

[54] **SOLID-STATE REGULATED VOLTAGE SUPPLY**

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Related U.S. Patent Documents

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 [58] Field of Search 307/296 R, 297; 323/1, 323/4, 16, 19, 22 T, 23, 25

[56]

References Cited

U.S. PATENT DOCUMENTS

- 3,617,859 11/1971 Dobkin et al. 323/4
 3,754,181 8/1973 Kreitz et al. 323/1

OTHER PUBLICATIONS

Kuijk, "A Precision Reference Voltage Source", IEEE Journal of Solid State Circuits, vol. SC-8, No. 3, pp. 222-226, Jun. 1973.
 Brokaw, "A Simple Three-Terminal IC Band Gap Reference", IEEE Journal of Solid State Circuits, vol. SC-9, No. 6, pp. 388-393, Dec. 1974.

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[57]

ABSTRACT

A solid-state (IC) regulated voltage supply compensated for effects of changes in temperature comprising first and second transistors operated at different current densities. Associated circuitry develops a voltage proportional to the ΔV_{BE} of the two transistors and having a positive temperature coefficient. This voltage is connected in series with the V_{BE} voltage of one of the two transistors, having a negative temperature coefficient, to produce a resultant voltage with nearly zero temperature coefficient. A feedback circuit responsive to current flow through the two transistors automatically adjusts the base voltages to maintain a predetermined ratio of current density for the two transistors. Other embodiments provide higher-level DC outputs and compensation for base current flow.

