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Reply to Attn of: GP

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(NASA-Case-MSC-11235) TEMPERATURE COMPENSATED CURRENT SOURCE Patent (NASA) 6 p CSCL 09C

N78-17294

Unclas 00/33 05410

TO: NHB/Scientific & Technical Information Office

FROM: GP-4/Office of Assistant General Counsel for Patent Matters

SUBJECT: Announcement of NASA-Owned U.S. Patents in STAR

In accordance with the procedures agreed upon by Code GP-4 and Code NHB, the enclosed NASA-owned U.S. Patent is being forwarded for abstracting and announcment in NASA STAR.

The following information is provided:

U.S. Patent No. : 3,573,504

Government or Corporate Employee : TRW, Inc. Redondo Beach, CA

Supplementary Corporate Source (if applicable) :

NASA Patent Case No. : MSC-11,235

NOTE - Is this an invention made by a corporate employee of a NASA contractor? YES [X] NO [ ]

If "YES" is checked, the following is applicable: Pursuant to Section 305(a) of the National Aeronautics and Space Act, the name of the Administrator of NASA appears on the first page of the patent; however, the name of the actual inventor (author) appears at the heading of column No. 1 of the Specification, following the words "...with respect to an invention of ..."

Elizabeth A. Carter

Enclosure

No patent appl.

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Malibu, Calif.
[21] Appl. No. 698 239
[22] Filed Jan. 16, 1968
[45] Patented Apr. 6, 1971
[73] Assignee TRW Inc.
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[54] TEMPERATURE COMPENSATED CURRENT SOURCE

3 Claims, 3 Drawing Figs.

[52] U.S. Cl. 307/270, 307/297, 323/4, 328/172
[51] Int. Cl. G05f 1/40
[50] Field of Search 307/270, 297; 328/172, 183, 184; 323/4, 20

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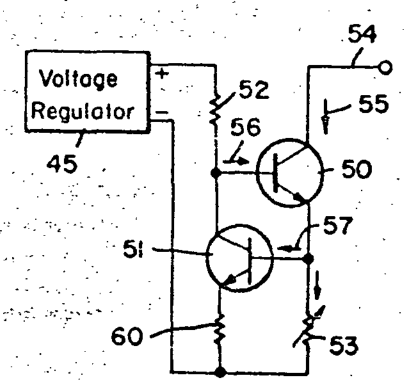
ABSTRACT: A current source which is substantially independent of variations of temperature. Thus the current source may be made either to have a linear dependence upon changes of temperature or, by the simple addition of a resistor, may be made substantially independent of temperature variations. Since the current source consists only of transistors of one conductivity type and resistors, it is ideally suited for manufacture in the form of a monolithic integrated circuit. The invention described herein was made in the performance of work under a NASA contract and is subject to the provisions of Section 305 of the National Aeronautics and Space Act of 1958, Public Law 85-568.



