Title: THERMAL PROTECTION CIRCUIT FOR A HIGH VOLTAGE LINEAR REGULATOR

Abstract

A circuit and methods for protecting a high voltage linear regulator from failure due to over-heating, including a heat generating transistor in the regulator protected by limiting the collector current during operation above normal operating temperatures. Limiting the collector current reduces the heat generating load on the transistor and thus allows operation of the transistor at less than full capacity rather than allowing the transistor to catastrophically fail. The invention is applicable in an integrated circuit, which may be combined with circuits for the protection of a transistor against excessive current and over voltage.
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THERMAL PROTECTION CIRCUIT FOR A HIGH VOLTAGE LINEAR REGULATOR

BACKGROUND OF THE INVENTION

The present invention relates to a circuit and a method for detecting an over voltage condition and for protecting a transistor in response thereto, which circuit and method were integrated with protection for an overcurrent condition as well as excessive heat.

The present invention relates to a circuit and method for sensing temperature in a circuit having a heat source, and more particularly to a circuit and method for providing thermal protection for a high voltage linear regulator.

Linear regulators typically include at least one semiconductor element that is a significant source of heat and such regulators may include a heat sink to carry the heat away from the source to prevent catastrophic failure of the regulator due to overheating. However, heat sinks require space, and in space sensitive devices such as integrated circuit high voltage linear regulators it desirable to use as little as space as possible for the heat sink. To this end, the heat sink is typically designed to be able to carry the heat generated by the source at the maximum power rating of the regulator, but not much more.

Limiting the size of the heat sink will, however, limit the tolerance of the voltage regulator to transients or faults that increase temperature beyond the capacity of the sink. It is desirable to decrease the load on the regulator (thus decreasing the amount of heat generated) and accept reduced performance for the duration of the transient or fault, rather than to allow the voltage regulator to catastrophically fail.

It is also known to provide thermal protection by placing a temperature regulation circuit on the semiconductor chip containing the voltage regulator. Such a circuit typically includes a thermal sensing transistor that is biased below its activation threshold so it does not affect voltage regulator operation, and that is placed within a specified distance (e.g., 1-2 mils) of the heat generating semiconductor element to minimize incorrect temperature sensing caused by temperature gradients in the chip. (For example, a temperature gradient of 100°C per 15 mils may exist in semiconductor power devices.) When the circuit senses that the chip has reached its maximum operating temperature, the circuit turns on and reduces output current to reduce chip temperature. The circuit senses junction temperature increases within milliseconds and is thereby able to react before voltage regulator failure. However, such circuits may be too sensitive to short duration temperature increases (e.g., transients or fluctuations) that do not affect voltage regulator operation, turning the regulator off (or reducing current) unnecessarily. The prior art circuits may also turn the voltage regulator back on too soon, permitting an undesirably quick hysteresis.

The present invention includes a temperature sensor for a voltage regulator including two temperature sensitive elements, a first of said elements being in immediate thermal contact with a heat
source in the voltage regulator to provide an immediate response and the second of said elements being in remote thermal contact with the heat source to provide a delayed response so that the effective response of the sensor to temperature variations in the source includes both short term and long term components and in which said two temperature sensitive elements are semiconductor transistors. An object of the present invention to provide a thermal protection circuit and method that obviates the problems of known prior art.

Another object is to provide a circuit and method for providing thermal protection for a linear regulator that is desensitized to short duration temperature changes.

A further object of the present invention to provide a circuit and method for providing thermal protection for a semiconductor chip in which the sensed temperature is an average of the temperatures at a heat source and at a position on the chip remote from the heat source.

Preferable a further object of the present invention to provide a integrated circuit for reducing the load current in a linear regulator in response to a change in sensed temperature that is an average of immediate and delayed temperature changes and to protect a transistor by reducing externally supplied base current responsive to detection of temperatures above a predetermined threshold.

Another object is to provide a circuit for detecting excessive voltage, current and heat in an integrated circuit linear regulator.

The invention will now be described, by way of example, with reference to the accompanying drawings in which:

Figure 1 is a graphical depiction of a transistor safe operating area illustrating in dashed lines the improvement in the present invention.