21 Claims, 4 Drawing Figures

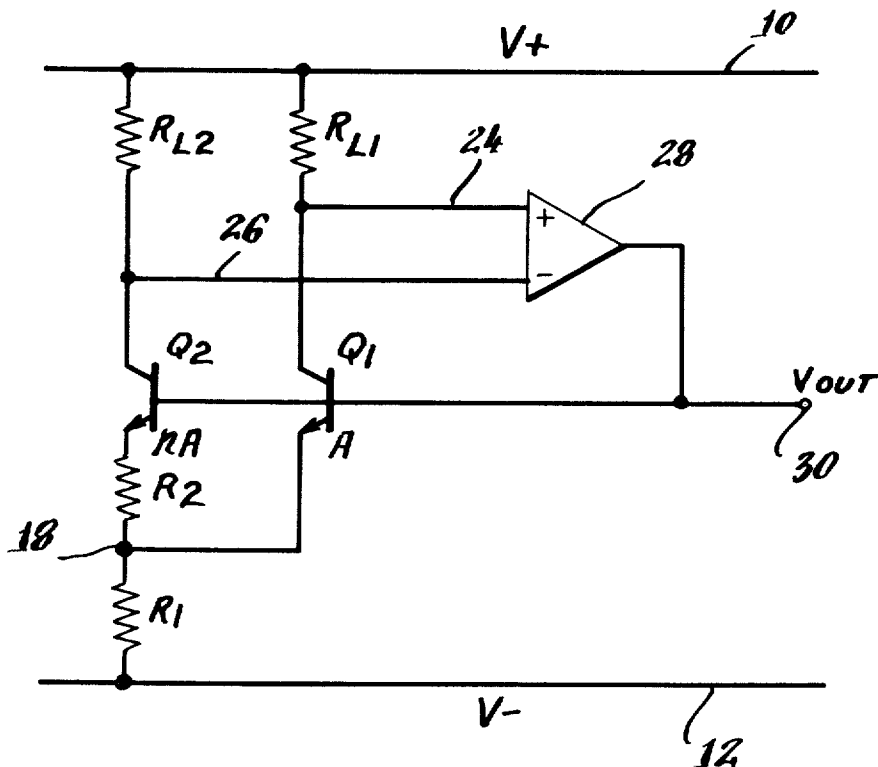


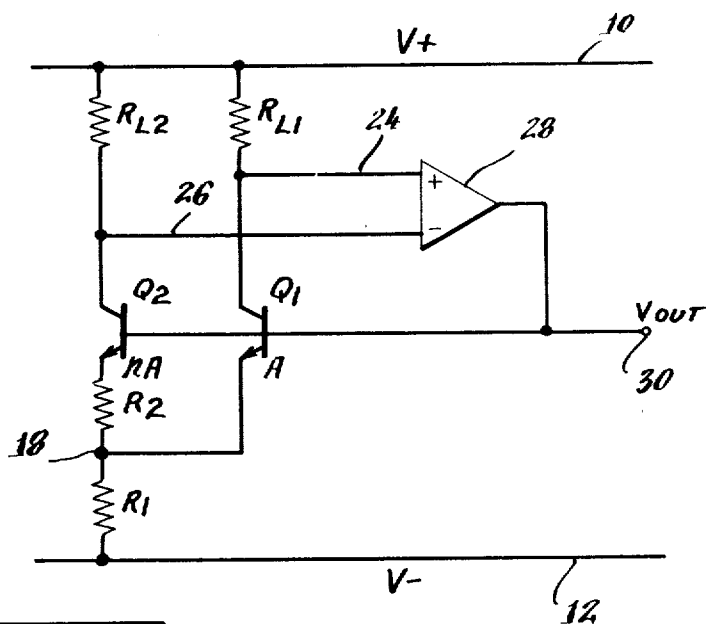
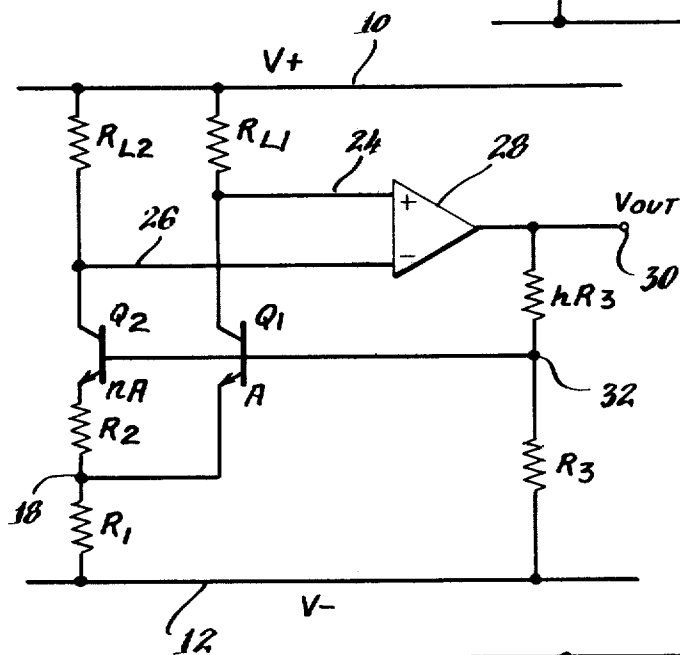
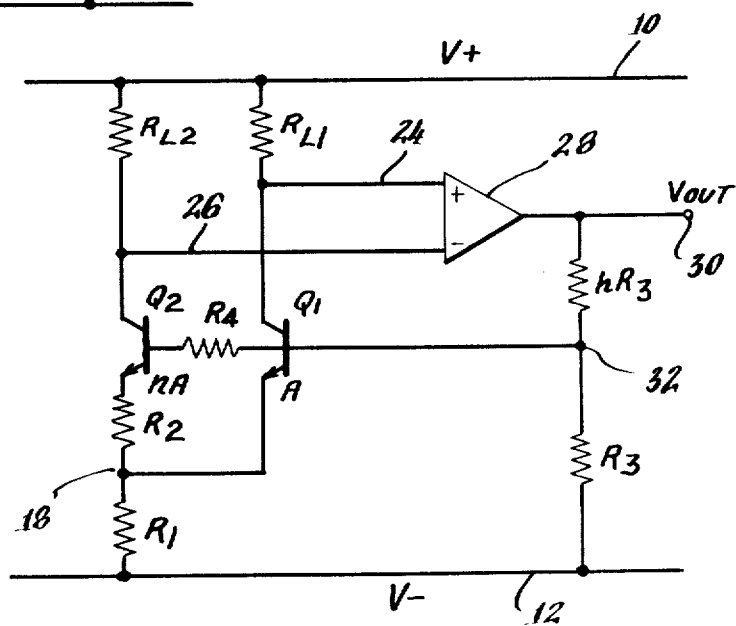
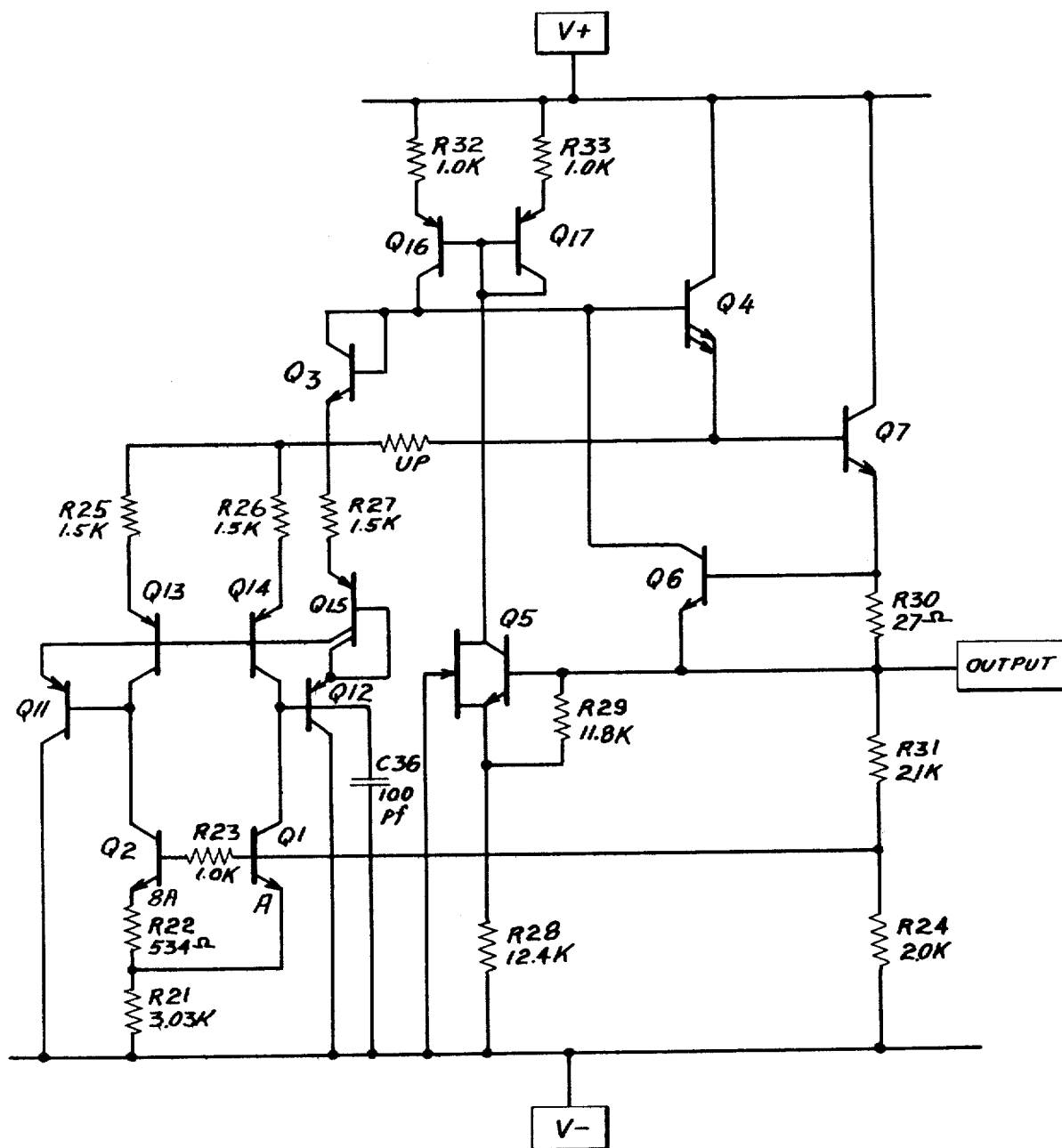
Fig. 1*Fig. 2**Fig. 3*

