specific sheet resistance and TCR for both portions, and TCT for the first portion).
2. The trimming range required for a given application is chosen.
3. The as-manufactured resistance ratio of two portions is defined (based on the known sheet resistances, TCR's and TCT), such that the compound resistor reaches ideal TCT-compensation (defined by eq.(4)) approximately at the middle of the desired trimming range, thus providing relatively "flat" TCR vs. trimming in that entire desired trimming range.

4. The actual layout of the two resistive portions is designed to reach the required absolute as-manufactured resistance value. (Note that in step (3) we define only resistance ratio.)

5. As part of the layout design, the resistive portions are distributed within the chip (and/or suspended microstructures) such that their thermal isolation provides self-heating of two portions (with positive and negative TCR) such that the net resistance modulation is minimized in operation.

Fig. 4 shows the schematic of the analogous compound resistor with two resistive parts connected in parallel. The resistance of the compound resistor and its TCR can be found as:

$$R_{comp} = \frac{R_1(x)R_{20}}{R_1(x) + R_{20}} \quad (6a)$$

$$\alpha_{comp} = \frac{\alpha(x)R_2 + \beta_0 R_1(x)}{R_1(x) + R_{20}} \quad (6b)$$

where $R_1(x)$ and $\alpha(x)$ are defined by eqs. (1) and (2).

TCT compensation for the (parallel) compound resistor is reached at

$$k = \frac{\alpha_0 - \beta_0 - \gamma_1}{\gamma_1} \quad (7)$$

Compensation of negative variation of TCR with trim-fraction of the trimmable resistor is possible when the ratio $k = R_{20}/R_{10}$ is positive, and

$$\beta_0 - \alpha_0 > -\gamma_1 \quad (8)$$

The compound resistor has a trimming range narrower than that of a single trimmable resistor by a factor of $k/(1+k)$. Therefore, to maintain a substantial trimming range for the compound resistor, it is again preferable to choose materials with high TCR difference $\beta_0 - \alpha_0$ so as to maximize the parameter k .

Fig. 5 plots the TCR of a single trimmable resistor R_1 and the TCR of a compound resistor composed of two resistors connected in parallel, as a function of resistance trimming relative to its middle value R_{10} . The parameters of the resistors in this example are: $\alpha_0=-800\text{ppm/K}$, $\beta_0=4000\text{ppm/K}$, $\gamma_1=-3000\text{ppm/K/trim-fraction}$. The resistance value of the resistor R_{20} used for TCT compensation and calculated from eq. (7) equals $0.6R_{10}$. The trimming range of the compound resistor is narrower than for single resistor R_1 by a factor $0.6/(1+0.6)=0.375$ and reaches $(\pm 15\%) \cdot 0.375 = \pm 5.6\%$.

The described compound trimmable resistors with compensated TCT can be used in designing various resistor networks. For example a resistor divider can be built from two TCT-compensated trimmable resistors. Resistance ratio adjustment of this divider can be performed with near-zero RTCR variations as will be explained further below.

It is known from prior art that thermally mutable materials, for example polysilicon doped with different types of dopants, may have significantly different TCT. In particular, it was reported that polysilicon doped with Boron has much lower TCT than polysilicon doped with Arsenic (D. Feldbaumer, J. Babcock, C. Chen, Pulse Current Trimming of Polysilicon Resistors, Trans. on Electron Devices, vol. 42 (1995), pp. 689-696). Polysilicon samples doped with one type of dopant but at different doping levels also may have different TCT (US patent 6306718).

Thermally trimmable single resistors with different TCR and TCT are proposed to be used in a compound resistor to provide independent adjustment of resistance value and TCR. Consider a compound resistor constructed from two resistors in series analogous to those shown in Fig. 1 but with the second resistor also being trimmable. Consider an example where TCR and TCT of the two resistive portions are: $\alpha_0=500\text{ppm/K}$, $\gamma_1=-$

500ppm/K/trim-fraction – for the first resistor and $\beta_0 = -1000\text{ppm/K}$, $\gamma_2 = -3000\text{ppm/K/trim-fraction}$ – for the second resistor. Each of the two single resistors are trimmable as $R_1(x) = R_{10}(1+x)$ and $R_2(x) = R_{20}(1+y)$, where x and y are the respective trimming fractions. The compound resistor is TCT-compensated (by trimming of the first resistive portion) when the resistance ratio is $k = R_{20}/R_{10} = \gamma_1/(\beta_0 - \alpha_0 - \gamma_1) = 0.5$

Fig. 6 shows the dependence of the TCR of this series-connected compound resistor R_{comp} as a function of its relative trimming. When resistor $R_1(x)$ is trimmed by fraction x , the TCR of the compound resistor remains almost constant while its total resistance, R_{comp} , changes. Meanwhile trimming of the resistor $R_2(y)$ by fraction y results in a significant change in the TCR of R_{comp} , with a slope of approximately -40ppm/K per 1% of trimming of the compound resistor, or -13ppm/K per 1% of trimming of the resistor R_2 . The possibility of trimming the resistance value of the compound resistor with different slopes of TCR vs. R_{comp} trimming fraction is useful for building resistor networks with independent adjustment of resistance ratio and RTCR.

Consider a resistor voltage divider consisting of two identical compound resistors ($R_{1comp}/R_{2comp} = 1$), each compound resistor having a first portion with TCT γ_1 and second portion with TCT γ_2 (shown in Fig. 7). Resistors R_{11} and R_{21} are the “first” resistors within each of the two compound resistors, and are made from the same material with resistance $R_{11}(x_1) = R_1(1+x_1)$, $R_{21}(x_2) = R_1(1+x_2)$ and TCR $\alpha_{11}(x_1) = \alpha_0 + \gamma_1 x_1$, $\alpha_{21}(x_2) = \alpha_0 + \gamma_1 x_2$, where x_1 and x_2 are relative trimming fractions for each of the “first” resistors in each compound pair. Analogously, the resistance and TCR of resistors R_{12} and R_{22} , (the “second” resistors in each compound pair), can be expressed as $R_{12}(y_1) = R_2(1+y_1)$, $R_{22}(y_2) = R_2(1+y_2)$, $\alpha_{12}(y_1) = \beta_0 + \gamma_2 y_1$, $\alpha_{22}(y_2) = \beta_0 + \gamma_2 y_2$, where y_1 and y_2 are relative trimming fractions for each of the “second” resistors in each compound pair.

The resistances and TCRs of the compound resistors are then equal to:

$$R_{1comp} = R_1(1 + x_1) + R_2(1 + y_1) \quad (9a)$$

$$\alpha_{1comp} = \frac{R_1(1 + x_1)(\alpha_0 + \gamma_1 x_1) + R_2(1 + y_1)(\beta_0 + \gamma_2 y_1)}{R_1(1 + x_1) + R_2(1 + y_1)} \quad (9b)$$

$$5 \quad R_{2comp} = R_1(1 + x_2) + R_2(1 + y_2) \quad (9c)$$

$$\alpha_{2comp} = \frac{R_1(1 + x_2)(\alpha_0 + \gamma_1 x_2) + R_2(1 + y_2)(\beta_0 + \gamma_2 y_2)}{R_1(1 + x_2) + R_2(1 + y_2)}$$

(9d)

Suppose that two compound resistors are TCT-compensated with parameters analogous to those given in the previous example above (see Fig. 6). Independent adjustment of the resistance (voltage divider) ratio R_{1comp}/R_{2comp} and RTCR $\Delta\alpha = \alpha_{1comp} - \alpha_{2comp}$ to specific target values is possible by joint trimming of at least two of the four single resistors in the two compound resistors.

15 Example 1: Suppose the target resistance ratio is $R_{1comp}/R_{2comp} = 0.95$ and target RTCR $\Delta\alpha = 0\text{ppm/K}$. An approximate simplified trimming procedure is based on the assumption that trimming of resistors R_{11} or R_{21} does not change TCR of the compound resistors while trimming of the resistors R_{12} or R_{22} changes TCR of the compound resistors linearly with a slope of -13ppm/K per 1% of trimming of the resistors R_{12} or R_{22} (see Fig. 6). Therefore one
20 could begin by trimming resistor R_{11} down by $x_1 = 0.05 \cdot (1+k) = 0.075$. As a result of this trimming, the TCR of the first compound resistor becomes $\alpha_{1comp} = -2\text{ppm/K}$ while the TCR of the second compound resistor remains unchanged ($\alpha_{2comp} = 0$).

Next, accurate adjustment would require use of another single resistor to compensate for the small R_{TCR} shift which was caused by trimming R_{11} . Resistor R_{22} (whose trimming significantly changes the TCR of the compound resistor), can be used for this purpose.

- 5 In general, the desired trimming fractions x_1 and y_2 can be found from by solving the system of two equations derived from Equations (9a-d):

$$\frac{1+k+x_1}{1+k+ky_2} = 0.95 \quad (10a)$$

$$(1+x_1)(\alpha_0 + \gamma_1 x_1) + k\beta_0 - (\alpha_0 + k(1+y_2)(\beta_0 + \gamma_2 y_2))0.95 = 0 \quad (10b)$$

- 10 For the above example, the accurate solution is $x_1=-0.074$, $y_1=0$, $x_2=0$, $y_2=0.0015$, ($\alpha_{1comp}=-1.9\text{ppm/K}$, $\alpha_{2comp}=-1.9\text{ppm/K}$).

- Example 2: Consider the target: $R_{1comp}/R_{2comp}=0.95$, $\Delta\alpha=-100\text{ppm/K}$. In an approximate simplified trimming procedure, first, resistor R_{22} is chosen for trimming by fraction $y_2=(100\text{ppm/K})/(-13\text{ppm/K})/100 = -0.077$ to increase the
15 TCR of the second compound resistor by 100ppm/K. Then resistor R_{11} is trimmed by fraction x_1 to reach the target resistance ratio: $x_1=-0.112$. An approximate solution: $x_1=-0.112$, $y_2=-0.077$ ($\alpha_{1comp}=-4.5\text{ppm/K}$, $\alpha_{2comp}=99.3\text{ppm/K}$). The accurate solution, found by solving the two equations 10a,b is: $x_1=-0.11$, $y_1=0$, $x_2=0$, $y_2=-0.074$ ($\alpha_{1comp}=-4.4\text{ppm/K}$,
20 $\alpha_{2comp}=95.6\text{ppm/K}$).

Note that errors in a simplified procedure are caused by the nonlinearity of the variation of TCR of a compound resistor as function of trimming fraction.

- Example 3: Consider a different target, $R_{1comp}/R_{2comp}=0.95$, $\Delta\alpha =$
25 100ppm/K. However, in this case, resistors R_{12} and R_{21} are chosen for trimming, resistor R_{12} (x_2) being "responsible" for R_{TCR} adjustment and R_{21}

(y_1) "responsible" for resistance ratio adjustment ($x_1 = y_2 = 0$). Approximate solution: $y_1 = -0.077$, $x_2 = 0.038$ ($\alpha_{1comp} = 99.3 \text{ ppm/K}$, $\alpha_{2comp} = -0.5 \text{ ppm/K}$). Accurate solution: $y_1 = -0.0772$, $x_2 = -0.038$, $y_2 = 0$, $x_1 = 0$, ($\alpha_{1comp} = 99.5 \text{ ppm/K}$, $\alpha_{2comp} = -0.5 \text{ ppm/K}$).

- 5 Example 4: $R_{1comp}/R_{2comp} = 1$, $\Delta\alpha = 100 \text{ ppm/K}$. Resistors R_{12} and R_{21} are trimmed by fractions y_1 and x_2 ($x_1 = y_2 = 0$). Approximate solution: $y_1 = -0.077$, $x_2 = -0.039$ ($\alpha_{1comp} = 99.3 \text{ ppm/K}$, $\alpha_{2comp} = -0.5 \text{ ppm/K}$). Accurate solution: $y_1 = -0.0772$, $x_2 = -0.039$, $x_1 = 0$, $y_2 = 0$, ($\alpha_{1comp} = 99.5 \text{ ppm/K}$, $\alpha_{2comp} = -0.5$).

10 In general, it is not obligatory that the two compound resistors be TCT-compensated (such as in the example in Fig. 5 where $k = 0.5$), but rather must each contain two single resistors with different TCT's which give different slopes for the TCR vs. trimming fraction of each compound resistor. The numerical examples below demonstrate the possibility of independent resistance ratio and RTCR adjustment for a voltage divider containing two
15 compound resistor each having $R_1 = R_2$. In the set of four examples below, the trimming targets are farther deviated from the initial conditions, as compared to the four previous examples. The same resistor positions were chosen for trimming as in the previous examples.

- 20 Example 5. $R_{1comp}/R_{2comp} = 0.9$, $\Delta\alpha = 0 \text{ ppm/K}$. Resistor R_{11} and resistor R_{22} are trimmed by fractions x_1 and y_2 ($x_2 = y_1 = 0$). Accurate solution: $x_1 = -0.184$, $y_2 = 0.0183$ ($\alpha_{1comp} = -284.5 \text{ ppm/K}$, $\alpha_{2comp} = -284.5 \text{ ppm/K}$).

Example 6. $R_{1comp}/R_{2comp} = 0.9$, $\Delta\alpha = -200 \text{ ppm/K}$. Resistors R_{11} and R_{22} are trimmed by fractions x_1 and y_2 ($x_2 = y_1 = 0$). Accurate solution: $x_1 = -0.269$, $y_2 = -0.0767$ ($\alpha_{1comp} = -309.7 \text{ ppm/K}$, $\alpha_{2comp} = -109.7 \text{ ppm/K}$).

Example 7. $R_{1comp}/R_{2comp}=0.9$, $\Delta\alpha=200\text{ppm/K}$. Resistors R_{12} and R_{21} are trimmed by fractions y_1 and x_2 ($x_1 = y_2 = 0$). Accurate solution: $y_1=-0.116$, $x_2=0.094$ ($\alpha_{1comp}=-40\text{ ppm/K}$, $\alpha_{2comp}=-240\text{ ppm/K}$).

Example 8. $R_{1comp}/R_{2comp}=1$, $\Delta\alpha=200\text{ppm/K}$. Resistors R_{12} and R_{21} are
5 trimmed by fractions y_1 and x_2 ($x_1 = y_2 = 0$). Accurate solution: $y_1=-0.1013$, $x_2=-0.1013$ ($\alpha_{1comp}=-66\text{ppm/K}$, $\alpha_{2comp}=-266\text{ ppm/K}$).

The examples above demonstrate that approximate solutions are readily available for the divider consisting of two TCT-compensated resistors, giving errors in RTCR up to 4ppm/K. It should be understood that depending
10 on the technical requirements (precision and trimming range), an appropriate method of calculation of trimming values should be chosen. It could be based on analytical or numerical solution of equations (9a-d), or usage of look-up tables.

Note that the necessity to adjust the resistance ratio of two trimmable
15 resistors and their RTCR may exist not only for the resistor divider circuit as described in the examples, but also for other resistor networks where two trimmable resistors are not necessarily connected in series. The principle of the adjustment of such a circuit remains the same as described in the examples 1 – 8. In general, the overall circuit output may depend on (a)
20 ratio(s) (or relationship) of a number of resistors, not necessarily in a simple series or parallel combination (not necessarily connected directly to each other). The main idea is that the compound resistor behaves differently when we trim one or the other, provided that they have different TCT.

