

WAFER-STAGE TEMPERATURE COMPENSATION FOR IC COMPONENTS**Field of the Invention**

The present invention relates generally to the correction for mismatches between or among temperature dependent circuit components of an integrated circuit, and more particularly to the adjustment at the wafer stage for the correction of certain mismatches between or among circuit components which are a part of the same integrated circuit structure and which for operational purposes are required to be matched over a temperature range.

Background of the Invention

There are many circuit designs which include circuit components, both active (such as transistors) and passive (such as resistors), which are required to be matched during their operation, over a temperature range. Where the circuits are constructed of discrete components, if necessary for optimizing system performance, adjustments typically must be made during the manufacturing process when assembling the circuits to insure component matching. This can be costly due to the labor required to make the adjustment for each manufactured circuit. Often times such adjustments provide correction only at the temperature at which the initial adjustment is made, which may not be satisfactory for other operational temperatures. In addition, some settings may be subject to shifts due to mechanical vibration. Implementing these circuits in integrated or monolithic form often necessarily requires the provision of external circuitry for providing these adjustments following the manufacture of the IC part, but does not overcome the above-noted problems.

For example, it is well known that the class of electronic gain control circuits, known as log-antilog electronic multipliers or VCAs (voltage controlled amplifiers), requires adjustment means (generally referred to as symmetry adjustment) to compensate for mismatches among the various transistors that implement the gain-control function. The requirement for such adjustment is mentioned in U.S. Patents Nos. 3,714,462, and 4,403,199 issued to David E.

1 Blackmer on January 30, 1973 and September 6, 1983 respectively; 4,234,804 issued
2 to Gary Bergstrom on November 18, 1980; 4,331,931 issued to Robert W. Adams
3 on May 25, 1982; and 4,225,794 and 4,341,962 issued to Paul C. Buff on
4 September 30, 1980 and July 27, 1982, respectively. This adjustment has
5 historically been made via a potentiometer and associated fixed resistors, arranged
6 to apply an adjustable potential to one or more of the bases of the transistors in the
7 gain-control circuit. Such an adjustment method is costly due to the parts
8 themselves, and the labor required to adjust the potentiometer during the
9 manufacturing process of each circuit board. Further, such methods often yield a
10 correction potential that is only correct at the temperature at which the initial
11 adjustment was made. Finally, the potentiometer setting is subject to shifts due to
12 mechanical vibration.

13 The most prevalent modern examples of such gain-control circuits are
14 implemented in monolithic IC technology, which is well suited to these circuits as
15 they require well-matched transistors that operate at substantially the same
16 temperature. An example of a VCA is shown in Fig. 1.

17 The VCA shown in Fig. 1 includes an eight transistor cell. Eight transistor
18 cell VCAs are known. See, for example, U.S. Patent No. 4,331,931 issued to
19 Robert W. Adams on May 25, 1982 and U.S. Patent No. 4,341,962 issued to Paul
20 C. Buff on July 27, 1982. As shown in Fig. 1, an input information signal (e.g.,
21 an audio signal) I_{in} is applied to the input terminal 10. Terminal 10 is connected to
22 the collector of primary log (pnp) transistor Q_3 and the collector of the primary log
23 (npn) transistor Q_5 . The collectors of primary antilog transistors Q_4 and Q_6 (pnp and
24 npn transistors respectively) are joined at junction 12 so as to form output terminal
25 14 for output current I_{out} . One gain control signal is applied to the positive-sense
26 gain-control port 16 as E_{cp} , and to the negative-sense gain-control port 18 as E_{cn} .
27 The symmetry adjust signal E_{sym} is applied to the symmetry port 22. As shown, the
28 positive control signal input terminal 16 is connected to the base of the primary log
29 transistor Q_3 , while the negative control signal input terminal 18 is connected to the
30 base of primary log transistor Q_5 and primary antilog transistor Q_4 . The emitter of
31 each primary transistor Q_3 , Q_4 , Q_5 and Q_6 is connected to the emitter of a respective
32 secondary transistor Q_1 , Q_2 , Q_7 and Q_8 , with each secondary transistor being of a

conductivity type opposite to that of the primary transistor to which it is connected. The bases and collectors of transistors Q_1 and Q_2 are tied together, and similarly the bases and collectors of transistors Q_7 and Q_8 are tied together. A voltage bias source V_{bias} is connected between the bases and collectors of transistors Q_1 and Q_2 and the bases and collectors of transistors Q_7 and Q_8 . In addition, the bases and collectors of transistors Q_7 and Q_8 are connected to a current source indicated as I_{power} . The input terminal 10 is also connected to the inverting input of operational amplifier 20, with the non-inverting input connected to system ground and the output connected to the bases and collectors of transistors Q_1 and Q_2 .