Fig. 4.

SOLID-STATE REGULATED VOLTAGE SUPPLY

Matter enclosed in heavy brackets [] appears in the original patent but forms no part of this reissue specification; matter printed in italics indicates the additions made by reissue.

This is a continuation of U.S. Pat. application Ser. No. 799,760 filed May 23, 1977, which is a Reissue application of U.S. Pat. No. 3,887,638 dated June 3, 1975.

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates to regulated DC voltage supplies. More particularly, this invention relates to solid-state (IC) regulators capable of maintaining a substantially constant DC output voltage in the face of temperature variations.

2. Description of the Prior Art

Conventional prior-art regulated voltage supplies commonly have included an internal reference source and an error amplifier arranged to compare the reference voltage with a pre-set fraction of the regulated DC output voltage. The output of the error amplifier is directed to a control element, such as a controllable impedance or the like, arranged to adjust the output DC voltage so as to maintain the two compared voltages equal. Fluctuations in the DC output voltage are thereby reduced.

In transistorized voltage-regulator circuits, the reference source typically has been a Zener diode. However, as is known in the art, Zener diodes have certain inherent characteristics which undesirably restrict the capability of a voltage regulator. An alternative type of solid-state regulator has been developed which does not use a Zener diode reference, relying instead on certain temperature-dependent characteristics of the base-to-emitter voltage (V_{BE}) of a transistor.

U.S. Pat. No. 3,617,859 discloses a circuit of the latter type which includes a diode-connected transistor operated at one current density, and a second transistor operated at a different current density. These two transistors are interconnected with associated circuitry so as to develop a voltage proportional to the difference in the respective base-to-emitter voltages (ΔV_{BE}). This difference voltage has a positive temperature-coefficient (TC), and is connected in series with the V_{BE} voltage of a third transistor, having a negative TC, to produce a composite resultant voltage which serves as the output of the regulator. Since the temperature coefficients of the two individual voltages are of opposite sign, the output voltage can be made relatively insensitive to temperature variations by proper choice of certain parameters.

Although such regulators based on the V_{BE} characteristic of transistors have significant advantages, the circuit arrangements proposed and used heretofore suffer from serious limitations. It is a principal object of the present invention to provide a solid-state voltage regulator which avoids or significantly minimizes such limitations of prior art regulators.

SUMMARY OF THE INVENTION

In an exemplary embodiment of the present invention, to be described in detail hereinbelow, there is provided a two-transistor voltage-regulator circuit wherein the ratio of current densities of the two transistors is automatically controlled to a predetermined value (dif-

ferent from unity) by a negative feedback arrangement. A voltage corresponding to the ΔV_{BE} of the two transistors is developed, having a positive TC, and this voltage is connected in series with the V_{BE} voltage of one of the two transistors, having a negative TC. The circuit parameters are selected so that the resultant combined voltage has a very low temperature coefficient. The regulator of this invention provides important advantages over previous regulators, as will be outlined hereinbelow in describing specific embodiments of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a circuit diagram of one embodiment of the present invention;

FIG. 2 is a circuit diagram of a modified arrangement to provide higher regulated output voltages;

FIG. 3 shows a further circuit arrangement modified to reduce base current effects; and

FIG. 4 is a circuit diagram of a voltage reference source including means to establish bias levels and to provide current limiting.