Patented April 6, 1971 3,573,504

Fig. 1

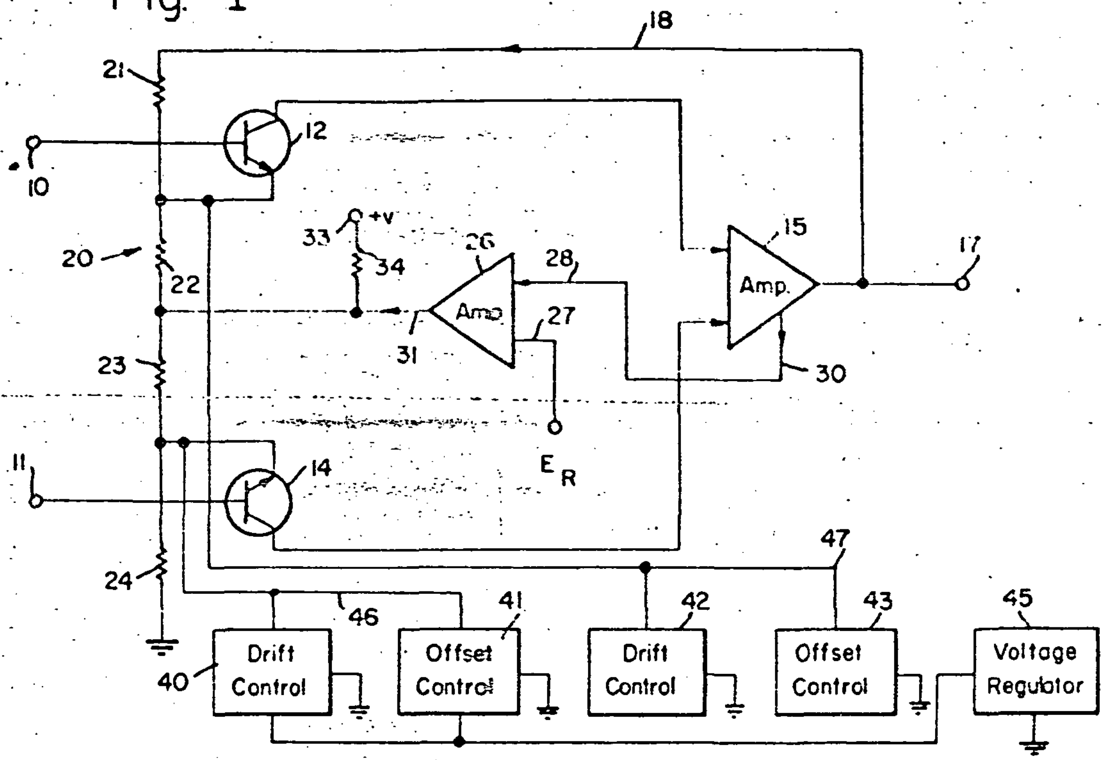


Fig. 2

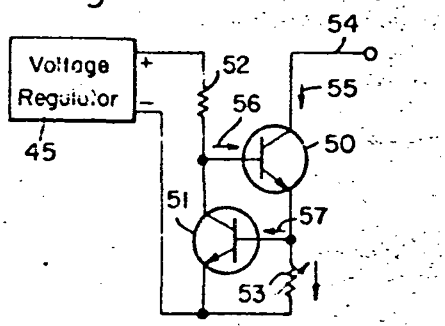
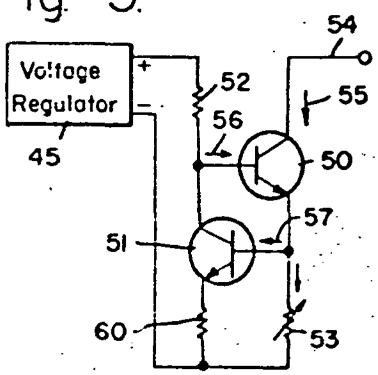


Fig. 3



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TEMPERATURE COMPENSATED CURRENT SOURCE

BACKGROUND OF THE INVENTION

This invention relates generally to current sources, and particularly to a current source which may be made either substantially temperature independent or linearly dependent upon temperature variations.

For many purposes current sources are needed where the output current substantially does not vary with temperature over a wide temperature range. For example, in order to have a precision analog circuit such current sources may be needed as the energy sources of the amplifiers. Also amplifier drift may be compensated by utilizing a current source having a known linear dependency on temperature.

It is accordingly an object of the present invention to provide a current source, the output current of which varies linearly with variations of temperature.

Another object of the invention is to provide a current source of the character discussed which may be made substantially independent of temperature variations over a wide temperature range by the simple addition of a resistor.

A further object of the present invention is to provide a temperature stable current source consisting of resistors and transistors so that it may readily be manufactured in the form of a monolithic integrated circuit.

SUMMARY OF THE INVENTION

In accordance with the present invention there is provided a current source for providing an output current which is approximately independent of temperature variations. Thus the output current may be made either independent of or linearly dependent upon temperature changes. Such a current source is ideally suited to compensate the inherent temperature drift of a direct-coupled differential-input amplifier.