In general, because of the logarithmic relationship between base to emitter voltage V_{be} and the collector current I_c of a bipolar transistor, the log transistors will provide a voltage signal at the collectors of the secondary transistors which is proportional to the logarithm of the input current. The antilog transistors will provide the output current I_{out} as a function of the antilogarithm of the voltage signal. Because the control voltage E_c is applied to opposing polarities of both the log and antilog transistors, varying E_c will vary the ratio of the output current I_{out} to the input current I_{in} . The symmetry adjustment signal, E_{sym} , is applied to the symmetry adjust terminal 22. The requirement for symmetry adjustment arises from mismatches in the base-to-emitter voltage (V_{be}) - collector current (I_c) characteristics among the log and antilog transistors in the gain-control circuit. This may be seen by observing Fig. 1 and the VCA transfer function:

$$(1) \quad I_{out} = G \left[\frac{I_b}{2} \left(e^{\frac{E_{sym} - E_c}{2V_T}} \sqrt{\frac{I_{s1} I_{s2}}{I_{s1} I_{s3}}} + \sqrt{\frac{I_{s2} I_{s4}}{I_{s1} I_{s3}}} \right) + \sqrt{\frac{I_{in}^2}{2} + \frac{I_b^2}{G}} \left(e^{\frac{E_{sym} - E_c}{2V_T}} \sqrt{\frac{I_{s1} I_{s2}}{I_{s1} I_{s3}}} - \sqrt{\frac{I_{s2} I_{s4}}{I_{s1} I_{s3}}} \right) \right]$$

wherein I_{out} is the VCA output current;

I_{in} is the VCA input current;

G is the nominal VCA current gain $\left(e^{\frac{E_{cp} - E_{cn}}{2V_T}} \right)$;

E_{cp} is the potential applied to the positive-sense gain-control port;

E_{cn} is the potential applied to the negative-sense gain-control port;

E_{sym} is the potential applied to the symmetry port;

I_b is the nominal bias current in the logging and anti-logging transistors when the gain-control circuit is set for unity gain;

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1 $V_T = \frac{kT}{q}$ is the "thermal voltage", a constant proportional to the absolute
 2 temperature (PTAT); and
 3 I_{s1} through I_{s8} are the respective saturation currents for the logging and anti-
 4 logging transistors Q_1 through Q_8 .

6 If all of the individual log/antilog pairs of transistors (Q_1/Q_2 , Q_3/Q_4 , Q_5/Q_6 ,
 7 and Q_7/Q_8) are identically matched for their $V_{be} - I_c$ characteristics such that:

9 (2) $I_{s1} = I_{s2}$, $I_{s3} = I_{s4}$, $I_{s5} = I_{s6}$, and $I_{s7} = I_{s8}$,

11 and E_{sym} is set to equal E_{cp} , then equation (1) reduces to:

13 (3) $I_{out} = GI_{in}$,

15 which is the ideal case in which the output current is a linearly scaled version of the
 16 input current. In practice, however, there exist mismatches among the pairs of
 17 transistors, such that, without proper adjustment of the potential E_{sym} , the output
 18 current will consist of, in addition to a scaled version of the input current, second
 19 harmonic distortion and gain-dependent dc offset components represented by the
 20 second term in equation (1) reproduced as follows:

22 (4)
$$\sqrt{\frac{I_{in}^2}{2} + \frac{I_b^2}{G}} \left(e^{\frac{E_{sym} - E_{cp}}{2V_T}} \sqrt{\frac{I_{s6}I_{s8}}{I_{s3}I_{s7}}} - \sqrt{\frac{I_{s2}I_{s4}}{I_{s1}I_{s5}}} \right)$$

24 These distortion and gain-dependent offset components are undesirable in high-
 25 quality audio applications, as well as other applications where a faithful scaled
 26 replica of an input signal is desired.

27 It is possible to properly adjust E_{sym} to completely eliminate these undesirable
 28 components in the output signal. E_{sym} must be adjusted such that the second term
 29 in equation (1) goes to zero. Thus, it is desirable that:

31 (5)
$$e^{\frac{E_{sym} - E_{cp}}{2V_T}} \sqrt{\frac{I_{s6}I_{s8}}{I_{s3}I_{s7}}} = \sqrt{\frac{I_{s2}I_{s4}}{I_{s1}I_{s5}}}$$

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1 Solving for E_{sym} :

2

$$3 \quad (6) \quad E_{sym} = E_{cp} + 2V_T \ln \sqrt{\frac{I_{s2}I_{s4}I_{s5}I_{s7}}{I_{s1}I_{s3}I_{s6}I_{s8}}}$$

4

5 In practice the transistor matching achievable with modern IC processes is
6 such that the desired E_{sym} potential is no more than a few millivolts different from
7 E_{cp} with E_{cp} typically being in the range of -700 to +400 millivolts. Thus, it is
8 convenient to consider the difference between these two potentials:

9

$$10 \quad (7) \quad E_{adj} = E_{sym} - E_{cp} = 2V_T \ln \sqrt{\frac{I_{s2}I_{s4}I_{s5}I_{s7}}{I_{s1}I_{s3}I_{s6}I_{s8}}}$$

11

12 as the desired adjustment potential. From the foregoing it can be seen that because
13 V_T is proportional to absolute temperature, the required E_{adj} also must be
14 proportional to absolute temperature (PTAT).

15 It should be noted that the circuit used in deriving the equations above is used
16 for illustrative purposes. The effects of base currents, Early effect, and non-ideal
17 log conformance due to finite ohmic base and emitter resistances in the logging and
18 anti-logging transistors have been ignored for clarity. The techniques taught in US
19 Patent No. 4,234,804 (Bergstrom) and US Patent No. 4,403,199 (Blackmer) to
20 mitigate the effects of finite ohmic base and emitter resistances in the logging and
21 anti-logging transistors are entirely compatible with the invention to be described,
22 and in fact serve to bring the behavior of actual gain-control circuits closer to the
23 ideal behavior of the simple circuit described in Fig. 1. The same is true of the
24 technique taught in US Patent No. 4,454,433 (Welland) for mitigating the effects of
25 Early effect mismatch among the log and antilog transistors. For gain-control
26 circuits utilizing a cell of only four transistors, such as that described in US Patent
27 No. 3,714,462 (Blackmer), it is easily shown that the required E_{adj} is of the same
28 form as that of equation (7) and that the present invention is equally applicable to
29 such circuits.