DESCRIPTION OF PREFERRED EMBODIMENTS

Referring now to FIG. 1, there is shown a circuit diagram representing basic components and interconnections of a regulated voltage source in accordance with the present invention. The circuit includes a pair of transistors Q_1 and Q_2 which are supplied with operating voltages by positive and negative voltage lines 10 and 12. The emitter of the left-hand transistor Q_2 is coupled through two series-connected resistors R_2 and R_1 to the negative voltage line 12, and the emitter of the other transistor Q_1 is connected to the common junction 18 between the two resistors.

The invention proceeds on the concept of (1) developing a first voltage, having a positive temperature coefficient (TC), (2) combining that voltage serially with a second voltage having a negative TC, and (3) relating the two temperature coefficients in a complementary sense such that the resultant composite voltage has a very low TC, approximately zero. To develop the positive TC voltage, the two transistors Q_1 and Q_2 are controllably operated at markedly different current densities (i.e., referring to density of current flowing through the emitters), and a voltage is produced proportional to the difference in the two transistor base-to-emitter voltages, referred to as ΔV_{BE} .

In the specific embodiment disclosed herein, transistor Q_2 is operated at a smaller current density than the other transistor Q_1 . Such difference in current densities can be produced (1) by using identical transistors operating at unequal currents, (2) by using transistors having unequal emitter areas operating at equal currents, or (3) by some combination of the latter two arrangements. Simply by way of example, in the described embodiment the emitter areas of the transistors Q_1 and Q_2 are specified as A and nA respectively, with n being greater than one, and the currents through the two transistors are equal.

The transistor currents are forced to be equal by a negative feedback arrangement comprising current-sensing means in the form of equal-resistance load resistors R_{L1} and R_{L2} in the collector circuits of transistors Q_1 and Q_2 . These load resistors develop voltages which are proportional to the respective collector currents, and which are directed by leads 24, 26 to the input

terminals of a high-gain operational amplifier 28. The output of this amplifier is connected to a common base line of the two transistors Q₁ and Q₂, and also to an output terminal 30 presenting the DC output voltage of the regulator. The amplifier 28 drives the common base line until the voltage drops across the load resistors R_{L1} and R_{L2} are equal, thereby forcing the transistor collector currents to be equal. By using well matched transistors Q₁ and Q₂, the emitter currents also will be equal.

Since the bases of transistors Q₁ and Q₂ are connected together, the difference voltage ΔV_{BE} will appear across emitter resistor R₂, and the current through that resistor thus will be directly proportional to ΔV_{BE} . The series connected resistor R₁ also carries this emitter current, and additionally carries the emitter current of the second transistor Q₁. Since the latter emitter current is directly proportional to the first emitter current (actually equal, in this particular example), it will be evident that the total current through resistor R₁, and hence the voltage across that resistor, also will be directly proportional to ΔV_{BE} .

It has previously been established that, for two transistors operating at different current densities, the difference in base-to-emitter voltage is given by:

$$\Delta V_{BE} = kT/q \ln J_1/J_2$$

where T is absolute temperature, k is Boltzman's constant, q is the charge of an electron, and J₁/J₂ is the ratio of the transistor current densities. Accordingly, the voltage developed across resistor R₁ is independent of absolute emitter current, and is a linear function of absolute temperature with a positive temperature coefficient.

As is evident from the circuit lay-out, the voltage across resistor R₁ is in series with the V_{BE} voltage of transistor Q₁ and the resultant composite voltage constitutes the DC output voltage on terminal 30. Since V_{BE} has a negative temperature coefficient, changes in that voltage with temperature tend to complement the positive TC changes in the voltage across resistor R₁.

To approach zero TC, the output voltage at the regulator terminal 30, with respect to the negative voltage line 12, should be set approximately to the value of the energy band-gap voltage (V_{GO}), extrapolated to 0°. For silicon, this extrapolated voltage is 1.205V. A slightly higher voltage produces superior results. It can be shown mathematically, based on certain reasonable assumptions, that for zero TC the output voltage should be set at:

$$V_{OUT} = V_{GO} + (m-1)kT_0/q$$

where m $\approx$ 1.5 and T₀ is the nominal operating temperature.

This voltage V_{OUT} can be adjusted to the desired value by proper selection of resistor R₁, such that the resistive voltage drop complements the V_{BE} of Q₁ to optimize the total (sum) voltage for zero TC.

When the DC output voltage (V_{OUT}) at terminal 30 drops below the pre-established optimal level, the ratio of collector currents I₂/I₁ is larger than the ratio of load resistors R_{L1}/R_{L2} (i.e., larger than one), so that the input to amplifier 28 is positive. This causes the amplifier output to increase, so as to return the voltage V_{OUT} back up to the optimal level. If the DC output rises above optimal, the feedback action of amplifier 28 will have the opposite effect. Thus the voltage-control circuit continuously holds the DC output voltage at the

proper level to provide a very low overall temperature coefficient, close to zero.

