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(54) **LINEAR INTEGRATED CIRCUIT TEMPERATURE SENSOR APPARATUS WITH ADJUSTABLE GAIN AND OFFSET**

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(75) Inventor: **Paul K. Hartley**, Emmaus, PA (US)

Primary Examiner—Ngan Ngo

(73) Assignee: **Agere Systems Inc.**, Allentown, PA (US)

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(57) **ABSTRACT**

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Embodiments of the invention include a temperature sensor apparatus, method and system for providing an output voltage response that is linear to the temperature of the integrated circuit to which the temperature sensor belongs and/or the integrated circuit die on which the temperature sensor resides. The output voltage of the temperature sensor has an adjustable gain component and an adjustable voltage offset component that both are adjustable independently based on circuit parameters. The temperature sensor includes a conventional bandgap circuit, which generates an internal PTAT (proportional to absolute temperature) current to produce a bandgap reference voltage, and a current mirror arrangement that provides a scaled current that is proportional to the bandgap circuit's PTAT current. Conventionally, the scaled PTAT current is sourced through an output resistor to provide the output voltage of the temperature sensor. The inventive temperature sensor includes an offset circuit that diverts a portion of current from the scaled PTAT current before the current is sourced through the output resistor. Thus, the inventive temperature sensor subtracts an offset voltage from the output voltage, which offset voltage represents the desired voltage offset component. The offset circuit includes a bandgap circuit arrangement, a voltage to current converter arrangement, and a current mirror arrangement that are configured to provide a voltage offset that is adjustable based on independent circuit parameters such as resistor value ratios and transistor device scaling ratios. The gain component of the inventive temperature also is based on similar independent circuit parameters.

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(52) **U.S. Cl.** **257/467; 257/E23.08; 257/E31.131**

(58) **Field of Classification Search** **257/467, 257/470, E23.08, E31.131**

See application file for complete search history.

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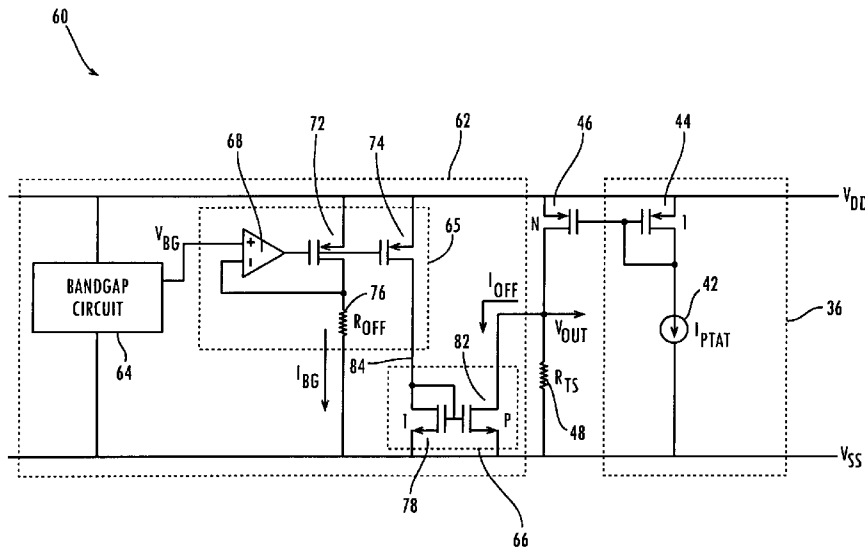
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18 Claims, 4 Drawing Sheets



