Processing Techniques and Applications of Positive Temperature Coefficient Thermistors*

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Summary—**Thermistors with positive temperature characteristics of resistance have been recently developed. Their distinguished temperature characteristics, being divided into two groups—type SW and TC—have various application fields in electronic and electrical engineering.**

The paper describes and surveys the processing techniques of major importance, the fundamental characteristics of this component, and design criteria for the desired component.

Various uses of the component, as a thermal controller, a current limiter, a current stabilizer, a temperature compensator, etc., are explained to serve as a guide to other applications.

I. Introduction

The thermistor, a thermally sensitive resistor widely used in the electronic engineering field, through common usage is usually regarded as a resistor displaying a negative resistance-temperature coefficient. As contrasted with the conventional thermistor, a new component with a large positive resistance-temperature characteristic appeared recently. The present paper describes the processing techinques and applications of this new component.

The positive temperature coefficient thermister shall be hereafter called a "posistor," and in contrast, the conventional negative temperature coefficient thermistor shall be called just a "thermistor." Posistors are divided into two types according to their resistance-temperature characteristics. The first type, which shall be called type SW, exhibits a negative resistance-temperature coefficient at low temperatures and a positive resistance-temperature coefficient at higher temperatures. The positive resistance-temperature coefficient characteristic tends to be quite large, from 11 per cent per degree C to greater than 30 per cent per degree C. The second type, which shall be called type TC, has a conventional linear log resistance vs temperature characteristic with a temperature coefficient in the range 3 to 8 per cent per degree C.

The posistor consists of barium titanate ceramics whose resistance has been markedly reduced by doping with certain elements. These modified ceramics have resistivity anomalies in their resistivity-temperature characteristics corresponding to the Curie points as will be shown later in Fig. 12.

The unique properties of the semiconducting barium titanates first appeared in the patent of Haayman et al.[1] and later were studied by several investigators.[2–4]

One of the present authors studied the resistivity anomaly in relation to the kind of doping elements, the crystal structure, and to other semiconducting properties,[5,6] and proved that the materials were semiconductors of n-type. He also studied the semiconducting bodies in the barium titanate family[7] and reported on various resistivity-temperature characteristics such as are required by posistors.

Attempts have been made to clarify the occurrence of the resistivity anomaly.[8–12] A possible conclusion is that the material is a semiconductor of exchange type and that the anomaly is caused by the polycrystalline structure of the material. The details, however, have not been completely clarified.

The literature[13,14] reveals several production techniques useful in the fabrication of these devices.

The methods and materials required for making ohmic contacts to the semiconducting barium titanates were

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[1] P. W. Haayman, R. W. Dam, and H. A. Klassens, "Method of producing semiconducting material," German Patent No. 929,350; June 23, 1955.

[2] H. A. Sauer and S. S. Flaschen, "Positive temperature coefficient of resistance thermistor materials for electronic applications," *Proc. 7th Electron. Components Symp.*, Washington, D. C., Engineering Publishers, New York, N. Y., pp. 41–46; May, 1956.

[3] G. G. Harman, "Electrical properties of $BaTiO_3$ containing samarium," *Phys. Rev.*, vol. 106, pp. 1358–1359; June, 1957.

[4] V. J. Tennery and R. L. Cook, "Investigation of rare-earth doped barium titanate," *J. Am. Ceram. Soc.*, vol. 44, pp. 187–193; April, 1961.

[5] O. Saburi, "Properties of semiconductive barium titanates," *J. Phys. Soc. Japan*, vol. 14, pp. 1159–1174; September, 1959.

[6] O. Saburi, "Piezoresistivity in semiconductive barium titanates," *J. Phys. Soc. Japan*, vol. 15, pp. 733–734; April, 1960.

[7] O. Saburi, "Semiconducting bodies in the family of barium titanates," *J. Am. Ceram. Soc.*, vol. 44, pp. 54–63; February, 1961.

[8] W. Heywang, "Bariumtitanat als Sperrshichthalbleiter," *Solid-State Electron.*, vol. 3, pp. 51–58; July, 1961.

[9] O. Saburi, "Experimental Researches in Semiconducting Barium Titanates," Murata Mfg. Co., Nagaoka, Kyoto, Japan, pp. 111–118; 1961.

[10] G. Goodman, "The electrical conduction anomaly in samarium-doped barium titanate," *J. Am. Ceram. Soc.*, vol. 46, pp. 48–54; January, 1963.

[11] F. M. Ryan and E. C. Subbaro, "The Hall effect in semiconducting barium titanate," *J. Appl. Phys. Lett.*, vol. 1, pp. 69–71; November, 1962.

[12] W. T. Peria, W. R. Bratschun, and R. D. Fenity, "Possible explanation of positive temperature coefficient in resistivity of semiconducting ferroelectrics," *J. Am. Ceram. Soc.*, vol. 44, pp. 249–250; May, 1961.

[13] H. A. Sauer and J. R. Fisher, "Processing of positive temperature coefficient thermistors," *J. Am. Ceram. Soc.*, vol. 43, pp. 297–301; June, 1960.

[14] E. M. Swiggard and W. Stanley Clabaugh, "Preparation of Barium Titanate Semiconductors Containing Controlled Amounts of Rare Earth," to be published. Preprint sent by courtesy of E. M. Swiggard *et al.* and G. G. Harman.

studied by several workers.[15-17] It has been shown that the nickel electrodes applied by electroless chemical deposition, indium-gallium alloy and hard gallium alloys, are suitable as ohmic contact materials.

Despite the above-mentioned research, some production problems have been left unsolved, and neither the production process of the posistor, nor its characteristics as a circuit component have ever been reported.

The intent of this paper is to outline the processing techniques for posistors, the way the processing variations affect their electrical properties (Section II), their fundamental characteristics (Section III) and typical examples of their application (Section IV).

II. Processing Techniques

A. The Processing System

The process for producing the posistor is illustrated schematically in Fig. 1. The steps in the production of semiconducting ceramics are essentially similar to those employed in the production of conventional cermics, except that special caution should be taken to insure the purity of the materials and careful process control, as the resistivity-temperature characteristics are very sensitive to impurities and to the micro-structure of the ceramics.

The fabrication steps shown in Fig. 1, are basically applicable to the disc-type posistor whose cross section is illustrated in Fig. 2, but may also apply the other posistors in Fig. 3 with very slight changes.

Raw Materials ($BaTiO_3$, TiO_2 $BaCO_3$, $SrCO_3$, SnO_2, Lanthaum oxalate)
- weighed
- mixed in ball-mill
- filtered & dried
- calcined at 1100–1200°C

White Crystalline Block
- crushed & milled
- filtered & dried
- pressed
- fired at 1350–1400°C

Semiconducting $BaTiO_3$ Ceramics
- electroless plating
- heat treatment at 400°C
- adjusting resistance
- wire leads soldered
- coated with resin on body
- cured & marked

Posistor

Fig. 1—Flow chart of posistor processing.

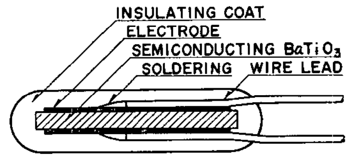


Fig. 2—Construction of a posistor.

B. Processing Semiconducting Barium Titanate Ceramics

The posistor materials chosen from the semiconducting bodies in the barium titanate family which are doped with rare earth elements, etc. The following describes the case of (Ba. Sr)-(Ti. Sn)O_3 doped with a rare earth element such as lanthanum.

Although the starting formulation can be a combination of $BaCO_3$, $SrCO_3$, TiO_2, SnO_2 and La_2O_3, a superior formulation is barium titanate and strontium titanate prepared from barium- and strontium-titanyl oxalate, tin oxide and lanthanum oxalate. The latter formulation is preferable because of the higher purity that can be attained and the superior stoichiometry of the material. Whatever raw materials are used, their purity should be sufficiently high, so that the amounts of impurity elements do not exceed traces. Alkaline metals and iron group elements should be most carefully eliminated, as they inhibit the reproducibility of resistance.

In practice, a slight excess of TiO_2 from stoichiometry is recommended, since the excess group II elements have

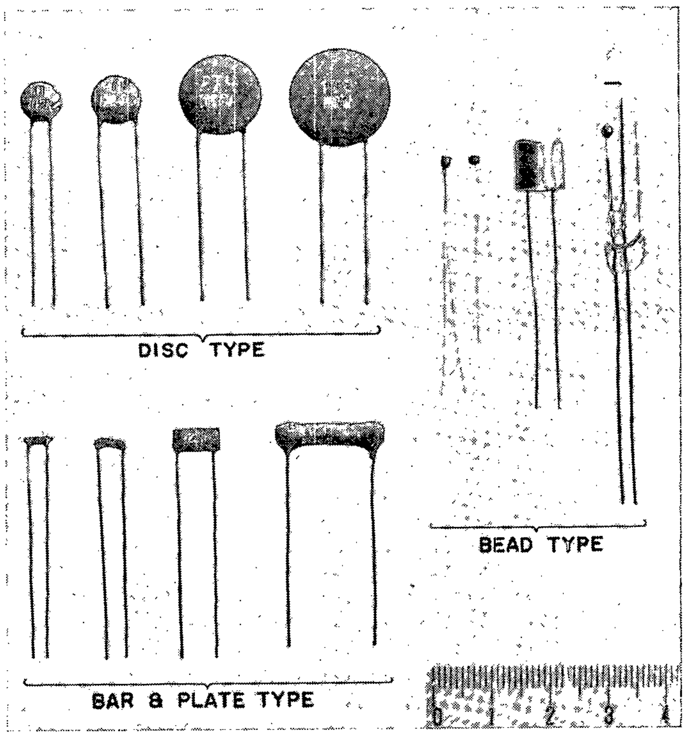


Fig. 3—Various types of posistors.