In some applications, DC output voltages higher than the energy band-gap voltage may be required. FIG. 2 shows an arrangement for that purpose. The basic operation of this circuit is similar to that of FIG. 1, and like reference numerals are used throughout for corresponding elements. However, FIG. 2 differs in that the output of amplifier 28 is connected to a voltage-dividing network comprising two series-connected resistors hR₃ and R₃. The common junction terminal 32 of these resistors provides a voltage which is a predetermined fraction of V_{OUT}, and this voltage is directed to the commonly connected bases of transistor Q₁ and Q₂.

As before, the amplifier 28 drives the transistor bases until their collector currents are equal. By proper selection of circuit parameters, the reference voltage (V_{REF}) at this stable point can be set to be optimum for achieving zero TC. The output voltage (V_{OUT}) then will be some predetermined multiple of V_{REF}, specifically (h+1)·V_{REF}.

This arrangement of FIG. 2 provides a quite accurate result. It is degraded only a small amount due to the base current of the transistors. This base current is relatively low, and in any event the positive TC of the transistor beta tends to act with the positive TC of the emitter current to stabilize the base current and reduce any drift.

Where further reduction of such small drift effects may be desirable, a controlled beta PNP may be used to reflect the base current from a pair matched to Q₁ and Q₂ and connected in cascode with them into the base of Q₁ and Q₂. Alternatively, the base of transistors Q₁ and Q₂ can be connected together through a resistor R₄, as illustrated in FIG. 3. Here, the voltage across resistor R₂ is no longer ΔV_{BE} , since the bases are no longer at the same voltage. However, it can be shown that this arrangement may, with matched betas, produce the basic regulation of the FIG. 2 embodiment, but with reduced drift due to base current, providing R₄ is selected such that:

$$R_4 = hR_3/h + 1 \times R_2/R_1$$

To take into account the possible effects of base spreading resistance of the two transistors, further analysis indicates that the base-connecting resistor R₄ should be selected such that:

$$R_4 = R_{b1} C_1 (1 + 1/C_2(C_1 + 1)) - R_{b2}$$

where R_{b1} and R_{b2} are the base spreading resistances of transistors Q₁ and Q₂; C₁ = I_{e1}/I_{e2} (emitter currents of Q₁ and Q₂); and C₂ = R₁/R₂.

The above-derived expression for R₄ also indicates that the use of a base-connecting resistor may be helpful in the basic circuit configuration of FIG. 1. For R₄ to be zero, R_{b2} must be larger than R_{b1}; typically, however, Q₂ is the larger transistor with a very low base resistance, and design considerations thus suggest that the base resistance of Q₁ should be minimized. It may be possible to correct for the effect with a pinched base resistor in series with the large transistor.

Voltage-regulated supplies in accordance with the present invention have a number of important and beneficial features. Foremost, such voltage supplies provide a highly stable output voltage in the face of changing

ambient temperature. Only two matched active elements are required, rather than three as in the above-identified U.S. Pat. No. 3,617,859. Advantageously, the reference voltage in the disclosed circuits appears in the control loop at a point with a high impedance, so that it can readily be driven. Moreover, the reference voltage may be multiplied as desired to produce output voltages higher than the band-gap voltage, by means of a single control loop, and without stacking junctions. In the FIG. 2 configuration, the reference voltage can first be adjusted to minimize temperature coefficient, and then the output voltage can separately be adjusted to a predetermined voltage without affecting the temperature coefficient. The basic circuit is convenient to trim by adjusting a single resistor (R_1). Finite beta and beta drift does not result in uncorrectable errors; only beta matching is required.

Referring now to FIG. 4, there is shown a voltage reference source including transistors Q_1 and Q_2 used to establish the reference voltage in the manner generally as described hereinabove. In this circuit, these transistors are driven so that they will operate at equal collector currents. Neglecting R_{23} , for the moment, the bases of these transistors are driven from the circuit output by the voltage divider consisting of R_{31} and R_{24} . The output current is provided by Darlington-connected transistors Q_4 and Q_7 , which draw operating current from the input voltage terminal. The base of Q_4 is driven by a bias current from Q_{18} .

The circuit output voltage is controlled by adjusting the base voltage of Q_4 , so that Q_4 and Q_7 form a voltage follower. A voltage drop provided by Q_3 approximately matches the V_{BE} of Q_4 , with R_{27} and Q_{15} providing a voltage drop matching other circuit voltages. The base voltage of Q_4 is controlled by the emitter follower Q_{12} which is driven by Q_1 and Q_{14} .

In operation the collector current of Q_2 drives the base of Q_{11} negative. Acting as an emitter follower, Q_{11} turns on Q_{13} and drives it until its collector current approximately equals the collector current of Q_2 . The base of Q_{13} connects to Q_{14} , a matching transistor. Since R_{25} and R_{26} are also matched, the collector current of Q_{14} will approximately equal that of Q_{13} and hence of Q_2 . If the collector current of Q_2 exceeds the collector current of Q_1 , Q_{14} will drive the base of Q_{12} positive. Alternatively, if the collector current of Q_1 exceeds the collector current of Q_2 , it will also exceed that of Q_{14} and will, therefore, drive the base of Q_{12} negative. The circuit output voltage will follow the base voltage at Q_{12} as previously explained.