Fig. 8 shows a schematic of a resistor divider consisting of a compound
25 TCT-compensated trimmable resistor R_{comp} plus a single trimmable resistor R_3 , connected in series. The circuit can be used in applications where one needs essentially non-zero RTCR of the voltage divider. As an example,

consider a voltage divider with the resistor R_{comp} having TCR 900ppm/K higher than that of resistor R_3 . The TCT-compensated compound resistor is selected to be analogous to those shown in Fig. 2 ($\alpha_0=500\text{ppm/K}$, $\beta_0=-1200\text{ppm/K}$, $\gamma=-500\text{ppm/K}$, $k=0.417$). The trimmable resistor R_3 is made from
5 thermally trimmable material with TCR $\beta_0=-1200\text{ppm/K}$ and TCT $\gamma_3=-3000\text{ppm/K}$. To reach RTCR equal to 900ppm/K, resistor R_3 must be trimmed "down" by 10% (trimming fraction $z = -10\% = -0.1$). Its TCR is changed by trimming from its "as-manufactured" value to: $(-1200\text{ppm/K}) + (-3000\text{ppm/K}) \cdot (-0.1) = 900\text{ppm/K}$. After the target RTCR is reached, the divider
10 resistance ratio can be adjusted by trimming of the TCT-compensated compound resistor R_{1comp} without significant RTCR changes, as was described above (e.g. in Fig. 6). In this case, if the "operating" resistance values of R_{comp} and R_3 are known in advance, the as-manufactured resistance value of R_3 should be chosen intentionally 10% higher, so that subsequent
15 trimming down by -10% allows both the required RTCR adjustment and the required resistance ratio.

In general, the present invention is suitable in a broad range of cases where thermal trimming of thermally-mutable resistance is possible. This does not necessarily require special thermal isolation of the resistors beyond what
20 is typically found in standard integrated circuit host processes. The present invention does not necessarily require bidirectional trimming, and can function effectively even if individual resistors are trimmed largely only in a downward direction. It can also function effectively in cases where the range is limited for trimming upwards from a trimmed-down value. Since thermal trimming is
25 typically much faster in the downward direction than in the upward direction, the required trim signals may be short enough that special thermal isolation is not needed (and thus this technique may work with thermally-trimmable resistors which are integrated on the same chip with other circuitry, such as those provided by standard CMOS processes).

The available trimming precision and efficiency may be enhanced by using devices having greater thermal isolation. However this raises the question of self-heating of the trimmable resistors during operation. The analysis below addresses accompanying techniques for managing resistance changes due to self-heating.

Self-heating of a compound resistor: consider the series compound resistor shown in Fig. 1 with two resistive portions R_1 and R_2 , having corresponding thermal isolation G_1 and G_2 (measured in K/mW). Electric current I passing through the compound resistor results in resistance change of the two portions and the whole resistor:

$$\Delta R_1 = R_1(\alpha_0 \Delta T_1) = R_1(\alpha_0 I^2 R_1 G_1) = \alpha_0 G_1 I^2 R_1^2 \quad (11a)$$

$$\Delta R_2 = R_2(\beta_0 \Delta T_2) = R_2(\beta_0 I^2 R_2 G_2) = \beta_0 G_2 I^2 R_2^2 \quad (11b)$$

$$\Delta R = \Delta R_1 + \Delta R_2 = I^2 R_1^2 (\alpha_0 G_1 + \beta_0 G_2 k^2) \quad (11c)$$

where ΔT_1 and ΔT_2 are overheating temperatures of each of the two portions due to power $I^2 R_1$ and $I^2 R_2$ dissipated in them.

Zero resistance modulation is possible when the two resistive portions R_1 and R_2 of the compound resistor are designed so that their thermal isolation complies with a condition:

$$\frac{G_1}{G_2} = -k^2 \frac{\beta_0}{\alpha_0} \quad (12)$$

Consider the compound resistor shown in Fig. 3 with two resistive portions R_1 and R_2 , connected in parallel and having corresponding thermal isolation G_1 and G_2 (measured in K/mW). Voltage U applied the compound resistor results in resistance change of the two portions and the whole resistor:

$$\Delta R_1 = R_1(\alpha_1 \Delta T_1) = R_1(\alpha_1 G_1 \frac{U^2}{R_1}) = \alpha_1 G_1 U^2 \quad (13a)$$

$$\Delta R_2 = R_2(\alpha_2 \Delta T_2) = R_2(\alpha_2 G_2 \frac{U^2}{R_2}) = \alpha_2 G_2 U^2 \quad (13b)$$

$$\Delta R = \Delta R_1 + \Delta R_2 = U^2(\alpha_1 G_1 + \alpha_2 G_2) \quad (13c)$$

where ΔT_1 and ΔT_2 are overheating temperatures of each of the two
5 portions due to power U^2/R_1 and U^2/R_2 dissipated in them.

Zero resistance modulation is possible when the two resistive portions
 R_1 and R_2 of the compound resistor are designed so that their thermal
isolation complies with the condition:

$$\frac{G_1}{G_2} = -\frac{A}{\alpha_2} \quad (14)$$

10

A practical example of a specially designed TCT-compensated
compound resistor with near-zero TCR and near-zero resistance modulation
due to self-heating may be constructed as follows. A compound resistor with
parameters analogous to those given in examples 5 – 8 is chosen ($R_1=2R_2$).
15 The two resistive portions are designed so that their thermal isolation ratio is
 $G_1/G_2=1/2$. Fig. 8 shows one possible configuration of the compound resistor.
The first portion R_1 consists of two sub-portions, each having resistance $R_1/2$.
In this case, each sub-portion, and the second portion R_2 , have the same
thermal isolation. This condition is fulfilled if all three parts of the compound
20 resistor have approximately the same area, and their thermal contact with the
substrate or other heat sink is the same. If all three parts are placed on the
microstructures such as MEMS-type structures, such as those seen in PCT
publication PCT/CA02/01366, it is preferable to use identical supporting
microstructures with the same thermal isolation from the substrate. Electric
25 current passing through the series connection heats all three parts up to the

same temperature, but the power dissipated in the first portion (consisting of two sub-portions) is twice as great as that dissipated in the second portion. This is why the overall thermal isolation of the resistor R_1 needed to be two times lower than the thermal isolation of resistor R_2 . The negative shift of resistance R_2 is twice as great as the positive shift of each of two sub-portions of the resistor R_1 . As a result, the net resistance deviation of the compound resistor remains zero even when operated at varying power levels. Note that the single resistor R_2 in the compound resistor shown in Fig. 9 can be trimmable ("active") or not ("passive").

The invention can be used in a variety of applications, such as for zero compensation of a Wheatstone bridge. Consider a Wheatstone bridge built from four resistors (which are commonly all nominally equal, but which may not be in some configurations). Let us call each of the equal resistors " R_b ", for this analysis. "Zero offset" of a Wheatstone bridge (mismatch, imbalance (Δu) of the voltages at the two midpoints of the bridge), can be translated into a relative resistance mismatch $\Delta R_b/R_b$, of one of the four resistors, and a mismatch of the TCR of that resistor with respect to the others (which nominally have identical TCR's). If the voltage drop across the entire bridge is U , and one of the four nominally-identical resistors has an undesired resistance shift of ΔR_b , then the zero offset is equal to:

$$\Delta u = \frac{U}{4} \frac{\Delta R_b}{R_b} \quad (15) \quad \text{or} \quad \frac{\Delta R_b}{R_b} = 4 \frac{\Delta u}{U} \quad (15a)$$

Analogously, the relative shift of TCR of one resistor by an amount ΔTCR results in temperature drift of that bridge midpoint voltage mismatch (also called "temperature coefficient of zero offset"):

$$\Delta TCR = \frac{4}{U} \frac{d(\Delta u)}{dT} \quad (16)$$

Substituting examples of values for Zero Offset ($\pm 5\text{mV/V}$) into eq. (15a) and Temperature Coefficient of Zero $\pm 25\mu\text{V/V/K}$ into eq. (16), one obtains an example of the range of resistance and ΔTCR variability that one would want to trim out (or compensate for): $\Delta R_b/R_b = \pm 2.0\%$, $\Delta\text{TCR} = \pm 100\text{ppm/K}$.

5 The scheme depicted in Fig.10 is an example of the invented method applied for zero compensation (compensation of zero offset and temperature coefficient of zero offset) of the Wheatstone bridge. Four trimmable compound resistors R_{comp1} , R_{comp2} , R_{comp3} , R_{comp4} are each connected in parallel to the corresponding bridge resistors R_{b1} , R_{b2} , R_{b3} , R_{b4} . Each pair of resistors thus
10 forms a new compound resistor, represented in the figure by R_{b_comp1} , R_{b_comp2} , R_{b_comp3} , R_{b_comp4} .

Consider the flexibility of trimming options of trimmable compound resistors, each consisting of two trimmable portions $R_1(x)$ and $R_2(y)$ made from different materials (where x and y are the trimming fractions of each
15 single resistor within a compound resistor). These portions can be connected in series or in parallel, as shown in Fig. 11. Each resistive portion is independently trimmable:

$$R_1(x) = R_{10}(1+x) \quad (17a) \quad R_2(y) = R_{20}(1+y) \quad (17b)$$

where R_{10} and R_{20} are as-manufactured resistance values. The TCR of
20 each of these single resistors varies with trimming according to the equations:

$$\alpha(x) = \alpha_0 + \gamma_1 x \quad (18a) \quad \beta(y) = \beta_0 + \gamma_2 y \quad (18b)$$

where α_0 and β_0 are as-manufactured values of TCR of two resistive portions; γ_1 and γ_2 are trimming-induced shifts of TCR per trimming fraction (called "TCT", measured in ppm/K/trim-fraction).

25 Figures 12 – 14 show three different examples, plotting the overall ("net") TCR of one of the compound resistors (parallel combination of one of the bridge resistors R_b with its corresponding R_{comp} , called generically

R_{b_comp}), as a function of its own normalized resistance (R_{b_comp}). In Fig. 12, for example, R_b (by itself) has TCR of 1600ppm/K, and when this is connected in parallel with R_{comp} , (having the parameters specified in Fig. 12), the overall TCR of the resultant R_{b_comp} is approximately 1275ppm/K. In these examples, all of the compound resistors R_{comp} have equal resistive sub-portions $R_1 = R_2$, connected in series (as shown in the upper part of Fig. 11). Note that the trimming range of the single resistors R_1 and R_2 is -35% (down 35% from the as-manufactured resistance value). In these examples, the resistance value of the compound resistor, R_{comp} is approximately 5 times (Figs. 12 and 13), and 10 times (Fig. 14), greater than the resistance of the bridge resistor R_b . The as-manufactured TCR and TCT of resistors R_1 and R_2 are $\alpha_0=500\text{ppm/K}$; $\gamma_1=-500\text{ppm/K}$, $\beta_0=-1200\text{ppm/K}$ and $\gamma_2=-3000\text{ppm/K}$ (Figs. 12 and 14) and $\beta_0=850\text{ppm/K}$, $\gamma_2=-3000\text{ppm/K}$ (Fig. 13).

If, in Fig. 12, we trim down only R_1 in the compound resistor R_{comp} , then the trimming-induced ΔTCR in R_{b_comp} could reach about -70ppm/K. Since R_1 is only about half of the resistance of R_{comp} , and R_{comp} is in parallel with R_b and 5 times greater than R_b , then a 3% decrease in R_{b_comp} requires a decrease of approximately 31% in R_1 . If instead of trimming only R_1 , we trim down only R_2 leaving R_1 untrimmed, then for an equal ~31% decrease in R_2 , the trimming-induced ΔTCR in R_{b_comp} would be about +50ppm/K.

The fact that there are different slopes of net TCR as a function of trimming fraction of the compound resistor R_{b_comp} , enables ΔTCR adjustment independent of relative resistance mismatch adjustment of the bridge. To illustrate this, assume that we will trim down only portions of resistors R_{comp1} and R_{comp3} (see Fig. 10), having trimming properties shown/listed in Fig. 12. Assume that R_{b_comp1} and R_{b_comp3} are each trimmed "down" by ~3%, but that said trimming is the result of trimming "down" of resistor R_1 by ~31% in the compound resistor R_{comp1} , and trimming "down" of resistor R_2 by ~31% in the

compound resistor R_{comp3} . In this case, the trimming-induced ΔTCR in R_{b_comp1} is about -70ppm/K, while the trimming-induced ΔTCR in R_{b_comp3} , on the opposite side of the bridge, is about +50ppm/K, for a total ΔTCR having magnitude approximately 120ppm/K. Note that these trimming operations did
5 not change the state of bridge resistance match (or mismatch), since R_{b_comp1} and R_{b_comp3} , in corresponding positions on opposite arms of the bridge, were each reduced by the same 3%. Only the relative TCRs were changed in such a way that the effective temperature coefficient of zero was changed by 120ppm/K, which corresponds to a temperature coefficient of zero of
10 approximately 30uV/V/K.

It is also possible to trim "down" resistors R_1 and R_2 of a single given compound resistor, for example R_{comp1} , say by 20% each. As a result, the total resistance of resistor R_{b_comp1} is reduced by ~4% with virtually no change in its TCR. In this way, the bridge zero offset can be significantly adjusted using
15 thermally-trimmable resistors, without significantly unbalancing the relative TCR of the system (without causing additional ΔTCR). In general, trimming of at least two of four single resistors included in two compound resistors R_{comp1} and R_{comp3} , one can reach both a target trimming-induced ΔTCR and a target relative resistance change ($\Delta R_b/R_b$) of the bridge.

20 The range of bridge zero offset adjustment can be further doubled if the corresponding (same-numbered) single resistors R_1 or R_2 in pair R_{comp1} , R_{comp4} , and in pair R_{comp2} , R_{comp3} , are trimmed simultaneously. For example, one would trim down R_1 in R_{comp1} and R_{comp4} , and trim down R_2 in R_{comp2} and R_{comp3} .

25 Figs. 15 – 17 show examples similar to those shown in Figs. 12 – 14, where the single trimmable resistors R_1 and R_2 are connected in parallel instead of in series. Again the overall (net) TCR of the compound resistor

R_{b_comp} is shown as a function of normalized resistance R_{b_comp} when single trimmable resistors R_1 and R_2 are trimmed down.

The examples in Figs. 12 - 17 show that certain combinations of single resistor parameters provide favorable trimming properties of the compound resistor for application in adjusting the bridge zero offset and temperature coefficient of zero offset. For example, a suitable range of ΔTCR adjustment is reached for the combination of two trimmable resistors (connected in series) with $\alpha_0=500\text{ppm/K}$; $\gamma_1=-500\text{ppm/K}$, $\beta_0=-1200\text{ppm/K}$ and $\gamma_2=-3000\text{ppm/K}$ (Fig. 12). Parallel connection of two trimmable resistors is most favorable (widest range of ΔTCR adjustment) when $\alpha_0=500\text{ppm/K}$; $\gamma_1=-500\text{ppm/K}$, $\beta_0=850\text{ppm/K}$ and $\gamma_2=-3000\text{ppm/K}$ (Fig. 6).

Fig. 18 shows the trimming behaviour of compound resistor R_{b_comp} with several different values of the nominal TCR (β_b) of each of the four bridge resistors (R_b). Note that in Fig. 18 the slope of this overall bridge TCR with trimming depends on the value of β_b while trimming range of ΔTCR and relative resistance change remains almost the same, for each of the three values of β_b .

In summary, trimming-compensation circuit (Fig. 10) consisting of four compound resistors with resistance value of approximately 5 times higher than resistance of resistors of the bridge allows RTCR adjustment in the range of $\pm 240\text{ppm/K}$ ($2 \times 120\text{ppm/K}$) and relative resistance adjustment of $\pm 12\%$ ($2 \times 2 \times 3\%$).

In addition to zero offset compensation, the present invention can also be applied to change the overall TCR of the bridge (modeling the four-resistor bridge network as a single resistor whose overall TCR will be nominally the same (β_b) as the TCR of one of the resistors.) For example, if β_b = nominally 1600ppm/K , and the target is to reduce it to be within a range $1225 -$

1530ppm/K, this can be considered as a goal for the invented trimming scheme.

Some sensor-based applications, where the sensing element(s) is/are configured in a Wheatstone bridge, require increasing the bridge-voltage (e.g. U_b in Fig. 21) with temperature (applying a positive bridge-voltage tempco), to compensate for negative temperature-induced drift of the sensitivity of the sensing element(s). Examples of these types of sensors include piezo-resistive pressure sensors and resistive magnetic field sensors. Usually the calibration procedure of a particular sensor involves adjustment of bridge-voltage tempco, in order to achieve temperature-stable full-scale output.