The current source comprises two transistors which are interconnected in such a manner as to provide a feedback loop. To this end the base of the first transistor is connected directly to the collector of the second transistor, while the emitter of the first transistor is connected directly to the base of the second transistor. A first resistor is connected between one terminal of a source of regulated voltage and the collector of the second transistor as well as the base of the first transistor. Finally, a second resistor is provided between the junction point of the emitter of the first transistor and the base of the second transistor on the one hand, and the other terminal of the voltage source on the other hand. Further, the emitter of the second transistor is also connected to the other terminal of the voltage source.

Accordingly an output current is available from the collector of the first transistor which is substantially linearly dependent on temperature. This is true as long as the reciprocal value of the beta of each transistor is substantially negligible compared to 1.

In order to make the output current substantially independent of temperature variations, all that is necessary is to connect a third resistor between the emitter of the second transistor and the other terminal of the voltage regulator.

The novel features that are considered characteristic of this invention are set forth with particularity in the appended claims. The invention itself, however, both as to its organization and method of operation, as well as additional objects and advantages thereof, will best be understood from the following description when read in connection with the accompanying drawings, in which:

BRIEF DESCRIPTION OF THE DRAWING

FIG. 1 is a circuit diagram, partly in block form, of a differential-input amplifier which may utilize the current sources of the present invention;

FIG. 2 is a circuit diagram of a current source embodying the present invention for delivering an output current which is linearly dependent on temperature variations and which may be used with the amplifier of FIG. 1; and

FIG. 3 is a circuit diagram of a modified current source in accordance with the present invention for delivering an output current which is substantially independent of temperature variations and which may also be used with the amplifier of FIG. 1.

DESCRIPTION OF THE PREFERRED EMBODIMENT

Referring now to the drawing, there is illustrated in FIG. 1 a differential-input amplifier. This amplifier is claimed in the copending application of the present inventor, entitled "Direct-Coupled Differential-Input Amplifier," filed concurrently herewith and assigned to the assignee of the present invention. The current sources of FIGS. 2 and 3 which embody the present invention may be used with the amplifier of FIG. 1, although this amplifier may use other previously known current sources.

The differential amplifier of FIG. 1 has a pair of input terminals 10 and 11 from which the differential-mode input signal is available. As explained before, the differential-mode signal is the desired signal between terminals 10 and 11 and preferably is an input voltage. The undesired common-mode component is that component which is common to the two input terminals 10 and 11. Typically the common-mode component may be on the order of volts, while the desired differential-mode signal may be as low as microvolts.

The input signal is impressed on a pair of input transistors 12 and 14 which, as shown may be of the NPN type. In any case they should both be of the same conductivity type. The input signals are impressed on the two bases of the input transistors 12 and 14, and accordingly the input terminals 10 and 11 are respectively connected to the two bases.

The output signal is obtained from the two collectors of the two input transistors 12 and 14 and is directly impressed on the two input terminals of an amplifier 15 which may be called the differential-mode amplifier. The differential-mode amplifier 15 has a single-ended output terminal 17 on which the amplified differential-mode signal is obtained.

A feedback connection 18 is provided between the output terminal 17 of the differential-mode amplifier 15 and ground and includes a resistive feedback network 20 consisting of resistors 21, 22, 23 and 24 connected in series with each other and between the amplifier output terminal 17 and ground. The feedback connection is completed to the emitters of the two input transistors 12 and 14. This emitter feedback connection is important for the operation of the amplifier of the invention. Accordingly, the junction point between resistors 21 and 22 is connected to the emitter of transistor 12. Similarly, the junction point between resistors 23 and 24 is connected to the emitter of transistor 14.