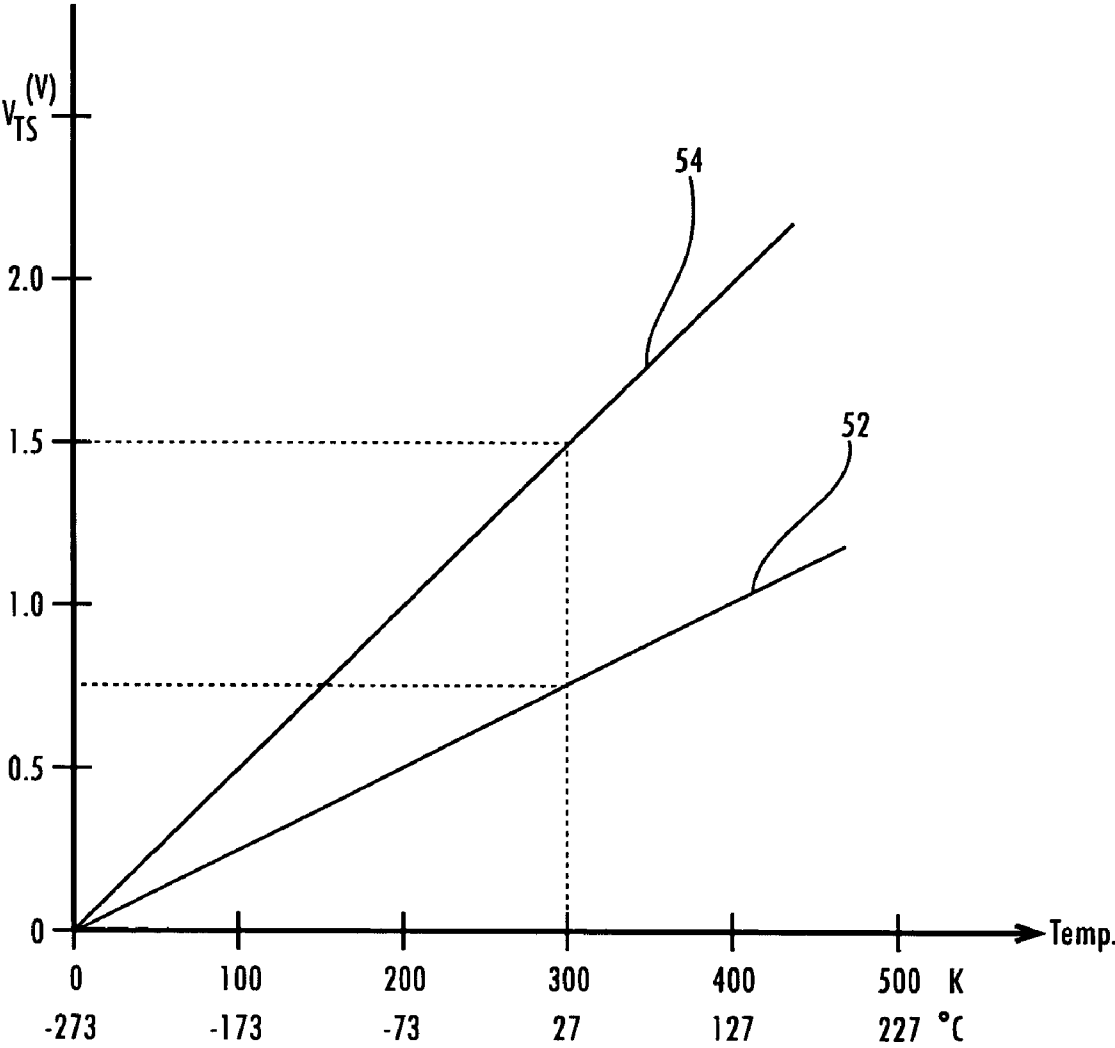


Fig. 3

60 ↗

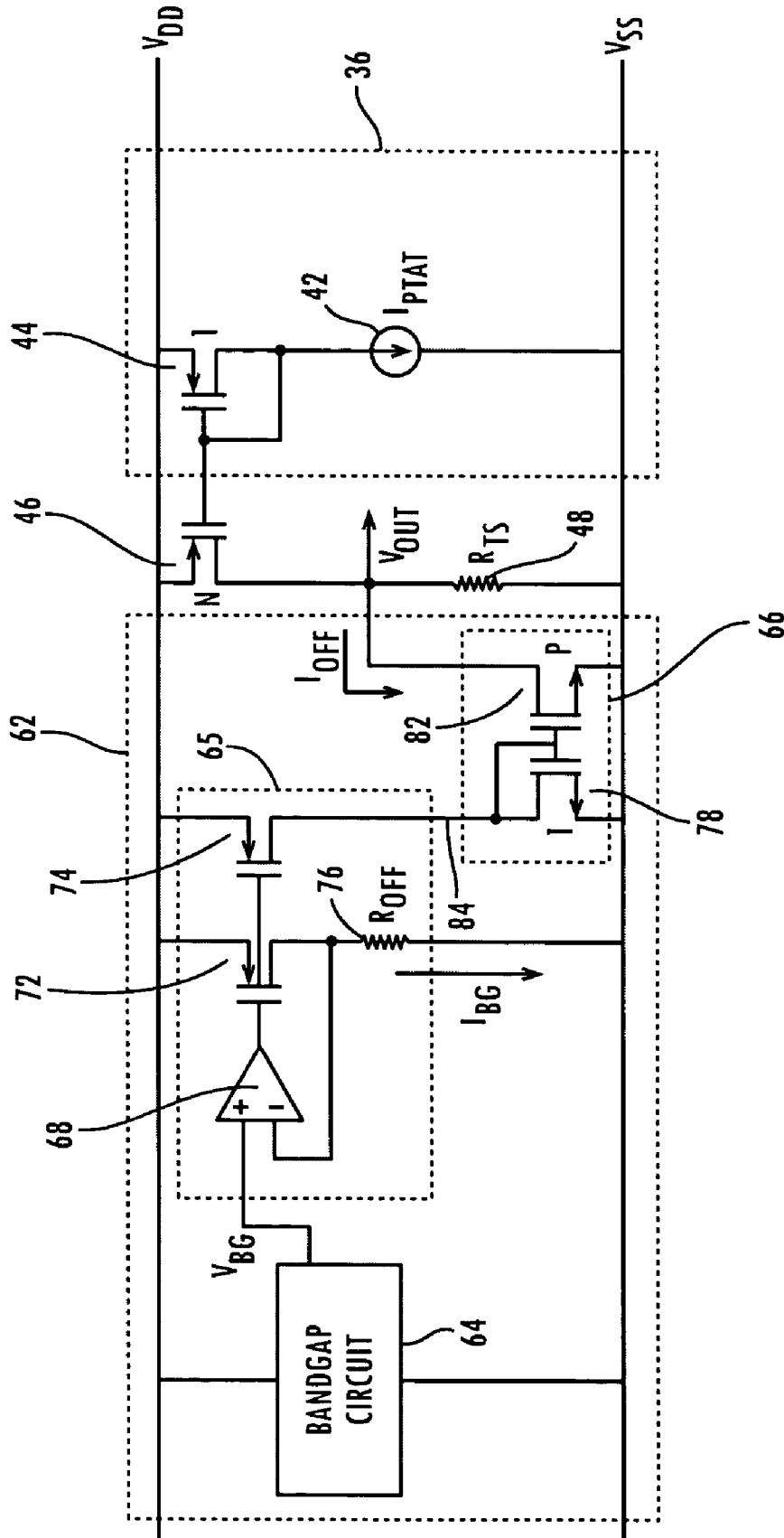


Fig. 4

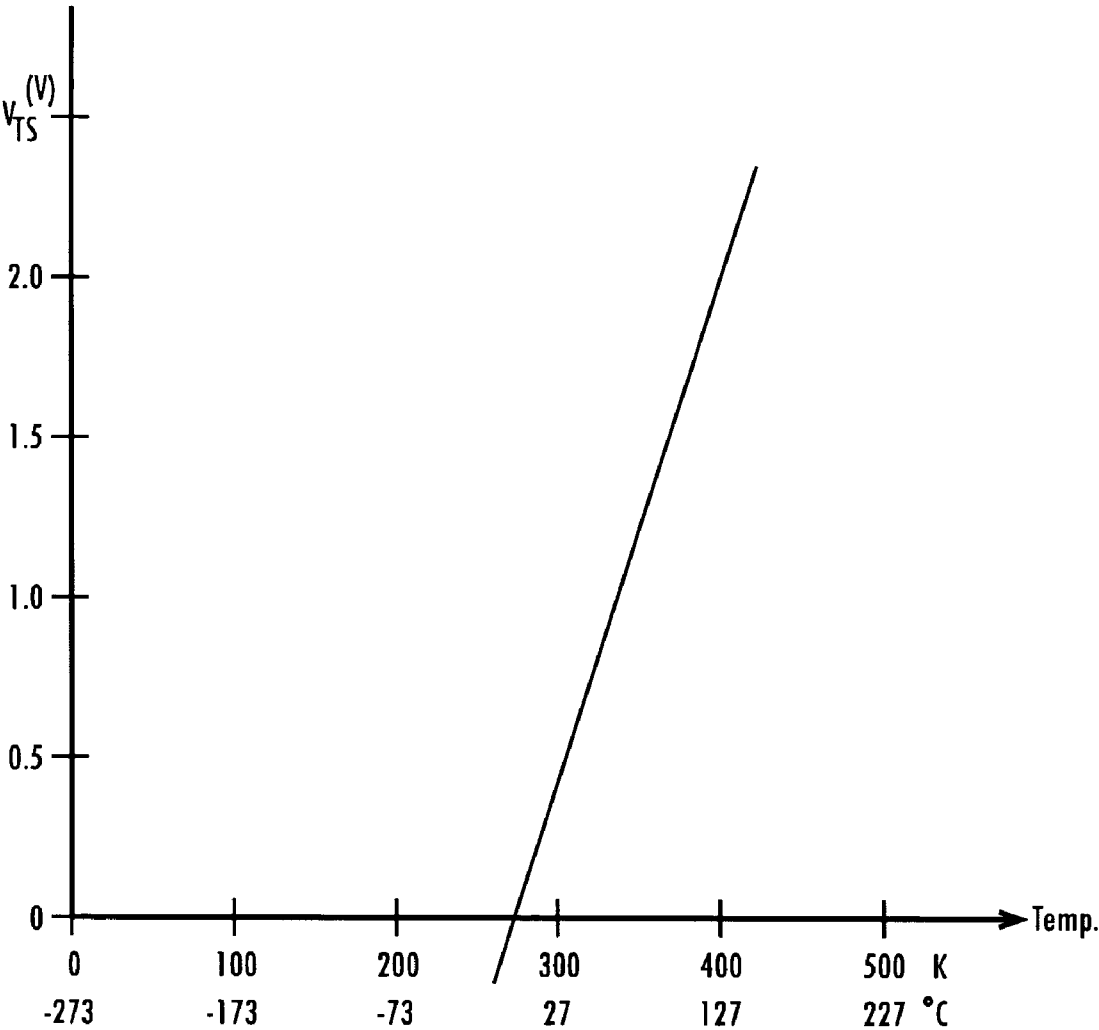


Fig. 5

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LINEAR INTEGRATED CIRCUIT TEMPERATURE SENSOR APPARATUS WITH ADJUSTABLE GAIN AND OFFSET

BACKGROUND OF THE INVENTION

1. Field of the Invention

The invention relates to temperature sensors. More particularly, the invention relates to integrated circuit (IC) temperature sensors having linear response, adjustable gain and adjustable offset.

2. Description of the Related Art

Integrated circuit (IC) temperature sensors are used to determine the die or substrate temperature of an integrated circuit in which the temperature sensors are embedded. Since these temperature sensors are on the same die as the active circuitry whose temperature is to be measured, the temperature sensors can determine the junction temperature (the primary temperature of interest) of the active circuitry more accurately than, e.g., measuring the external IC package temperature. In general, it is known that the base-emitter voltage V_{be} of a forward-biased transistor is a linear function of absolute temperature (T) in degrees Kelvin ($^{\circ}$ K), and is useful as the basis for a stable and relatively linear temperature sensor.

One such type of conventional temperature sensor typically involves a bandgap circuit that generates a current proportional to absolute temperature (I_{PTAT}), which, after being scaled by a current mirror or other suitable arrangement, is sourced through a temperature sensor resistor R_{TS} to provide the output voltage V_{OUT} of the temperature sensor. Since the temperature sensor resistor R_{TS} is the same type of resistor as the resistor (R_{PTAT}) used in the bandgap circuit to generate I_{PTAT} , the output of the temperature sensor circuit is linearly proportional to temperature. Also, the gain (in volts/degrees Kelvin) of the temperature sensor, which is a function of the ratio of the temperature sensor resistor R_{TS} to the bandgap circuit resistor R_{PTAT} , is adjustable. However, in this type of conventional temperature sensor, there is no voltage offset, i.e., the output voltage at 0° K (-273° Celsius) is 0 volts.