Bridge TCR compensation scheme (trimmable resistor in parallel with the bridge): First, note that the shift of the bridge TCR (shown in Figs. 12-17) caused by connection of "zero-offset-compensation" compound resistors R_{comp1} - R_{comp4} (Fig.10), must be included into consideration. Assume that the "zero-offset-compensated" bridge with parameters shown in Fig. 15 is to be "TCR-compensated" using the scheme depicted in Fig. 19. In this case, the bridge TCR is already shifted (prior to any trimming), from its initial 1600ppm/K to approximately 1450ppm/K.

Usage of a trimmable resistor with high TCT is preferable for the adjustment. Fig. 20 shows that resistor R_5 , consisting of one single trimmable resistor R_1 with $\alpha_0=850\text{ppm/K}$; $\gamma_1=-3000\text{ppm/K}$ and as-manufactured resistance value $R_{10}=2R_b$, allows variation of bridge TCR in a range between ~1240ppm/K and ~1630ppm/K. Assuming that the variation of bridge TCR required by a particular user's application must instead be between 1100 and 1500ppm/K. In this case, the obtained range of bridge TCR adjustment is offset slightly above the desired target. It is possible to shift the whole trimming range "lower" on the TCR scale by connecting, as a part of R_5 , an additional resistor R_2 , having negative TCR, in parallel with the resistor R_1 ,

described above in this paragraph. (This would transform the resistor R_5 into a compound resistor.) If this resistor R_2 has $R_{20}=8R_{10}$, and TCR $\beta=-1200\text{ppm/K}$, then it would have the effect of lowering the bridge TCR trimming range to a range between 1150 and 1530ppm/K, much closer to the desired range.

5 Bridge TCR compensation scheme (trimmable resistor in series with the bridge): Adjustment of the bridge-voltage tempco (temperature coefficient) is possible not only by the scheme shown in Fig. 19, with trimmable resistor $R_5(x)$ connected in parallel with the bridge, but also with trimmable resistor $R_6(x)$ connected in series with the bridge (having equivalent resistance R_b ,
10 since all four bridge resistors have resistance R_b), as shown in Fig. 21.

Fig. 22 shows bridge voltage tempco and ratio U_b/U (where U is the excitation voltage) as functions of normalized resistance of the trimmable resistor $R_6(x)$. The effectiveness of the compensation scheme substantially depends on the as-manufactured TCR α_0 and trimming-induced shift of TCR
15 per trimming fraction γ of the trimmable resistor.

For example, if a trimmable resistor having constant, nominally-zero TCR is used for compensation, it must be trimmed from 0 to 85%-down from its as-manufactured resistance, in order to cover a particular desired bridge voltage temperature coefficient range between 1100 and 1500ppm/K. It is
20 also important to note that the as-manufactured resistance value of the trimmable resistor, 15 times greater than the bridge resistance, results in reduction of ratio U_b/U to 0.1 – 0.3, with corresponding reduction in sensor sensitivity. Therefore, a desired normal operating bridge voltage of, say, 1V requires 3-10V of excitation voltage.

25 Usage of a trimmable $R_6(x)$ resistor with high constant negative TCR helps to alleviate this problem. If, for example, $\alpha_0 = -1200\text{ppm/K}$, then the required trim range is only 0 to 40%-down, covering the same bridge voltage

tempco range. A substantially greater ratio U_b/U of 0.45 – 0.55 is achieved in this case, as shown in Fig. 22 (right side).

If the TCT (γ) of $R_6(x)$ is zero, then the bridge voltage tempco behaves as shown in the upper-right curve in Fig. 22. However, usage of a trimmable resistor with negative TCR $\alpha_0 = -1200\text{ppm/K}$, and trimming-induced shift of TCR per trimming fraction $\gamma = -3000\text{ppm/K}$, requires even smaller trimming (0 to 15%-down), to cover the same bridge voltage tempco range (also shown in the upper-right portion of Fig. 22).

The TCR and TCT values of the single trimmable resistors used in the above analysis correspond to the following materials:

TCR = 500ppm/K (approx.); TCT = -500ppm/K (approx.) → a variant of polysilicon doped primarily with Boron;

TCR = -1200ppm/K (approx.); TCT = -3000ppm/K (approx.) → a variant of polysilicon doped primarily with Arsenic;

TCR = 850ppm/K (approx.); TCT = -3000ppm/K (approx.) → a variant of polysilicon doped primarily with Phosphorus;

Calculation of overall TCR of the compound resistor – 1. Compound resistor R_{comp} consisting of two single trimmable resistors R_1 and R_2 connected in series (Fig. 11) and bridge resistor R_b (Fig. 11) form net compound resistor R_{b_comp} .

Resistance and TCR of single resistors are functions of their trimming fraction x and y correspondently:

$$R_1(x) = R_{10}(1+x) \quad (19a) \quad R_2(y) = R_{20}(1+y) \quad (19b)$$

$$\alpha(x) = \alpha_0 + \gamma_1 x \quad (19c) \quad \beta(y) = \beta_0 + \gamma_2 y \quad (19d)$$

where R_{10} , R_{20} , α_0 , β_0 , γ_1 , γ_2 are as-manufactured resistance, TCR and TCT values of single resistors.

Resistance of the compound resistor R_{b_comp} equals:

$$R_{b_comp}(x, y) = \frac{R_b(R_1(x) + R_2(y))}{R_b + R_1(x) + R_2(y)} \quad (20)$$

5 Derivative of the R_{b_comp} over temperature T equals:

$$\frac{dR_{b_comp}}{dT} = \frac{\partial R_{b_comp}}{\partial R_b} \frac{dR_b}{dT} + \frac{\partial R_{b_comp}}{\partial R_1} \frac{dR_1}{dT} + \frac{\partial R_{b_comp}}{\partial R_2} \frac{dR_2}{dT} \quad (21)$$

Using definition of TCR α of a resistor R : $\alpha = \frac{1}{R} \frac{dR}{dT}$ and substituting

$$\frac{\partial R_{b_comp}}{\partial R_b} = \frac{(R_1(x) + R_2(y))^2}{(R_b + R_1(x) + R_2(y))^2} \quad (22a) \text{ and}$$

$$10 \quad \frac{\partial R_{b_comp}}{\partial R_1} = \frac{\partial R_{b_comp}}{\partial R_2} = \frac{R_b^2}{(R_b + R_1(x) + R_2(y))^2} \quad (22b)$$

into eq.(21), obtain TCR for the compound resistor :

$$\alpha_{b_comp}(x, y) = \frac{1}{R_b + R_1(x) + R_2(y)} \left[R_b \left(\frac{\alpha(x)R_1(x)}{R_1(x) + R_2(y)} + \frac{\beta(y)R_2(y)}{R_1(x) + R_2(y)} \right) + (R_1(x) + R_2(y)) \right] \quad (23)$$

where β_b is TCR of the resistor R_b .

15 Figs. 12 – 14 show TCR α_{b_comp} (eq.(23)) vs. normalized resistance R_{b_comp} (eq.(20)) where both are functions of the parameter x (when $y=0$) or y (when $x=0$).

Calculation of net TCR of the compound resistor – 2. Compound resistor R_{comp} consisting of two single trimmable resistors R_1 and R_2

connected in parallel (Fig. 11) and one bridge resistor R_b (Fig. 10) form net compound resistor R_{b_comp} .

Resistance of the compound resistor R_{b_comp} equals:

$$R_{b_comp}(x, y) = \frac{R_1(x)R_2(y)R_b}{R_1(x)R_b + R_2(y)R_b + R_1(x)R_2(y)} \quad (24)$$

5 Derivative of the R_{b_comp} over temperature T is presented by eq. (21), where:

$$\frac{\partial R_{b_comp}}{\partial R_b} = \left[\frac{R_1(x)R_2(y)}{R_1(x)R_b + R_2(y)R_b + R_1(x)R_2(y)} \right]^2 \quad (25a)$$

$$\frac{\partial R_{b_comp}}{\partial R_1} = \left[\frac{R_b R_2(y)}{R_1(x)R_b + R_2(y)R_b + R_1(x)R_2(y)} \right]^2 \quad (25b)$$

$$\frac{\partial R_{b_comp}}{\partial R_2} = \left[\frac{R_b R_1(x)}{R_1(x)R_b + R_2(y)R_b + R_1(x)R_2(y)} \right]^2 \quad (25c)$$

10 TCR of the compound resistor can be expressed as:

$$\alpha_{b_comp}(x, y) = R_{b_comp}(x, y) \left[\frac{\alpha(x)}{R_1(x)} + \frac{\beta(y)}{R_2(y)} + \frac{\beta_b}{R_b} \right] \quad (26)$$

Figs. 15 – 17 show TCR α_{b_comp} (eq.(26)) vs. normalized resistance R_{b_comp} (eq.(24)) where both are functions of the parameter x (when $y=0$) or y (when $x=0$).

15 As another example of an application of the present invention, one may build a circuit for compensation of non-linear temperature variations. Such a circuit generates an output voltage as a polynomial function of temperature T . It could be used, for example, for temperature compensation of crystal oscillators (US Patent 4560959). Typically such generation of higher-order
20 temperature compensation is done with analog multiplication using bipolar

devices, and analog or digital summing of the desired higher order components for the compensation signal. This typically requires the host process capabilities of a BiCMOS process. The present invention enables the implementation of such higher-order temperature compensation needing less-
5 complex analog circuitry, as demonstrated in Figs. 23a, 23b, and in the associated text below. The circuitry shown in Figs. 23a, 23b can be more-easily implemented in a CMOS process, (without requiring a BiCMOS process).

Fig. 23a shows a schematic of a single module containing a resistor
10 bridge with two compound trimmable resistors R_{1_comp} and R_{2_comp} (analogous to those described above), and an amplifier with gain K_1 . The resistors R_1 and R_2 on the opposite side of the bridge, are not necessarily trimmable. The output voltage of the module, with the bridge initially balanced at ambient temperature T_0 (zero output voltage), equals:

$$15 \quad U_{out} = \frac{U_{in} K_1}{(1+\eta)^2} [\Delta\eta + \eta \Delta TCR (T - T_0)],$$

(27)

where $\eta = \frac{R_{1_comp}}{R_{2_comp}}$; $\Delta\eta$ is the change in resistance ratio of two compound resistors resulting from trimming; ΔTCR is the difference in TCR of the two compound resistors resulting from trimming.

20 Eq. (27) can be rewritten as:

$$U_{out} = U_{in} K_1 [a_1 + b_1 (T - T_0)],$$

(28)

where coefficients a_1 and b_1 depend on resistance mismatch and TCR mismatch of the two trimmable compound resistors. It follows from the

previous description that the coefficients a_i and b_i can be adjusted independently and may have arbitrary polarity.

If several (N) of such modules are connected so that the output voltage of the previous module is applied to the input of the next module, then the output voltage of the final module is an N-order polynomial function of temperature. For the scheme, shown in Fig. 23b, the output voltage of the third module equals:

$$U_{out} = U_0 K_1 K_2 K_3 [a_1 + b_1(T - T_0)] [a_2 + b_2(T - T_0)] [a_3 + b_3(T - T_0)],$$

(29a)

which can be rearranged into the form:

$$U_{out} = A_0 + A_1(T - T_0) + A_2(T - T_0)^2 + A_3(T - T_0)^3$$

(29b)

where the coefficients A_j can be derived from the coefficients a_i and b_i (where $i, j = 1, 2, 3$).

Adjustment of coefficients a_i and b_i (where $i = 1, 2, 3$), by trimming of the compound resistors as was described above, allows generation of the desired polynomial function of temperature (29b).

Note that the output voltages of the first and second modules can also be used to generate the polynomial function of temperature by summing all three output voltages.

It should be understood that the number of modules can be different from three. Also, the resistor bridges in the modules can be initially intentionally unbalanced to simplify generation of the desired polynomial function of temperature. For example, the scheme shown in Fig. 23b may have the first module with an initial (as-manufactured) bridge being unbalanced, which generates an output voltage as a linear function of

temperature. Then the trimming of only the compound resistors from modules 2 and 3 (responsible for coefficients a_2 , a_3 , b_2 , b_3) may be sufficient to generate a desired function (29b).

It should be understood that the given examples do not limit the variety
5 of the possible schemes based on trimmable compound resistors. Such parameters as number of single and compound resistors in the network, resistance values, resistance ratios, etc., are application-specific, and can be different from those described above. Also, the physical parameters of the resistor materials, such as TCR and TCT, may differ, which changes the
10 "optimal" resistor ratios.

It is possible that, in certain cases, it may not be possible to realize exactly and simultaneously more than one of the imperatives suggested by the fundamental equations in this invention (for example Eq. (4) simultaneously with Eq. (12)). Therefore, a prioritization may be done, in
15 which features which are "less critical" for a particular application may be partially sacrificed, or "near-optimal" matching of the resistor network parameters may be used as a trade-off.

WE CLAIM:

1. A method for providing a trimmable resistive component having a predetermined behavior of temperature coefficient of resistance (TCR) as a function of trimming, the method comprising:

selecting materials to form a compound resistor having at least a first portion and a second portion, at least said first portion including a first resistor that is thermally trimmable and has a first resistivity, a first temperature coefficient of resistance value α_0 , and a value of trimming-induced shift of temperature coefficient γ_1 , which defines a change in said α_0 per fraction of trimming x of said first resistivity, said second portion including at least a second resistor having a second resistivity value, and a second temperature coefficient of resistance value β_0 ;

determining how said TCR value of said resistive component changes as at least said first portion is trimmed, by generating a function of said TCR versus trim-fraction x , with R_1 and R_2 as variable parameters and α_0 , β_0 , and γ_1 as fixed parameters; and

selecting specific values for R_1 and R_2 or R_1/R_2 to provide said resistive component with said predetermined behavior of said TCR, thereby incorporating an effect of said γ_1 in said resistive component.

2. A method as claimed in claim 1, wherein said first resistor and said second resistor are connected in series.

3. A method as claimed in claim 1, wherein said first resistor and said second resistor are connected in parallel.

4. A method as claimed in claim 2, wherein said predetermined behavior of TCR corresponds to a negligible variation of said TCR with said fraction of trimming x over a range of trim-fraction.

5. A method as claimed in claim 3, wherein said predetermined behavior of TCR corresponds to a negligible variation of said TCR with said fraction of trimming x over a range of trim-fraction.

6. A method as claimed in claim 2, wherein said predetermined behavior of TCR corresponds to a substantially non-zero variation of said TCR with said fraction of trimming x .

7. A method as claimed in claim 3, wherein said predetermined behavior of TCR corresponds to a substantially non-zero variation of said TCR with said fraction of trimming x .

8. A method as claimed in claims 2, 4 or 6, wherein said selecting materials comprises choosing materials such that $\alpha_0 - \beta_0 > -\gamma_1$.

9. A method as claimed in claims 2, 4 or 8 wherein said selecting specific values comprises choosing values such that $\frac{R_2}{R_{10}} = \frac{\gamma_1}{\beta_0 - \alpha_0 - \gamma_1}$, wherein R_{10} is a resistance value of said first resistor at a predetermined trim-fraction within a trimming range of said first resistor.

10. A method as claimed in claims 3, 5 or 7, wherein said selecting materials comprises choosing materials such that $\beta_0 - \alpha_0 > -\gamma_1$.

11. A method as claimed in claims 3, 5 or 10 wherein said selecting specific values comprises choosing values such that $\frac{R_2}{R_{10}} = \frac{\alpha_0 - \beta_0 - \gamma_1}{\gamma_1}$, wherein R_{10} is a resistance value of said first resistor at a predetermined trim-fraction within a trimming range of said first resistor.