Further in accordance with the present invention, there is provided a high-gain common-mode feedback loop including a stabilizing amplifier 26. The amplifier 26 has one input terminal 27 connected to a point of reference potential shown as E_R. *This may be any suitable stable voltage including ground. The other input terminal 28 of the stabilizing amplifier 26 is connected to an output terminal 30 of the differential-mode amplifier 15. From this output terminal 30 there is available the common-mode signal. This may be considered proportional to the average collector currents of the input transistors 12 and 14. The stabilizing amplifier 26 accordingly develops an output current at its output terminal 31 having a magnitude which depends on the difference of the voltages at its input terminals 27 and 28. In other words, it develops an output current which varies with variations of the common-mode signal.*

In order to complete the common-mode feedback loop, the output terminal 31 of the stabilizing amplifier 26 is connected to the junction between resistors 22 and 23. Thus the emitter currents of the input transistors 12 and 14 are held constant under conditions of changing currents in the resistive feedback network 20. A positive voltage source 33 may be connected to the amplifier output terminal 31 by a resistor 34 as shown.

As stated above, it is the function of the stabilizing amplifier 26 to develop an output current of a magnitude and direction to compensate for variations of the common mode voltage component at the input terminals 10 and 11. Stated another way, the common mode feedback loop including the stabilizing amplifier 26 controls the operating bias levels for the transistors 12 and 14 so that the overall gain of the differential-mode amplifier remains constant in spite of variations of the common-mode input voltage component.

The amplifier circuit as described so far has a differential input and a single-ended output and affords a high rejection of the common-mode component. The common-mode rejection may be at least as large as 100 db. (decibels). On the other hand, the amplifier circuit as described so far does not compensate for possible temperature drift nor for inherent voltage offset. Thus the amplifier is operative if it is maintained at a constant temperature and if the inherent voltage offset can be minimized for any particular application. However, if the ambient temperature varies over a wide range, say, from −40° C. (centigrade) to +100° C., some provision must be made to prevent output signal variations with temperature variations.

In accordance with the present invention, this is effected by the provision of a drift control circuit 40 and an offset control circuit 41 for supplying current to the emitter of transistor 14, and a similar drift control circuit 42 and offset control circuit 43 for supplying operating current to the input transistor 12. The two drift control circuits 40 and 42 are designed to develop an output current which varies linearly with temperature variations. Hence they compensate for temperature drifts. On the other hand, the offset control circuits 41 and 43 control current offset and deliver an output current which is substantially independent of temperature variations.

To explain the functions of the drift control circuits 40,42 and of the offset control circuits 41,43, we may consider a plot of the voltage as a function of temperature variations. It is the function of the drift control circuits to control the slope of the voltage-versus-temperature curve. On the other hand, the offset control circuit controls the absolute value of the voltage. In other words, this makes it possible to have a zero output voltage for a zero input voltage, provided the slope of the curve has been made 0° by proper control of the drift control circuits.

The control circuits 40 through 43 may each have an input connected to a voltage regulator 45 for supplying thereto a regulated input voltage. As shown, the other terminal of the voltage regulator 45 and of the control circuits 40 to 43 may be grounded. The drift and offset control circuits 40 and 41 have an output lead 46 connected to the emitter of transistor 14. Similarly, the drift and offset control circuits 42 and 43 have an output lead 47 connected to the emitter of input transistor 12.

It has been found that by adjusting the relative components of the currents delivered by the drift and offset control circuits 40 and 41, or 42 and 43, the amplifier can be so adjusted that the differential-mode signal obtained at output terminal 17 is rendered substantially independent of temperature variations. Also the differential-mode signal at output terminal 17 may be made zero for a zero input signal. Actually it has been found that the temperature drift for a temperature range between −40° C. and +100° C. may be maintained to be less than 0.05 uv/° C. (uv indicating microvolts).

It will also be appreciated that current sources such as the drift control circuits 40 and 42 which deliver an output current linearly dependent on temperature variations are well known. Similarly, offset control circuits such as 41 and 43 which deliver an output current substantially independent of temperature variations are also well known. However, it has been found that the circuits illustrated in FIGS. 2 and 3 are particularly suitable for this purpose.