30 In considering the prior art, as each gain control circuit is made it is not
31 necessarily known whether E_{adj} should be a positive voltage, or a negative voltage.
32 The log transistors, as well as the antilog transistors, are matched as closely as

possible so that any mismatching is necessarily unpredictable and random. This would suggest therefore that just as many circuits would require a positive E_{adj} as would require a negative E_{adj} . Accordingly, the source of E_{adj} not only should include the means for adjusting the level of E_{adj} in order to correct for $V_{be} - I_e$ mismatches, but also for adjusting the polarity of E_{adj} so that E_{adj} can be made positive or negative. The most common prior art approach for adjusting E_{adj} to the desired polarity and value is illustrated in Fig. 2. A resistor R_1 is connected between the bases of antilog transistor Q_6 and log transistor Q_3 , and a resistor R_2 is connected between the base of transistor Q_6 and the wiper of a potentiometer R_3 . The ends of potentiometer R_3 are connected between potentials V_{pos} and V_{neg} (typically, but not necessarily, equal and opposite voltages) to create a variable potential at the wiper. The values of these components are typically chosen such that the resistance of R_2 is much larger than the resistance of R_3 , and the ratio of R_2 to R_1 is chosen to restrict the range of voltages across R_1 , to the few millivolts necessary to correctly adjust the VCA symmetry. Further, R_1 is typically chosen to be less than 100 ohms so as not to add excessively to the base resistance of antilog transistor Q_6 . Finally, E_{cp} is typically driven by a very low-impedance voltage source. Under these conditions E_{sym} may be approximated by:

$$(8) \quad E_{sym} = V_{wiper} \left(\frac{R_1}{R_1 + R_2} \right) + E_{cp} \left(\frac{R_2}{R_1 + R_2} \right)$$

where V_{wiper} is the voltage at the wiper of R_3 . The net adjustment voltage E_{adj} developed across R_1 will be:

$$\Theta E_{adj} = E_{sym} - E_{cp} = V_{wiper} \left(\frac{R_1}{R_1 + R_2} \right) + E_{cp} \left(\frac{R_2}{R_1 + R_2} - 1 \right) = (V_{wiper} - E_{cp}) \left(\frac{R_1}{R_1 + R_2} \right)$$

The symmetry adjustment is typically made with E_{cp} and E_{cm} both set to 0 volts so that the current gain of the VCA is unity. As can be seen from equation (9), if the positive-sense gain control port 16 is then used for adjusting the gain of the VCA, either in conjunction with or instead of the negative-sense gain control port 18, the E_{adj} potential will deviate from the desired value as the E_{cp} potential is

1 varied. This leads to degraded distortion and offset-versus-gain performance at gains
2 other than unity.

3 When this technique is implemented using discrete components for R_1 , R_2 ,
4 and R_3 , approximate temperature compensation of the E_{adj} potential can be achieved
5 by using a temperature-dependent resistor for R_1 . If R_2 is much larger than R_1
6 (which is typically the case) and R_1 's value varies .33% for every one degree
7 centigrade variation from room temperature while R_2 's value remains fixed, then E_{adj}
8 will vary approximately in PTAT fashion. Of course, it is difficult to ensure that the
9 discrete resistor stays at exactly the same temperature as transistors Q_1 through Q_5 .
10 While integrating the resistors onto the same IC with the transistors might solve this
11 problem, it is difficult with current IC technology to fabricate integrated resistors
12 with specific, well-controlled temperature coefficients.

13

14 Objects of the Invention

15 A principal object of the present invention is to reduce or substantially
16 overcome the disadvantages described above in connection with the prior art.

17 Another object of the present invention is to adjust at the wafer stage for the
18 correction of mismatches between or among circuit components which are a part of
19 the same integrated circuit structure so that the components are matched over a
20 temperature range.

21 And another object of the present invention is to provide means, on the same
22 integrated circuit incorporating a gain-control circuit, for providing proper symmetry
23 adjustment for mismatches in the $V_{be} - I_c$ characteristics between or among transistors
24 independently of temperature variations.

25 Still another object of the present invention is to implement a gain control
26 circuit of the type having two gain control ports so that symmetry adjustment is
27 unaffected by the potential at either of the two gain control ports, thus leaving them
28 both available for use.

29 Yet another object of the present invention is to exploit the use of resistors,
30 fabricated in accordance with IC manufacturing techniques, that track over a wide
31 range of temperatures, in providing symmetry adjustment for a gain control circuit
32 implemented in IC form.

1 And still another object of the present invention is to provide an adjustable
2 bipolar symmetry adjustment signal to one or more transistors of a transistor cell of
3 a gain control circuit so that the polarity and level of the symmetry adjustment signal
4 can be appropriately adjusted during the manufacture of the gain control circuit as
5 a wafer so as to substantially eliminate the need to compensate for any mismatches
6 in the transistors following manufacture.

7 And yet another object of the present invention is provide a symmetry adjust
8 signal to a gain control integrated circuit, independent of the absolute power supply
9 used with the integrated circuit over a reasonable range of voltage levels of the
10 power supply.