12. A method as claimed in claims 2 or 3, wherein said second resistor is also thermally trimmable and has a value of trimming-induced shift of temperature

coefficient γ_2 , which defines a change in said β_0 per fraction of trimming y of said second resistivity, and said predetermined behavior of TCR corresponds to two substantially different curves representing variation of said TCR with said trim fraction x and variation of said TCR with said trim fraction y .

13. A method as claimed in claim 12, wherein said two curves have slopes of different signs.

14. A method as claimed in any one of claims 1 to 13, further comprising thermally isolating said first portion and said second portion on at least one thermally isolated micro-platform.

15. A method as claimed in claim 14, wherein said first portion and said second portion are provided on separate thermally isolated micro-platforms.

16. A method as claimed in claim 1, wherein said second portion is part of an application specific circuit, and said selecting specific values for R_1 and R_2 or R_1/R_2 comprises selecting said specific values to provide a predetermined behavior of a temperature coefficient of voltage across said second portion as a function of trimming said first resistor.

17. A trimmable resistive component having a predetermined behavior of temperature coefficient of resistance (TCR) as a function of trimming comprising:

a first portion composed of a first resistor that is thermally trimmable and has a first resistivity, a first temperature coefficient of resistance value α_0 , and a value of trimming-induced shift of temperature coefficient γ_1 , which defines a change in said α_0 per fraction of trimming x of said first resistivity; and

a second portion composed of at least a second resistor having a second resistivity value and a second temperature coefficient of resistance value β_0 , said first portion and said second portion having specific values for R_1 and R_2 or R_1/R_2 to provide said compound resistor with said predetermined behavior of said TCR value;

wherein said predetermined behavior of said TCR is defined by a function of said TCR versus trim-fraction x , with R_1 and R_2 as variable parameters and α_0 , β_0 , and γ_1 as fixed parameters, thereby incorporating an effect of said γ_1 in said resistive component.

18. A trimmable resistive component as claimed in claim 17, wherein said first resistor and said second resistor are connected in series.

19. A trimmable resistive component as claimed in claim 17, wherein said first resistor and said second resistor are connected in parallel.

20. A trimmable resistive component as claimed in claim 18, wherein said predetermined behavior of TCR corresponds to a negligible variation of said TCR with said fraction of trimming x over a range of trim-fraction.

21. A trimmable resistive component as claimed in claim 19, wherein said predetermined behavior of TCR corresponds to a negligible variation of said TCR with said fraction of trimming x over a range of trim-fraction.

22. A trimmable resistive component as claimed in claim 18, wherein said predetermined behavior of TCR corresponds to a substantially non-zero variation of said TCR with said fraction of trimming x .

23. A trimmable resistive component as claimed in claim 19, wherein said predetermined behavior of TCR corresponds to a substantially non-zero variation of said TCR with said fraction of trimming x .

24. A trimmable resistive component as claimed in claims 18, 20 or 22, wherein $\alpha_0 - \beta_0 > -\gamma_1$.

25. A trimmable resistive component as claimed in claim 18, 20 or 24, wherein $\frac{R_2}{R_{10}} = \frac{\gamma_1}{\beta_0 - \alpha_0 - \gamma_1}$, wherein R_{10} is a resistance value of said first resistor at a predetermined trim-fraction within a trimming range of said first resistor.

26. A trimmable resistive component as claimed in claims 19, 21 or 23, wherein $\alpha_0 - \beta_0 > -\gamma_1$.

27. A trimmable resistive component as claimed in claims 19, 21 or 26, wherein $\frac{R_2}{R_{10}} = \frac{\alpha_0 - \beta_0 - \gamma_1}{\gamma_1}$, wherein R_{10} is a resistance value of said first resistor at a predetermined trim-fraction within a trimming range of said first resistor.

28. A trimmable resistive component as claimed in claims 18 or 19, wherein said second resistor is also thermally trimmable and has a value of trimming-induced shift of temperature coefficient γ_2 , which defines a change in said β_0 per fraction of trimming y of said second resistivity, said predetermined behavior of TCR corresponds to two substantially different curves representing variation of said TCR with said trim fraction x and variation of said TCR with said trim fraction y .

29. A trimmable resistive component as claimed in claim 28, wherein said two curves have slopes of different signs.

30. A trimmable resistive component as claimed in claim 17, wherein said second portion is part of an application specific circuit, and wherein a predetermined behavior of a temperature coefficient of voltage across said second portion as a function of trimming said first resistor is also defined by said specific values for at least one of R_1 and R_2 or R_1/R_2 .

31. A trimmable resistive component as claimed in any one of claims 17 to 30, wherein said first portion and said second portion are on at least one thermally isolated micro-platform.

32. A trimmable resistive component as claimed in claim 31, wherein said first portion and said second portion are on separate thermally isolated micro-platforms.

33. A trimmable resistive component as claimed in any one of claims 17 to 32, wherein said first resistor is made of boron-doped polysilicon and said second resistor is made of arsenic-doped polysilicon.

34. A trimmable resistive component as claimed in any one of claims 17 to 33, wherein said second portion is part of an application specific circuit.

35. A trimmable resistive component as claimed in any one of claims 17 to 34, wherein said second portion is composed of four interconnected resistors.

36. A trimmable resistive component as claimed in claim 35, wherein said four interconnected resistors is a Wheatstone bridge circuit.

37. An application specific circuit having an adjustable parameter of the circuit and an adjustable temperature coefficient of said parameter, the circuit comprising:

at least one compound resistor including:

a first portion composed of a first resistor that is thermally trimmable and has a first resistivity, a first temperature coefficient of resistance (TCR) value α_0 , and a value of trimming-induced shift of temperature coefficient γ_1 , which defines a change in said α_0 per fraction of trimming x of said first resistivity; and

a second portion composed of a second resistor having a second resistivity value and a second TCR value β_0 , said first portion and said second portion having specific values for at least one of R_1 and R_2 and R_1/R_2 to provide said compound resistor with said predetermined behavior of said TCR value;

control circuitry for thermally trimming said at least one compound resistor; and

circuitry for said application connected to said at least one compound resistor;

wherein said predetermined behavior of said TCR is defined by a function of said TCR versus trim-fraction x , with R_1 and R_2 as variable parameters and α_0 , β_0 , and γ_1 as fixed parameters, thereby incorporating an effect of said γ_1 in said compound resistor.

38. A circuit as claimed in claim 37, wherein said first resistor and said second resistor are connected in series.

39. A circuit as claimed in claim 37, wherein said first resistor and said second resistor are connected in parallel.

40. A circuit as claimed in claims 38 or 39, wherein said second resistor is also thermally trimmable and has a value of trimming-induced shift of temperature coefficient γ_2 , which defines a change in said β_0 per fraction of trimming y of said second resistivity, said predetermined behavior of TCR corresponds to two substantially different curves representing variation of said TCR with said trim fraction x and variation of said TCR with said trim fraction y .

41. A circuit as claimed in claim 40, wherein said two curves have slopes of different signs.

42. A circuit as claimed in claim 37 or 40, wherein said at least one compound resistor is part of said circuitry for said application specific circuit.

43. A circuit as claimed in claim 42, wherein said circuitry is a Wheatstone bridge.

44. A circuit as claimed in claim 43, wherein said at least one compound resistor comprises four compound resistors, and said four compound resistors make up said Wheatstone bridge.

45. A circuit as claimed in claim 44, wherein only two of said four compound resistors are trimmed to adjust said temperature coefficient of said parameter, and said two are selected in accordance with a measured offset of said parameter.

46. A circuit as claimed in any one of claims 43 to 45, wherein said parameter is an overall bridge resistance.

47. A circuit as claimed in any one of claims 43 to 45, wherein said parameter is a zero offset of a sensor stimulus.

48. A circuit as claimed in claim 42, wherein said circuitry is a voltage divider.

49. A circuit as claimed in claim 48, wherein said at least one compound resistor comprises two compound resistors, and said two compound resistors make up said voltage divider.

50. A circuit as claimed in claims 38, wherein said predetermined behavior of TCR corresponds to a negligible variation of said TCR with said fraction of trimming x over a range of trim-fraction.

51. A circuit as claimed in claims 39, wherein said predetermined behavior of TCR corresponds to a negligible variation of said TCR with said fraction of trimming x over a range of trim-fraction.

52. A circuit as claimed in claim 38, wherein said predetermined behavior of TCR corresponds to a substantially non-zero variation of said TCR with said fraction of trimming x .

53. A circuit as claimed in claim 39, wherein said predetermined behavior of TCR corresponds to a substantially non-zero variation of said TCR with said fraction of trimming x .

54. A circuit as claimed in claims 38, 50 or 52, wherein $\alpha_0 - \beta_0 > -\gamma_1$.

55. A circuit as claimed in claim 38, 50 or 54, wherein $\frac{R_2}{R_{10}} = \frac{\gamma_1}{\beta_0 - \alpha_0 - \gamma_1}$,
wherein R_{10} is a resistance value of said first resistor at a predetermined trim-fraction within a trimming range of said first resistor.

56. A trimmable resistive component as claimed in claims 39, 51 or 53, wherein $\alpha_0 - \beta_0 > -\gamma_1$.

57. A circuit as claimed in claims 39, 51 or 56, wherein $\frac{R_2}{R_{10}} = \frac{\alpha_0 - \beta_0 - \gamma_1}{\gamma_1}$,
wherein R_{10} is a resistance value of said first resistor at a predetermined trim-fraction within a trimming range of said first resistor.

58. A circuit as claimed in any one of claims 37 to 57, wherein said first portion and said second portion are on at least one thermally isolated micro-platform.

59. A circuit as claimed in claim 58, wherein said first portion and said second portion are on separate thermally isolated micro-platforms.

60. A circuit as claimed in any one of claims 37 to 59, wherein said first portion is made of boron-doped polysilicon and said second portion is made of arsenic-doped polysilicon.

61. A circuit as claimed in claim 38, wherein said circuit has an output that is a linear function of an input, with a substantially linear temperature-induced drift.

62. A circuit as claimed in claim 61, wherein said circuit is a differential bridge circuit with an amplified output.

63. A circuit as claimed in claims 61 or 62, wherein said circuit is a cascade of a plurality of said differential bridge circuit with an amplified output.

64. A circuit as claimed in claim 63, wherein said circuit is three cascaded differential bridge circuits.

65. A circuit as claimed in claim 37, wherein said second portion is part of an application specific circuit, and wherein a predetermined behavior of a temperature coefficient of voltage across said second portion as a function of trimming said first resistor is also defined by said specific values for at least one of R_1 and R_2 or R_1/R_2 .

66. A method for providing a resistor having a predetermined resistance value and temperature coefficient of resistance value, the method comprising:

providing a trimmable resistive component having a predetermined behavior of temperature coefficient of resistance (TCR) as a function of trimming, the method comprising:

selecting materials to form a compound resistor having at least a first portion and a second portion, at least said first portion including a first resistor that is thermally trimmable and has a first resistivity, a first temperature coefficient of resistance value α_0 , and a value of trimming-induced shift of temperature coefficient γ_1 , which defines a change in said α_0 per fraction of trimming x of said first resistivity, said second portion including at least a second resistor having a second resistivity value, and a second temperature coefficient of resistance value β_0 ;

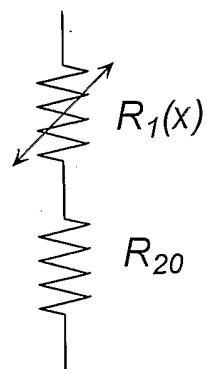
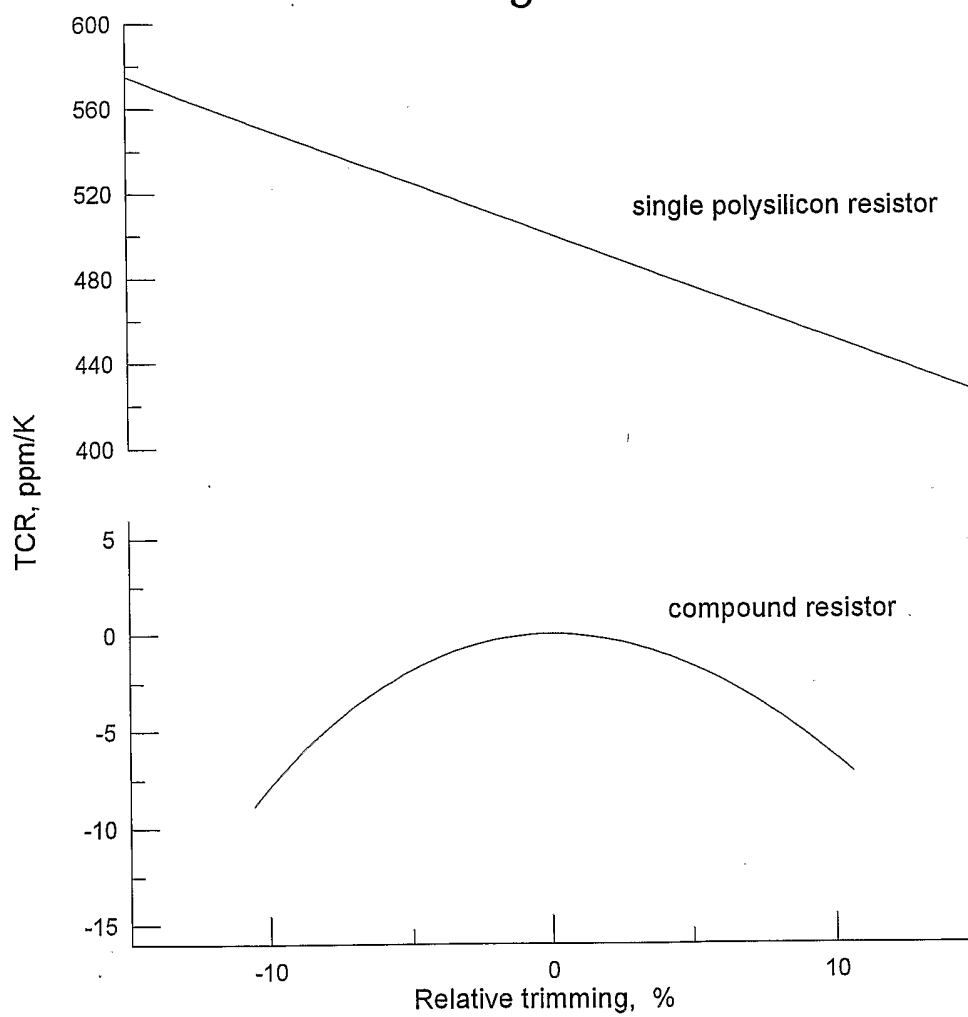
determining how said TCR value of said resistive component changes as at least said first portion is trimmed, by generating a function of said TCR versus trim-fraction x , with R_1 and R_2 as variable parameters and α_0 , β_0 , and γ_1 as fixed parameters; and