Figure 2 is a circuit diagram of a prior art high current, linear voltage regulator.
Figure 3 is a diagram of one embodiment of a voltage protection circuit.
Figure 4 is a diagram of a second embodiment of a voltage protection circuit.
Figure 5 is a diagram of a third embodiment of a voltage protection circuit.
Figure 6 is a diagram of a fourth embodiment of a voltage protection circuit.
Figure 7 is a diagram of a fifth embodiment of a voltage protection circuit.
Figure 8 is a diagram of one embodiment of a voltage, current and thermal protection circuit.
Figure 9 is a second embodiment of a voltage, current and thermal protection circuit.
Figure 10 is a functional block diagram of the present invention.
Figure 11 is an embodiment of the circuit of the present invention.
Figure 12 is a further embodiment of the circuit of the present invention.
Figure 13 is an embodiment of the voltage, current and thermal protection circuit of the present invention.
Figure 14 is pictorial representation of a vertical cross section of a monolithic semiconductor chip embodying the present invention.

Figure 15 is pictorial representation of an overhead plan view of a monolithic semiconductor chip embodying the present invention.

DESCRIPTION OF PREFERRED EMBODIMENTS

Transistor operation in a forward active state is usually limited to a safe operating area ("SOA") that is defined in the collector voltage/collector current plane, an example as may be seen in Figure 1. Operation outside the SOA can result in transistor failure from high temperatures caused by excessive power dissipation.

With reference to Figure 1, the line A-B represents the upper limit of the transistor’s current carrying capability and the line B-C illustrates the basic thermal limitation associated with the maximum allowable junction temperature, i.e., the first breakdown condition. The line C-D-E illustrates the limit imposed by the second breakdown discussed below, and the line E-F is the collector-emitter breakdown voltage \( BV_{CEO} \), i.e., the maximum voltage that can be applied from the collector to the emitter with the transistor’s base open circuited (\( I_B = 0 \)). The invention in the copending application is directed to extending the SOA limits defined by the line C-D-E-F as suggested by dashed line C-G-H in Figure 1; that is, in the areas limited by second breakdown and the \( BV_{CEO} \).

The second breakdown limitation may be the result of several mechanisms. One mechanism is localized thermal run-away; that is, non-homogeneous current densities in the transistor that cause localized "hot spots". This mechanism can be controlled by keeping the current density uniform across the emitter. To this end, the transistor can be modified to include multiple emitters with small ballasting resistors.

The second mechanism, is related to a phenomena known as avalanche multiplication with reference to Figure 2. Figure 2, assumes transistor Q1 is operating with a collector current \( I_C \) that is much greater than an externally supplied base (biasing) current \( I_B \) and that the collector to base voltage \( V_{CB} \) is increasing. As the collector electrons pass through the collector-base depletion region, they gain energy from the electric field \( (V_{CB}) \). At some voltage, a few of the collector electrons have enough energy to generate electron-hole pairs when they collide with a lattice atom. The number of collector electrons that generate electron-hole pairs increases exponentially with the electric field as is shown in Equation (1) below.
\[ M \approx \exp \left( \frac{V_{ce} - K_1}{K_2} \right) \]

where \( K_1 \) and \( K_2 \) are constants dependent on the construction of the transistor, and where \( M \leq 1 \).

The generation of the electron-hole pairs causes the collector current to increase beyond that associated with the base current to the point of transistor failure.

Avalanche multiplication increases collector current in two ways, i.e., directly due to the new electrons, and indirectly due to the increase in base current from the new holes, assuming a constant external base current. In other words, the new electrons are added to the collector current \( I_c \) while the new holes go to the base and are added to the externally base current \( I_b \). At \( B V_{CEO} \), the component of base current generated by the new holes is sufficient to keep the transistor on without any base current from an external source. Above \( B V_{CEO} \), the base current \( I_b \) actually reverses direction from that shown in Figure 2. As may be seen in Figure 1, the situation where voltage is increasing and current is increasing (due to avalanche multiplication) will quickly drive transistor operation out of the SOA.