11

12 Summary of the Invention

13 These and other objects of the invention are achieved by an integrated circuit
14 of the type having at least two components, each of which operate interdependently
15 as a function of temperature and at least one physical parameter associated with each
16 of the components when implemented in integrated form. The circuit further includes
17 compensation means, disposed in the integrated circuit, for generating and applying
18 a bipolar compensation signal to at least one of the components so that the level and
19 polarity of the bipolar compensation signal can be adjusted during the manufacture
20 of the integrated circuit such that the two components interdependently operate
21 predictably, consistently and independently of temperature variations and differences
22 between the physical parameter of the two components.

23 Preferably, the integrated circuit is of the type that comprises a gain control
24 circuit for generating an output signal as a function of the product of an input signal
25 and a gain control signal. The gain control circuit includes at least two transistors
26 required to be matched so that the operational characteristics of the transistors are
27 identical in order to minimize signal distortion by the gain control means. In
28 accordance with the present invention, the integrated circuit further includes means,
29 disposed within the integrated circuit, for generating a bipolar signal for providing
30 symmetry adjustment between the two transistors as a function of any mismatch
31 between the $V_{be} - I_c$ characteristics of the transistors so that the transistors' operation
32 is matched independently of temperature variations and the gain control signal.

Brief Description of the Drawings

Fig. 1 is a schematic diagram of a example of a prior art gain-control circuit of the voltage controlled amplifier (VCA) type employing log-antilog pairs of transistors and showing the need for transistor symmetry adjustment;

Fig. 2 is a schematic diagram of the gain control circuit shown in Fig. 1 and modified in accordance with a prior art technique of generating a symmetry adjust signal;

Fig. 3 is a schematic diagram of a first preferred embodiment of the present invention for providing a symmetry adjust signal as a function of a compensation current;

Fig. 4 is a schematic diagram showing a general implementation of a bipolar current source for producing the symmetry adjust signal;

Fig. 5 is a schematic diagram showing a more detailed implementation of one of the current sources shown in the Fig. 4 embodiment;

Fig. 6 is a schematic diagram showing a more detailed implementation of the Fig. 4 embodiment;

Fig. 7 is a schematic diagram showing a more detailed implementation of the Fig. 6 embodiment and the preferred embodiment; and

Fig. 8 is a schematic diagram of a second preferred embodiment of the present invention for providing a symmetry adjust signal as a function of a compensation current.

Detailed Description of the Drawings

In the drawings, the same letters and numbers are used to identify the same or similar parts.

A preferred embodiment for achieving proper symmetry adjustment independent of temperature variations and gain-control voltages is illustrated in Fig. 3. In this embodiment a variable current source I_{sym} is connected to the base of antilog transistor Q_6 , replacing the resistor R_2 and potentiometer R_3 shown in Fig. 2. The magnitude of I_{sym} is proportional to V_T/R where R is a resistance having characteristics (primarily temperature coefficient) matching those of R_1 . The resulting symmetry adjustment potential E_{adj} will be approximately:

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$$(10) \quad E_{adj} = E_{sym} - E_{cp} = KV_T \left(\frac{R_1}{R} \right)$$

if I_{sym} is much greater than the base current of transistor Q_6 .

A bipolar current source circuit with such characteristics, and which can be implemented in IC form, is shown in Fig. 4.

In Fig. 4, a positive current source 30 provides a positive current A into junction 34, while the negative current source 32 provides a negative current B from junction 34. The sources 30 and 32 are designed so that the output of each is proportional to V_T/R . Thus $(A - B)$ is proportional to V_T/R whether the magnitude of A is greater than the magnitude of B ($A > B$), or the magnitude of A is less than the magnitude of B ($A < B$). The exact value of $A - B$ is I_{sym} , and as described above I_{sym} is proportional to V_T/R where R is a resistance having characteristics (primarily temperature coefficient) matching those of R_1 of Fig. 2. One such example of a known unipolar current source for providing a current proportional to absolute temperature is illustrated in Fig. 5.

In Fig. 5, a pair of npn transistors Q_1 and Q_2 are connected so that the collector of transistor Q_2 receives an input current I_{in} , while the collector of transistor Q_1 provides the output current I_{out} . The collector and base of transistor Q_2 are tied together and to the base of transistor Q_1 with the voltage at the juncture being defined as V_3 . Transistors Q_3 and Q_4 are also provided, with the collector and base of transistor Q_3 connected respectively to the base and collector of transistor Q_4 , with the emitter of transistor Q_3 connected through resistor R to system ground, and the emitter of transistor Q_4 connected to system ground. The emitter of transistor Q_1 is connected to the collector of transistor Q_3 , and the emitter of transistor Q_2 is connected to the collector of transistor Q_4 . The voltage at the juncture of the emitter of transistor Q_1 , the base of transistor Q_4 and the collector of transistor Q_3 is defined as V_2 , while the voltage at the juncture of the emitter of transistor Q_2 , the base of transistor Q_3 and the collector of transistor Q_4 is defined as V_1 . Assuming that transistors Q_1 , Q_2 , and Q_4 have identical characteristics (including saturation current I_s) and that transistor Q_3 is similar, but with emitter area A times larger than the other three, and ignoring base currents, the following can be stated from inspection of Fig. 5:

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$$(11) \quad V_1 = I_{out} R + V_T \ln \left(\frac{I_{out}}{A I_s} \right)$$

$$(12) \quad V_2 = V_T \ln \left(\frac{I_{in}}{I_s} \right)$$

$$(13) \quad V_3 = V_2 + V_T \ln \left(\frac{I_{out}}{I_s} \right) = V_1 + V_T \ln \left(\frac{I_{in}}{I_s} \right)$$