The emitter area of Q_2 is eight times larger than that of Q_1 . When the voltage at the base of Q_1 and Q_2 is low, the current through R_{21} and R_{22} is low. The resulting voltage drop across R_{22} will be low, and the base-emitter voltages of Q_1 and Q_2 will be nearly equal. As a result of the area ratio mismatch the emitter current in Q_2 will be nearly eight times the current in Q_1 . This current mismatch will cause Q_{14} to drive the base of Q_{12} , and, thereby, the output - positive.

If the base voltage applied to Q_1 and Q_2 is made larger, the current through R_{21} and R_{22} will also be larger. At a sufficiently high base voltage the voltage drop across R_{22} will limit the current in Q_2 , and it will drop below the current in Q_1 . The excess collector current in Q_1 will drive the base of Q_{12} negative, and with it the circuit output.

Between these two extremes of base voltage there will be a voltage at which the collector currents of Q_1

and Q_2 are equal. At this voltage the current in Q_{14} will balance the current in Q_1 , and the base of Q_{12} will be held at a voltage which maintains the circuit output and the Q_1 - Q_2 base voltage constant. Changes in output loading or other disturbances which tend to change the output voltage will change the voltage on the bases of Q_1 and Q_2 . This will disturb their collector current balance so as to drive Q_{12} to restore the output voltage. This control loop forcing the collector currents of Q_1 and Q_2 to be equal satisfies the condition, previously described, to hold constant $C_1 = 1$.

With the collector currents of Q_1 and Q_2 forced to be equal, the voltage drop across R_{22} will be $(kT/q) \ln J_1/J_2 = (kT/q) \ln 8$. The current in R_{21} will be just twice that in R_{22} so that the voltage across R_{21} will be proportional to the drop across R_{22} . Therefore, the voltage at the base of Q_1 which results in the balance condition is the sum of the V_{BE} of Q_1 and the temperature-dependent voltage on R_{21} . This voltage is set (by selecting the ratio of R_{21} and R_{22}) so that this voltage is just above the bandgap voltage and satisfies the conditions previously outlined for zero temperature coefficient.

The stabilized base voltage of Q_1 is a fraction of the circuit output voltage determined by R_{31} and R_{24} . The output voltage is, therefore, a temperature stable multiple of the bandgap voltage determined by the resistor ratio. The interbase resistor R_{23} corrects for the offset and drift due to base current flow in R_{31} . It also corrects for the base spreading resistance of Q_1 , as previously noted.

The voltage divider R_{28} and R_{29} is connected across the circuit output voltage. It is selected to have a Thevenin equivalent output voltage which differs from the circuit output voltage by the bandgap voltage. The equivalent resistance at the divider output is set at twice the resistance of R_{21} . Transistor Q_5 is designed to match Q_1 . As a result of the equivalent voltage and resistance applied across its base and emitter, its emitter and collector currents will be approximately equal to those of Q_1 . This current drives the common base of Q_{16} and Q_{17} , a matched transistor pair. The matched emitter resistors, R_{32} and R_{33} , force the emitter currents of Q_{16} and Q_{17} to be equal and raise the output impedance of Q_{16} . This current mirror "reflects" the collector current of Q_5 down through Q_3 , R_{27} and Q_{15} . A small fraction of this current drives the base of Q_4 which in turn drives Q_7 and also supplies the current for Q_{13} and Q_{14} . Since the current in the Q_5 , Q_{17} , Q_{16} and Q_3 path approximates the current in Q_2 , it is approximately half the current in Q_{13} and Q_{14} combined. This combined current is the majority of the emitter current in Q_4 . By making the emitter area of Q_4 twice that of Q_3 , the current densities and hence the base-emitter voltages of Q_3 and Q_4 are made nearly equal. Therefore, the voltage at the top of R_{27} approximately equals the voltage applied to R_{25} and R_{26} . The currents in R_{25} , R_{26} and R_{27} are approximately equal so that the voltage drops across them are approximately equal. Similarly, Q_{15} is sized so that its emitter current density approximates that of Q_{13} and Q_{14} . In this way the base voltage of Q_{15} is made nearly equal to the base voltage of Q_{13} and Q_{14} . This equality is translated through the base-emitter voltage of the matched transistors Q_{11} and Q_{12} to the collectors of Q_2 and Q_1 . This keeps the collector voltages of these transistors approximately equal at all temperatures and bias conditions. This minimizes problems resulting from different base width modulation in Q_1

and Q_2 which might result from unbalanced collector voltage.

The bias voltage stabilization also keeps the free collector voltage of Q_{15} nearly equal to the base voltage. This helps to insure an equal split of the current in the forced beta transistor Q_{15} ($\beta=1$). This current split ensures equal emitter currents in Q_{11} and Q_{12} , thereby minimizing errors due to differences between their base currents.

The circuit as described so far would have a stable "off" state. The epitaxial layer FET portion of Q_5 eliminates this possibility. The FET provides a small starting current that turns on the circuit when voltage is applied. Although it diverts some of the current from R_{28} , it has only a small effect on the current delivered to Q_{17} . This total current is determined largely by the voltage drop across the equivalent R_{28} , R_{29} resistance. The slight change in $Q_5 V_{BE}$ which results from the diverted current is a small fraction of the total voltage applied to R_{28} and R_{29} .