Nevertheless, situations exist where it is desirable to have a transistor that is able to operate outside of its traditional SOA to its \( B V_{CES} \) (or \( B V_{CEO} \)). For example, there are applications where a transistor is normally operating at voltages only slightly below its \( B V_{CEO} \) and there may be disturbances on the high voltage supply which would take the collector-emitter voltage of the transistor above \( B V_{CEO} \). The transistor may not have to supply full load current during such a disturbance, but it is desirable that the transistor survive. A transistor with this ability may be useful, for example, in a prior art high voltage linear voltage regulator such as illustrated in Figure 2.

A transistor can be operated at voltages above \( B V_{CEO} \) if its collector current is sensed and controlled. This may be accomplished by using a high voltage, voltage sensing element. However, unless the collector current is limited to a small value, the need to dissipate power from such an element will present space and/or heat problems. For example, a high voltage resistor divider network (or a combination of a resistor network and a Zener diode) could be used, but the area of the resistor would be quite large and would not likely find application in most integrated circuits where space is typically a major concern.

Figure 3 shows the detector circuit and method of the invention may be used to protect an NPN transistor Q1 at voltages above the transistor's \( B V_{CEO} \). A reverse current at the base of transistor Q1 may be detected with a suitable conventional sensor 30 and, in response to the sensed current, may be used to adjust an externally supplied base bias voltage, \( V_{BIAS} \).

The load 34 may have a fixed or variable impedance and may be connected to either the emitter or collector of transistor Q1. Similarly transistor Q1 may be any bipolar junction transistor (BJT), either

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PNP or NPN, and the circuit may be constructed as in integrated circuit or with discrete circuit components.

The adjustment of the externally supplied base bias voltage may, as shown in Figure 3, be made by adjusting the variable element 32 of a voltage divider network comprising elements 32 and 33 or by selectively tapping a single element (not shown). In a preferred embodiment, the impedance of element 32 may be infinite (an open circuit) to place the entire $V_{\text{BIAS}}$ on the base of the transistor Q1 in the absence of an overvoltage condition.

The SOA of a transistor may be extended by limiting the collector current because the second breakdown mechanism that defines a portion of the SOA limit (line C-D-E in Figure 1) is shifted to a higher voltage level (dashed line C-G in Figure 1.) The second breakdown limit is shifted in the invention in the copending application by reducing the external base current in the presence of internal base current to thereby limit the total base current.

By way of further explanation, total base current $I_B\text{ total}$ is the measurable terminal base current and has two components,

$$I_{B\text{ total}} = I_{B\text{ ext}} \cdot M I_c$$

where $I_{B\text{ ext}} = I_c/B_F$ and is related to the applied base-emitter voltage $V_{BE}$, and is thus the base current which flows through the base-emitter junction due to the external bias, and where $M$ is set forth in Equation (1) above and increases with increasing collector-base voltage, $V_{CB}$.

If $I_{B\text{ ext}}$ is fixed, an increase in $V_{CB}$ to the point that $I_{B\text{ total}}$ becomes negative indicates that the avalanche multiplication process has occurred and that the transistor will exceed its SOA limits, unless the avalanche is controlled. This detection may be used to provide an alarm, but may also be used as shown in Figure 3 to perform a control function and to protect the transistor.

The invention reduces $I_{B\text{ ext}}$ when $I_{B\text{ total}}$ reaches a predetermined negative value and the reduction in $I_{B\text{ ext}}$ will reduce the effects of avalanche multiplication. $I_{B\text{ ext}}$ may be reduced as required, and may even become negative so as to absorb the avalanche generated current. In this way, $I_c$ may be controlled and the transistor's SOA extended.

With reference again to Figure 3, the element 32 normally has a very high impedance (effectively does not conduct). When the sensor 30 senses a reverse base current above a predetermined value, the impedance of the element 32 is reduced to connect the external source of biasing voltage $V_{\text{BIAS}}$ to ground across the element, and the resulting voltage drop reduces the voltage at the base of transistor Q1 and thus the total base current $I_{B\text{ total}}$. In other words, the transistor Q1 can operate with voltages between its $BV_{CEO}$ and $BV_{CES}$ (or $BV_{CBO}$) by controlling the transistor base bias voltage to limit the total base current $I_{B\text{ total}}$.
of the transistor to a predetermined maximum value.