[15] D. R. Turner and H. A. Sauer, "Ohmic contacts to semiconducting ceramics," *J. Electrochem. Soc.*, vol. 107, pp. 250–251; March, 1960.
[16] H. A. Sauer and S. S. Flaschen, "Choice of electrodes in study and use of ceramic semiconducting oxides," *Ceram. Bull.*, vol. 39, pp. 304–306; June, 1960.
[17] G. G. Harman, "Hard gallium alloys for use as low contact resistance electrodes and for bonding thermocouples into samples," *Rev. Sci. Instr.*, vol. 30, pp. 717–720; July, 1960.

more effect on the resistivity of the end product than group IV elements, as shown in Fig. 4 (next page).

As previously described,[2,5] the doping elements are chosen from those elements which have ionic radii similar to Ba^{2+} and valences larger than two, or from those which have ionic radii similar to Ti^{4+} and valences larger than four.

The concentrations of the doping elements have a large effect on the resistivity; the resistivity decreases with increasing quantity of the doping element until a certain quantity is reached. Beyond this point, however, the resistivity goes up very rapidly so that the material does not appear to be a semiconductor when excessively doped. This behavior is dependent upon the kind of doping element, as shown in Fig. 5. Cerium, lanthanum, and niobium, when added in the form of their oxides, had the critical point at 0.4 atomic per cent, and the excess amount beyond this point could not produce semiconducting ceramics. On the other hand, yttrium oxide had a critical point at a larger impurity level, 0.6 atomic per cent. The above -mentioned effect of the doping amount is presumably dependent upon the dispersion of the doping elements in the ceramics, and hence, upon the method of adding the doping elements to the main body. Neodymium, when coprecipitated with barium titanyl oxalate, gave minimum resistivity at 0.05 atomic per cent and the critical point at 0.12 atomic per cent.[14] Such a low critical point is considered to be implemented by well dispersing the doping element. Various methods of adding cerium as the doping element are compared in Table I. Addition of cerium in the form of oxalate resulted in the poorest reproducibility, presumably because the cerium was poorly dispersed, whereas cerium oxalate coprecipitated with barium titanyl oxalate provided the lowest resistivity and the best reproducibility.

A small amount of certain compounds such as silicates promotes the sintering of ceramics and hence is called a mineralizer. The voltage dependency of the resistivity of semiconducting ceramics, which will be referred to later in Section III-H, is greatly affected by the addition of the mineralizer. Fig. 6 shows the effects of mineralizer content on the resistivity and on the voltage coefficient. The resistivity was a minimum for a mineralizer content of 0.6 per cent. The voltage coefficient varied inversely with the amount of mineralizer till the mineralizer reached 0.6 per cent, after which the voltage coefficient remained constant at about 0.2. Microscopic study showed that increasing the mineralizer content caused markedly reduced grain size.

The batch ingredients are mixed in a ball-mill with a suitable amount of water. Special care should be taken to insure that the grinding media and the wall material of the ball-mill will not contaminate the ingredients. Sauer *et al.*[13] preferred mulite balls over alumina balls as grinding media to minimize any significant poisoning action by the aluminium ions.

The slurry is dried, pulverized, and calcined for 1 hour at 1100° to 1200°C. During the calcination, the materials usually form white and brittle lumps. The lumps are crushed in a ball-mill with water, then dried and pulverized into powder.

The powder is pressed into discs, plates or bars under a hydraulic pressure. The effects of the forming pressure on the resistivity, the dielectric constant and on the impedance angle of the end products are shown in Fig.7. With increasing pressure, the dielectric constant and the impedance angle rapidly decreased, and the resistivity tended to increase. Microscopic observation disclosed that the grain size grew with increasing pressure. In practice, pressures between 0.5 and 2 tons/cm^2 are applied.

The pressed bodies are fired at a specific temperature between 1300° and 1400°C for 0.5 to 2 hours in an electric furnace. The firing temperature and the soaking time critically effect the properties of the end products. Firing the body shown in Fig. 8 at temperatures not more than 1315°C produced no semiconducting ceramics. The resistivity rapidly went down as the firing temperature was increased reaching a minimum at 1360°C. The optimum soaking time was about 20 minutes, for the case shown in Fig. 9. Longer soaking made the grain size larger and resulted in higher resistivity.

The results described above were obtained by firing in air, which is the most practical technique for producing semiconducting barium titanates. Sauer *et al.*[13] studied firing in O_2 enriched air and that in N_2 enriched, and found that firing in an atmosphere less oxidizing than the muffle air resulted in lower resistivity and lower positive temperature coefficient of resistivity.

A set of electrodes is then applied to the semiconducting ceramic. The electrodes should make good electrical contact to the ceramic so that no appreciable contact resistance exists. Indium amalgam and indium-gallium alloy rubbed on the surface of ceramics, are easiest to apply and provide good electric contact, but because they have very poor mechanical strength, they are not practical for the posistor application. Electrodes applied by electroless nickel deposition developed by Turner *et al.*[15] are most promising for the present purpose, as their bond to ceramics is mechanically strong and they have practically no contact resistance. The method of deposition consists of activating the surface to be coated with nickel by dipping in palladium chloride solution, depositing nickel by dipping the ceramic in the electroless nickel solution, and then heat treating the deposited nickel film. The heat treatment changes the non-ohmic deposited contact into a low resistance ohmic contact. Turner *et al.*[15] found that heat treatment at 400°C for 10 minutes produced the lowest contact resistance having the smallest aging effect. To avoid oxidation of the nickel the heat treatment must be conducted in an inert atmosphere or in a vacuum. This heat treatment causes a large reduction in the positive temperature coefficient and resistivity of some ceramics. The authors of this paper found that introduction of the mineralizer mentioned previously made the ceramics insensitive to the heat treatment. Hard gallium alloys developed by Harman[17] for use as low contact resistance

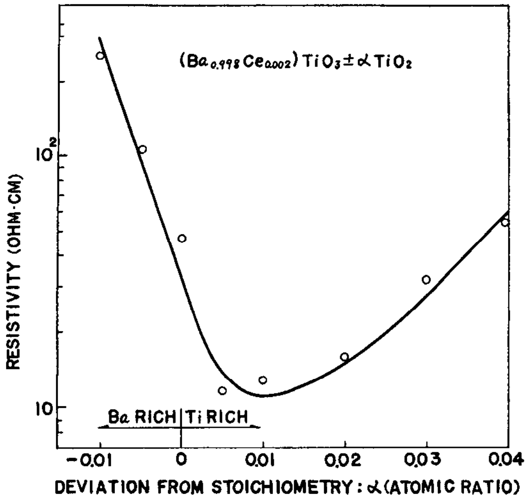


Fig. 4—Effect of deviation from stoichiometry on resistivity.

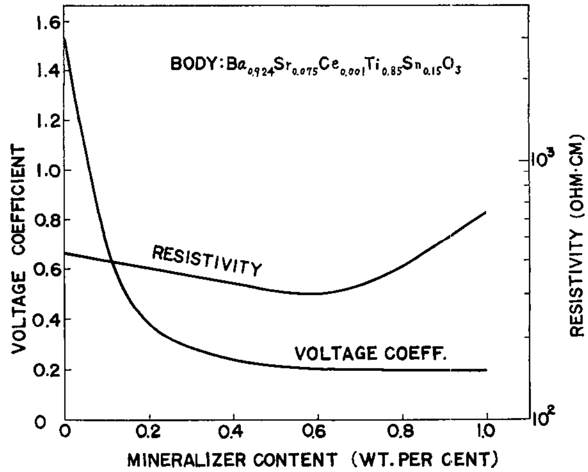


Fig. 6—Effects of mineralizer content on resistivity and on voltage coefficient.

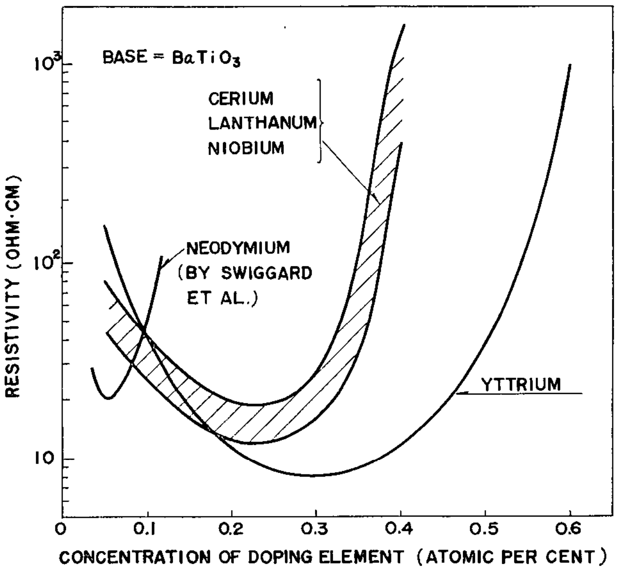


Fig. 5—Effect of concentration of doping elements.

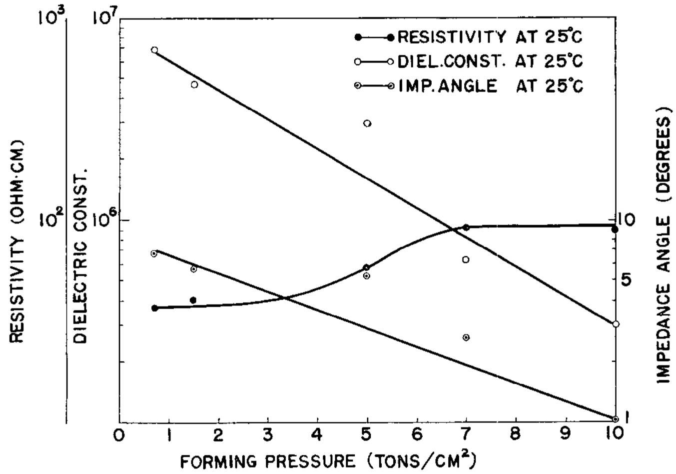


Fig. 7—Effects of forming pressure on resistivity, dielectric constant and on impedance angle.