The frequency stability of the output control loop is established by C_{36} . This capacitance rolls off the open-loop gain to unity below the frequency at which excess phase shift in the PNP's might cause instability.

Output overload protection is provided by Q_6 and R_{30} . The output current flows through R_{30} and produces a small voltage drop across it. In the event of overload, this voltage will rise and drive Q_6 on. As Q_6 comes on it will divert the drive current from the base of Q_4 into the load. As a result, the output current is limited to that necessary to drive Q_6 on by way of R_{30} .

The overall circuit consists of a current input amplifier which operated the control loop stabilizing the reference voltage. The amplifier input circuit, Q_{13} and Q_{14} , is bootstrapped to the regulated output. This bootstrap connection minimizes the effects of power supply voltage variation on the amplifier which improves the overall supply voltage rejection of the circuit.

Although several preferred embodiments of the invention have been described hereinabove in detail, it is desired to emphasize that such details have been disclosed for the purpose of illustrating the nature of the invention, and should not be considered as necessarily limiting of the invention which can be expressed in many modified forms to meet particular requirements.

I claim:

1. A solid-state temperature-compensated voltage supply comprising:

first and second transistors;

a resistor connected between the emitter of said first transistor and the emitter of said second transistor, circuit means for furnishing supply voltage to said two transistors to develop current flow there-through with the current through said first transistor also flowing through said resistor;

means for sensing the magnitudes of the respective currents flowing through said two transistors;

voltage-control means responsive to the currents sensed by said sensing means and operable to adjust the base potentials of said transistors to maintain the magnitudes of said transistor currents at levels which provide a predetermined non-unity ratio of current densities within the two transistors and thereby cause the current through said resistor to vary positively with respect to temperature of said two transistors;

means for developing a first voltage proportional to said resistor current and for combining said first

voltage with a second voltage which varies negatively with respect to temperature to produce a combined voltage having minimal overall variation with respect to temperature; and

output means coupled to said last-named means and including an output terminal providing an output voltage proportional to said combined voltage.

2. Apparatus as in claim 1, wherein said voltage-control means comprises a high-gain amplifier serving as a comparator responsive to signals proportional to said transistor currents to produce an output signal corresponding to the difference between said signals proportional to said currents; and

means coupling a voltage proportional to said output signal to the bases of said transistors to drive the base potentials to values providing the desired ratio of current densities in said transistors.

3. Apparatus as in claim 2, including a voltage-dividing network coupled in the output of said amplifier and having a network terminal providing a voltage which is a predetermined fraction of the amplifier output; and means coupling said network terminal to the bases of said transistors.

4. Apparatus as in claim 2, wherein said sensing means comprises first and second load resistors connected in the collector circuits of said transistors, respectively.

5. Apparatus as in claim 1, wherein said transistor bases are connected together to provide equal base potentials.

6. Apparatus as in claim 1, wherein said transistor bases are coupled together by resistor means to compensate for the effects of change in base current.

7. A solid-state temperature-compensated voltage supply comprising:

first and second transistors;

positive and negative voltage lines;

means coupling one of said voltage lines to the transistor collectors;

a resistor connected in a circuit between the emitter of said first transistor and the other of said voltage lines, to carry the current flowing through said first transistor;

means connecting the emitter of said second transistor to the end of said resistor which is remote from said first transistor emitter;

means for sensing the magnitudes of the respective currents flowing through said first and second transistors;

voltage-control means responsive to said transistor currents and operable to adjust the base potentials of said transistors to maintain the magnitudes of said transistor currents at levels which provide a predetermined non-unity ratio of current densities within the two transistors and thereby cause the current through said resistor to vary positively with respect to temperature of said two transistors; means for developing a first voltage proportional to said resistor current and for combining said first voltage with a second voltage which varies negatively with respect to temperature to produce a combined voltage having minimal variation with respect to temperature; and

output means coupled to said last-named means and including an output terminal providing an output voltage proportional to said combined voltage.

8. Apparatus as in claim 7, including first and second load resistors in the collector circuits of said transistors,

respectively, to develop voltage drops proportional to the transistor currents flowing therethrough;

an amplifier having its input terminals connected to said collector circuits respectively to receive therefrom voltages proportional to the corresponding collector currents; and

means connecting the output of said amplifier to the bases of said transistors to apply thereto a voltage proportional to the amplifier output to drive the base potentials to a value providing a null voltage at the input of said amplifier.

9. Apparatus as in claim 8, including a voltage-divider network connected to the output of said amplifier; and means coupling an intermediate point of said network to said transistor bases to provide thereto a control voltage which is a predetermined fraction of the amplifier output.

10. A solid-state regulated-voltage supply comprising:

first and second transistors;

positive and negative supply voltage lines;

means coupling one of said supply voltage lines to the collectors of said two transistors;

first and second resistors connected in series between the emitter of said first transistor and the other of said supply voltage lines to carry the current flowing through said first transistor;

means connecting the emitter of said second transistor to the junction between said first and second resistors, whereby said second resistor also carries the current flowing through said second transistor;

means establishing a predetermined relationship between the base potentials of said two transistors;

circuit means for establishing different current densities in said two transistors with the ratio of current densities being set at a predetermined value to cause the currents through said resistors to vary positively with respect to temperature; and

output circuit means connected to the base of said second transistor for developing at an output terminal an output voltage proportional to the voltage across said second resistor combined serially with the V_{BE} voltage of said second transistor.