The variable impedance element 32 may conveniently take the form of a suitable convention semiconductor device such as the single NPN transistor Q2 illustrated in Figure 4.

The sensor 30 of Figure 3 is the detector. It may take various embodiments, with those adaptable to an integrated circuit being preferred. Such sensors desirably do not use excessive space and do not pose power dissipation problems that may be encountered with large resistors. By way of example, and with reference to Figure 4, sensor 30 may include a small resistive sensing element 40 and a source 42 of reference voltage as input signals to an error amplifier 44. The amplifier 44 provides an output signal when the voltage across element 40 related to a reverse base current equals the reference voltage provided by the source 42.

The output signal from the amplifier 44 is the output signal from the detector and may in turn be used to turn on transistor Q2. When transistor Q2 conducts, the externally applied base emitter voltage is connected to ground, thereby decreasing the total base current to transistor Q1 and providing overvoltage protection for the transistor Q1.

With reference to Figure 5, a second embodiment of the detector is illustrated in a high voltage, linear voltage regulator. In this embodiment, the voltage reference source 42 and amplifier 44 of Figure 4 are replaced with a single PNP transistor Q3, with the transistor Q2 turned on when the voltage across the sensor 40 related to the reverse base current is sufficient to cause the transistor Q3 to conduct and to provide an output signal at the collector thereof.

The output signal from the detector may also be used to protect the transistor by controlling the conduction of NPN transistor Q2, to thereby control the base bias voltage provided by a voltage divider network comprising resistors 33 and 35, the transistor Q1 and a Zener diode.

The sensing of reverse base current as a detector of high voltage may also be as shown in Figure 6 where a unidirectional circuit element such as a diode 60 allows biasing current to reach the base of transistor Q1 while blocking a reverse base current. The voltage drop across the diode 60 due to the reverse base current controls the conduction of transistor Q4 and is applied to a comparator 44. When the reverse base current exceeds the reference, the comparator 44 provides an output signal indicating that transistor Q1 is carrying a voltage that is about to exceed a specified limit, such as that defined by the SOA.

The voltage level to be detected must be above the $BV_{CEO}$ of the sensor transistor Q4 and the maximum applied voltage $V$ must be less than the $BV_{CES}$ of the transistor Q1.

As discussed above, this indication of an overvoltage condition may be used as is shown in Figure 6 to control the conduction of a transistor Q2 to provide overvoltage protection for the transistor Q1 by reducing the external base bias.
As shown in Figure 6, the transistor Q1 is biased with a current sink I1, which fixes the emitter and collector current passing through the load (not shown). The high voltage threshold may be adjusted upwardly by reducing the sensitivity of the amplifier 44, by adjusting the current sink I1 or the resistor R7, or by placing a Zener diode or other breakdown device in series with the collector of transistor Q1.

As shown in Figure 7, the output signal from the detector 30 may be applied as a control signal to the current sink I1 to provide protection for the transistor Q1.

A more complex high voltage linear regulator is shown in Figure 8 where protection for excessive voltage, current and heat is provided. As shown in Figure 8, the sensor 30 is responsive to the detection of a reverse base current as indicative of an excessive voltage across the transistor Q1. A suitable conventional load current sensor 46 may be located in the collector-emitter path of the transistor Q1 to detect an excessive current. A third sensor 48 may be used to detect excessive heat in the transistor Q1.

The thermal sensor may be used in the circuit illustrated in Figure 8 (as, for example, the sensor 48), which sensor need not be electrically connected to the transistor Q1 so long as it is in thermal communication therewith, e.g., connected to a common heat sink.

The output signals from each of the three sensors 30, 46 and 48 may be used to independently control the impedance of the element 32 to change the base bias voltage and thus the current through the transistor Q1 as earlier described in connection with Figures 3 - 7. This circuit is particularly advantageous when implemented in an integrated circuit, where the element 32 and each of the three sensors may be transistors.