The following formula shows why the output voltage of the amplifier of FIG. 1 can be made independent of temperature. In the following formula v_o is the output voltage obtained at output terminal 17. I_A indicates the current flowing in the lead 47. Similarly, I_B is the current flowing in lead 46. Furthermore, vA is the input voltage at input terminal 10, while vB is the other input voltage at the terminal 11. Finally, R_1 is the combined resistance of resistors 22 and 23, and R_2 is the combined resistance of resistors 21 and 24. The following formula is thus obtained for v_o:

$$v_o = (I_A - I_B) R_2 + (v_{IA} - v_{IB}) \frac{(R_2 + R_1)}{R_1} \qquad (1)$$

Formula (1) shows that v_o may be made temperature independent by a proper adjustment of the currents I_A and I_B, because both currents contain separately a temperature independent and a linearly temperature dependent component. Thus by adjustment of the relative currents obtained from the drift control circuits 40 and 42 compared to the currents obtained from the offset control circuits 41 and 43, the output voltage v_o may be made temperature independent. The voltage v_o may also be made zero for a zero input signal, that is, when vA equals vB. This is the function of the offset control.

Referring now to FIG. 2, there is illustrated a transistor circuit which may be considered as a current source delivering an output current which is a linear function of the temperature. Accordingly the circuit of FIG. 2 may be used to obtain the drift control shown at 40 and 42 in FIG. 1. The circuit of FIG. 2 includes a pair of transistors 50 and 51 which may be of the NPN type as shown. In any case they should both be of the same conductivity type.

The two transistors 50 and 51 are connected directly to each other to form a feedback loop. Accordingly the collector of transistor 51 is connected directly to the base of transistor 50. Similarly, the emitter of transistor 50 is directly connected to the base of transistor 51.

As mentioned before, the transistors are preferably supplied with a regulated voltage from the voltage regulator 45. Thus the positive terminal of the voltage regulator may be connected by a resistor 52 to the base of transistor 50 and the collector of transistor 51. The negative terminal of the voltage regulator 45 is directly connected to the emitter of transistor 51. The emitter of transistor 50 and the base of transistor 51 are connected through a resistor 53 to the emitter of transistor 51 and to the negative terminal of the voltage regulator. Finally, the output current is obtainable from the output terminal 54 connected to the collector of transistor 50.

With the voltages of the voltage regulator and the conductivity types of the two transistors as shown, current flows into the collector of transistor 50, as shown by the arrow 55. There is further a closed current loop which may be traced from the collector of transistor 51 to the base of transistor 50, as shown by arrow 56, and then through the emitter of transistor 50 and the base of transistor 51, as shown by the arrow 57.

It will be realized that the alpha of a junction transistor generally varies nonlinearly with temperature. The alpha of a transistor is defined as the variation of the collector current with variations of the emitter current, the voltage between collector and emitter being maintained constant. Similarly, the beta of a transistor is defined as the variation of the emitter current with variations of the base current, the voltage between collector and base being maintained constant.

For further discussion it will be assumed that the two transistors 50 and 51 are closely matched with respect to their alphas and betas. In other words, we have to assume that the collector currents of the two transistors, as well as the betas of the two transistors, are approximately equal. In that case their base currents will also be equal. Accordingly, if the collector current of transistor 51 is approximately constant with temperature, the change of the voltage drop between base and emitter of transistor 51 will be extremely linear with temperature. Accordingly, the current through resistor 53 equals the output current which is shown by the arrow 55. The reason is that equal currents flow as shown by the arrows 56 and 57. Therefore the output current is also a very linear function of temperature.

Since equal currents flow in the directions shown by arrows 56 and 57, it will be apparent that the output current also flows through resistor 53. Therefore the magnitude of the output current may be controlled by varying the resistance of the resistor 53 as shown. This is the manner in which the drift control circuits 40 and 42 may be adjusted.