TABLE I

EFFECT OF THE METHODS OF ADDING DOPING ELEMENT (Ce) ON RESISTIVITY

Method	Description	Resistivity (ohm. cm)
A	$BaCO_3$, TiO_2 and cerium oxalate were milled in a ball-mill and calcined.	10 to 25
B	$BaCO_3$, TiO_2, $CeCl_3$ solution and $(NH_4)_2CO_3$ solution were milled in a ball-mill and calcined.	10 to 20
C	$BaCO_3$ and $Ce_2(CO_3)_3$ were coprecipitated, then milled in a ball-mill with TiO_2 and calcined.	9 to 15
D	Barium titanyl oxalate and cerium oxalate were coprecipitated and calcined.	5 to 11

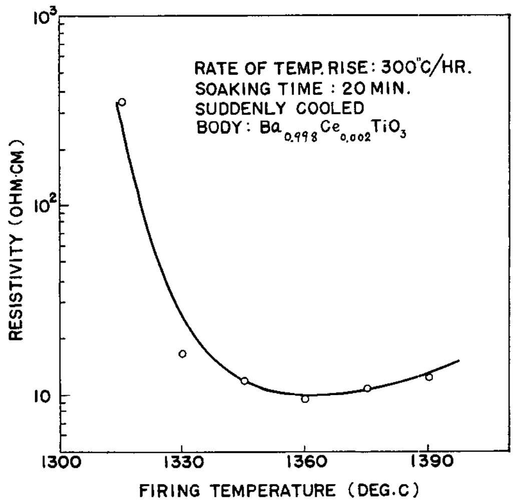


Fig. 8—Effect of firing temperature on resistivity.

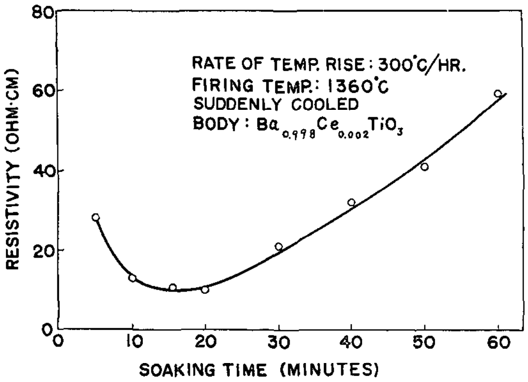


Fig. 9—Effect of soaking time on resistivity.

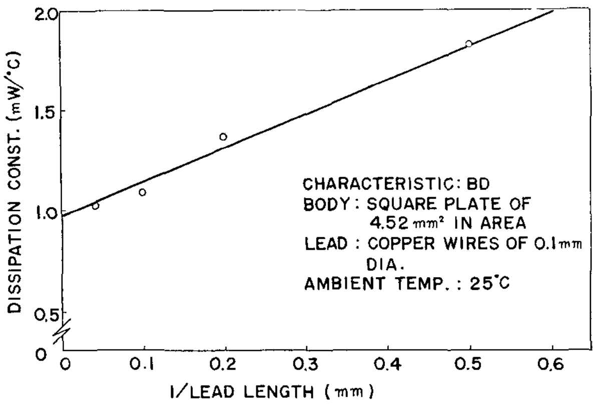


Fig. 10—Variation of dissipation constant with lead length.

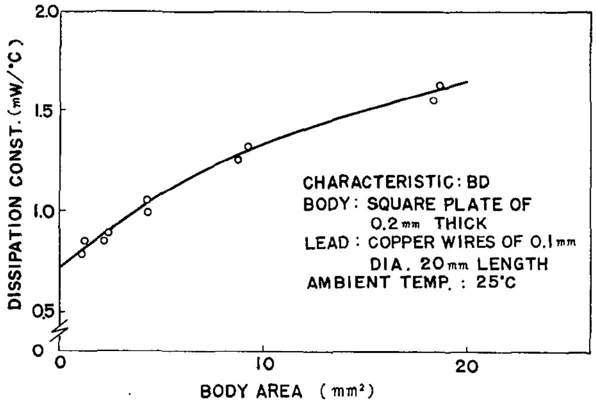


Fig. 11—Variation of dissipation constant with body area.

electrodes having good mechanical strength give another possible method of applying electrodes to the semiconducting ceramics.

To regulate the resistance of the posistor the areas of deposited nickel electrodes are frequently adjusted by sand-blasting. Then, a set of connecting leads are attached, usually by soldering, to the electrodes. Much of the heat dissipated in the posistor is dissipated through the leads, as will be discussed later in Section III-C. Fig. 10 shows an example of the manner in which the dissipation constant varies with lead length, when copper wires of 0.1 mm diameter were used Heat dissipation through the leads of 0.17 mW cm/°C in this instance, was comparable to that of the body shown in Fig. 11. Nickel wires are preferable because of their low thermal conductivity, when a smaller dissipation constant is desirable.

The final process is the application of an insulting coating, with or without markings to the body of the posistor. The coating materials must withstand the maximum operating temperature of the posistor. Thermosetting type epoxy- and silicone-resins are suitable for the purpose. The posistors in Fig. 3 that are coated with an epoxy-resin can operate continuously with a 150°C skin temperature.

III. Fundamental Characteristics of the Posistor

A. The Resistance-Temperature Characteristics

Although various resistivity-temperature characteristics are obtained in the semiconducting family of barium titanates as previously reported[7], the six typical characteristics shown in Fig. 12 are selected as the standards for practical applications.

Each characteristic in Fig. 12 can be regarded as a part of the prototype characteristic shown in Fig. 13, which has a negative resistivity-temperature characteristic up to a temperature T_P, a positive characteristic between temperatures T_P and T_N with a maximum temperature coefficient at T_M, and another negative portion above T_N.

Figs. 12 and 13 can be applied to the resistance-temperature characteristic of a posistor by the use of simple conversion factors.

If a logarithm of resistance R is proportional to the temperature (this is partially valid between T_P and T_N),

$$\log R = A'T + A'', \tag{1}$$

or

$$R = R_0 \exp AT. \tag{2}$$

The temperature coefficient α of the resistance defined by

$$\alpha = \frac{1}{R}\frac{dR}{dT} \tag{3}$$

is deduced from (2):

$$\alpha = A \tag{4}$$

If R_1 and R_2 are the resistances of the posistor at temperatures T_1 and T_2, respectively,

$$A = 2.303\,\frac{\log R_2/R_1}{T_2 - T_1} \tag{5}$$

$$R_0 = \frac{R_1}{\exp AT_1}. \tag{6}$$

Numerical values of A and R_0 can be calculated from the experimental data using these equations.

In the temperature regions above T_N and below T_P, $\log R$ is approximately proportional to the inverse absolute temperature,

$$\log R = \frac{B'}{T} + B'', \tag{7}$$

or

$$R = R_0 \exp \frac{B}{T}. \tag{8}$$

The temperature coefficient α is given by

$$\alpha = -\frac{B}{T^2}. \tag{9}$$

The constant B corresponds to the thermistor constant of the conventional thermistor. If R_1 and R_2 are the resistances of the posistor at temperatures T_1 and T_2, respectively,

$$B = 2.303 \frac{\log R_2/R_1}{1/T_2 - 1/T_1} \tag{10}$$

$$R_0 = \frac{R_1}{\exp B/T_1}. \tag{11}$$

Numerical values of B and R_0 can be calculated from the experimental data using these equations.

The constants A, B, and R_0 calculated for each characteristic in Fig. 12 are shown in Table II.

B. Types, Resistance Values

The posistor can be fabricated in various types as shown in Fig. 3. It is useful for practical applications to discuss examples of types and sizes, since the range of resistance values, available for each posistor type, is dependent on the physical dimensions and the resistance-temperature characteristic. The dissipation constant, the heat capacity, and the thermal time constant also are dependent on the type and the size.

Table III shows the dimensions of the posistor types illustrated in Fig. 14, the resistance ranges and characteristics available for each type. The resistance values in Table III are those measured at 25°C and at a sufficiently low applied voltage (0.1 to 1 volt) so that no appreciable self-heating of the posistors will occur. The resistance of the posistor measured at the above condition shall be hereafter denoted by R_{PO}.

C. Dissipation Constant

When a posistor whose temperature is T°C is in thermal equilibrium at an ambient temperature of T_0 °C, the electrical energy W fed into the posistor per unit time, and the thermal energy dissipated from the posistor per unit time, follow the relation:

$$W = VI = D(T - T_0) \tag{12}$$

where D (watt/°C) is the dissipation constant. It is assumed that no radiant energy is dissipated from the posistor. The dissipation constant is dependent on the style and the construction, as well as on the environmental conditions such as the thermal conductivity of the surrounding material, the flowing speed of the environmental fluid and the method of mounting the posistor. The dissipation constant should, therefore, be specified for the environmental conditions. Table IV lists typical values of dissipation constant obtained for each posistor type when mounted with lead wires 25 mm long in stationary air.