Some other types of conventional temperature sensors offer both adjustable gain and adjustable offset. For example, see the temperature sensor disclosed in Pease, "A New Fahrenheit Temperature Sensor," IEEE Journal of Solid-State Circuits, Vol. SC-19, No. 6, December 1984, pages 971-977. However, the temperature sensor in Pease requires that the gain be calibrated by trimming the offset error at room temperature. That is, one or more resistors, e.g., the resistor R_4 and a resistor in the I_{PTAT} current source circuit, must be trimmed to calibrate the gain.

Trimming, e.g., resistor trimming, is a conventional technique for calibrating sensor circuit performance. It involves, e.g., including a network of fusible links or buried fuses in the circuit to modify resistor values by blowing one or more of the fuses. Although trimming helps to compensate for component tolerances, manufacturing variations, and the effects of temperature and aging, trimming is relatively costly, time consuming in terms of extra test time for calibration, and requires additional process technology, e.g., process technology that supports trim links, fuses and other forms of one-time programmable devices.

Another conventional temperature sensor is disclosed by Audy in U.S. Pat. No. 5,529,354. The temperature sensor in Audy offers a less complex circuit design than the temperature sensor disclosed in Pease, and provides a programmable voltage offset for the temperature sensor. The programmable offset is provided by adding an offset resistor to a conventional band gap temperature cell and by generating the sensor

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output voltage at a different point in the circuit. However, to program the desired offset, Audy too requires trimming the offset resistor. Also, to program the gain of the temperature sensor, Audy requires trimming another resistor in the band-gap cell. As discussed hereinabove, resistor trimming is not an efficient calibration or offset adjustment technique.

Accordingly, it would be desirable to have an IC temperature sensor that generates an output voltage that is linearly proportional to the IC die temperature and also allows for both the gain and the voltage offset to be adjusted independently by IC parameters, without trimming.