Substituting the first two equations into the third yields:

$$(14) \quad V_T \ln \left(\frac{I_{in}}{I_s} \right) + V_T \ln \left(\frac{I_{out}}{I_s} \right) = I_{out} R + V_T \ln \left(\frac{I_{out}}{A I_s} \right) + V_T \ln \left(\frac{I_{in}}{I_s} \right)$$

and solving for I_{out} :

$$(15) \quad V_T \ln \left(\frac{I_{out}}{I_s} \right) = I_{out} R + V_T \ln \left(\frac{I_{out}}{A I_s} \right)$$

$$(16) \quad I_{out} = \frac{V_T}{R} \ln A$$

It should be noted that the assumption that base currents may be ignored in the foregoing analysis will be valid if the magnitude of I_{in} is of the same order as that of I_{out} . It should also be noted that small mismatches among the transistors will have the effect of slightly altering the value of the constant A.

A current source such as that shown in Fig. 5 will not fulfill the requirements of I_{sym} in Fig. 3 because I_{sym} must be bidirectional or bipolar. That is, it must be adjustable to both positive and negative values of current since the required adjustment potential E_{adj} may be positive or negative. Fig. 6 shows an embodiment that fulfills all of the requirements connected to an eight transistor cell gain control circuit.

Referring to Fig. 6, the current source includes a positive voltage rail V_{pos} and a negative voltage rail V_{neg} . The positive voltage rail V_{pos} is connected through resistor R_3 to the emitter of pnp transistor Q_{15} and directly to the emitter of pnp transistor Q_{16} . The base and collector of transistor Q_{15} are connected respectively to the collector and base of transistor Q_{16} . The base of transistor Q_{16} and the collector of transistor Q_{15} are connected to the emitter of pnp transistor Q_{13} , while

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1 the base of transistor Q_{15} and the collector of transistor Q_{16} are connected to the
 2 emitter of pnp transistor Q_{14} . The base and collector of transistor Q_{14} are connected
 3 to the base of transistor Q_{13} , while the collector of transistor Q_{13} provides current I_{13} .
 4 The remaining portion of the current source, including transistors Q_9 and Q_{10} (which
 5 correspond to transistors Q_{15} and Q_{16}), transistors Q_{11} and Q_{12} (which correspond to
 6 transistors Q_{13} and Q_{14}) and resistor R_2 (which corresponds to resistor R_3) duplicates
 7 the circuit to the extent described so as to provide current I_{11} . I_{sym} is formed as the
 8 difference between the currents I_{13} and I_{11} . A resistor R_4 is provided between the
 9 collectors of transistors Q_{12} and Q_{14} . In this circuit resistor R_4 sets the current
 10 through transistors Q_{10} , Q_{12} , Q_{14} , and Q_{16} (which corresponds to I_m in the circuit of
 11 Fig. 7) at approximately

$$(17) \quad \frac{V_{pos} - V_{neg} - 4V_{be}}{R_4}$$

15 where V_{be} represents the base-emitter forward voltage of Q_{16} , Q_{14} , Q_{12} and Q_{10} ,
 16 approximately equal to 0.7V. This current is chosen, as mentioned above, so that
 17 it is of the same order of magnitude as the desired range of I_{13} and I_{11} to minimize
 18 the effects of base currents. The collector currents of transistors Q_{11} and Q_{13} are
 19 then (via an analysis similar to that above for Fig. 6):

$$(18) \quad I_{11} = \frac{V_1}{R_2} \ln A$$

$$(19) \quad I_{13} = \frac{V_T}{R_3} \ln A$$

25 I_{sym} is then:

$$(20) \quad I_{sym} = I_{13} - I_{11} = \frac{V_T}{R_3} \ln A - \frac{V_T}{R_2} \ln A = \left(\frac{R_2 - R_3}{R_2 R_3} \right) V_T \ln A$$

29 and, thus, the adjustment potential E_{adj} will be:

$$(21) \quad E_{adj} = E_{sym} - E_{cp} = R_1 I_{sym} = \left[\frac{R_1 (R_2 - R_3)}{R_2 R_3} \right] V_T \ln A$$

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If resistors R_1 , R_2 , and R_3 are of like types so that they exhibit similar temperature coefficients then the adjustment potential will be PTAT as desired, and will be independent of the potential at either control port to the extent that Early effect in transistors Q_{11} and Q_{13} may be ignored. The potential may be adjusted by trimming resistors R_2 and/or R_3 using any of the common techniques known in the art. Resistor R_1 is, again, typically chosen to be less than 100 ohms in order to avoid adding significantly to the base resistance of transistor Q_5 .