The circuit of FIG. 2 may be mathematically analyzed and the following formula may be obtained:

$$I=\frac{\left(1-\frac{R}{\beta_1 R_1}\right)\frac{V_1}{R}+\frac{1}{\beta_1 R_1}(E-V_2)}{1+\frac{1}{\beta_1}+\frac{1}{\beta_1\beta_2}} \quad (2)$$

In the above formula, I is the output current, that is, the current flowing through the output terminal 54. R is the resistance of resistor 53. β_1 is the beta of transistor 51. β_2 is the beta of transistor 50. R_1 is the resistance of resistor 52. E is the output voltage developed by voltage regulator 45. V_1 is the base-emitter voltage of transistor 51, and V_2 is the base-emitter voltage of transitor 50.

Assuming that $1/\beta_1$ may be neglected with respect to 1, and that $1/\beta_2$ may be neglected with respect to 1, formula (2) may be simplified as follows:

$$I\simeq\frac{V_1}{R} \quad (3)$$

This condition may be expressed another way, namely, if β_1 and β_2 is each larger than 100, the reciprocal of beta certainly can be neglected with respect to 1.

Formula (3) shows that I, the output current, is a linear function of temperature because V_1 is a linear function of temperature, as are the betas of the transistors.

Accordingly the circuit of FIG. 2 will deliver an output current which is a linear function of temperature under the conditions referred to above. The circuit may be used for the drift control circuits 40 and 42. Also the magnitude of the output current may be adjusted by adjusting the resistance of resistor 53.

By a simple modification the circuit of FIG. 2 may be made to deliver an output current which is substantially independent of temperature. This is illustrated in FIG. 3. The circuit of FIG. 3 is identical to that of FIG. 2 except that a resistor 60 is connected between the emitter of transistor 51 and the negative terminal of the voltage regulator 45.

In the circuit of FIG. 3 there is a 100 percent feedback loop between the two transistors 50 and 51. Accordingly the voltage across resistor 53 is stabilized with temperature if the ratio of the resistance of resistor 60 to that of resistor 52 is equal to the alpha of transistor 51 which is in the neighborhood of one. It should also be assumed that the voltage gain of the network consisting of transistor 51, resistor 52 and resistor 60 is unity. It has already been explained that the output current flow through output terminal 54 is equal to the current through resistor 53. Therefore it will be apparent that the output current is constant with temperature and is inversely proportional to the resistance of resistor 53. In other words, the magnitude of the output current may again be adjusted by an adustment of the resistance of resistor 53. As pointed out before, this affords a simple manner in which the output current of the offset control circuits 41 and 43 may be adjusted.

The temperature independence of the output current of the voltage source of FIG. 3 may also be shown mathematically as follows. Assuming that the resistances of resistors 52 and 60 are equal, the output current I is determined by the following formula:

$$I=\frac{1}{R}\times\frac{\left[1+\frac{1}{\beta_1}\left(1+\frac{R}{R_1}\right)\right]E+\left(1+\frac{1}{2\beta_1}\right)(V_1-V_2)-\left[\frac{1}{2\beta_1}\left(1+\frac{2R}{R1}\right)(V_1+V_2)\right]}{2\left[1+\frac{1}{2\beta_1}+\frac{1}{\beta_2}\left(1+\frac{1}{\beta_1}\right)\left(1+\frac{R_1}{2R}\right)\right]} \quad (4)$$

This formula (4) may again be simplified provided the previous assumption is true that the reciprocals of the betas of the two transistors may be neglected compared to 1; or, put in other words, that the betas of the two transistors should be no less than 100. Furthermore, we assume that the input voltage E is greater than $2V_1$ or $2V_2$. The reason for that is that the input voltage should be larger than the voltage drops between the base and emitters of the two transistors connected in cascade. Practically, the input voltage E should be greater than $10V_1$ or $10V_2$. With these assumptions, formula (4) may be simplified as follows:

$$I\simeq\frac{E}{2R} \quad (5)$$

Formula (5) shows that the output current is indeed independent of temperature because both E, the input voltage, and R, the resistance of resistor 53, are assumed to be temperature independent.