SUMMARY OF THE INVENTION

The invention is embodied in a temperature sensor apparatus, method and system for providing an output voltage response that is linear to the temperature of the integrated circuit to which the temperature sensor belongs and/or the integrated circuit die on which the temperature sensor resides. Also, the output voltage of the temperature sensor has an adjustable gain component and an adjustable voltage offset component that both are adjustable independently based on circuit parameters. The temperature sensor includes a conventional bandgap circuit, which generates an internal PTAT (proportional to absolute temperature) current to produce a bandgap reference voltage, and a current mirror arrangement that provides a scaled current that is proportional to the bandgap circuit's PTAT current. Conventionally, the scaled PTAT current is sourced through an output resistor to provide the output voltage of the temperature sensor. According to embodiments of the invention, the temperature sensor also includes an offset circuit that diverts a portion of current from the scaled PTAT current before the current is sourced through the output resistor. In this manner, the inventive temperature sensor subtracts an offset voltage from the output voltage, which offset voltage represents the desired voltage offset component. The offset circuit includes a bandgap circuit arrangement, a voltage to current converter arrangement, and a current mirror arrangement that are configured to provide a voltage offset that is adjustable based on independent circuit parameters such as resistor value ratios and transistor device scaling ratios. The gain component of the inventive temperature sensor also is based on similar independent circuit parameter ratios. Thus, the temperature sensor is configured to provide an output voltage that is linearly dependent on temperature, and that has an adjustable gain and an adjustable offset that both are based on independent circuit design parameters.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a simplified schematic diagram of a conventional integrated circuit (IC) temperature sensor;

FIG. 2 is a simplified schematic diagram of an equivalent circuit for the conventional temperature sensor circuit shown in FIG. 1;

FIG. 3 is a graphical diagram of the output voltage of the conventional temperature sensor of FIG. 1, for various gain values (2 different gains), as a function of temperature;

FIG. 4 is a simplified schematic diagram of an IC temperature sensor according to embodiments of the invention; and

FIG. 5 is a graphical diagram of the output voltage of the inventive temperature sensor shown in FIG. 4, for a single gain value and offset value, as a function of temperature.

DETAILED DESCRIPTION OF EXEMPLARY EMBODIMENTS

In the following description, like reference numerals indicate like components to enhance the understanding of the invention through the description of the drawings. Also, although specific features, configurations and arrangements are discussed hereinbelow, it should be understood that such is done for illustrative purposes only. A person skilled in the relevant art will recognize that other steps, configurations and arrangements are useful without departing from the spirit and scope of the invention.

Referring now to FIG. 1, shown is a simplified schematic diagram of a conventional integrated circuit (IC) temperature sensor 10. As discussed previously herein, many conventional temperature sensors typically include some type of a bandgap circuit coupled between an upper supply voltage (V_{DD}) 12 and a lower supply voltage (V_{SS}) 14. In this particular conventional circuit arrangement, a portion of the bandgap circuit is shown generally as circuitry 16. The upper supply voltage V_{DD} 12 is, e.g., 1.0 volts or 2.5 volts; the lower supply voltage V_{SS} 14 is, e.g., ground potential.

The circuitry 16 includes several unit devices (i.e., scale is 1): two field effect transistor (FET) unit devices 22, 24 and a bipolar unit device 26. Also, the circuitry 16 includes an M-scaled bipolar device 28 (i.e., M bipolar unit devices connected in parallel), a resistor R_{PTAT} 32 connected in series with the M-scaled device 28, and an operational amplifier (op-amp) 34 connected as shown between the two legs of the circuitry 16.

The op-amp 34 forces the voltage at its input terminals to be equal by controlling the gate voltage of the two FET unit devices 22 and 24, and hence the drain-source current through them. Since devices 22 and 24 both are of unit size, and share a common gate voltage, the drain-source current is the same in both devices. In this manner, the circuitry 16 generates a current proportional to absolute temperature (PTAT), shown as I_{PTAT} . Also, in this arrangement, the voltage across the resistor R_{PTAT} 32, shown as V_{PTAT} , is equal to $\ln(M)*V_T$, where M is the scaling factor of the M-scaled bipolar device 28 and V_T , which is the thermal voltage of the M-scaled bipolar device, is a constant value equal to kT/q , where k is Boltzman's constant, T is the absolute temperature in degrees Kelvin ($^{\circ}$ K), and q is the electron charge ($k/q=86.17$ microvolts/ $^{\circ}$ K). Based on these values, the current I_{PTAT} through the resistor R_{PTAT} 32 is equal to the voltage across the resistor (V_{PTAT}) divided by its resistance R_{PTAT} , i.e., $I_{PTAT}=V_{RPTAT}/R_{PTAT}$. Substituting for V_{RPTAT} , I_{PTAT} is equal to $(\ln(M)*V_T)/R_{PTAT}$.

For purposes of clarity and simplicity in describing the operation of the conventional temperature sensor 10 shown in FIG. 1, at least a portion of the circuitry 16 can be represented by an equivalent circuit. Referring now to FIG. 2, with continuing reference to FIG. 1, shown is an equivalent circuit 36 to the circuitry 16 shown in FIG. 1. A portion of the equivalent circuit 36 is shown as an ideal current source 42 of value I_{PTAT} and a field effect transistor (FET) device 44 coupled together between the upper supply voltage V_{DD} 12 and the lower supply voltage V_{SS} 14, as shown. The FET device 44, which is a metal oxide field effect transistor (MOSFET) or other suitable transistor device, is a unit device, i.e., the device has a scaling factor of 1.

The conventional temperature sensor 10 also includes an N-scaled FET device 46 (i.e., NFET devices coupled together in parallel) and a temperature sensor resistor R_{TS} 48 coupled in series between the upper supply voltage V_{DD} 12 and the lower supply voltage V_{SS} 14. The voltage V_{TS} (shown as 50)

generated across the temperature sensor resistor R_{TS} is the output voltage for the temperature sensor 10.

The current mirror or current mirror arrangement formed by the unit FET device 44 in the equivalent circuit 36 and the N-scaled device 46 keeps the ratio of the current I_{TS} to I_{PTAT} constant. The current I_{TS} is scaled by a factor of N by the N-scaled device 46. That is, $I_{TS}=(N)(I_{PTAT})$. Also, the current source arrangement sources this N-scaled PTAT current through the temperature sensor resistor R_{TS} . Since, as discussed hereinabove, $I_{PTAT}=(\ln(M)*V_T)/R_{PTAT}$, by substituting for I_{PTAT} , I_{TS} is equal to $(N)(\ln(M)*V_T)/R_{PTAT}$.