Thus the transistor Q1 is protected against excessive voltage, current and heat, all operable through the control of a variable impedance which controls the base bias of the transistor.

The circuit of Figure 8 may be implemented by the circuit of Figure 9. With reference to Figure 9, where like elements have been accorded like numerical designations, a transistor Q1 to be protected is illustrated as parallel NPN transistors. It is to be understood that transistor Q1 in Figure 9, as in all other embodiments, may be any number of transistors ganged together in a conventional manner, typically to share the load current and thus spreading the heat. Other elements may also include multiple components.

In operation, the resistor 40 converts the reverse base current into a voltage signal compared in the error amplifier 44 with the threshold voltage across resistor 42. The output signal from the amplifier 44 is used to control the operation of the element 32. Because the reverse base current is proportional to the collector current and to the factor M which contains the collector-base voltage V_{CB} as an exponent (Equation 1), feedback can be used to control the base voltage and thus the collector current, i.e., the maximum reverse base current can be limited to a fixed value for all voltages between BV_{CBO} and BV_{CBO}.

Further, because the voltage dependent or avalanche current is being limited, response times are much
faster than available in a shutdown circuit.

As shown in Figure 9, a conventional band gap reference generator 52 provides a stable regulated voltage for the circuit. A bias circuit 33 provides an essentially constant current through the resistor 40 to the base of the transistor Q1. The circuit 33, together with the variable impedance provided by the transistor Q2, provide a voltage divider which controls the base bias voltage to the transistor Q1.

The current sensor 46 may include a resistor 50 in the emitter circuit of one of the transistors in Q1, here assumed to carry a known percentage of the total load current. As the current through the resistor 50 increases, the increase in the resultant voltage at the base of the transistor Q1 will cause conduction of the transistor Q1, which in turn causes a change in the output signal of the comparator 44 within the voltage sensor 30. This causes the conduction of the transistors QV and Q4, and ultimately transistor Q2 in the variable impedance element 32 to change the base bias of the transistor Q1.

The voltage sensor 30 of Figure 8 may take the form of the comparator 44 and is responsive to the comparison of the voltages across the resistors $R_s$ and $R_{REF}$ to provide an output signal to the base of transistor QV, the conduction of which reduces the base bias of the transistor Q1 by the conduction of the transistor Q2 as earlier described.

The thermal sensor 48 of Figure 8 is shown as the transistor QT in Figure 9 and may be located in communication with the transistor Q1 by a common heat sink or perhaps by physical location on a common semiconductor material in an integrated circuit. The transistor QT may be biased just short of conduction, and because of its temperature response characteristics, can be caused to conduct upon the detection of excessive heat in the transistor Q1. The conduction of transistor QT changes the output signal of the comparator 44 to cause the conduction of the transistor QV as described above, ultimately reducing the base bias of the transistor Q1 by the conduction of the transistor Q2.

In the thermal sensor of the present invention, a transistor provides a predictable output current $I_o$ when the transistor reaches a predetermined temperature. As is known, the relationship between output current and temperature of a transistor is determined from,

$$I_o = I_s \exp(-V_{be}/V_t)$$

(3)

where $I_s$ is saturation current that increases exponentially with temperature,

$V_{be}$ is the applied reference voltage, and

$V_t = kT/q$, where $k$ is Boltzman's constant, $T$ is absolute temperature, and $q$ is electron charge.

With reference now to Figure 10, the circuit 100 may include two transistors to sense temperature in a sensor 102. One transistor 104 may be located in thermal communication with the heat source 106,
such as by physically locating the transistor with the heat source or by placing the transistor and the heat source in thermal communication with a common heat sink. The other transistor 108 may be remote from the heat source 106 so that the thermal effect of the heat source is not as great as, or is delayed in time from, the effect on the first transistor 104. These two transistors are electrically connected so that together they provide an output signal indicative of the average temperature of two transistors. This average temperature is compared to a temperature-independent reference signal from source 110. If the comparison indicates an overtemperature condition, the circuit of the invention provides a signal 112 to a load reduction mechanism 114 in the linear regulator to reduce the external bias voltage.