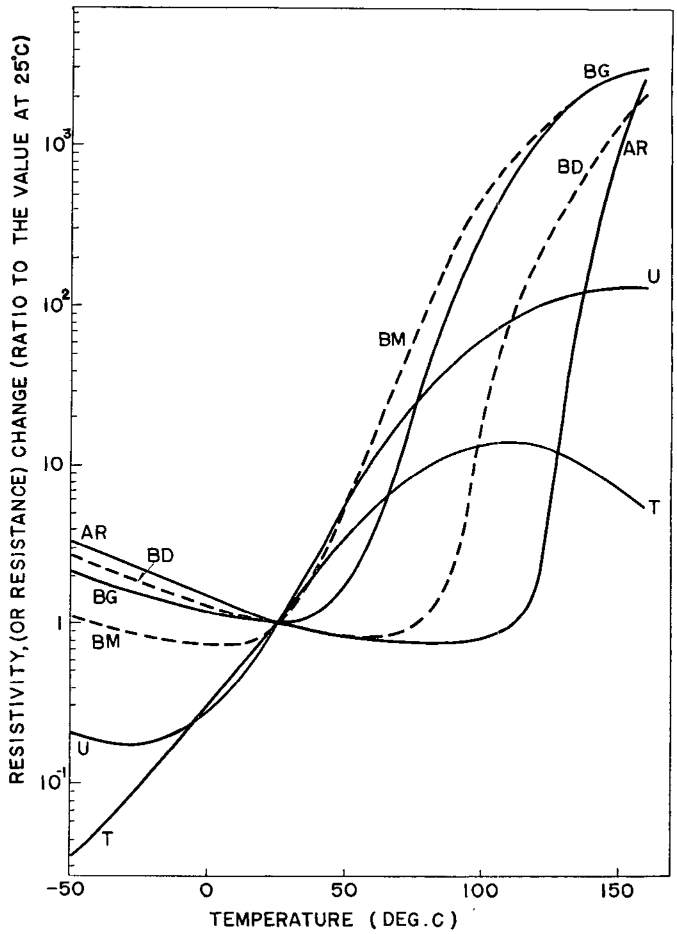


Fig. 12—Resistivity-temperature characteristics of posistor materials (resistance-temperature characteristics of the posistor).

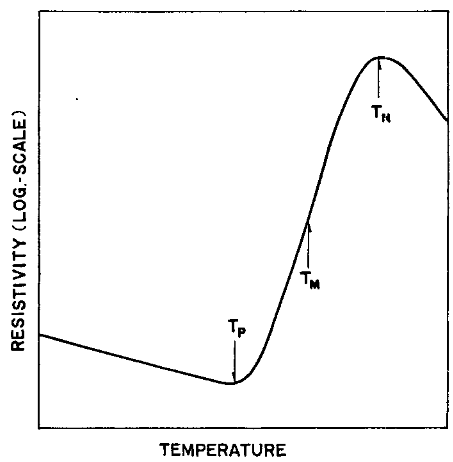


Fig. 13—Prototype resistivity-temperature characteristic of the posistor material.

D. Thermal Capacity

The thermal capacity H (watt sec/°C), a factor which governs the dynamic characteristic of the posistor, is determined by the mass and the specific heat of the

TABLE II

CONSTANTS OF RESISTANCE-TEMPERATURE CHARACTERISTICS OF POSISTORS

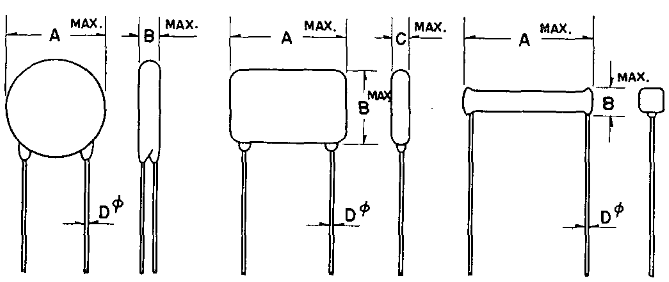
	Temp. Range								
	below T_P			between T_P and T_N			above T_N		
	Constants			Constants			Constants		
Characteristics	T_P (°C)	p^* —	B (°K)	T_M (°C)	p^* —	A (%/°C)	T_N (°C)	p^* —	B (°K)
AR	110	9.1×10^{-2}	6.8×10^2	130	1.6×10^{-16}	>30	>180	—	—
BD	80	9.1×10^{-2}	6.8×10^2	110	2.2×10^{-7}	>18	>180	—	—
BG	50	7.1×10^{-2}	7.5×10^2	75	1.5×10^{-3}	>14	>180	—	—
BM	15	1.0×10^{-1}	5.3×10^2	65	2.7×10^{-2}	>11	>180	—	—
U	−20	7.1×10^{-3}	7.5×10^2	55	1.7×10^{-1}	7.4	>170	—	—
T	<−50	—	—	50	3.2×10^{-1}	4.8	110	5.2×10^{-3}	3.1×10^3

* The values of R_0 are given by $R_0 = pR_{PO}$, where R_{PO} is the resistance value of individual posistor at 25°C.

TABLE III

DIMENSIONS AND AVAILABLE NOMINAL RESISTANCES OF POSISTORS

Type No.		60	61	62	63	40	81
Figure		Fig. 14(a)	Fig. 14(a)	Fig. 14(a)	Fig. 14(a)	Fig. 14(b)	Fig. 14(c)
dimensions (mm)	A	7.4	9.6	15.1	19.1	9.0	5.8
	B	5.0	5.0	5.0	5.0	4.8	3.0
	C	—	—	—	—	4.0	—
	D	0.5	0.65	0.65	0.65	0.5	0.5
Available Nominal Resistances (ohm)	Char. *AR*	8.4 ~ 60	4.8 ~ 33	2 ~ 19	1.2 ~ 8	200 ~ 1.8K	260 ~ 1.8K
	Char. *BD*	3.5 ~ 25	2 ~ 14	0.8 ~ 7.8	0.5 ~ 3.3	85 ~ 760	110 ~ 760
	Char. *BG*	42 ~ 300	24 ~ 165	9 ~ 93	6 ~ 39	1K ~ 9K	1.3K ~ 9K
	Char. *BM*	50 ~ 350	28 ~ 190	10.5 ~ 110	7 ~ 46	1K ~ 10K	1.4K ~ 10K
	Char. *U*	280 ~ 2K	160 ~ 1.1K	60 ~ 620	40 ~ 260	17K ~ 58K	9K ~ 58K
	Char. *T*	14K ~ 100K	8K ~ 55K	3K ~ 31K	2K ~ 13K	330K ~ 3M	440K ~ 3M



(a) (b) (c)

Fig. 14—Standard posistor styles.

TABLE IV

DISSIPATION CONSTANTS, THERMAL CAPACITIES, TIME CONSTANTS AND MAXIMUM ALLOWABLE POWERS OF POSISTORS

	Type No.					
	60	61	62	63	40	81
Dissipation Const.: D (mW/°C)	8	14	18	21	12	6
Thermal Capacity: H (watt/ sec/°C)	0.24	0.5	1.0	1.7	0.29	0.1
Time constant: T (sec)	30	37	53	80	24	17
Max. Allowable W_A Power: (watts)	1.0	1.8	2.3	2.6	1.5	0.7

All values in the table were obtained for typical examples.
Thermal capacity was calculated by (18).
Maximum allowable power: $W_A = 125\ D$.

posistor. The density of semiconducting barium titanate is about 5.6 gm/cm^3 and its specific heat is 0.12 to 0.14 cal/gm deg C. Representative values of the thermal capacity are shown in Table IV.

E. Static Characteristic

The static characteristic is the current vs voltage relationship when the posistor is in thermal equilibrium. The static characteristic of the posistor is distinguished by a current maximum as shown in Fig. 15, where static characteristics of posistors of various resistance-temperature characteristics are compared with those of the conventional thermistor. The static characteristic can be calculated as follows:

If the ambient temperature T_0 and the dissipation factor D are given, the input power W is calculated from (12) and the applied voltage V and the current I are given by

$$V = (RW)^{1/2}, \qquad I = (W/R)^{1/2},$$

if the resistance R is a function of the temperature. Plotting V against I provides the static characteristic. Should the resistance-temperature characteristic follow (2), the current I_m, the voltage V_m, the power W_m, the resistance R_m, and the posistor temperature T_m at the current maximum, are given by the relationships:

$$
\left.\begin{aligned}
I_m &= \frac{D}{AR_0}\exp\,(AT_0 - 1)^{1/2}\\
V_m &= \frac{DR_0}{A}\exp\,(AT_0 + 1)^{1/2}\\
W_m &= D/A\\
R_m &= R_0\exp\,(AT_0 + 1)\\
T_m &= 1/A + T_0.
\end{aligned}\right\} \tag{13}
$$

For type SW resistance-temperature characteristics (like AR in Fig.12) the formula:

$$R = R_{01}\exp AT + R_{02}\exp\,(B/T) \tag{14}$$

is valid as an approximation.

The first term, $R_{01}\exp AT$, in (14) gives the positive slope portion of the resistance-temperature characteristic, and the second term, $R_{02}\exp\,(B/T)$, the negative slope portion. No current maximum appears in the static characteristic insofar as the resistance has a negative temperature characteristic, hence, I_m, V_m and other terms at the current maximum in the static characteristic of the type SW positor are determined by expressions similar to those of (13), except that R_{01} is substituted for R_0.

Experimentally, it is shown that the static characteristics (in log V vs log I form) of posistors of different dissipation constant are very similar in their forms insofar as they have the same resistance-temperature characteristic and are at the same ambient temperature. Examples are shown in Fig. 16.

F. Dynamic Characteristic, Time Constant

In the transient state after a voltage is applied to a posistor, the current varies as shown in Fig. 17. When the applied voltage exceeds a certain value, the initial large current flow rapidly decays to a steady-state value owing to the increased resistance caused by the self-heating of the posistor.