Therefore, the voltage V_{TS} 50 across the resistor R_{TS} 48, which voltage is the output of the temperature sensor 10, is equal to $R_{TS}*I_{TS}$, or substituting for I_{TS} , $V_{TS}=(R_{TS}/R_{PTAT})*N\ln(M)V_T$. Substituting kT/q for V_T (e.g., as discussed hereinabove), $V_{TS}=(R_{TS}/R_{PTAT})*N\ln(M)(kT/q)$. Expressed another way, $V_{TS}=K_1T$, where $K_1=(R_{TS}/R_{PTAT})(N\ln(M))(kT/q)$. As shown by this equation, the output voltage V_{TS} 50 of the temperature sensor 10 is dependent on temperature T, with K_1 being based on a number of constants and various component value ratios in the circuit of the temperature sensor 10.

Referring now to FIG. 3, shown is a graphical diagram of the output voltage V_{TS} of the conventional temperature sensor 10, as a function of temperature. The output voltage V_{TS} is shown for two different gain values of the temperature sensor 10. The gain is measured in volts per degrees Kelvin. As discussed previously hereinabove, the gain of the temperature sensor 10 is a function of the ratio of the temperature sensor resistor R_{TS} 48 to the bandgap circuit resistor R_{PTAT} 32, and therefore is adjustable.

The conventional temperature sensor 10 provides an output voltage that is proportional to temperature. Also, since the temperature sensor resistor R_{TS} 48 is the same type of resistor as the resistor R_{PTAT} 32 used in the circuitry 16, the output voltage V_{TS} 50 of the conventional temperature sensor 10 is linearly proportional to temperature, as shown by the linearity of the output voltage plots.

However, as discussed previously herein, there is no voltage offset. That is, the output voltage at $T=0^{\circ}$ K (-273° Celsius) is 0 volts, and it can not be adjusted. Therefore, for an operating region of interest, e.g., between 27 and 127 $^{\circ}$ Celsius ($^{\circ}$ C.), relatively large output voltages would be required by the temperature sensor 10, since all the plots of the output voltage V_{TS} must pass through 0 for $T=0^{\circ}$ K (i.e., -273° C.). But, with a typical voltage supply being in the range of, e.g., 1.0 to 2.5 volts, the output temperature swing is very limited across a typical operating temperature range of interest.

For example, for a 2.0 volt supply, the output voltage V_{TS} of the temperature sensor 10 swings between a range of, e.g., 0.75 volts and 1.00 volts, for a first gain value (shown as plot 52), and a range of, e.g., 1.50 volts and 2.00 volts, for a second first gain value (shown as plot 54). Thus, the swing of the output voltage V_{TS} varies from 0.25 volts to 0.50 volts across the useful operating temperature range, e.g., between 27 $^{\circ}$ C. and 127 $^{\circ}$ C. Such relatively small voltage swings offer relatively poor resolution for the temperature sensor 10. Furthermore, because the plots must always pass through 0 volts V_{TS} for $T=0^{\circ}$ K, increasing the gain (i.e., increasing the slope of the plots 52 or 54) quickly moves V_{TS} beyond the circuit supply voltage (e.g., 2.0 volts) for the entire operating temperature range of interest (e.g., 27 $^{\circ}$ C. and 127 $^{\circ}$ C.).

As just discussed, without a voltage offset, the conventional temperature sensor 10, while providing a linear response and having an adjustable gain, lacks the needed resolution or robustness. Ideally, for a 2.0 volt supply, the output temperature V_{TS} should be between approximately 0 volts and approximately 2.0 volts (or approximately 2.5 volts

for a 2.5 volt supply) across the operating temperature range of interest. Such response is possible with the proper circuit design parameters and both an adjustable gain and an adjustable voltage offset.

Referring now to FIG. 4, shown is a simplified schematic diagram of an IC temperature sensor 60 according to embodiments of the invention. The temperature sensor 60 is an integrated circuit (IC) or, along with other circuitry, a portion of an IC. According to embodiments of the invention, the temperature sensor 60 provides an output voltage V_{OUT} that is linearly proportional to the absolute temperature T (e.g., the temperature of the IC die). The temperature sensor 60 also allows for both the gain (volts/° K) and the voltage offset (output voltage at 0° K) to be adjusted independently via circuit parameter ratios in the temperature sensor 60.

As in the conventional temperature sensor described hereinabove, the temperature sensor 60 according to embodiments of the invention includes the equivalent circuit (shown as 36), which includes the ideal current source I_{PTAT} 42 and the unit FET device 44 coupled together as shown between the upper supply voltage V_{DD} 12 and the lower supply voltage V_{SS} 14. The inventive temperature sensor 60 also includes the N-scaled FET device 46 and the temperature sensor resistor R_{TS} 48 coupled in series between the upper supply voltage V_{DD} 12 and the lower supply voltage V_{SS} 14. As with the conventional temperature sensor 10, in the inventive temperature sensor 60, the output voltage V_{OUT} (shown as 61) for the temperature sensor 60 is the voltage generated across the temperature sensor resistor R_{TS} 48.

According to embodiments of the invention, the temperature sensor 60 also includes an offset circuit, shown generally as 62, that diverts or subtracts a portion of current (I_{OFF}) from the N-scaled I_{PTAT} current that conventionally would pass through the resistor R_{TS} 48. In this manner, the offset circuit 62 subtracts a fixed voltage offset V_{OFF} from the output voltage V_{OUT} across the resistor R_{TS} , thus adjusting or reducing the voltage offset of the temperature sensor 60 as desired. Moreover, according to embodiments of the invention, the offset circuit 62 allows the voltage offset to be adjusted independently by various circuit parameter ratios, as will be discussed in greater detail hereinbelow.

The offset circuit 62 includes a bandgap circuit, shown generally as 64; a voltage to current converter or voltage to current converter arrangement, shown generally as 65; and a current mirror or current mirror arrangement, shown generally as 66. In general, the bandgap circuit 64 and the voltage to current converter 65 function as a current source that establishes a bandgap current I_{BG} . The current mirror 66, via its coupling between the N-scaled FET device 46 and the output resistor R_{TS} 48 diverts an offset current (I_{OFF}) from the N-scaled I_{PTAT} current that was to pass through the output resistor R_{TS} 48. The diverted current is a scaled version of the bandgap current I_{BG} , as will be discussed in greater detail hereinbelow.