An embodiment that may find application in the circuit of Figure 8 is illustrated in Figure 11. As seen therein, the first transistor 104 may be an NPN transistor having a common collector with heat generating NPN transistor Q1, and is in thermal communication with transistor Q1. The base of the first transistor 104 may be connected to the base of the transistor Q1 so that base-emitter voltage changes at transistor Q1 are also sensed by transistor 104. The second transistor 108 may be a PNP transistor having a common emitter with the first transistor 104. A voltage across Zener diode 114 that connects the base of the first transistor 104 to the collector of the second transistor 108 may be impressed across a parallel string of nichrome resistors 116-120 to provide a temperature independent reference signal.

In Figure 12, components have been identified with numbers corresponding to those in Figures 10 and 11. The transistors 104 and 108 provide a signal to transistor 122 that may operate to reduce or shutoff the load at transistor Q1 using transistor Q2 as illustrated or in conjunction with the base voltage limiting circuit of the copending application (not illustrated in the interest of clarity).

The reference voltage is given by the following:

$$V_{REF} = V_z \frac{R_{114}}{(R_{116} + R_{118} + R_{120})}$$

where $V_z$ is the Zener diode 114 voltage.

The circuit not only provides a signal to reduce the load to stop the overtemperature condition, but also provides a hysteresis function to prevent cycling. By way of further explanation, the collector current of transistor 108 (representing the average sensed temperature) is applied to bases of transistors 122 and 124 and is used to reduce the load. Transistor 124 provides a feedback for the reference voltage that latches the thermal protection mode on until the temperature decreases. The amount of feedback provided by transistor 124 is determined by driving transistor 124 into saturation. The feedback current $I_{thk}$ drawn through the reference setting resistor 126 is determined from:
\[ I_{404} \approx \frac{I_{ref} R_{120} V_{8124}}{R_{126}} \] (5)

This feedback causes an increase in the voltage reference, that in turn causes more drive to be applied to the bases of transistors 122 and 124, thereby latching them until released when the temperature decreases. The change in the reference voltage determines the temperature drop required before unlatching.

The temperature at which the present invention takes effect may be determined from the following:

\[ T - 273 = \frac{V_2 R_{116}}{R_{116} + R_{118} + R_{120}} \ln \left( \frac{\alpha_{108} I_{2108}^2}{\alpha_{104} I_{8104} I_{8108}} \right) \] (6)

where \( \alpha \) is the ratio of collector current to emitter current, subscript \( s \) denotes saturation current, and subscript \( c \) denotes collector current.

A further embodiment in a high voltage linear regulator is shown in Figure 13. With reference to Figure 13, where like elements have been accorded like numerical designations to facilitate a comparison with prior figures, a conventional band gap reference generator 52 provides 16 a stable regulated voltage for the circuit and a bias circuit 33 provides an essentially constant current through the resistor 40 to the load 34. The transistor Q1 is illustrated as two series connected transistors Q5 and Q6, and the conduction of the transistor Q5 is controlled, not by the base bias, but by the conduction of the transistor Q6.

The current sensor 46 may include a resistor 50 in the emitter circuit of the transistor Q6. As the current through the resistor 50 increases, the increase in the resultant voltage at the base of the transistor Q1 will cause conduction of the transistor Q1, which in turn decreases the base bias from the transistor Q6 and thus its conduction. Because they are series connected, a reduction in the conduction of the transistor Q6 reduces the conduction of the transistor Q5.