11. In a voltage supply of the type comprising means to produce a first voltage having a positive temperature coefficient for combination with a second voltage having a negative temperature coefficient so as to develop a combined voltage having a substantially reduced overall temperature coefficient;

the improvement in said means for producing said first voltage having a positive temperature coefficient which comprises;

first and second transistors arranged to conduct respective currents therethrough;

means connecting the bases of said two transistors together to provide for tracking of the base potentials;

sensing means coupled to both of said transistors and responsive to said currents passing therethrough;

voltage-control means coupled to said sensing means and having an output circuit for producing a control voltage responsive to the change in the relative levels of said transistor currents;

means connecting said output circuit to the base of at least one of said transistors for automatically adjusting the base voltage thereof responsive to said control voltage so as to maintain the ratio of said transistor currents at a value which provides a

non-unity ratio of current densities within said transistors; and

means connected to the emitters of both of said transistors to produce a voltage proportional to the difference in base-to-emitter voltage of said two transistors to serve as said first voltage having a positive temperature coefficient.

12. A voltage supply as claimed in claim 11, wherein said voltage-control means comprises a high-gain amplifier producing said control voltage at its output.

13. A voltage supply as claimed in claim 12, including means coupling to said one transistor base a voltage proportional to the output voltage of said amplifier.

14. A voltage supply as claimed in claim 13, wherein said coupling means comprises voltage-dividing means to couple to said transistor base a voltage which is a pre-set fraction of the amplifier output voltage.

15. A voltage supply as claimed in claim 11, wherein the emitters of said two transistors have substantially different areas.

16. A voltage supply as claimed in claim 15, wherein said transistor currents are maintained equal.

17. A solid-state temperature-compensated voltage supply comprising:

first and second transistors arranged to conduct respective currents;

voltage means to provide base voltage to said transistor bases to produce current densities therein having a non-unity ratio;

circuit means including resistance means connected to the emitters of said two transistors to develop a first voltage proportional to the difference in base-to-emitter voltages of said transistors and to apply said first voltage to the emitter of said second transistor;

means coupling the bases of said two transistors together to provide for tracking of the base potentials;

an output terminal; and

means coupling said output terminal to the base of said second transistor to provide at said output terminal an output voltage proportional to said first voltage combined with the base-to-emitter voltage of said second transistor.

18. A voltage supply as claimed in claim 17, wherein said voltage means comprises an amplifier the input of which is coupled to said two transistors to receive signals therefrom corresponding to the transistor currents; and

means coupling the output of said amplifier to the bases of said two transistors to automatically maintain the base potentials at the value which produces the required transistor currents to maintain the transistor current densities at the desired non-unity ratio.

19. A voltage supply as claimed in claim 18, wherein said coupling means comprises a voltage dividing network arranged to apply to the base of said second transistor a voltage which is a predetermined fraction of the amplifier output voltage, whereby said amplifier output serves as said output terminal developing an output voltage which is greater than the base voltage at said second transistor.

20. A solid-state band-gap reference circuit comprising: first and second transistors each having a base, emitter and collector;

positive and negative supply leads;

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first and second sensing resistor means connected between said positive supply lead and said collectors respectively;
third and fourth series resistor means connected between the emitter of said first transistor and said negative supply lead;
means connecting the emitter of said second transistor to a junction between said third and fourth resistor means;
means coupling said transistor bases together to provide for tracking of the base voltages thereof;
means to apply a control voltage to said bases;
said resistor means being arranged to set the currents through said transistors at levels providing a non-unity ratio of current densities therein; and
amplifier means having a pair of input terminals coupled respectively to said first and second resistor means to develop an amplifier input voltage responsive to variations in the relative magnitude of the currents flowing through said two transistors respectively, whereby the magnitude of the output of said amplifier reflects a comparison between the base voltage of said transistors and a predetermined band-gap reference voltage developed as a composite voltage consisting of a first voltage proportional to the difference in base-to-emitter voltages of said two transistors, and a second

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voltage corresponding to the base-to-emitter voltage of said second transistor.
 21. *A solid-state band-gap reference device comprising: first and second transistors having their bases coupled together;*
means for supplying commonly controllable and tracking base voltages to said two transistors;
means coupled to said transistors for developing there-through currents of magnitude providing a non-unity ratio of current densities in said transistors;
means for producing a first voltage responsive to the difference between the base-to-emitter voltages of said two transistors;
means to connect said first voltage to the emitter of one of said transistors, said first voltage and the base-to-emitter voltage of said one transistor defining a composite voltage compensated for temperature;
means to sense the changes in relative magnitudes of current through said two transistors responsive to changes in said commonly controllable and tracking base voltages of said two transistors; and
an amplifier coupled to said sensing means to produce an output the magnitude of which reflects a comparison of said changes in current through said two transistors produced by changes in said commonly controllable base voltages.

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