The input power during dt time, $VIdt$, is equal to the sum of the thermal energy stored by the temperature rise of the posistor, HdT, and the thermal energy dissipated from it, $D(T - T_0)dt$, that is

$$VI\,dt = HdT + D(T - T_0)\,dt. \tag{15}$$

If VI is equal to zero, (15) is reduced to

$$H\,dT + D(T - T_0)\,dt = 0 \tag{16}$$

and the formula expressing the cooling characteristic of the posistor is given by

$$(T - T_0)/(T_i - T_0) = \exp\,(-Dt/H), \tag{17}$$

where T_i is the temperature of the posistor at $\tau = 0$. When the time t is equal to

$$\tau = H/D, \tag{18}$$

(17) is reduced to

$$(T - T_0)/(T_i - T_0) = 1/e. \tag{19}$$

The time τ, which is called the time constant of the

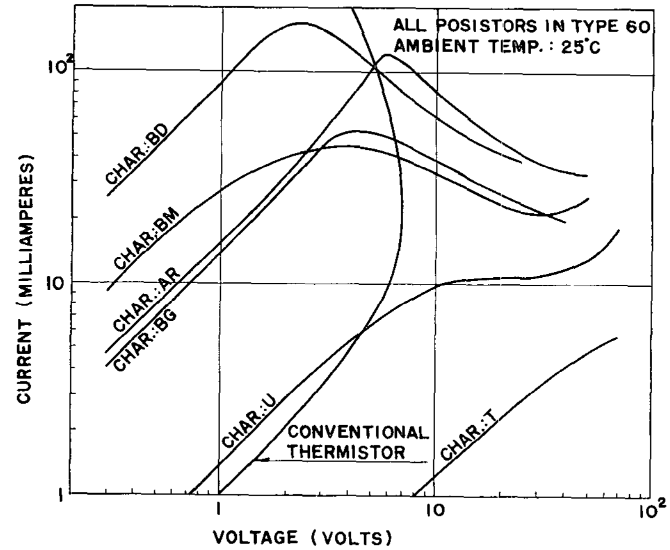


Fig. 15—Static characteristics of posistors having various resistance-temperature characteristics compared with that of a conventional thermistor.

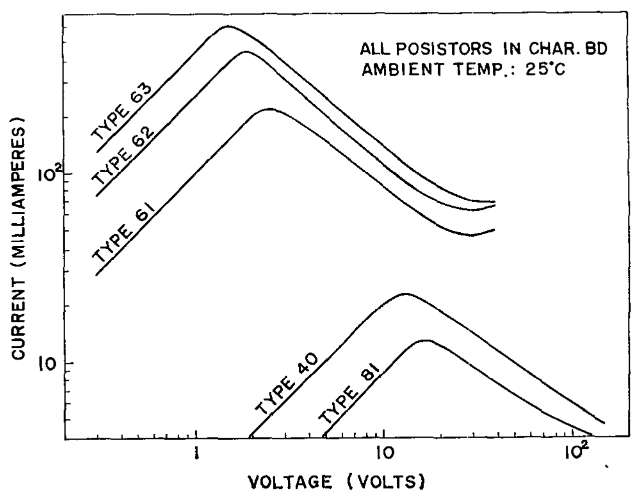


Fig. 16—Variation of static characteristic by the style of the posistor.

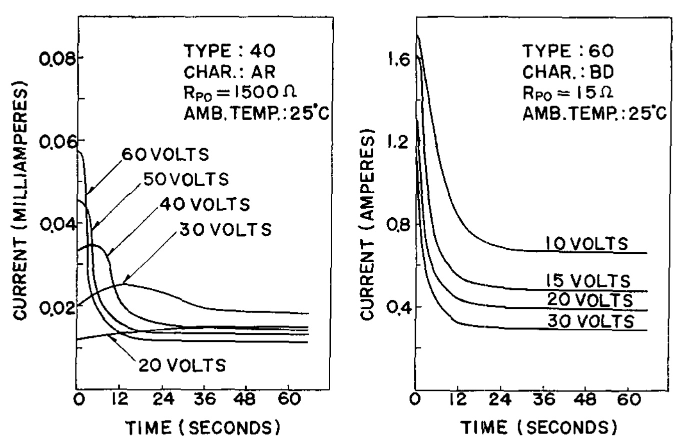


Fig. 17—Dynamic characteristics of posistors.

positor, can be obtained empirically from the cooling curve of the positor. Representative values of the time constant are shown in Table IV.

When the positor temperature is expressed as a function of the resistance R, $T = f(R)$, the relation of R vs time is reduced from (15) to

$$dt = \frac{\tau f'(R)R}{V^2/D - R\{f(R) - T_0\}} dR. \tag{20}$$

Because it is generally difficult to solve (20) a graphical method should be applied in practice.

G. Maximum Allowable Power

The damage to the positor under overload is considered to be caused only by overheating, hence the electric power required for heating the positor up to the maximum working temperature is the maximum operating power. The thermal damage takes the form of melted solder, burned coating materials, or a burned ceramic body. Unlike the negative resistance-temperature characteristic body which tends to run away when self-heating takes place, the positive resistance-temperature characteristic body has no run-away problem. However, run-away must still be considered for the positor when the temperature exceeds T_N, at which time the negative characteristic region is reached as shown in Fig. 13. Since the temperature T_N is higher than 180°C for most temperature characteristics, the maximum working temperature is usually limited by the melting point of the solder or the maximum allowable temperature of the coating materials. The maximum allowable power, W_A shown in Table IV is determined from (12) with $T = 150$°C and $T_0 = 25$°C.

H. Voltage Coefficient

Resistivity of the positor material is, to some extent, dependent on applied voltage as described in Section II. The voltage dependency is affected by the composition of the materials, and by the crystal phase, as well as by the sintering state. The resistivity is more dependent on applied voltage in the paraelectric phase, namely in the temperature region above T_P, than in the ferroelectric phase, namely in the temperature region below T_P. Fig. 18 shows the voltage dependencies of the resistivity for various positor materials whose characteristics have been improved by introducing mineralizers. Regardless of the nonlinear voltage dependency of the resistivity, the present paper conventionally applies the voltage coefficient defined as

$$\beta = \log (R_1/R_{10}),$$

where R_1 and R_{10} are the resistivities at applied voltages of 1 volt per mm and 10 volts per mm, respectively.

I. Noise in Positors

Fig. 19 shows an example of the noise characteristic in the positor, where V_n denotes the noise voltage pee applied voltage, for the noise spectrum between 300 and 3000 cps. Although the complete picture of the noirs

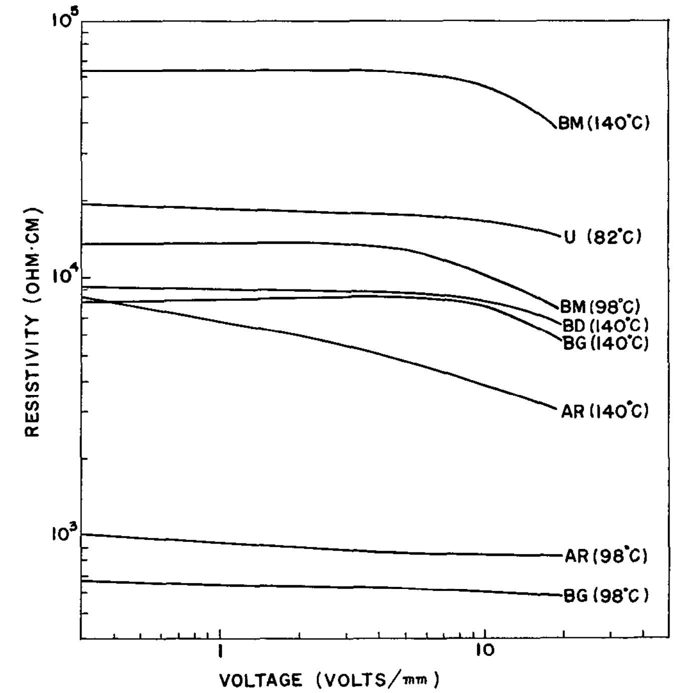


Fig. 18—Voltage dependencies of resistivity of positor materials.

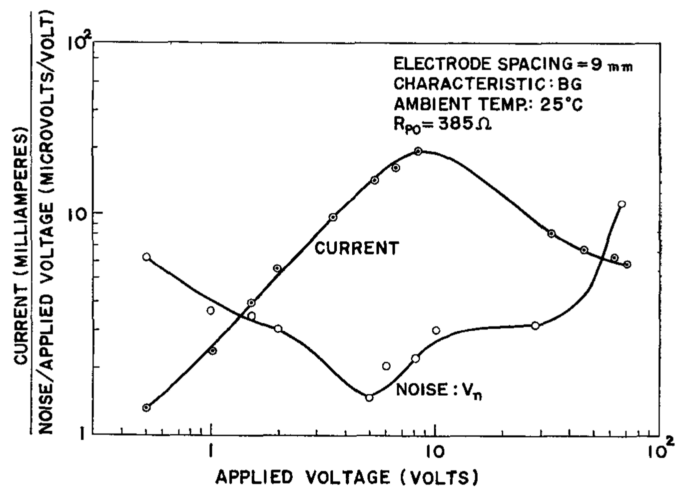


Fig. 19—Voltage dependency of noise in a positor.

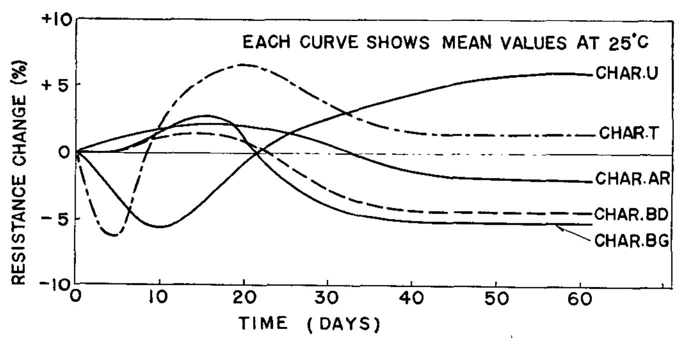


Fig. 20—Aging characteristics of positors.

characteristic is not yet known, the noise level seems to be similar to that of solid carbon resistors in the above frequency spectrum.