The thermal sensor 102 of the present invention is shown in communication with the transistor Q5. The transistors 104 and 108 may be biased just short of conduction, and because of their temperature response characteristics, can be caused to conduct upon the detection of excessive heat in the transistor Q5. The conduction of transistors 104 and 108 causes the conduction of the transistor 122 to reduce the base bias of the transistor Q6, thus reducing the conduction of the transistor Q5 as earlier described.
Figures 14-15, show a monolithic semiconductor regulator device 130. By way of example, Figures 14-15 illustrate the placement of a first thermal sensor 132 in a dielectrically isolated island 134 with a power device 136, and of a second thermal sensor 138 remote from the dielectrically isolated island 134 in the same monolithic chip. The dielectric 140 provides heat insulation, as well as electrical isolation, so that a power device 136 temperature increase sensed at the first sensor 132 is not sensed in its entirety by the second sensor 138 (or the arrival of the increase at the second sensor is at least delayed). The second sensor 138 will likely sense some of the temperature increase due to thermal conduction, albeit limited, through the chip 130. The first sensor 132 is preferably within the heat source less than about 3 mils from the power device 136, and the second sensor 138 is preferably outside the dielectrically isolated island 134 in which the power device 136 is located (e.g., spaced at least the thickness of dielectric 140, typically about one-half mil, from the island 134.)

In a preferred embodiment, one of the thermal sensors is a PNP transistor and the other is an NPN transistor. This arrangement reduces the variability of the circuit response that is otherwise inherent in the manufacturing process. That is, normal manufacturing processes are able to produce NPN transistors having a turn-on temperature in a predictable range (e.g., a Gaussian probability distribution with a known standard deviation), and to produce PNP transistors having a turn-on temperature in a different predictable range. When the two transistors are arranged as set forth in the present invention, the range of turn-on temperatures narrower than either one of the two transistors alone (e.g., a Gaussian probability distribution with a smaller standard deviation). This result increases the accuracy of the thermal protection circuit of the present invention over that achievable in the prior art by providing a narrower range of temperatures at which the circuits of the present invention are activated.

In an alternative embodiment and with reference again to Figure 13, the range of temperatures at which the circuit of the present invention turns on may be further narrowed by adding a diode 150 between the two transistors 104 and 108. The diode 150 has yet a third range of temperatures at which it turns on and this range may be used to advantage to further improve the predictability of temperature response in the present invention (e.g., by further reducing the standard distribution of turn-on temperatures).

A circuit and method for protecting a high voltage linear regulator from failure due to overheating, including a heat generating transistor in the regulator protected by limiting the collector current during operation above normal operating temperatures. Limiting the collector current reduces the heat generating load on the transistor and thus allows operation of the transistor at less than full capacity rather than allowing the transistor to catastrophically fail. The invention is applicable in an integrated circuit, which may be combined with circuits for the protection of a transistor against excessive current and over voltage.
WHAT IS CLAIMED IS:

1. A temperature sensor for a voltage regulator including two temperature sensitive elements, a first of said elements being in immediate thermal contact with a heat source in the voltage regulator to provide an immediate response and the second of said elements being in remote thermal contact with the heat source to provide a delayed response so that the effective response of the sensor to temperature variations in the source includes both short term and long term components, and in which said two temperature sensitive elements are semiconductor transistors.

2. A sensor as claimed in claim 1 wherein one of said transistors is a PNP transistor and the other of said transistor is an NPN transistor.

3. A sensor as claimed in claim 1 or 2 wherein one of said transistors is located in a dielectrically isolated island with the heat source and the other of said transistors is not and in which one of said transistors has a base connected to a base for the heat source so as to be responsive to bias variations in the base of the heat source and said two transistors have different temperature ranges at which they turn on and said sensor has a turn-on temperature range narrower than either of said two transistors.

4. A sensor as claimed in claim 3 including another semiconductor element connected to said transistors so that the range of turn-on temperatures is further narrowed.

5. A sensor as claimed in any of claims 1 to 4 including a diode electrically connecting the emitters of said two transistors, and said first temperature sensitive element and the heat source being transistors having a common collector.

6. The sensor of Claim 9 wherein second temperature sensitive element is a transistor having an emitter connector to an emitter of said first element.

7. An over temperature protection circuit for a semiconductor heat source in an dielectrically isolated island comprising a first temperature sensor located within said dielectrically isolated island; a second temperature sensor not located within said dielectrically isolated island, and means responsive to said first and second sensors for modifying conduction of the semiconductor heat source, with said first sensor and the heat source have a common terminal, in which, said first and second sensors are transistors of opposite conductivity types, and further comprising a diode connecting the emitters of said two sensors.