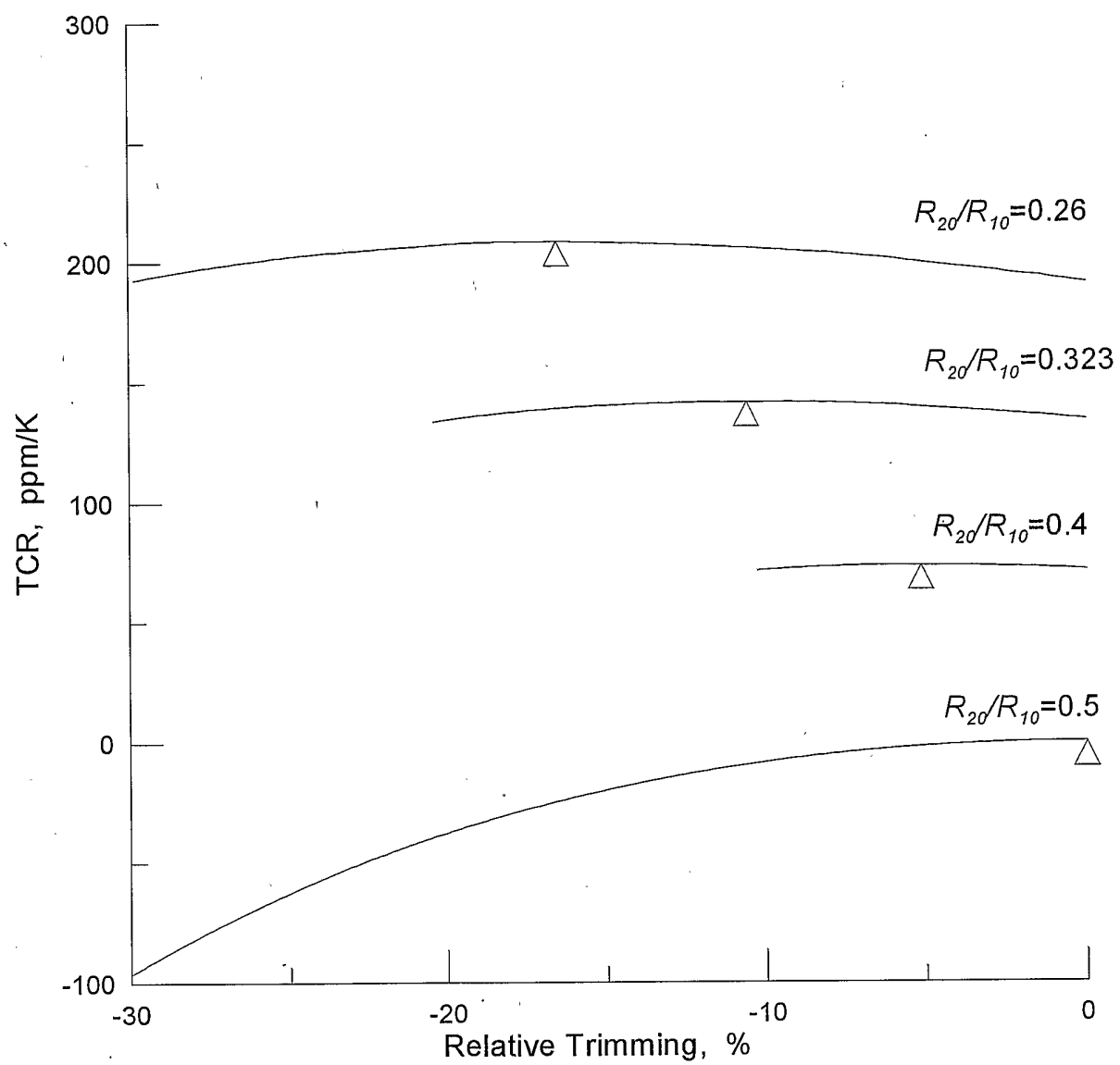
selecting specific values for R_1 and R_2 or R_1/R_2 to provide said resistive component with said predetermined behavior of said TCR, thereby incorporating an effect of said γ_1 in said resistive component; and

thermally trimming said first resistor to obtain said predetermined resistance value and temperature coefficient of resistance value.

67. A method as claimed in claim 66, wherein said second resistor is also thermally trimmable and has a value of trimming-induced shift of temperature coefficient γ_2 , which defines a change in said β_0 per fraction of trimming y of said second resistivity, said predetermined behavior of TCR corresponds to two substantially different curves representing variation of said TCR with said trim fraction x and variation of said TCR with said trim fraction y .

68. A method as claimed in claim 67, wherein said thermally trimming comprises thermally trimming said first resistance value and said second resistance value to different values.

*Fig. 1**Fig. 2*

*Fig. 3*

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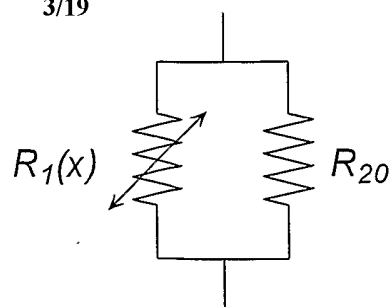
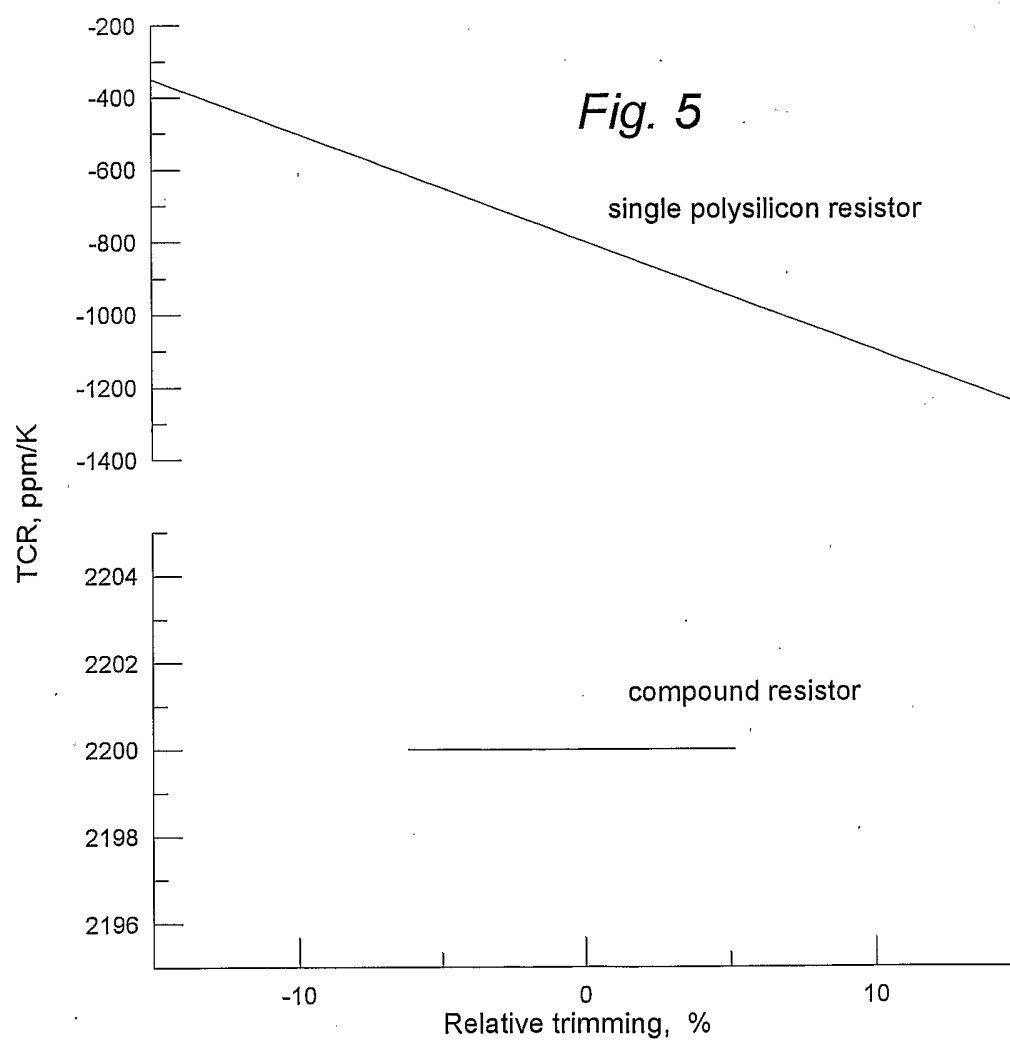
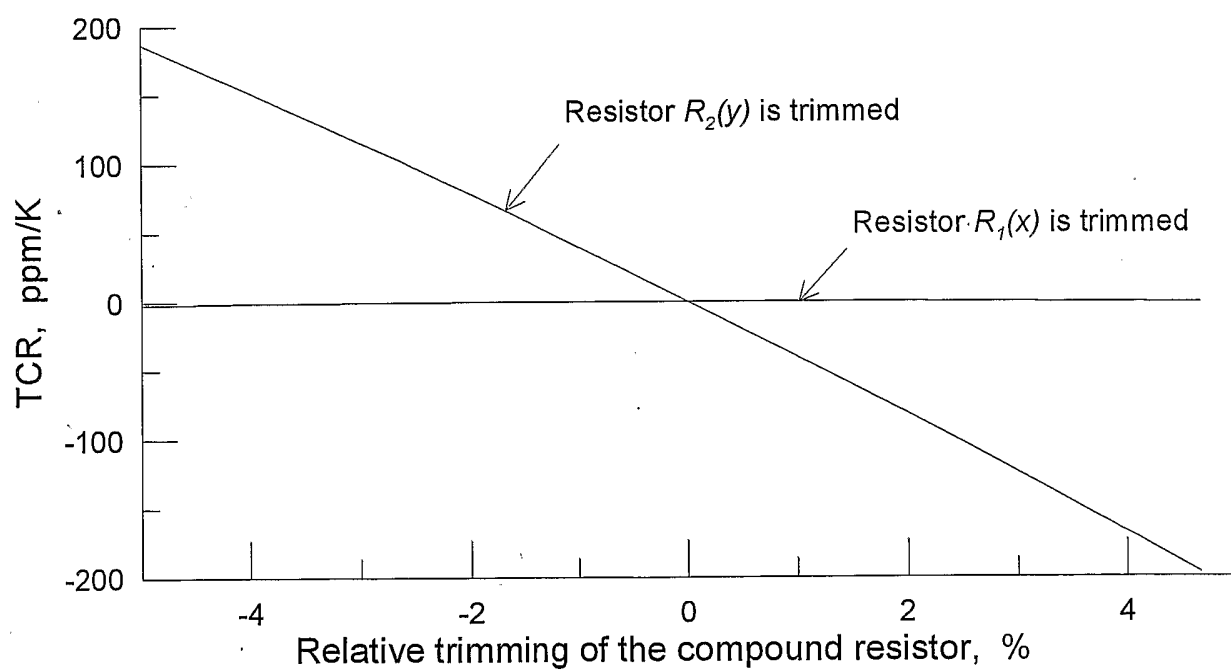
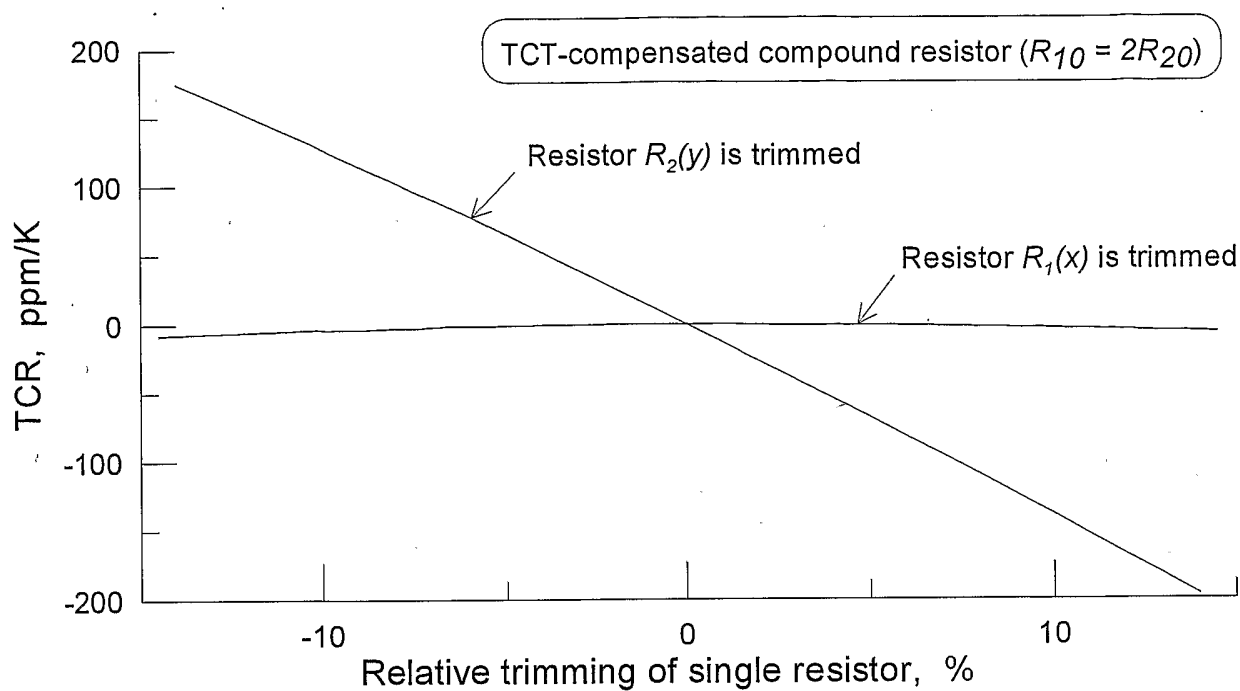
*Fig. 4*