J. Long Term Stability

The long term stability of the posistors is not completely known, since it is effected by various factors such as the kind of materials, ambient temperature, humidity and applied voltage.

Fig.20 shows some examples of aging characteristics for posistors having various resistance-temperature characteristics, in a 25°C ambient temperature when no voltage is applied. Although the aging characteristics showed large variations for each of the various resistance-temperature characteristics, they seemed to settle down to within 6 per cent of an average value after 60 days.

IV. Applications of the Posistor

A. Classification

Each member of the two groups of the posistor characteristics, type SW and type TC, has its particular applications. The applications of the posistor may also be classified from different points of view, heat sensing element applications and heat dissipating element applications. Various applications of the posistor are listed in Table V according to the above classifications.

Some major applications of the posistor will be described in detail in Section IV-B and C.

B. Applications of the Type SW Posistor

Temperature Indicator: Application of the type SW posistor as a temperature indicator is easily imagined; for example the simple circuit shown in Fig. 21 is useful for indicating any overheating of power diodes when operated in parallel. A similar circuit is useful as a fire alarm. (Note: The posistor is hereafter denoted by the symbol shown in Fig. 21; resistor symbol and letter "P" surrounded by a circle.)

Temperature Control: The posistor, when used as a temperature sensing element, is able to control the power dissipated in a heater element connected in series with it (Fig. 22). However, in this instance, there is a limitation that the power to be consumed in the heater should be much less than the heat capacity of the posistor; otherwise, the posistor will self-heat above T_P. Hence, a relay must be introduced to control heavier power. Precise control may be obtained with the posistor combined with a silicon controlled rectifier (Fig. 23) or with a power transistor (Fig.24). Fig. 25 shows the temperature dependence of the collector current in the circuit of Fig. 24.

Thermal Protection: The posistor can be used to provide thermal protection for electric machines and apparatus. At least one American motor manufacturer makes a motor that is protected against overheating by a positive temperature coefficient thermistor (equivalent to the type SW posistor) mounted in the windings. Similarly, CdS batteries, used for controlling outdoor lamps, can be protected by a posistor.

TABLE V
Applications of the Posistor

Char.	Applications	
AR, BD, BG, BM	as a sensing element	Thermal indicator, Thermal regulator, Fire alarm, Level meter, Over-heat protector, No-contact switch.
	as a heat dissipater	Current limiter, Current stabilizer, Voltage stabilizer, Automatic volume control, Relay protection, Timer, Thermal chamber.
T, U	as a sensing element	Temperature compensation of electronic apparatus, voltage stabilizer, Thermometer, Humidity meter.
	as a heat dissipater	Current limiter, Current stabilizer, Voltage stabilizer.

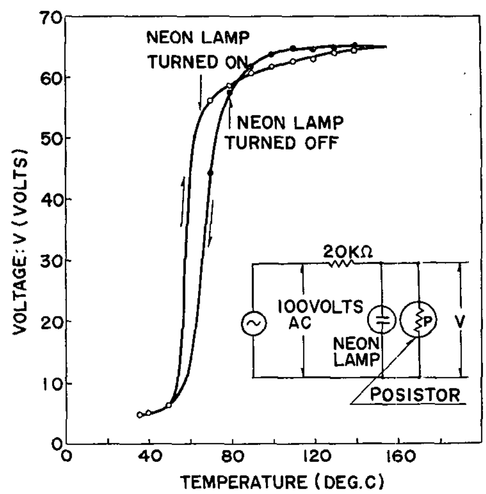


Fig. 21—Thermal indicator with a posistor.

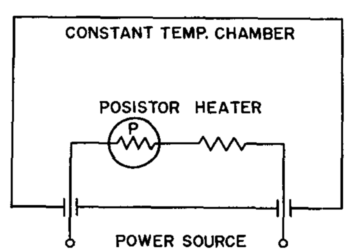


Fig. 22—Direct control of constant temperature chamber with a posistor.

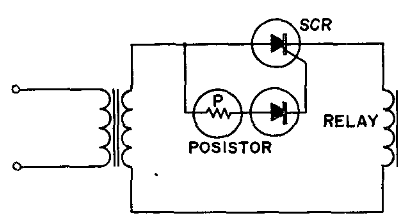


Fig. 23—Thermal relay with a posistor and a silicon controlled rectifier.

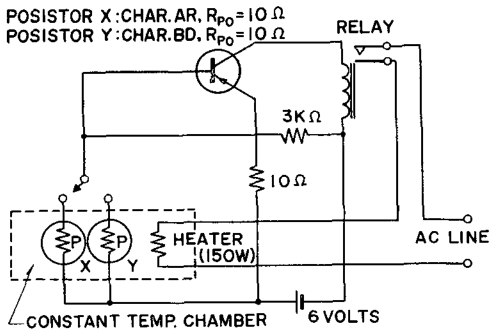


Fig. 24—Control of constant temperature chamber with posistors and a relay.

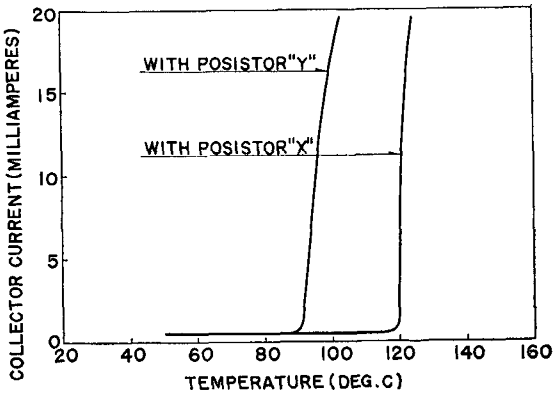


Fig. 25—Temperature dependency of the collector current in Fig. 24.

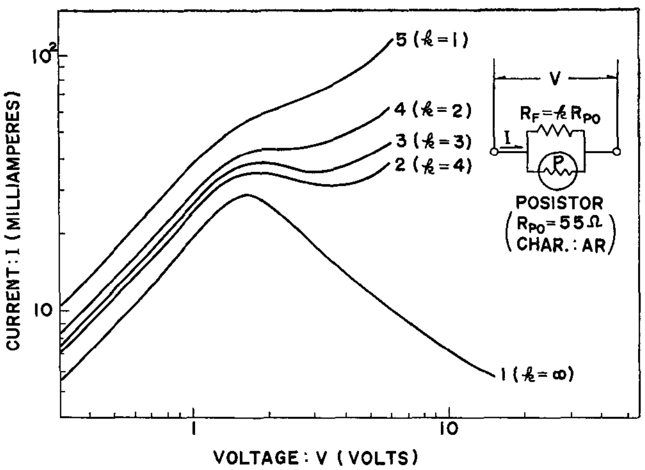


Fig. 26—Effect of a parallel resistance on the static characteristic of a posistor.

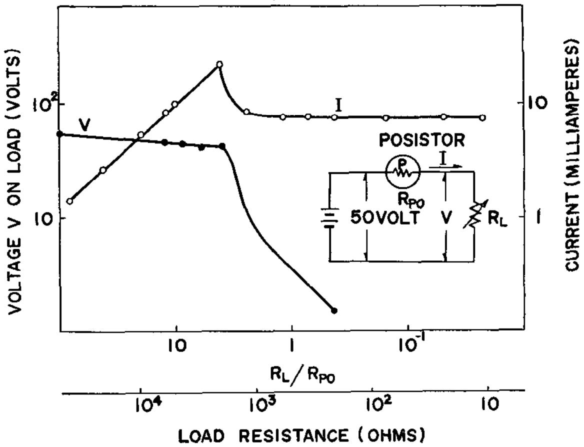


Fig. 27—Posistor as a current limiter.

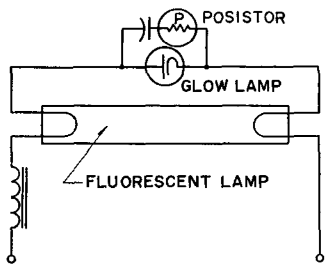


Fig. 28—Posistor protection of a fluorescent lamp.

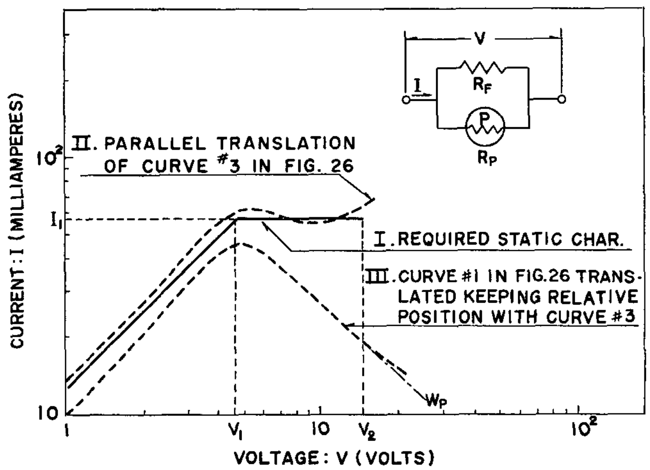


Fig. 29—Obtaining a posistor for a current stabilizer.

Modifying The Static Characteristics: The static characteristics described in Section III-E can be modified by connecting fixed resistors in parallel with a posistor (examples are shown in Fig. 26). The variety of the static characteristics obtainable will prove useful in the following applications.

Current Limiter: The action of the posistor when used as a current limiter is illustrated in Fig. 27. The posistor, which is a series resistor having low resistance when the load resistance R_L is high, begins to heat itself when R_L drops below a certain value thus limiting the current. Power supplies for electronic circuits can be protected against accidental short circuits of their output connections by the above action of the posistor.