Fig. 7 shows a preferred embodiment of the current source used with a VCA, wherein cascode transistors Q_{17} and Q_{18} have been added in series with transistors Q_{13} and Q_{14} (with the emitters of pnp transistors Q_{17} and Q_{18} respectively connected to the collectors of transistor Q_{13} and Q_{14} , the bases of transistors Q_{17} and Q_{18} connected to each other and to the collector of transistor Q_{18} , and the collectors of transistors Q_{17} and Q_{18} connected to the output of the current source and resistor R_4 respectively). Similarly, cascode transistors Q_{19} and Q_{20} have been added in series with transistors Q_{11} and Q_{12} (with the emitters of pnp transistors Q_{19} and Q_{20} respectively connected to the collectors of transistor Q_{11} and Q_{12} , the bases of transistors Q_{19} and Q_{20} connected to each other and to the collector of transistor Q_{20} , and the collectors of transistors Q_{19} and Q_{20} connected to the output of the current source and resistor R_4 respectively). The cascode transistors Q_{17} and Q_{18} serve to increase the output impedance of the upper current source, as is well known in the art. Transistors Q_{19} and Q_{20} serve this function for the lower current source. This minimizes the effects of Early effect in the transistors and makes the circuit behave more ideally with regard to independence from changes in the potential at E_{cp} . The circuit is also designed so that only a single resistor, R_3 , need be adjusted. This resistor is typically adjusted between a maximum value that is essentially an open circuit to a minimum value of $R_3/2$. This yields a range of adjustment potential of:

$$(22) \quad \frac{R_1}{R_2} V_T \ln A \geq E_{adj} \geq -\frac{R_1}{R_2} V_T \ln A$$

Diode connected transistor Q_{21} is added to prevent the emitter of transistor Q_{13} from floating when R_3 is open circuited. It ensures that current I_{17} will be negligibly small

under these conditions (essentially equal to the base current of transistor Q_{16}) while not interfering with normal circuit operation.

An alternative to the current sources shown in Fig. 7, and another preferred embodiment is shown in Fig. 8. In Fig. 8, PNP transistors Q_{13} - Q_{18} and resistor R_3 function identically to the counterpart components of Fig. 7 so as to generate a current:

$$(23) \quad I_{13} = \frac{V_T}{R_3} \ln A$$

Resistor R_4 and diode-connected transistor Q_{21} also function identically with their counterparts in Fig. 7. PNP transistors Q_9 - Q_{12} , Q_{17} and Q_{18} and diode-connected transistor Q_{22} along with resistors R_2 and R_5 (all shown to the right in Fig. 8) form an identical circuit as the circuit formed by transistors Q_{13} - Q_{18} and Q_{21} , and resistors R_3 and R_4 (all shown to the left in Fig. 8) so as to generate a current:

$$(24) \quad I_{11A} = \frac{V_T}{R_2} \ln A$$

Transistors Q_{23} and Q_{24} form the simplest form of a current mirror circuit and are formed as two NPN transistors, wherein the NPN transistor Q_{23} has its collector connected to its base and to the collector of transistor Q_{17} , and its emitter connected to the negative voltage rail V_{NEG} . NPN transistor Q_{24} has its emitter connected to the negative voltage rail V_{NEG} , its base connected to the transistor Q_{23} and its collector connected with the collector of transistor Q_{17} (of the circuit portion shown in the left side of Fig. 8) to the symmetry adjust terminal 22. While NPN transistors Q_{23} and Q_{24} form a simple current mirror, it will be evident to those skilled in the art that other types of current mirrors can be used. The current mirror serves to replicate current I_{11} . This current serves the same function as its counterpart in Fig. 7.

In operation, when I_{11A} (which is identical to I_{11} by virtue of the current mirror) is less than I_{13} , I_{sym} will be of a positive polarity and flow in the direction shown in Fig. 8. If I_{11A} (and I_{11}) is greater than I_{13} , then I_{sym} will be of a negative polarity and flow in the opposite direction from that shown in Fig. 8.

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1 In the embodiment of Fig. 8, the PTAT current source is implemented with
2 the same polarity devices, and referenced to the same reference voltage (in this case,
3 V_{pos}) as the PTAT current source of Fig. 7. The current mirror is used to generate
4 the opposing polarity current I_{11} so that the bipolar nature of the correction current
5 I_{sym} can be realized.

6 With the addition of the current mirror, the implementation of Fig. 8 utilizes
7 a few more components than the realization shown in Fig. 7, but there are occasions
8 when it may be preferred. In the most commonly available junction-isolated bipolar
9 IC process the vertical NPN transistors exhibit high common-base current gain over
10 a wide range of operating currents, while the current gain of the lateral PNP
11 transistors is typically much lower, and falls off rapidly at collector currents above
12 a few tens of microamps. For this reason it may be desirable to implement both
13 PTAT current sources with NPN transistors (the opposite configuration from that
14 shown in Fig. 8).

15 Another occasion where the circuit of Fig. 8 may be preferred is when the
16 wafer-stage trimming method known as "zener zapping" is used to adjust R_2 and R_3 .
17 This technique involves creating selected connections between components at wafer
18 test by passing a short-duration high current through a zener diode. This method
19 requires metallic connections (pads) for probe tips to be attached to both ends of
20 each zener diode that may be selectively shorted. Having both PTAT current
21 sources attached to the same reference voltage as in Fig. 8 allows the reference
22 voltage node to serve as one end of all connections to be made, which reduces the
23 required die area. Additionally, since the initial state of all selected connections is
24 essentially an open circuit, R_2 and R_3 may be open circuits before any trimming is
25 done. Thus, an untrimmed version of the device may be manufactured with
26 minimum test time by merely omitting the trim procedure. This is in contrast to the
27 circuit in Fig. 7, where in order to provide for selective connection of R_3 , a probe
28 pad must be added at V_{NEG} , which may not be required otherwise.