The voltage to current converter arrangement 65 includes an op-amp 68, a pair of unit transistor devices (e.g., FETs 72 and 74), and a resistor or offset resistor R_{OFF} 76 coupled together as shown between the upper supply voltage V_{DD} 12 and the lower supply voltage V_{SS} 14. As noted previously herein, the resistor R_{OFF} 76 is the same type of resistor as the resistor used in the circuitry 16 shown in FIG. 1, i.e., the resistor R_{PTAT} 32.

Referring again to FIG. 4, the current mirror 66 includes a unit transistor device (e.g., FET 78) and a P-scaled transistor device (e.g., P-scaled FET 82) coupled together as shown between the voltage to current converter 65, the N-scaled FET 46, and the output resistor R_{TS} 48. As is conventional, the

P-scaled FET 82, which has a scaling factor of P, represents P FET devices coupled together in parallel.

In the voltage to current converter 65, the op-amp 68 controls the current through both of the unit FET devices 72, 74 based on the bandgap voltage V_{BG} from the bandgap circuit 64. The current is controlled such that the bandgap voltage V_{BG} is dropped across the resistor R_{OFF} , thus deriving a bandgap current I_{BG} through the unit FET device 72 and the offset resistor R_{OFF} . The unit FET device 74 mirrors the current I_{BG} . The bandgap voltage V_{BG} is a fixed voltage determined by, e.g., the bandgap circuit 64 and/or the overall circuit to which the temperature sensor 60 may belong. In this manner, the bandgap circuit 64 functions as a constant voltage source having the value V_{BG} .

The current mirror 66 formed by the unit device 78 and the P-scaled device 82 maintains the value of the current I_{BG} in the current mirror branch (shown generally as 84), except that the current is scaled by a factor of P. Therefore, the P-scaled current I_{BG} is the amount of current diverted from the N-scaled I_{PTAT} current that conventionally was to pass through the output resistor R_{TS} . That is, the diverted current, $I_{OFF}=(P)(I_{BG})$.

Therefore, the remaining, non-diverted portion of current that is sourced through the output resistor R_{TS} , hereinafter referred to as I_{OUT} is equal to the N-scaled I_{PTAT} current minus the diverted current I_{OFF} . That is, $I_{OUT}=(N)(I_{PTAT})-I_{OFF}$. Since I_{OFF} is I_{BG} scaled by a factor of P, substituting for I_{OFF} yields $I_{OUT}=(N)(I_{PTAT})-(P)(I_{BG})$. Because the current I_{BG} is equal to V_{BG}/R_{OFF} , substituting for I_{BG} yields $I_{OUT}=(N)(I_{PTAT})-(P)(V_{BG}/R_{OFF})$.

As discussed previously hereinabove, I_{PTAT} is equal to $(\ln(M)V_T)/R_{PTAT}$, where M is the scaling factor of the M-scaled bipolar device 28 (shown in FIG. 1), and V_T , which is the thermal voltage of the M-scaled bipolar device, is equal to the constant value kT/q . Substituting for I_{PTAT} yields $I_{OUT}=N(\ln(M)V_T)/R_{PTAT}-(P)(V_{BG}/R_{OFF})$.

The output voltage V_{OUT} 61 of the temperature sensor 60 is equal to I_{OUT} multiplied by the resistor R_{TS} . That is, $V_{OUT}=(I_{OUT})(R_{TS})$. Substituting for I_{OUT} yields $V_{OUT}=(R_{TS})\{N(\ln(M)V_T)/R_{PTAT}-(P)(V_{BG}/R_{OFF})\}$. Expressed another way, $V_{OUT}=(R_{TS}/R_{PTAT})N\ln(M)V_T-P(R_{TS}/R_{OFF})V_{BG}$. Substituting for V_T , which is equal to kT/q , $V_{OUT}=(R_{TS}/R_{PTAT})N\ln(M)(kT/q)-P(R_{TS}/R_{OFF})V_{OFF}$. Expressed another way, $V_{OUT}=K_1T-K_2V_{BG}$, where $K_1=(R_{TS}/R_{PTAT})(N\ln(M))(k/q)$ and $K_2=P(R_{TS}/R_{OFF})$.

As shown by the last equation, according to embodiments of the invention, the output voltage V_{OUT} 61 of the temperature sensor 60 still is dependent on temperature T, with K_1 being based on a number of constants and device ratios, e.g., scaling factors N and M, and the ratio of values of the output resistor R_{TS} 48 and the resistor R_{PTAT} 32 (shown in FIG. 1). As noted previously herein, since the resistor R_{TS} 48 is the same type of resistor as the resistor R_{PTAT} 32, the output voltage V_{OUT} 61 of the temperature sensor 60 is linearly proportional to temperature T.

Also, as discussed previously, the gain (volts/degrees K) of the temperature sensor 60 is a function of the ratio of the resistor R_{TS} 48 to the bandgap circuit resistor R_{PTAT} 32, and therefore is adjustable. Moreover, according to embodiments of the invention, the output voltage V_{OUT} 61 of the temperature sensor 60 also includes a y-intercept component, K_2V_{BG} , which represents the voltage offset V_{OFF} . As shown by the equation above, the voltage offset V_{OFF} is a function of the bandgap voltage V_{BG} and K_2 , with K_2 being determined by the scaling factor P and the ratio of values of the output resistor R_{TS} 48 and the offset resistor R_{OFF} 76.

Referring now to FIG. 5, shown is graphical diagram of the output voltage V_{OUT} as a function of temperature, of the temperature sensor 60 according to embodiments of the invention. The output voltage V_{OUT} is shown only for one gain value. Compared to the output voltage plots of the conventional temperature sensor 10, shown in FIG. 3, the y-intercept of the output voltage plot in FIG. 5 has been shifted down and the slope of the output voltage plot has been increased. That is, the output voltage plot ($V_{OUT}=K_1T-K_2V_{BG}$) has been adjusted via the voltage offset component (K_2V_{BG}) and via the gain component (K_1).

According to embodiments of the invention, subtracting a fixed voltage offset from the output voltage of the temperature sensor 60 brings down the y-intercept of its plot. Therefore, since the output voltage no longer has to be 0 volts for a temperature of 0° K, the output swing (i.e., the range of the output voltage) of the temperature sensor 60 can be adjusted as desired for a given temperature range of interest. By adjusting the various circuit parameter ratios, K_1 and K_2 can be made so that the output voltage plot substantially passes through the range of the supply voltage (e.g., 0 to 2.0 or 2.5 volts) for a given temperature range of interest, e.g., from approximately 27° C. to approximately 127° C. In this manner, the overall resolution of the temperature sensor 60 is improved.