The fluorescent lamp circuit shown in Fig. 28 can be protected by the posistor when the capacitor breaks down.

Current Stabilizer: The posistor with an appropriate parallel resistance acts as a current stabilizer as may be seen in Fig. 26. The method of obtaining the desirable elements is shown by the following:

Suppose there is a current stabilizer whose V-I characteristic should be as specified by curve I in Fig. 29. One may find a curve which best approximates curve I among the set of modified *V-I* characteristics of Fig. 26, by translating it in a parallel fashion and superimposing it on Fig. 29. A better curve might be found from the set of *V-I* characteristics derived from another resistance-temperature characteristic. Curve II in Fig. 29 denotes the one found by the above method, and curve III the corresponding *V-I* characteristic of the positor itself. The relative position of curve II to curve III in Fig. 29 is the same as that of curve III to curve I in Fig. 26. The initial resistance, R_{PO}, of the positor is calculated from the slope of the left side straight portion of curve III in Fig. 29. The right side straight portion of curve III is a constant power contour, W_P, and represents the power consumed in the positor when functioning in the current limiter mode. The dissipation constant D required for the positor is derived from (12);

$$D = W_P/(T_P - T_0),$$

where T_P is the temperature of resistance rise while T_0 is the ambient temperature.

Automatic Volume Control: The modified static characteristics shown in Fig. 26 can be used in automatic volume control devices. An example of such an application is illustrated in Fig. 30. In telephone systems, it is frequently necessary to maintain a relatively constant average current in the telephone transmitter to prevent drastic changes of response which sometimes even give rise to oscillation. A telephone transmitter, when used for a local line in a building, has a large feeding current because of the low line resistance. However, when the telephone is connected directly to an outer long distance line, the feeding current is decreased considerably due to the high line resistance. It is therefore advantageous to use an AVC device that tends to insert a variable damping resistance to compensate for these current changes.

Timing Applications: In the case of the conventional magnetic relay, it is desriable that the initial magnetizing current be large enough to permit the relay to close reliably, after which the current should be as small as required for holding the relay armature closed. Such changes in the magnetizing current, usually difficult to realize, can be readily attained by inserting a positor in series with the relay coil. The high initial magnetizing current is reduced by the self-heating of the positor after a short interval that is determined by the time constant of the positor. A typical example is shown in Fig. 31.

A magnetic relay can be operated as a timer when it is powered from a relatively constant current source and its closing time is controlled by a positor. In the circuit illustrated in Fig. 32 the positor will initially by-pass enough current to prevent the relay from being actuated. After a short period of time positor self-heating will cause the positor resistance to increase and permit the relay current to increase, thereby actuating the armature.

Other Applications: In addition to the applications previously discussed, the characteristics of the type SW positor can be utilized in various fields such as liquid

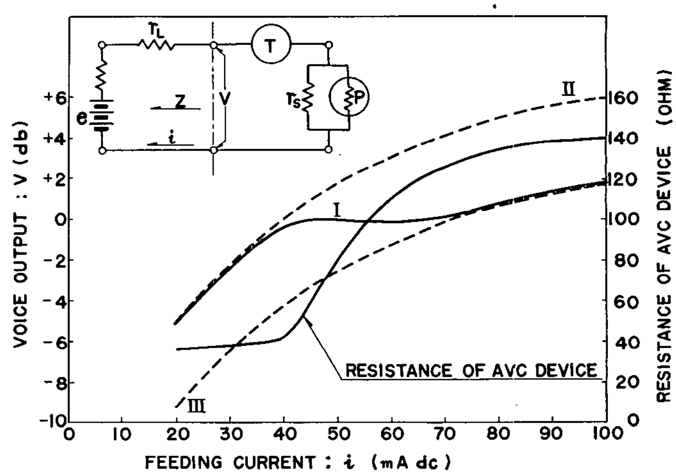


Fig. 30—Automatic volume control of a telephone transmitter with a positor. I. With AVC device consisting of a positor (bead type, *AR*, $R_{P0} = 47\Omega$) and a resistor ($r_s = 176\Omega$). II. With a fixed resistor (38Ω) instead of AVC device. III. With a fixed resistor (140Ω) instead of AVC device. $e = 48$ volt dc, r_L = line resistance $= 0 \sim 1.6\,K\Omega$, T = Transmitter ($Z_T = 60\Omega$), Z = line impedance $= 60\Omega$.

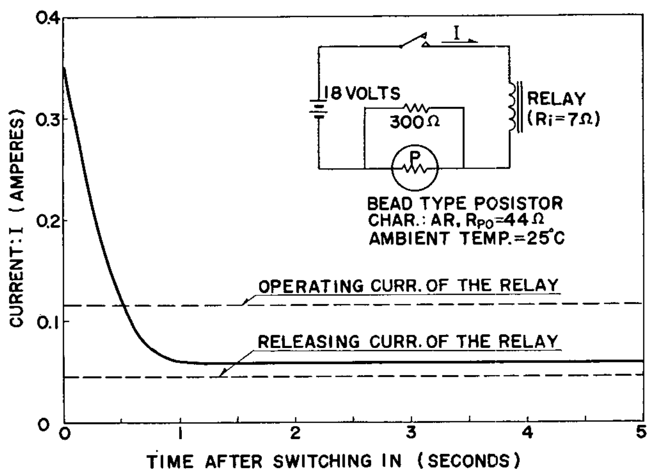


Fig. 31—Improving the operation of a relay with a positor.

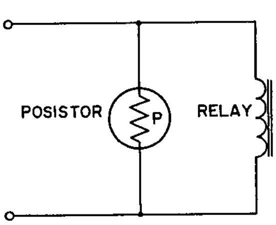


Fig. 32—Timer with a positor.

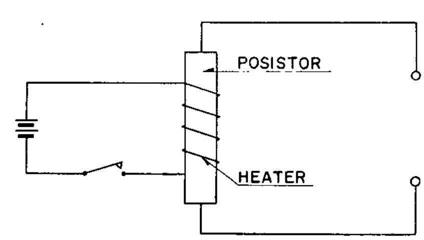


Fig. 33—No-contact switch with a positor.

level meters, over-current protection of transistors and diodes.

Fig. 33 shows an assembly of a no-contact switch. The posistor, when its temperature is controlled by a surrounding heater, can function as a switching element having no contact points.

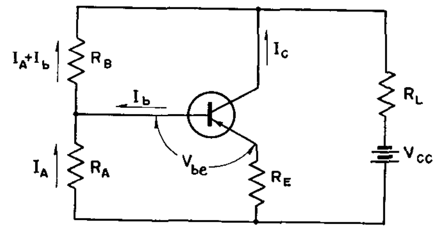


Fig. 34—Basic circuit of grounded-emitter transistor.

C. Temperature Compensation with the Posistor

The temperature compensation type posistors, type TC, have a sign opposite to the conventional thermistor; hence, they permit new techniques for compensating electronic circuits. Practical methods of compensation will be described, with examples of transistor circuits which require close temperature compensation due to their temperature-sensitive nature.

Temperature compensation of transistors should be, in a strict sense, the stabilizing of their performance for temperature variation. However, in practice, it is acceptable if the collector current I_c is stabilized. In the basic circuit of grounded-emitter transistor, Fig. 34, a conventional thermistor has been substituted for R_A to control the biasing voltage V_{be} and maintain I_c constant. In contrast, the posistor is to be substituted for R_B, R_E, or for R_L to accomplish the same purpose. The design considerations for compensating with posistors are as follows:

1) Above a certain temperature, say 50°C, the resistance of the thermistor used for R_A sometimes cannot be as low as required for complete compensation. In contrast, the resistance of a posistor used for R_B or R_E can change sufficiently to compensate the transistor up to its maximum operating temperature.

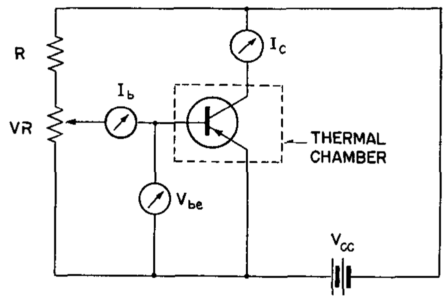


Fig. 35—Circuit for measuring basic temperature characteristics of a transistor.

mined first with the circuit shown in Fig. 35. As the temperature of the transistor is changed, V_R should be adjusted so that I_c is maintained constant, and I_b and V_{be} should be plotted against the temperature. A set of the temperature characteristics of I_b and V_{be} obtained through the above procedure shall be referred to as the basic temperature characteristics of the transistor.

In the circuit of Fig. 34, R_B, R_E and R_L are expressed by the following equations, respectively.

$$R_B = \frac{V_{cc} - V_{be} - R_E(I_c + I_b) - R_L\{V_{be}/R_A + (I_c + I_b)(1 + R_E/R_A)\}}{I_b(1 + R_E/R_A) + (V_{be} + R_E I_c)/R_A}, \qquad (21)$$

$$R_E = \frac{V_{cc} - V_{be}(1 + R_B/R_A) - R_B I_b - R_L(I_c + I_b + V_{be}/R_A)}{(I_c + I_b)(1 + R_B/R_A) + R_L(I_c + I_b)/R_A}, \qquad (22)$$

$$R_L = \frac{V_{cc} - I_b R_B - (1 + R_B/R_A)\{V_{be} + R_E(I_c - I_b)\}}{V_{be}/R_A + (I_c + I_b)(1 + R_E/R_A)}. \qquad (23)$$

2) A thermistor used for R_A , whose resistance has been decreased at high temperatures, lowers the input impedance and causes a power loss in the input circuit. However, a posistor used for R_B does not create these problems, as R_B usually has a much higher value than R_A.

3) Contrary to the case of the thermistor, which requires a bleeder current through R_A and R_B, the compensation with the posistor when it is used for R_B in a self-biasing circuit requires no bleeder current. Thus the load upon the battery is reduced.