29 The compensation circuits shown in Figs. 4-8 provide an easy way to adjust
30 at the wafer stage for the correction of operational mismatches in circuit components
31 which are a part of the same integrated circuit structure and which for operational
32 purposes are required to be matched over a temperature range. More specifically,

1 the current source I_{sym} provides the means, on the same integrated circuit
2 incorporating a gain-control circuit, for providing proper symmetry adjustment for
3 mismatches in the $V_{be} - I_c$ characteristics of the transistors independently of
4 temperature variations. The disclosed embodiments provide a way to implement a
5 gain control circuit of the type having two gain control terminals so that symmetry
6 adjustment is unaffected by the potential at either of the two gain control terminals,
7 thus leaving them both available for use. The approach exploits the use of resistors,
8 fabricated in accordance with readily available IC manufacturing techniques, that
9 track over a wide range of temperatures, in providing appropriately temperature-
10 dependent symmetry adjustment for a voltage controlled amplifier implemented as
11 an IC.

12 It is noted that while the compensation means has been described in
13 connection with the type of VCA shown and described in connection with Fig. 1, the
14 invention can be employed with other types of circuits which are manufactured in
15 IC form, and can be used with other types of VCAs, such as those shown in the
16 two Frey patents, US Patent Nos. 4,560,947 and 4,823,093. In addition, it should
17 be noted that the connection of the symmetry trimming circuitry to the base of
18 transistor Q_6 is but one form of implementation with respect to the VCA circuit
19 shown. It may just as easily be connected to any of the bases of the four primary
20 log or antilog transistors (Q_3 , Q_4 , Q_5 , or Q_6) with identical results. If the symmetry
21 adjustment apparatus were connected to the base of transistor Q_3 , then E_{cp} would be
22 applied to the base of transistor Q_6 . If it were connected to the base of transistor Q_4 ,
23 then R_1 would be connected between the bases of transistors Q_4 and Q_5 , with E_{cm}
24 applied to the base of transistor Q_5 , and E_{cp} applied to the bases of transistors Q_3 and
25 Q_6 . Similarly, if it were connected to the base of transistor Q_5 , then R_1 would again
26 be connected between the bases of transistors Q_4 and Q_5 , with E_{cm} applied to the base
27 of transistor Q_4 , and E_{cp} applied to the bases of transistors Q_3 and Q_6 . This is true
28 of all of the symmetry adjustment techniques described herein.

29 Since certain changes may be made in the above apparatus without departing
30 from the scope of the invention herein involved, it is intended that all matter
31 contained in the above description or shown in the accompanying drawings shall be
32 interpreted in an illustrative and not in a limiting sense.

**WHAT IS CLAIMED IS:**

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- 1 1. An integrated circuit comprising:
2 at least two components, each of which operate interdependently as a function
3 of temperature and at least one physical parameter associated with each of said
4 components when implemented in integrated form;
5 compensation means, disposed in said integrated circuit, for generating and
6 applying an adjustable bipolar compensation signal to at least one of said components
7 so that the level and polarity of said compensation signal can be adjusted during the
8 manufacture of the integrated circuit such that said two components interdependently
9 operate predictably, consistently and substantially independently of temperature
10 variations and differences between the physical parameter of said two components.
- 1 2. An integrated circuit according to claim 1, wherein said two components
2 are transistors, wherein said transistors operate interdependently as a function of
3 absolute temperature.
- 1 3. An integrated circuit according to claim 2, wherein said physical
2 parameter is the base-to-emitter voltage (V_{be}) to collector current (I_c) characteristics
3 of each of said transistors.
- 1 4. An integrated circuit according to claim 1, wherein said compensation
2 means for generating and applying said adjustable bipolar compensation signal
3 includes means for generating said adjustable bipolar compensation signal as a
4 function of absolute temperature.
- 1 5. An integrated circuit according to claim 4, wherein said means for
2 generating and applying said adjustable bipolar compensation signal includes means
3 for generating and applying an adjustable bipolar current.
- 1 6. An integrated circuit according to claim 5, wherein said means for
2 generating and applying said adjustable bipolar current includes at least one transistor



3 disposed in said integrated circuit, said bipolar current being a function of the
4 emitter area of said transistor.

1 7. An integrated circuit according to claim 6, wherein said integrated circuit
2 includes a resistive element coupled to one of said components and having a
3 predetermined resistance with a determinable temperature coefficient, and said means
4 for generating a bipolar current provides said compensation current as a function of
5 $\frac{V_T}{R} \ln A$, wherein V_T is a voltage proportional to absolute temperature, R represents
6 a resistance having a temperature coefficient characteristic matching the temperature
7 coefficient of said resistive element, and A is the emitter area of said transistor.

1 8. An integrated circuit according to claim 6, wherein said means for
2 generating and applying said adjustable bipolar current includes at least two
3 transistors, one for each polarity of said adjustable bipolar current, wherein the level
4 and polarity of said bipolar current is a function of the emitter areas of said two
5 transistors.

1 9. An integrated circuit according to claim 5, wherein said means for
2 generating and applying said adjustable bipolar current includes at least four
3 transistors, wherein three of said transistors have identical operating characteristics,
4 and said fourth transistor is identical to each of said three transistors but includes an
5 emitter area A times larger than the emitter area of each of the other three
6 transistors.

1 10. An integrated circuit according to claim 5, wherein said means for
2 generating and applying said adjustable bipolar current includes means for generating
3 said adjustable bipolar current as a function of $\left(\frac{R_2 - R_3}{R_2 R_3}\right) V_T \ln A$, wherein R_2 and R_3
4 are resistive elements having respective resistances, each adjustable during the
5 manufacture of said integrated circuit, V_T is a voltage proportional to absolute
6 temperature and A is the emitter area of said transistor.