It will be understood that the circuit specifications of the voltage source of FIG. 2 may vary according to the design for any particular application. However, the following circuit specifications have been found to be suitable for use with a direct-coupled differential input amplifier of the type shown in FIG. 1:

Resistor 52	130,000 ohms
Resistor 53	12,000 ohms
Transistor 50	Type 2N918
and	
Transistor 51	Type 2N918

With the circuit specifications given above, the current source of FIG. 2 develops an output current which is a linear function of temperature and which, when plotted, deviates less than 0.1 percent from a straight line over a temperature range between −40° C. and +100° C.

For the current source of FIG. 3, the same transistor types may be used and the following resistance values been found to be suitable for application as a drift control circuit of the type shown in FIG. 1:

Resistor 52	47,000 ohms
Resistor 60	47,000 ohms
Resistor 53	38,000 ohms

With the above circuit specifications, the current source of FIG. 3 is substantially independent of temperature within a range of −40° C. to +100° C. and is stable within 10 to 100 parts per million/° C.

As pointed out before, the circuits of FIGS. 2 and 3 are particularly suitable for use in the form of a monolithic integrated circuit. In that case the characteristics of transistors 50 and 51 will be very closely matched. It is also feasible to obtain at least a small adustment of the resistor 53. Thus assuming that the resistors are cermet resistors which may consist, for example, of chromium with silicon monoxide having a thickness on the order of 300 A. (Angstrom units), the resistance may be adjusted after the circuit has been made, for example, by heating the cermet material of a particular resistor such as 53.

There has thus been disclosed a current source which consists only of transistors of one conductivity type and resistors. Accordingly the current source is ideally suited for manufacture in the form of a monolithic integrated circuit. The current source may be made to deliver an output current which is very linear with variations of temperature over a wide temperature range. By the mere addition of a resistor, the current source may be made to be substantially independent of temperature within 10 to 100 parts per million/° C. Furthermore, the magnitude of the output current may be controlled by adjustment of one of the resistors of the circuit.

I claim:

1. A current source for providing an output current which is linearly dependent upon temperature variations, said source comprising:

a. a first and a second transistor, said transistors being of the same conductivity type and having substantially equal alphas and betas;

b. said first transistor having its base connected directly to the collector of said second transistor;

c. said first transistor having its emitter connected directly to the base of said second transistor;

d. a source of regulated voltage;

e. a first resistor connected between one of the terminals of said voltage source and the collector of said second transistor;

f. a second resistor connected between the junction point of the emitter of said first transistor and the base of said second transistor, and the other terminal of said voltage source, the emitter of said second transistor being coupled to said other terminal of said voltage source; and

g. means isolated from said source and connected to the collector of said first transistor for deriving an output current, said output current being substantially a linear function of temperature provided the reciprocal value of the beta of each of said transistors is substantially negligible compared to one.

2. A current source as defined in claim 1 wherein the magnitude of said output current is controllable by controlling the resistance of said second resistor.

3. A current source for providing an output current which is substantially independent of temperature variations, said source comprising:

a. a first and a second transistor, said transistors being of the same conductivity type and having substantially equal alphas and betas;

b. said first transistor having its base connected directly to the collector of said second transistor;

c. said first transistor having its emitter connected directly to the base of said second transistor;

d. a source of regulated voltage;

e. a first resistor connected between one of the terminals of said voltage source and the collector of said second transistor;

f. a second resistor connected between the junction point of the emitter of said first transistor and the base of said second transistor, and the other terminal of said voltage source, the emitter of said second transistor being coupled to said other terminal of said voltage source;

g. a third resistor connected between the emitter of said second transistor and the other terminal of said voltage source; and

h. means isolated from said source and connected to the collector of said first transistor for deriving an output current, said output current being substantially independent of temperature provided that the reciprocal value of the beta of each of said transistors is substantially negligible compared to one, and that the resistance of said first and third resistors are substantially zero.