Fig. 6



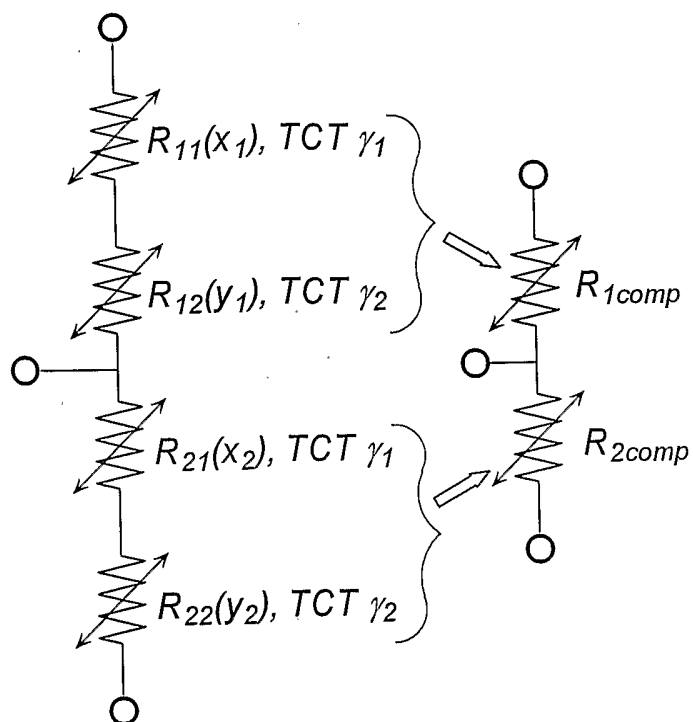


Fig. 7

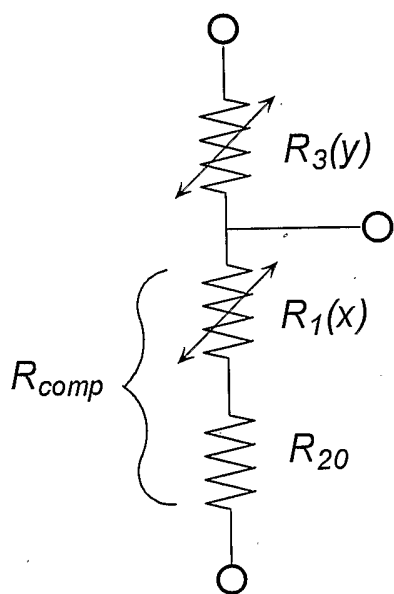


Fig. 8

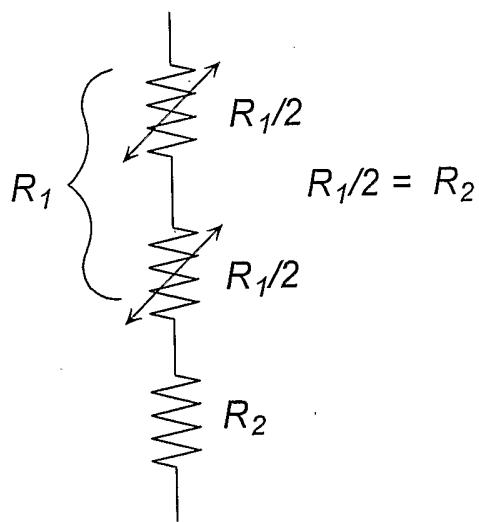


Fig. 9

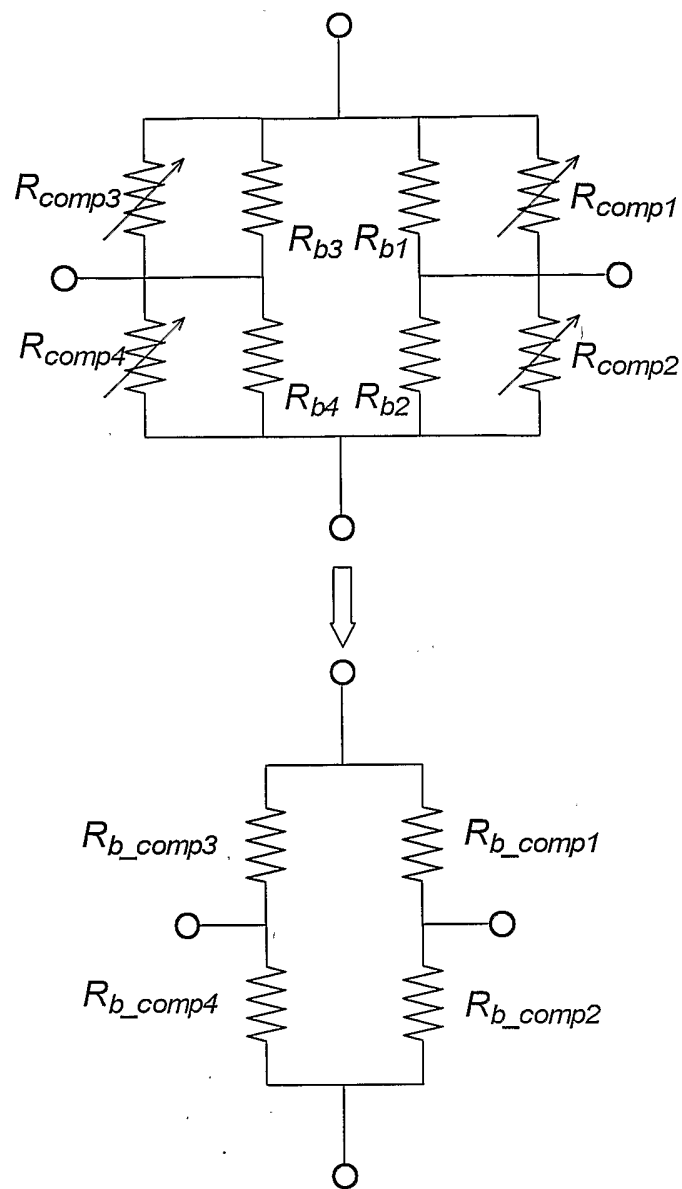


Fig. 10

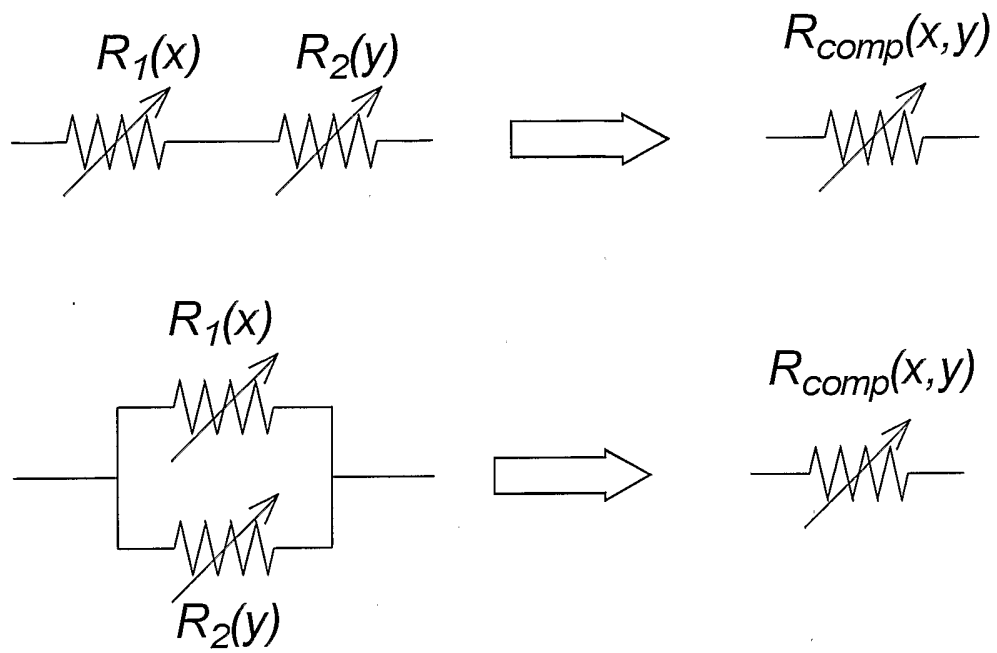


Fig. 11

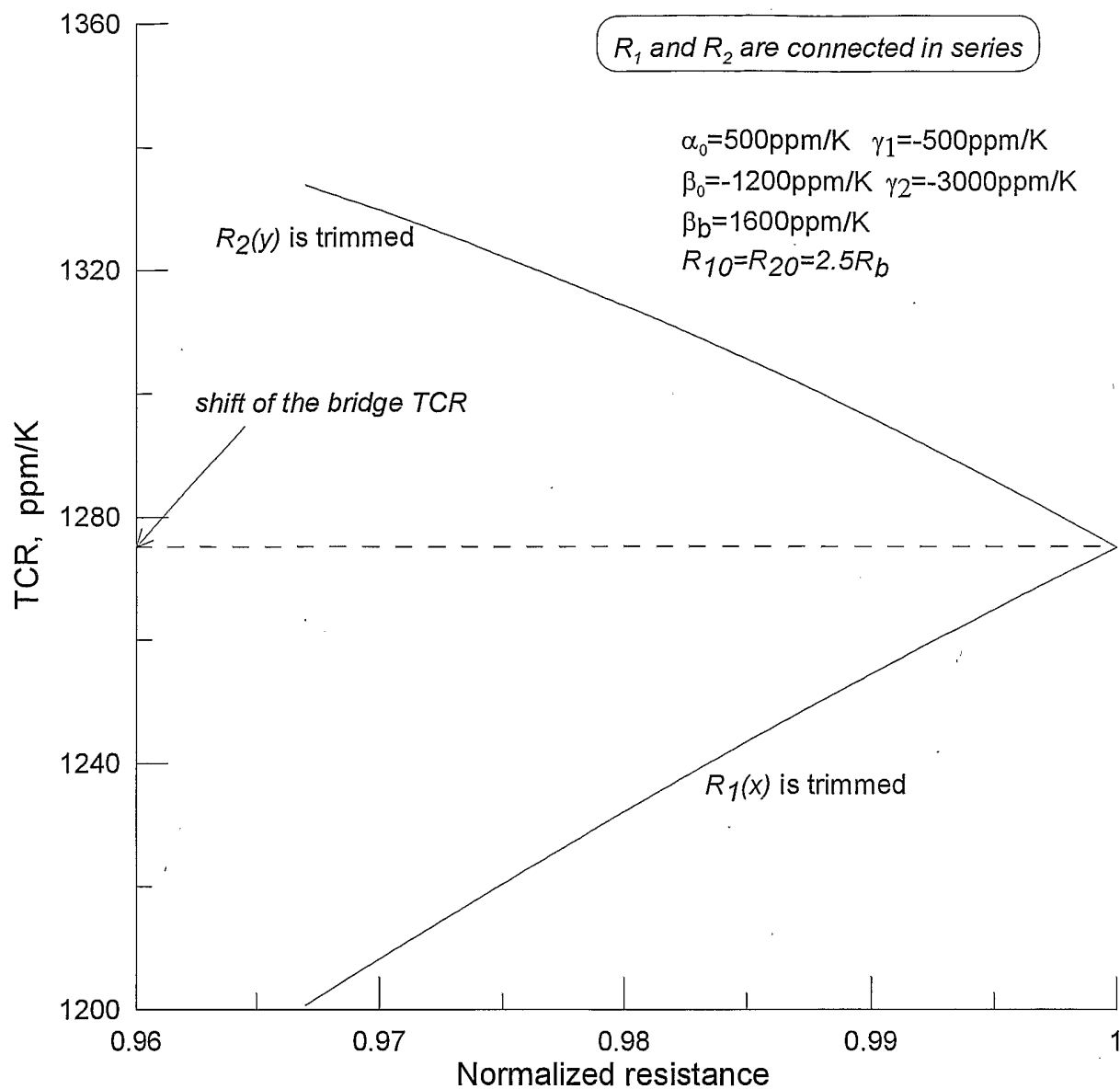


Fig. 12

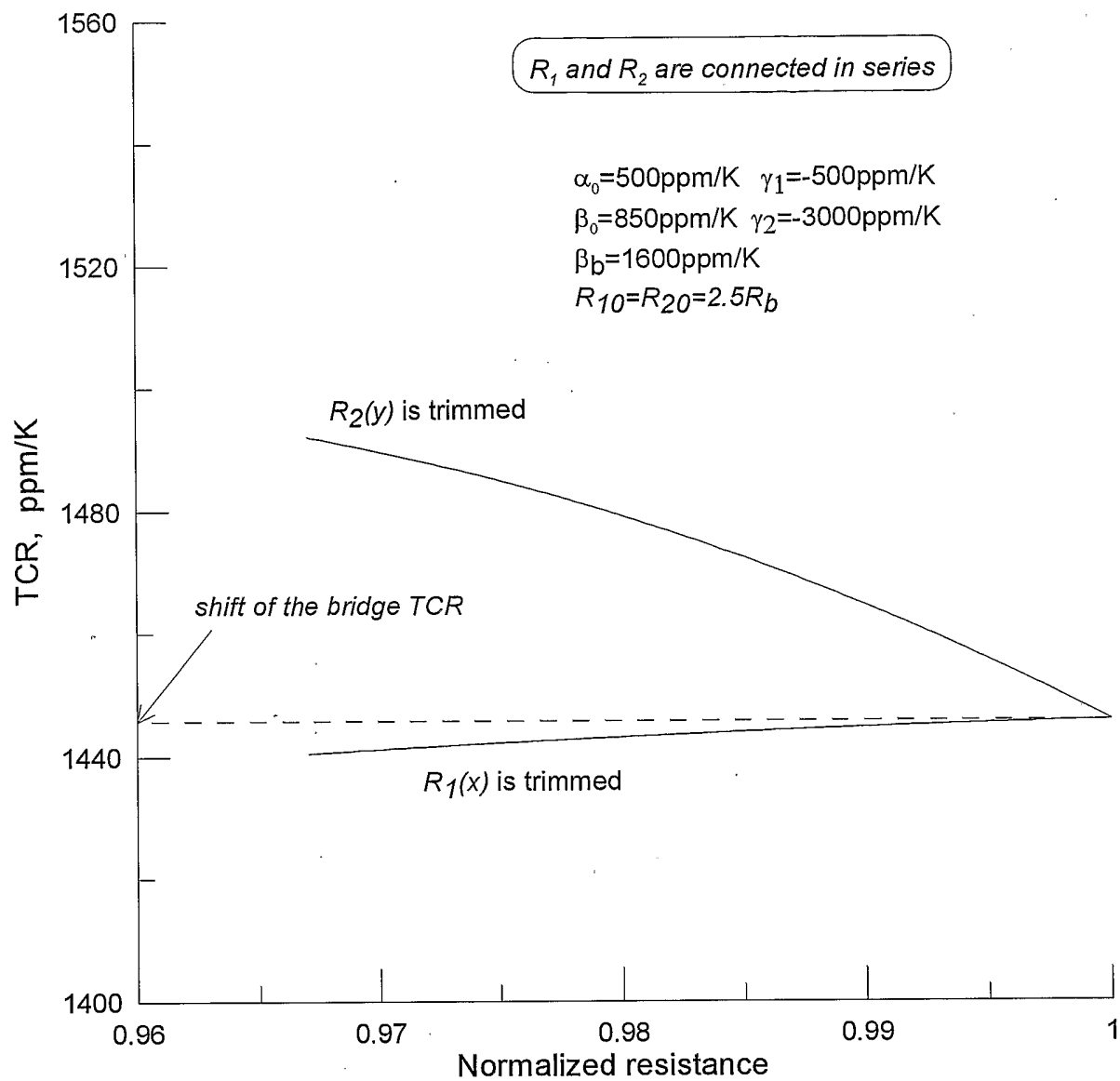


Fig. 13

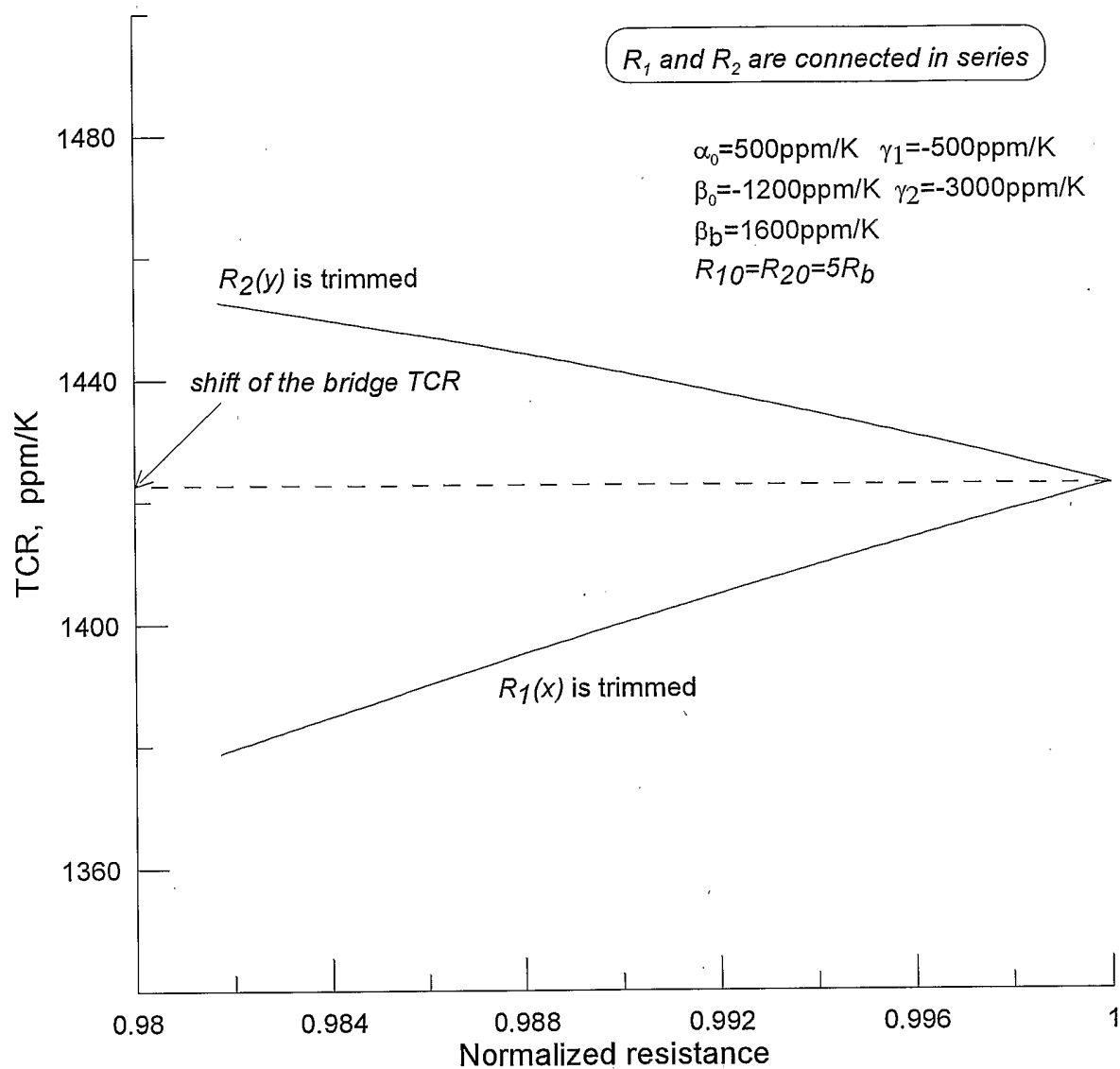


Fig. 14

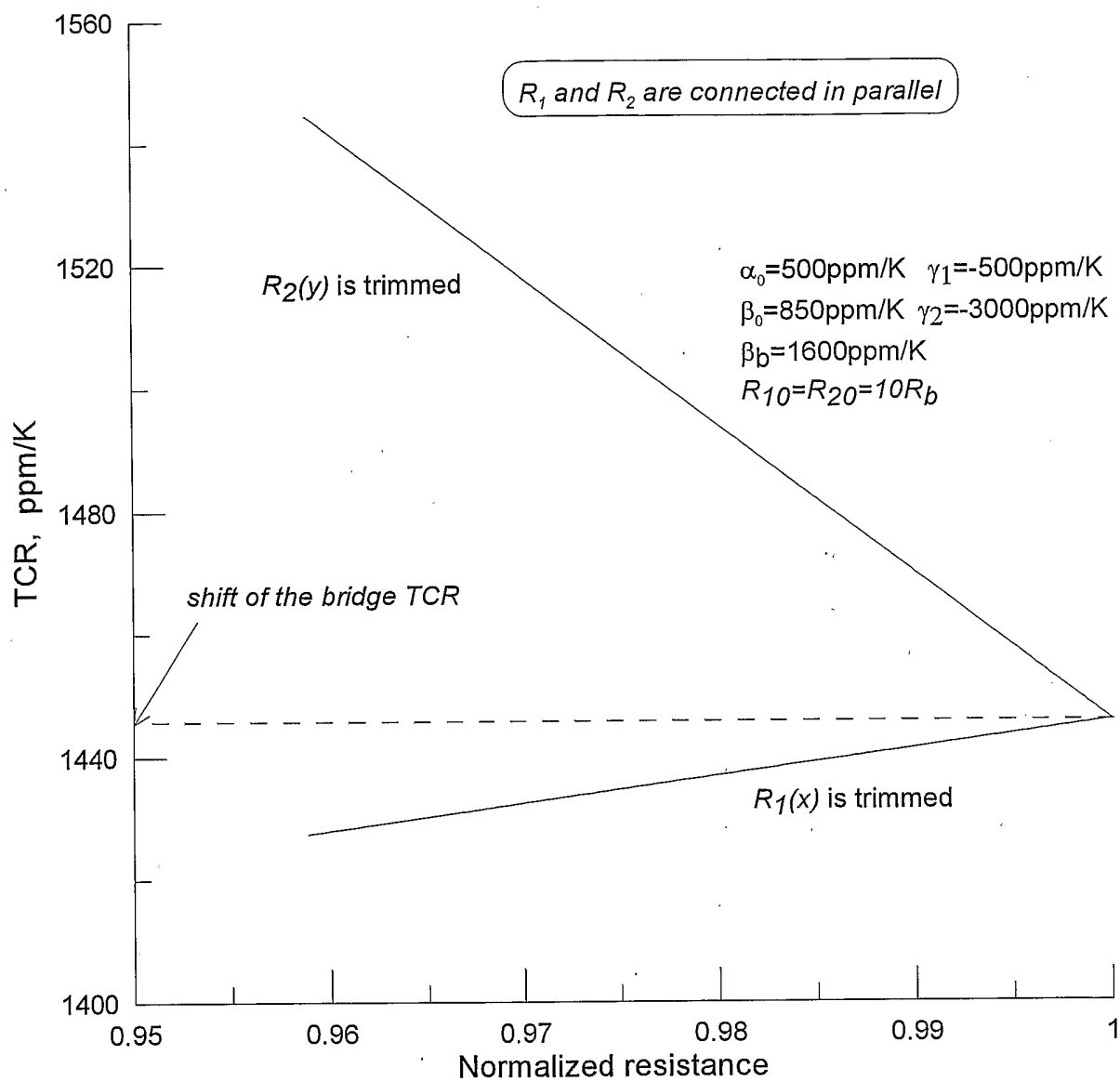


Fig. 15

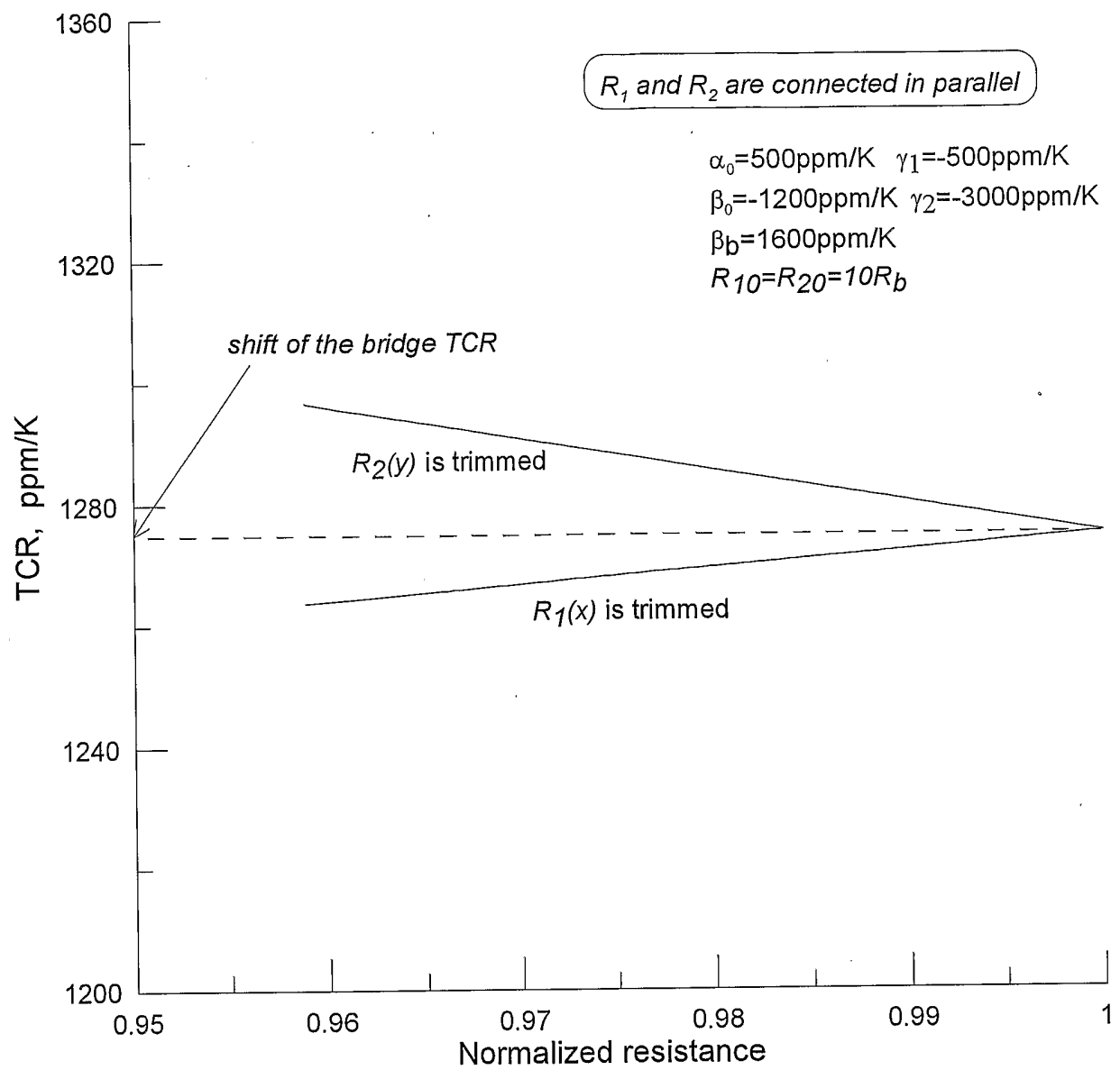


Fig. 16

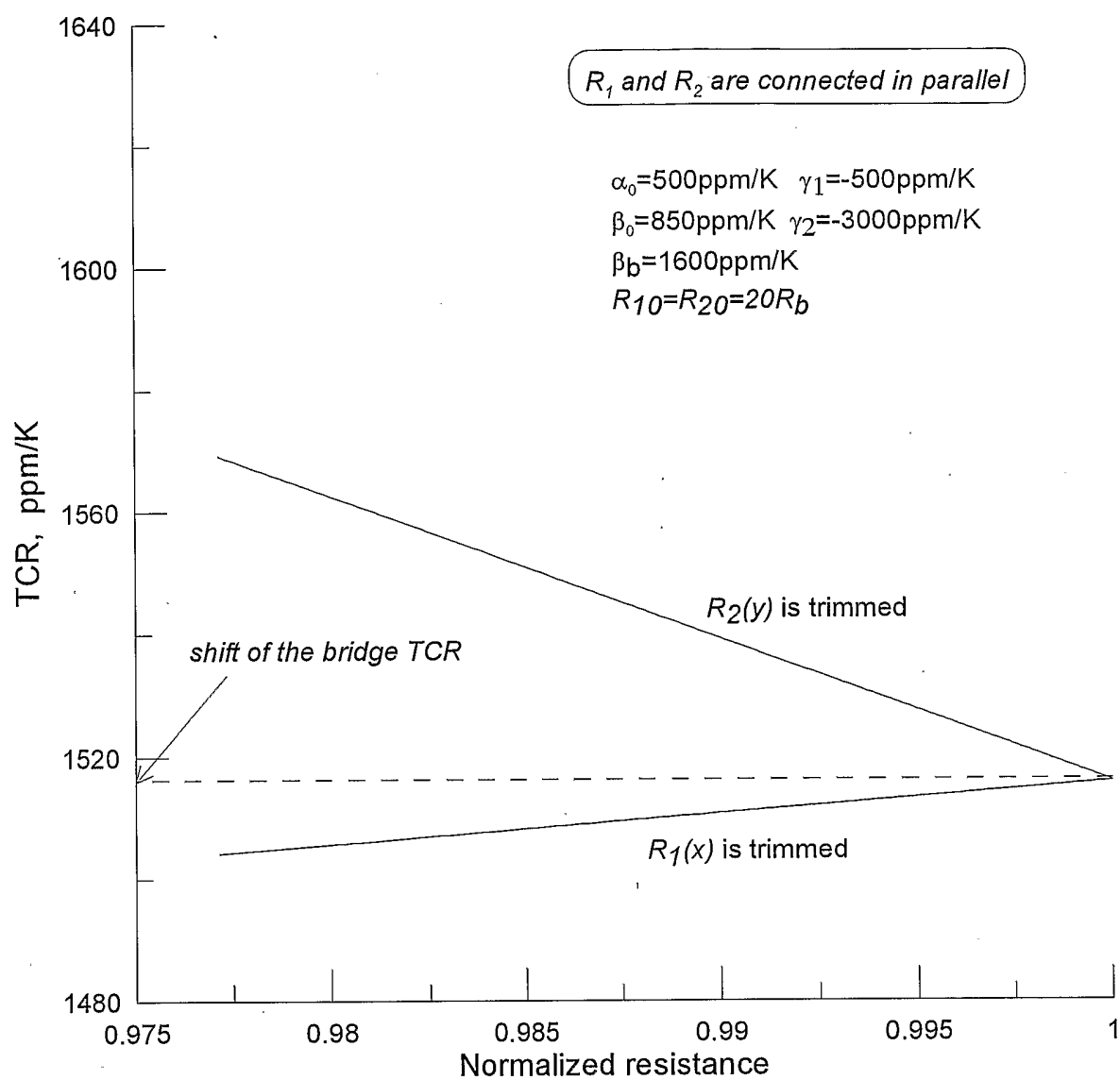


Fig. 17

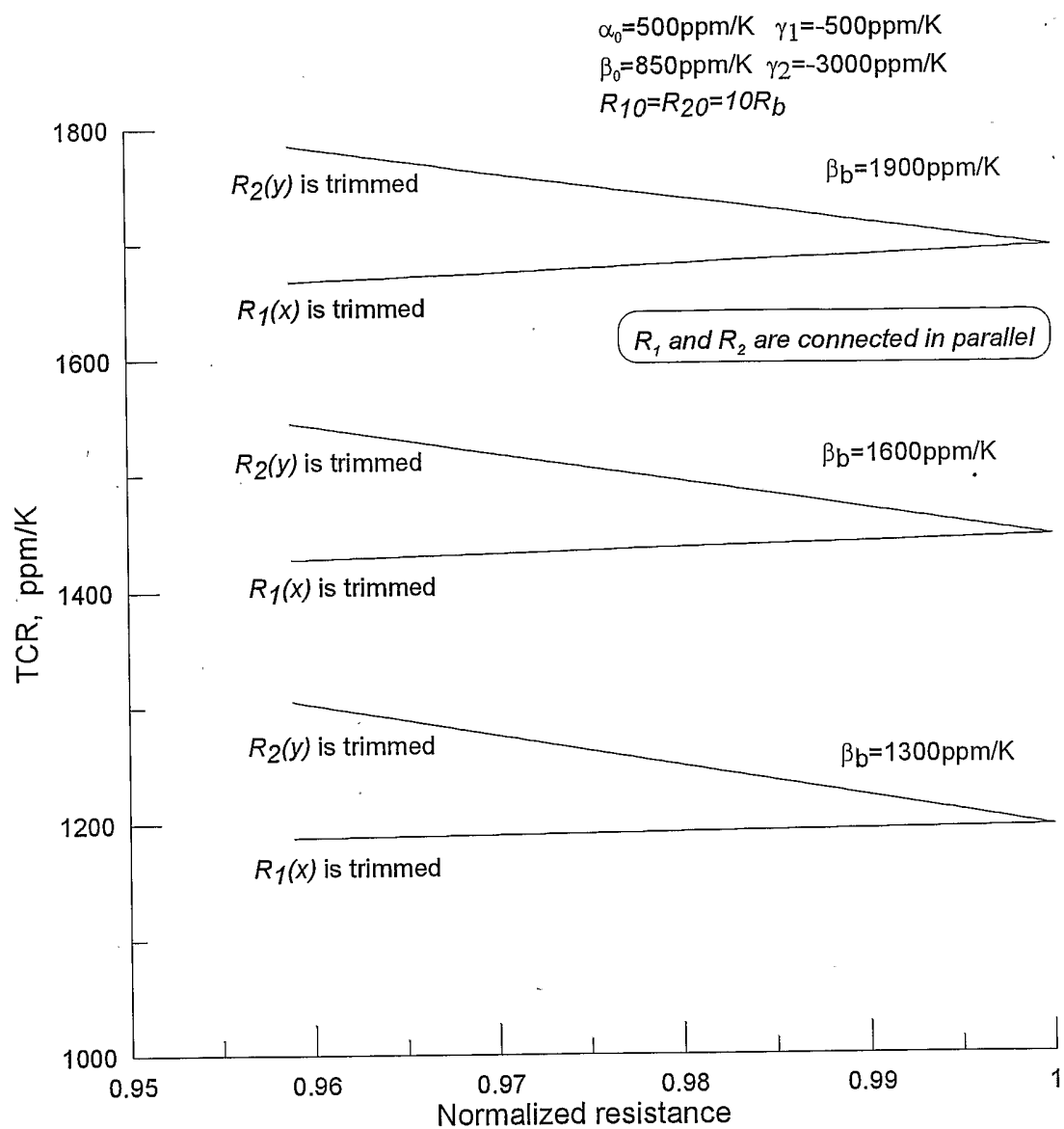
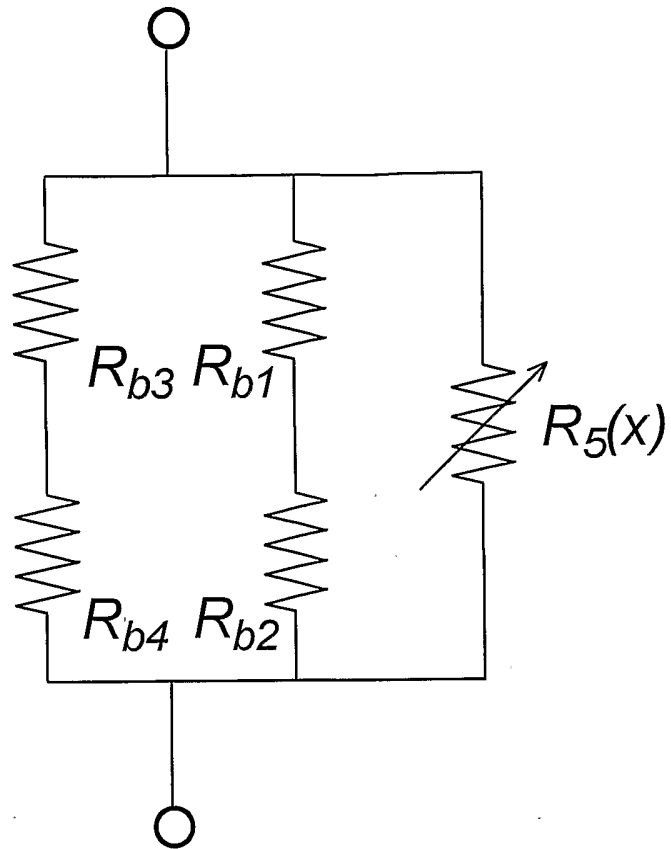
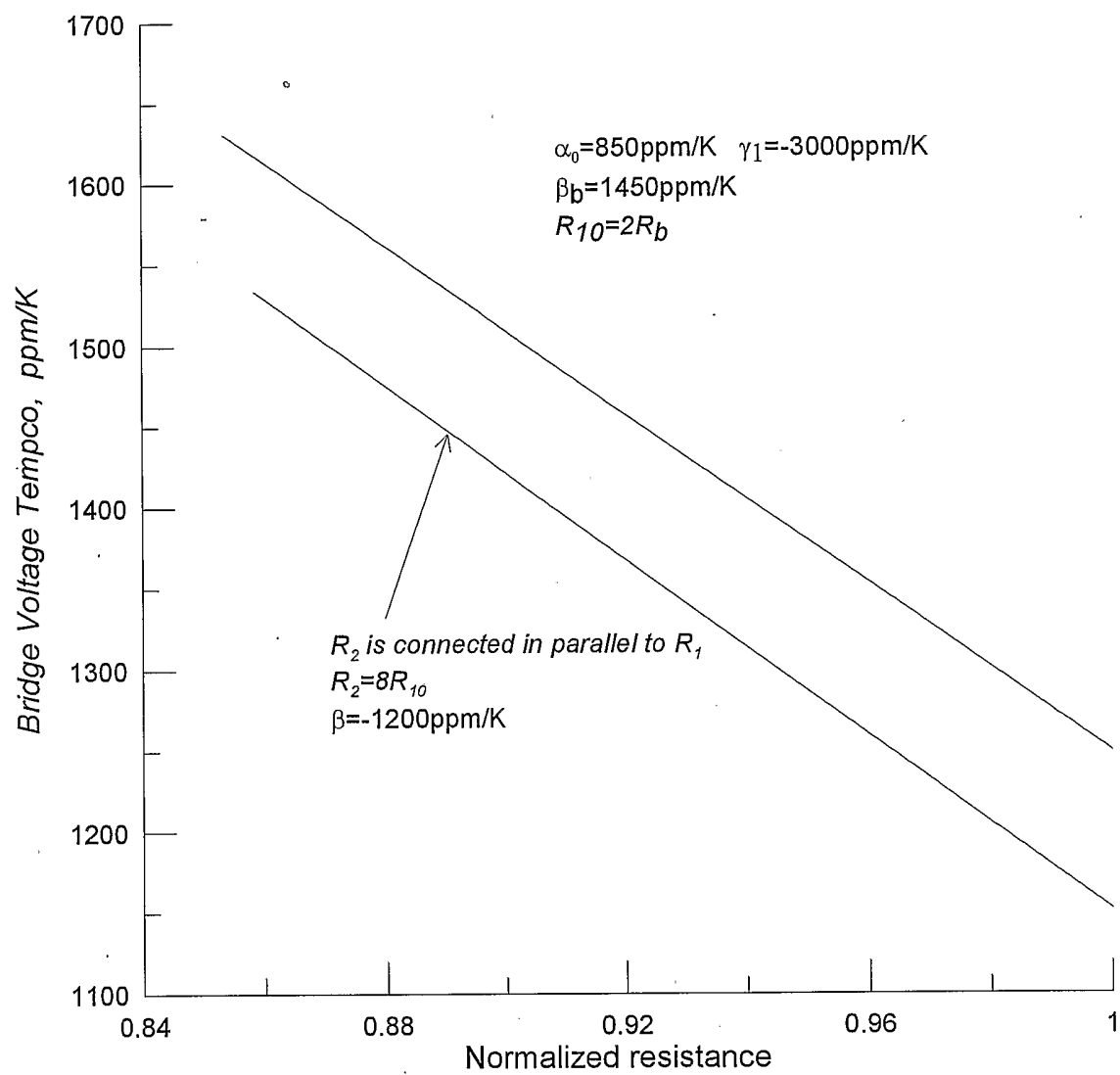


Fig. 18

*Fig. 19*

*Fig. 20*

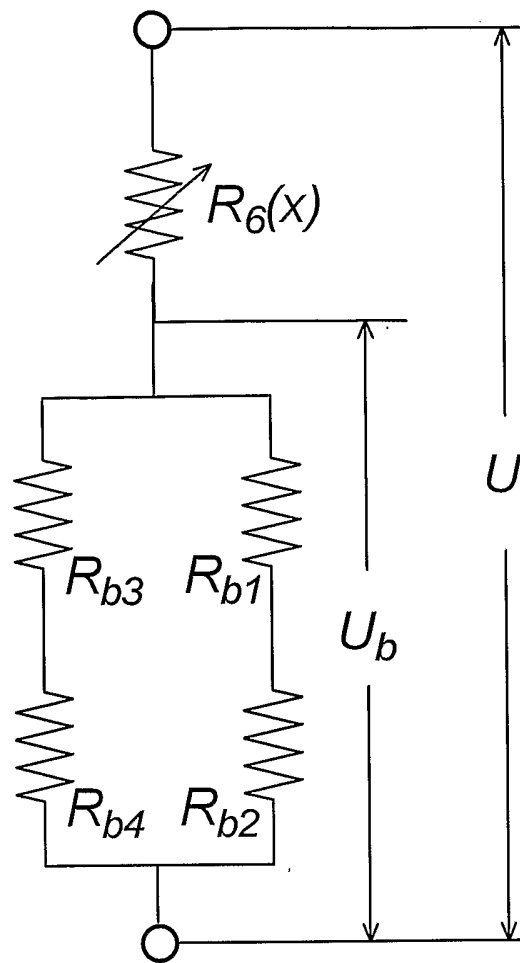


Fig. 21

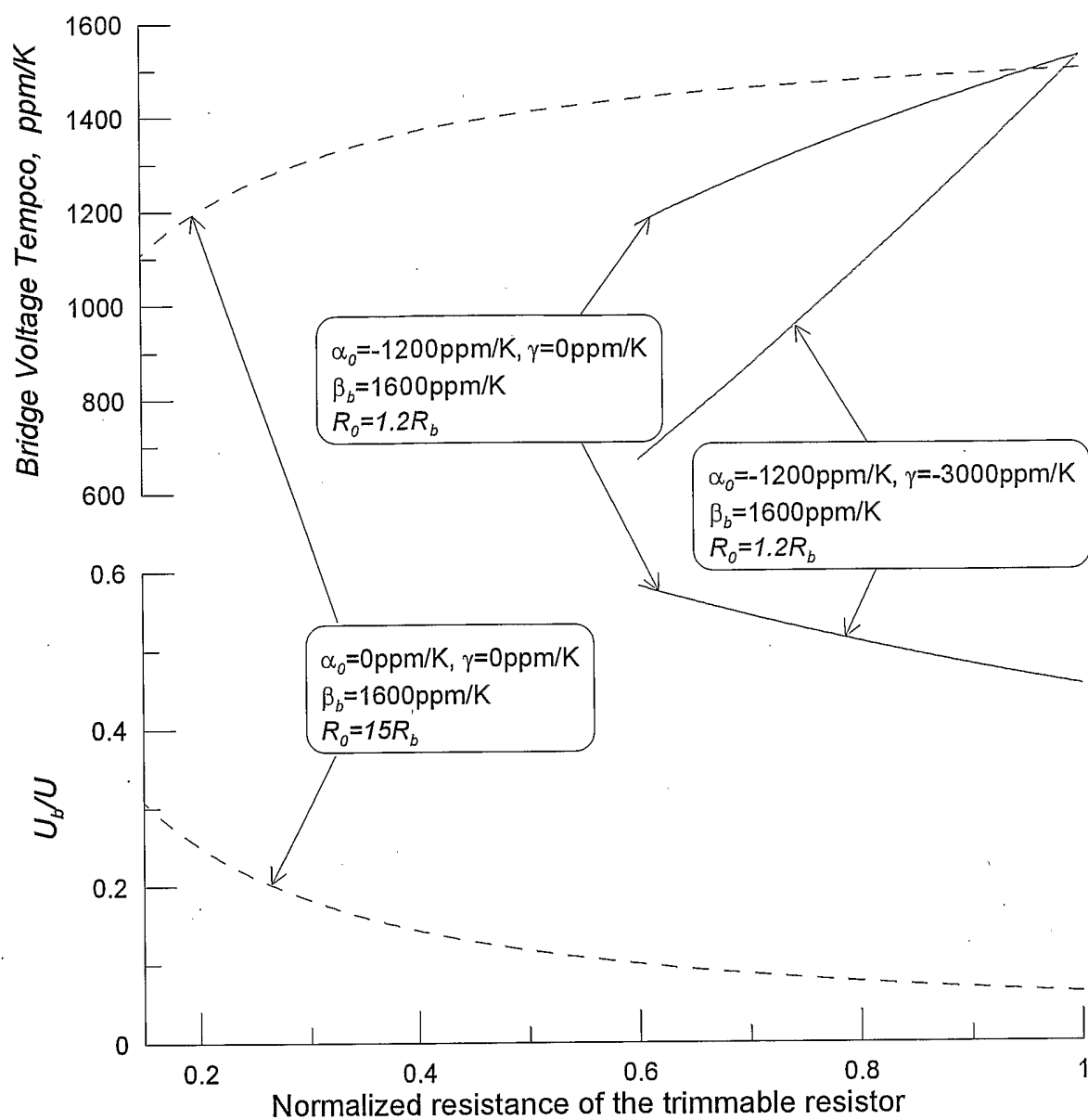


Fig. 22

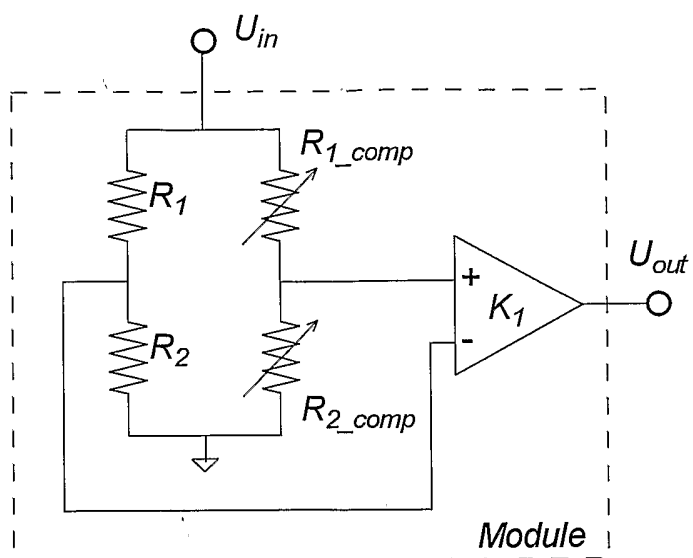


Fig. 23a

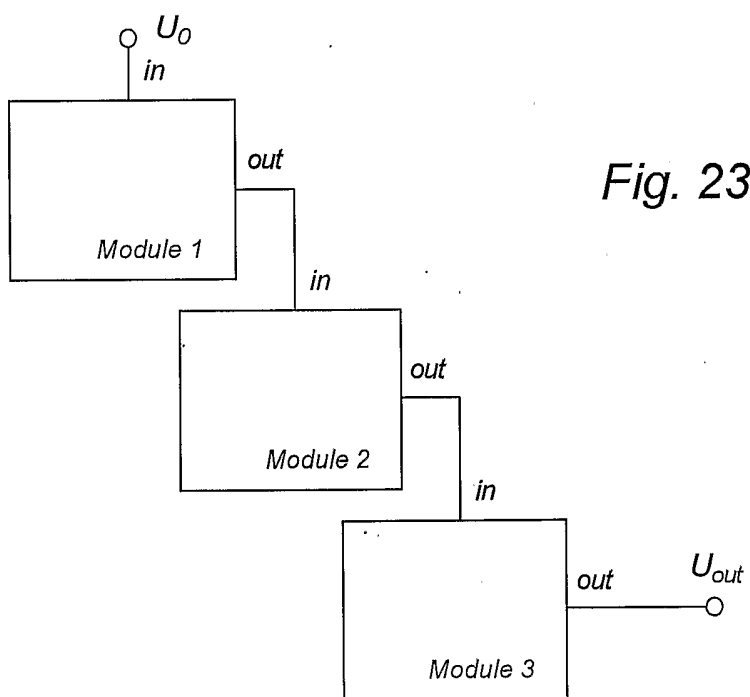


Fig. 23b

INTERNATIONAL SEARCH REPORT

International application No.