According to embodiments of the invention, the voltage offset component (K_2V_{BG}) of the output voltage of the inventive temperature sensor 60 allows the entire plot to be shifted downward. Such shifting allows the lower limit of the useful portion of the output voltage plot to be closer to the lower limit of the range of the temperature of interest. That is, as the output voltage plot is shifted downward, the value of the plot is made to be near 0 volts for temperatures near 27° C. Also, the gain component (K_1) of the output voltage of the inventive temperature sensor 60 allows the upper limit of the useful portion of the output voltage plot to be closer to the upper limit of the range of the temperature of interest. That is, by increasing the slope of the output voltage plot, the value of the plot is made to be near 2.0 or 2.5 volts for temperatures near 27° C. In this manner, the output voltage plot falls almost entirely within the useful voltage range of the temperature sensor 60, e.g., 0 to 2.0-2.5 volts, for the temperature range of interest, e.g., 27° C. to 127° C.

For example, as shown in FIG. 3, between a temperature range of 27° C. and 127° C., the output swing of the conventional temperature sensor 10 previously described is from, e.g., 1.50 volts to 2.00 volts (0.50 volt swing) for the first gain value plot 52, and from 0.75 volts to 1.00 volts (0.25 volt swing) for the second gain value plot 54. However, by comparison, according to embodiments of the invention, across the same temperature range, the output swing of the inventive temperature sensor 60 can be shifted down approximately 0.75 volts or approximately 1.50 volts (depending on which gain plot is used) so that the value of the output voltage plot is approximately 0 volts at a temperature of approximately 27° C. As shown in FIG. 5, such a voltage offset shift makes the voltage swing from approximately 0.250 volts to approximately 2.0 volts across the temperature range of 27° C. to 127° C. Such an output swing provides a more robust response by the inventive temperature sensor 60 compared to the response of the conventional temperature sensor 10.

As discussed hereinabove, the gain of the inventive temperature sensor 60 is a function of the ratio of the output resistor R_{TS} 48 to the bandgap circuit resistor R_{PTAT} 32. Also, the voltage offset V_{OFF} is a function of the bandgap voltage V_{BG} and K_2 , which is based on the scaling factor P and the ratio of values of the output resistor R_{TS} 48 and the offset

resistor R_{OFF} 76. Because the bandgap voltage V_{BG} is a constant value and may be set by the overall circuit design, the design parameters for the inventive temperature sensor 60 include the resistor values for resistors R_{TS} 48, R_{PTAT} 32, and R_{OFF} 76, and the transistor device scaling factors N and M.

It will be apparent to those skilled in the art that many changes and substitutions can be made to the embodiments of the invention herein described without departing from the spirit and scope of the invention as defined by the appended claims and their full scope of equivalents. For example, although the circuit components are described hereinabove as an integrated circuit or part of an integrated circuit, the various circuit components alternatively can be discrete components arranged and coupled together to form the various circuits shown and described.

The invention claimed is:

1. A temperature sensor, comprising:
 - a current source including a resistor R_{PTAT} and generating a proportional to absolute temperature (PTAT) current I_{PTAT} that is proportional to absolute temperature (T);
 - a first current mirror coupled to the current source and having a first scaling factor N for scaling the PTAT current I_{PTAT} by a factor of N to generate an N-scaled PTAT current;
 - a temperature sensor resistor R_{TS} coupled to the first current mirror; and
 - an offset circuit coupled to the first current mirror and the temperature sensor resistor R_{TS} , the offset circuit having a second scaling factor P and including an offset resistor R_{OFF} and having a bandgap voltage V_{BG} across the offset resistor R_{OFF} , wherein the temperature sensor generates an output voltage V_{OUT} across the temperature sensor resistor R_{TS} , and wherein the offset circuit offsets the voltage across the temperature sensor resistor R_{TS} by a voltage offset V_{OFF} , wherein the voltage offset V_{OFF} is the bandgap voltage V_{BG} multiplied by the second scaling factor P and multiplied by the ratio of the temperature sensor resistor R_{TS} to the offset resistor R_{OFF} .
2. The temperature sensor as recited in claim 1, wherein the current mirror further comprises a first current mirror, and wherein the offset circuit further comprises:
 - a bandgap circuit for generating the bandgap voltage V_{BG} ,
 - a voltage to current converter, coupled to the bandgap circuit, for generating a bandgap current I_{BG} based on the bandgap voltage V_{BG} and the offset resistor R_{OFF} , and
 - a second current mirror coupled between the voltage to current converter, the first current mirror and the temperature sensor resistor R_{TS} , the second current mirror having the second scaling factor P for scaling the bandgap current I_{BG} to determine the voltage V_{OFF} .
3. The temperature sensor as recited in claim 1, wherein the temperature sensor has a gain that is based on the ratio of the temperature sensor resistor R_{TS} to the current source resistor R_{PTAT} .
4. The temperature sensor as recited in claim 1, wherein the temperature sensor has a voltage offset that is based on the ratio of the temperature sensor resistor R_{TS} to the offset resistor R_{OFF} .
5. The temperature sensor as recited in claim 1, wherein the temperature sensor is fabricated as an integrated circuit (IC).
6. A temperature sensor, comprising:
 - a current source coupled between an upper supply voltage V_{CC} and a lower supply voltage V_{SS} , the current source including a resistor R_{PTAT} and generating a PTAT current I_{PTAT} that is proportional to absolute temperature T;

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a current mirror coupled to the current source and the upper supply voltage V_{CC} , the current mirror having a first scaling factor N for scaling up the PTAT current I_{PTAT} by a factor of N to generate an N -scaled PTAT current;

a temperature sensor resistor R_{TS} coupled to the current mirror and the lower supply voltage V_{SS} ; and

an offset circuit coupled to the current mirror and the temperature sensor resistor R_{TS} , the offset circuit including an offset resistor R_{OFF} and having a bandgap voltage V_{BG} across the offset resistor R_{OFF} ,

wherein the offset circuit diverts an offset current I_{OFF} from the N -scaled PTAT current generated by the current mirror,

wherein the remaining, non-diverted portion of the N -scaled PTAT current is sourced through the temperature sensor resistor R_{TS} as a temperature sensor current I_{OUT} ,

wherein the temperature sensor generates an output voltage V_{TS} by the flow of the temperature sensor current I_{OUT} through the temperature sensor resistor R_{TS} , the output voltage V_{TS} being a function of the absolute temperature T and a function of the bandgap voltage V_{BG} ,

wherein the temperature sensor has a gain that is based on the ratio of the temperature sensor resistor R_{TS} to the current source resistor R_{PTAT} , and

wherein the temperature sensor has a voltage offset that is based on the ratio of the temperature sensor resistor R_{TS} to the offset resistor R_{OFF} .