1 11. An integrated circuit according to claim 5, wherein said means for
2 generating and applying said adjustable bipolar current includes positive current
3 means for generating said adjustable bipolar current as a positive current; negative
4 current means for generating said adjustable bipolar current as a negative current;
5 and means for summing said positive and negative currents.

1 12. An integrated circuit according to claim 11, wherein each of said
2 positive current means and negative current means includes means for adjusting the
3 corresponding positive and negative currents.

1 13. An integrated circuit according to claim 12, wherein each of said
2 positive and negative current means includes at least four transistors, wherein three
3 of said transistors have identical operating characteristics, and said fourth transistor
4 is identical to each of said three transistors but includes an emitter area A times
5 larger than the emitter area of each of the other three transistors.

1 14. An integrated circuit according to claim 11, further including means for
2 increasing the output impedance of each of said positive current means and the
3 negative current means.

1 15. An integrated circuit according to claim 14, wherein said means for
2 increasing the output impedance of each of said positive current means and the
3 negative current means includes a pair of cascode transistors.

1 16. An integrated circuit according to claim 11, wherein one of said current
2 means includes (a) means for generating a current signal, and (b) a current mirror
3 for generating said adjustable bipolar current in response to said current signal.

1 17. An integrated circuit comprising:
2 gain control means for generating an output signal as a function of an input
3 signal and a gain control signal, said gain control means including at least two
4 transistors required to be symmetrically matched so that the operational





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5 characteristics of said transistors are identical in order to minimize signal distortion
6 by said gain control means and by changes in operating temperature; and
7 means, disposed within said integrated circuit, for generating a bipolar
8 symmetry adjustment signal for providing symmetry adjustment between said two
9 transistors as a function of any mismatch between said transistors so that the level
10 and polarity of said bipolar signal can be adjusted during the manufacture of the
11 integrated circuit such that said two transistors operate predictably, consistently and
12 substantially independently of temperature variations and said gain control signal.

1 18. An integrated circuit according to claim 17, wherein said gain control
2 means includes means for generating a first signal as a logarithmic function of the
3 input signal, and means for generating the output signal as an antilogarithmic
4 function of the gain control signal and the first signal.

1 19. An integrated circuit according to claim 17, wherein said means for
2 generating a bipolar symmetry adjustment signal includes means for generating a
3 bipolar current.

1 20. An integrated circuit according to claim 19, wherein said means for
2 generating said bipolar current includes at least one transistor disposed in said
3 integrated circuit, said bipolar current being a function of the emitter area of said
4 transistor.

1 21. An integrated circuit according to claim 20, wherein said integrated
2 circuit includes a resistive element coupled to at least one of said transistors and
3 having a predetermined resistance with a temperature coefficient, and said means for
4 generating said bipolar current provides said bipolar current as a function of
5 $\frac{V_T}{R} \ln A$, wherein V_T is a voltage proportional to absolute temperature, R represents
6 a resistance having a temperature coefficient characteristic matching the temperature
7 coefficient of said resistive element, and A is the emitter area of said transistor.





1 22. An integrated circuit according to claim 20, wherein said means for
2 generating said bipolar current includes at least four transistors disposed in said
3 integrated circuit, wherein three of said transistors have identical operating
4 characteristics, and said fourth transistor is identical to each of said three transistors
5 but includes an emitter area A times larger than the emitter area of each of the other
6 three transistors.

1 23. An integrated circuit according to claim 19, wherein said means for
2 generating said bipolar current includes at least two transistors, one for each polarity
3 of the bipolar current, wherein the level and polarity of the bipolar current is a
4 function of the emitter areas of said two transistors of said means for generating said
5 bipolar current.

1 24. An integrated circuit according to claim 19, wherein said means for
2 generating said bipolar current includes means for generating said bipolar current as
3 a function of $\left(\frac{R_2 - R_3}{R_2 R_3}\right) V_T \ln A$, wherein R_2 and R_3 are resistive elements having
4 respective resistances, each adjustable during the manufacture of said integrated
5 circuit, V_T is a voltage proportional to absolute temperature and A is the emitter area
6 of said transistor.

1 25. An integrated circuit according to claim 19, wherein said means for
2 generating said bipolar current includes positive current means for generating said
3 compensation current as a positive current; negative current means for generating
4 said current as a negative current; and means for summing said positive and negative
5 currents.

1 26. An integrated circuit according to claim 25, wherein each of said
2 positive current means and said negative current means includes means for adjusting
3 the corresponding positive and negative currents.

1 27. An integrated circuit according to claim 26, wherein each of said
2 positive and negative current means are disposed in said integrated circuit and





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3 includes at least four transistors, wherein three of said transistors have identical
4 operating characteristics, and said fourth transistor is identical to each of said three
5 transistors but includes an emitter area A times larger than the emitter area of each
6 of the other three transistors.

1 28. An integrated circuit according to claim 25, further including means,
2 disposed in said integrated circuit, for increasing the output impedance of each of
3 said positive current means and the negative current means.

1 29. An integrated circuit according to claim 28, wherein said means for
2 increasing the output impedance of each of said positive current means and the
3 negative current means includes a pair of cascode transistors.

1 30. An integrated circuit according to claim 25, wherein one of said current
2 means includes (a) means for generating a current signal, and (b) a current mirror
3 for generating said adjustable bipolar current in response to said current signal.

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