PCT/CA2005/001440

A. CLASSIFICATION OF SUBJECT MATTER
IPC(7): H01C 17/232, H01C 7/06

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC(7): H01C 17/232, H01C 7/06

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic database(s) consulted during the international search (name of database(s) and, where practicable, search terms used)
Databases searched: Canadian Patent Database, European Patent Database, Abstracts of Japan, US Patent Database, WIPO PCT Publications (Full text) and IEEE publications.
Keywords: "trimmable resistive component," "temperature coefficient," "resistance value," and ("trimming induced" or trimming-induced).

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US4,079,349 (Dorfeld), March 14, 1978. -see abstract; -see whole document.	1 - 68
A	US 4,210,996 (Amemiya et al.), July 8, 1980. -see abstract; -see whole document.	1 - 68
A	US 4,560,959 (Rokos et al.), December 24, 1985. -see abstract; -see whole document.	1 - 68
A	US 4,907,341 (Chapel et al.), March 13, 1990. -see abstract; -see whole document.	1 - 68
A	US 5,635,893 (Spraggins et al.), June 3, 1997. -see abstract; -see whole document.	1 - 68

☒ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

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"P" document published prior to the international filing date but later than the priority date claimed

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"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

23 November 2005 (23 - 11 - 2005)

Date of mailing of the international search report

01 December 2005 (01-12-2005)

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INTERNATIONAL SEARCH REPORT

International application No.
PCT/CA2005/001440

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 5,679,275 (Spraggins et al.), October 21, 1997. -see abstract; -see whole document.	I - 68

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.
PCT/CA2005/001440

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US5679275	21-10-1997	NONE	