7. The temperature sensor as recited in claim 6, wherein the offset circuit further comprises:

a first circuit portion that generates a bandgap current I_{BG} based on the bandgap voltage V_{BG} and the offset resistor R_{OFF} , and

a second circuit portion, coupled to the first circuit portion, that scales up the bandgap current I_{BG} to determine the offset current I_{OFF} diverted from the N -scaled PTAT current.

8. The temperature sensor as recited in claim 6, wherein the current mirror further comprises a first current mirror, and wherein the offset circuit further comprises:

a bandgap circuit coupled between the upper supply voltage V_{CC} and the lower supply voltage V_{SS} , the bandgap circuit having a bandgap voltage V_{BG} ,

a voltage to current converter, coupled to the bandgap circuit, for generating a bandgap current I_{BG} based on the bandgap voltage V_{BG} and the offset resistor R_{OFF} , and

a second current mirror coupled between the voltage to current converter, the first current mirror and the temperature sensor resistor R_{TS} , the second current mirror having a second scaling factor P for scaling up the bandgap current I_{BG} by a factor of P to determine the offset current I_{OFF} diverted from the N -scaled PTAT current.

9. The temperature sensor as recited in claim 8, wherein the voltage to current converter further comprises:

an op-amp having an inverting input, a non-inverting input, and an output,

a first field effect transistor (FET) having a gate coupled to the output of the op-amp, a source coupled to the upper supply voltage V_{CC} , and a drain coupled to the inverting input of the op-amp,

a second FET having a gate coupled to the output of the op-amp and the gate of the first FET, a source coupled to the upper supply voltage V_{CC} , and a drain coupled to the second current mirror, and

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a resistor coupled between the lower supply voltage V_{SS} and the drain of the first FET and the inverting input of the op-amp,

wherein the voltage potential at the non-inverting input of the op-amp is the bandgap voltage V_{BG} .

10. The temperature sensor as recited in claim 9, wherein at least one of the first and second FETs are p-type FETs.

11. The temperature sensor as recited in claim 8, wherein the second current mirror further comprises:

a third FET having a gate, a drain and a source, wherein the gate and the drain are coupled together, and wherein the source is coupled to the lower supply voltage V_{SS} , and

a fourth FET having a gate coupled to the gate of the third FET, a drain coupled to the first current mirror and the temperature sensor resistor R_{TS} , and a source coupled to the lower supply voltage V_{SS} .

12. The temperature sensor as recited in claim 11, wherein at least one of the third and fourth FETs are N-type FETs.

13. The temperature sensor as recited in claim 11, wherein the fourth FET is a scaling device having the second scaling factor P .

14. The temperature sensor as recited in claim 6, wherein the temperature sensor is fabricated as an integrated circuit (IC).

15. An integrated circuit (IC), comprising:

a die;

at least one integrated circuit chip coupled to the die; and

an integrated circuit temperature sensor coupled to the die for detecting the temperature of the at least one integrated circuit chip, the temperature sensor including

a current source coupled between an upper supply voltage V_{CC} and a lower supply voltage V_{SS} , the current source including a resistor R_{PTAT} and generating a PTAT current I_{PTAT} that is proportional to absolute temperature T ,

a current mirror coupled to the current source and the upper supply voltage V_{CC} , the current mirror having a first scaling factor N for scaling up the PTAT current I_{PTAT} by a factor of N to generate an N -scaled PTAT current,

a temperature sensor resistor R_{TS} coupled to the current mirror and the lower supply voltage V_{SS} , and

an offset circuit coupled to the current mirror and the temperature sensor resistor R_{TS} , the offset circuit having a first portion that generates a bandgap current I_{BG} based on a bandgap voltage V_{BG} across an offset resistor R_{OFF} , and a second portion, coupled to the first portion, that scales up the bandgap current I_{BG} to determine an offset current I_{OFF} ,

wherein the offset circuit diverts the offset current I_{OFF} from the N -scaled PTAT current generated by the current mirror,

wherein the remaining, non-diverted portion of the N -scaled PTAT current is sourced through the temperature sensor resistor R_{TS} as a temperature sensor current I_{OUT} ,

wherein the temperature sensor generates an output voltage V_{TS} by the flow of the temperature sensor current I_{OUT} through the temperature sensor resistor R_{TS} , the output voltage V_{TS} being a function of the absolute temperature T and a function of the bandgap voltage V_{BG} ,

wherein the temperature sensor has a gain that is based on the ratio of the temperature sensor resistor R_{TS} to the current source resistor R_{PTAT} , and

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wherein the temperature sensor has a voltage offset that is based on the ratio of the temperature sensor resistor R_{TS} to the offset resistor R_{OFF} .

16. The integrated circuit as recited in claim 15, wherein the current mirror further comprises a first current mirror, and wherein the offset circuit further comprises:

a bandgap circuit coupled between the upper supply voltage V_{CC} and the lower supply voltage V_{SS} , the bandgap circuit having a bandgap voltage V_{BG} ,

a voltage to current converter, coupled to the bandgap circuit, for generating a bandgap current I_{BG} based on the bandgap voltage V_{BG} and the offset resistor R_{OFF} , and

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a second current mirror coupled between the bandgap circuit, the first current mirror and the temperature sensor resistor R_{TS} , the second current mirror having a second scaling factor P for scaling up the bandgap current I_{BG} by a factor of P to determine the offset current I_{OFF} diverted from the N-scaled PTAT current.

17. The integrated circuit as recited in claim 15, wherein the bandgap voltage V_{BG} is based on the voltage potential of the integrated circuit.

18. The integrated circuit as recited in claim 15, wherein the lower supply voltage V_{SS} is ground potential.

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