The process of securing the posistor required for compensating transistor circuits shall be as follows: The temperature characteristics of the transistor should be deter-

The required temperature characteristic of R_B, R_E, or of R_L, that is the required temperature characteristic of the posistor, will be obtained by introducing the values of I_b and V_{be} at each temperature into (21), (22), or (23).

The general form equations shown above are reduced to simpler forms in practical circuits. For a fixed bias circuit, (21) reduces to

$$R_B = (V_{cc} - V_{be})/(I_b + V_{be}/R_A), \qquad (24)$$

as $R_L = R_E = 0$ in (21), similarly, for a self-bias circuit,

$$R_B = \frac{V_{cc} - V_{be} - R_L(V_{be}/R_A + I_c + I_b)}{I_b + V_{be}/R_A}, \qquad (25)$$

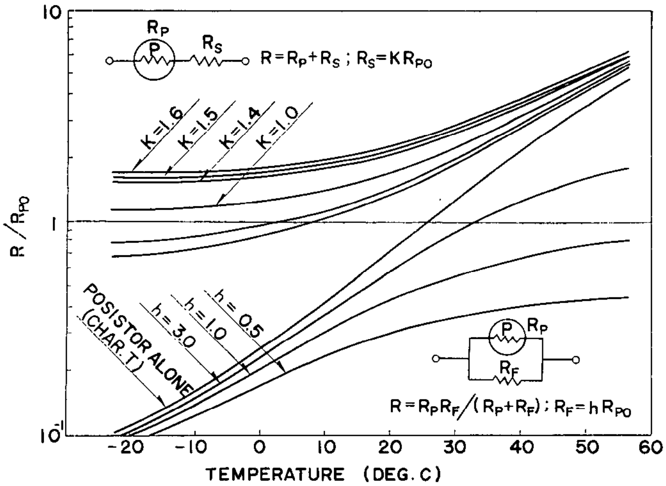


Fig. 36—Corrections of resistance-temperature characteristic of a posistor (For char. T).

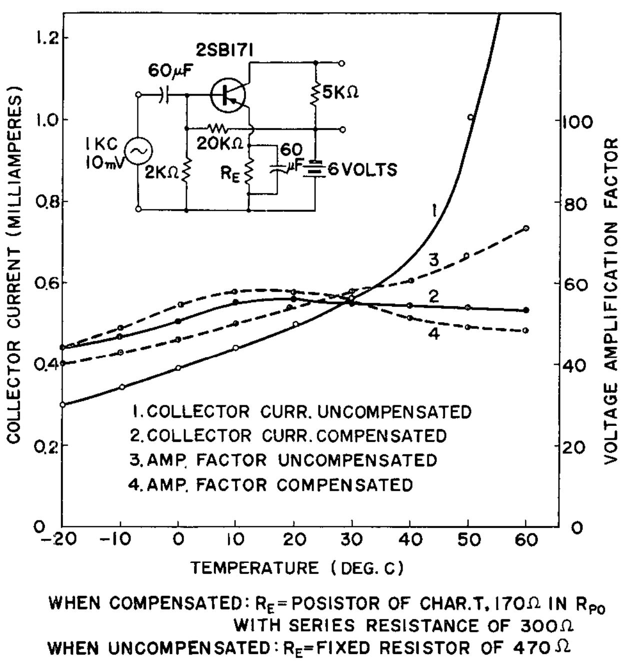


Fig. 37—Temperature dependencies of collector current and amplification factor in a transistor amplifier.

and for a current feedback circuit,

$$R_B = \frac{V_{cc} - V_{be} - R_E(I_c + I_b)}{I_b(1 + R_E/R_A) + (V_{be} + R_E I_c)/R_A} \tag{26}$$

$$R_E = \frac{V_{cc} - V_{be}(1 + R_B/R_A) - I_b R_B}{(I_c + I_b)(1 + R_B/R_A)}. \tag{27}$$

To obtain the best approximation of the required temperature characteristic, in practice, correction networks should be introduced. The fundamental characteristics of the posistor may be modified by the series and/or parallel resistors as shown in Fig. 36.

An example of a compensation application is shown in Fig. 37. The fixed resistor of 470 ohms, which had been used for R_E, was replaced by a posistor of characteristic T (see Fig. 36) and R_{PO} = 170 ohms and a series resistor of 300 ohms. The temperature dependance of the collector current and of the amplification factor were considerably reduced by the introduction of the posistor as shown in Fig. 37.

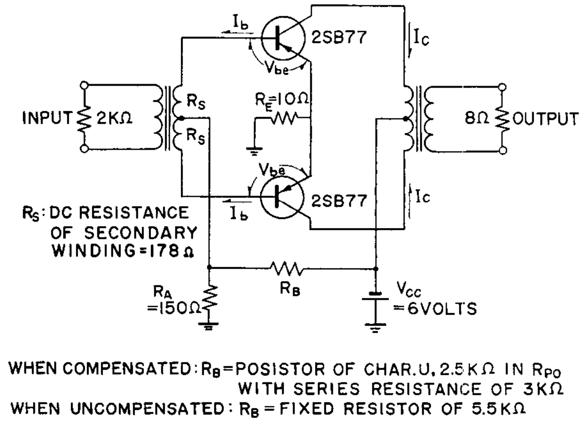


Fig. 38—Circuit of class B push-pull amplifier.

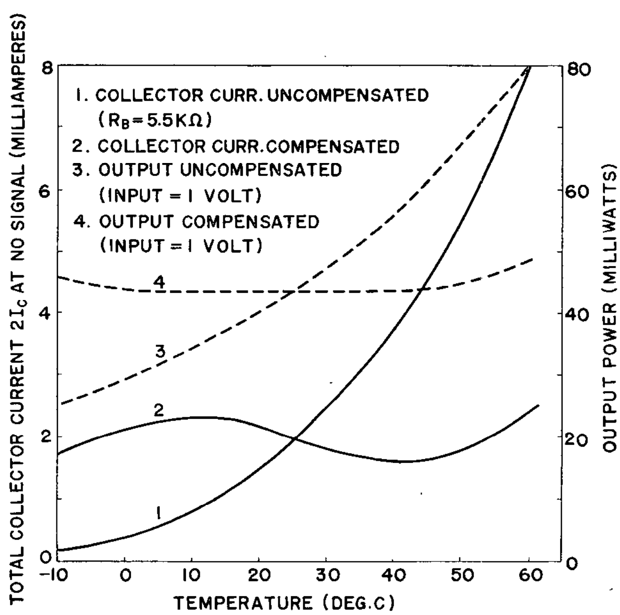


Fig. 39—Temperature dependencies of collector current and output power of the circuit in Fig. 38.

Another compensation application was studied for the case of a class B push-pull amplifier whose circuit is shown in Fig. 38. The bias resistance R_B is, in this instance, reduced to

$$R_B = \frac{V_{cc} - V_{be} - I_b(R_S + 2R_E) - 2R_E I_c}{V_{be} + I_b(R_S + 2R_E + 2R_A) + 2R_E I_c} R_A, \tag{28}$$

where I_c and I_b are the currents for a single transistor. A fixed resistor of 5500 ohms had been used for R_B when uncompensated. The posistor of characteristic U and R_{PO} = 2500 ohms and a series resistor of 3000 ohms was then substituted for R_B to attain the compensation. The results are shown in Fig. 39; the large temperature dependencies of the collector current and of the output power when uncompensated, were almost completely compensated in the temperature range studied. At temperatures below 10°C, the crossover distortion which had been appreciable due to the shift of operating point when uncompensated, was eliminated when the operation point was stabilized by compensation.

V. Conclusion

A survey of processing techniques for the posistor has been given with some detailed information to aid the readers' understanding of what posistors are and how they are produced.

The design criteria and fundamental characteristics of the posistor described in this paper, will be helpful when designing posistors into applications.

The various applications of the posistor shown in the paper, will familiarize the readers with this component, and also suggest additional applications.

Although the application of the posistor has some limitations because of its appreciable change in aging characteristics, it is believed that the posistor will find wide application because of its large positive temperature coefficient of resistance that has never been available in other resistive components.

List of Symbols

B = Thermistor constant (°K).
D = Thermal dissipation constant (watts/°C).
H = Thermal capacity (watt sec/°C).
R = Resistivity (ohm cm) or resistance (ohms).
R_{PO} = Resistance of the posistor measured at 25°C with sufficiently low applied voltage.
T = Temperature (°C or °K).
t = Time (sec).
T_O = Ambient temperature (°C or °K).
T_M = Temperature of maximum temperature coefficient of resistance (°C).
T_N = Temperature where negative characteristic appears with ascending temperature (°C).
T_P = Temperature where positive characteristic appears with ascending temperature (°C).
α = Temperature coefficient of resistance or of resistivity.
β = Voltage coefficient of resistivity.
τ = Thermal time constant (sec).

Acknowledgment

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Aspects Affecting the Reliability of a Carbon Composition Resistor*

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***Summary*—The mechanism of resistance drift of a 1-watt carbon composition resistor has been investigated, based on a study of the internal construction. Predominant physical and chemical processes under given environments are postulated. Aging mechanisms, the behavior of resistance drift under various environmental conditions over a period of time and failure modes are considered. Restrictions on application of the part and criteria for part selection are established. Failure analyses have also been performed to verify the postulated behavior mechanisms.**

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Introduction

In CONNECTION with component reliability, many life tests of carbon composition resistors have been performed and data obtained under various test conditions is available. However, no attempt has been made, so far, to discuss possible drift mechanisms, and hence even a qualitative prediction of resistance drift cannot be made.

The study of drift as well as of failure mechanisms is particularly useful not only when the application of a part is being considered but also for screening purposes,