8. A circuit as claimed in claim 7 wherein said first sensor and the heat source are within about 3 mils, and said second sensor and the heat source no closer than about one-half mils, and incorporated within a linear voltage regulator.

9. A semiconductor circuit comprising a first electrically isolated island having first and second transistors therein, a second electrically isolated island having a third transistor therein, means electrically connecting said second and third transistors to modify the conduction of said first transistor, and
means for modifying a base current of said first transistor in response to detection of an overvoltage in said first transistor.

10. A temperature sensing circuit for a high voltage linear regulator, preferably for an integrated circuit device, having a heat source therein, the circuit comprising:

   a first transistor for sensing the temperature of the heat source and a second transistor for sensing a temperature remote from the heat source, said first and second transistors being electrically connected to provide a signal related to an average of the temperatures sensed by said first and second transistors;

   means for providing a predetermined temperature reference signal to which the average sensed temperature signal may be compared; and

   means for comparing the average sensed temperature signal to the temperature reference signal and for reducing the current to the heat source in response to that comparison.

11. A circuit as claimed in claim 10 wherein the heat source and said first transistor are in the same dielectrically isolated island, in which said means for providing a temperature reference comprises a plurality of resistive elements substantially in parallel with said first and second transistors, comprising diode means for electrically connecting emitters of said first and second transistors.

12. A circuit for protecting a heat generating transistor having collector and emitter currents responsive to a total base current that includes an externally supplied base current and a reverse base current comprising first means for detecting the existence of the reverse base current a thermal sensor comprising a first transistor for sensing a temperature of the heat generating transistor and a second transistor for sensing a temperature remote from the heat generating transistor, said first and second transistors being electrically connected to provide a signal related to an average of the temperatures sensed by said first and second transistors, second means for detecting a difference between the average sensed temperature and a predetermined temperature reference voltage, third means responsive to said first and second means for limiting the total base current by limiting the externally supplied base current, and a load current sensor for sensing one of the collector and emitter currents of the heat generating transistor, in which said third means is further responsive to said load current sensor.

13. A method of increasing the uniformity of the response of a sensor to variations in temperature comprising the steps of providing two semiconductor elements of opposite conductivity type each having an independent manufacturing distribution of its response to variations in temperature, connecting the two elements in the same circuit to provide a single response, and to protecting a heat source against an over temperature condition with the steps of locating a first temperature response element in immediate heat transfer relationship with the heat source to sense a high temperature condition, locating a second temperature responsive element in a delayed heat relationship with the heat source, controlling the conduction of the heat source as a function of the first and second temperature responsive elements.
FIG. 1

FIG. 2
FIG. 12
# INTERNATIONAL SEARCH REPORT

**A. CLASSIFICATION OF SUBJECT MATTER**

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<th>IPC</th>
<th>GO5F1/569</th>
<th>GO1K7/00</th>
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According to International Patent Classification (IPC) or to both national classification and IPC

**B. FIELDS SEARCHED**

Minimum documentation searched (classification system followed by classification symbols)

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<th>IPC</th>
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Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

**Electronic data base consulted during the international search (name of data base and, where practical, search terms used)**

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

<table>
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<th>Category</th>
<th>Citation of document, with indication, where appropriate, of the relevant passages</th>
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<td>A</td>
<td>EP A 0 523 798 (PHILIPS ELECTRONICS UK LIMITED) 20 January 1993 see column 12, line 22 - line 56; figures 6,7</td>
<td>1, 3, 7, 9, 10, 13, 14</td>
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<td>DE A 0 15 760 (SALZGITTER ELEKTRONIK GMBH) 19 November 1992 see column 3, line 9 - column 4, line 35; figure 1</td>
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<td>A</td>
<td>EP A 0 160 836 (ROBERT BOSCH GMBH) 13 November 1985 see page 6, line 1 - page 8, line 9; figures 2-5</td>
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- "A" document defining the general state of the art which is not considered to be of particular relevance
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- "&" document member of the same patent family

Date of the actual completion of the international search

23 September 1994

Date of mailing of the international search report

17. 10. 94

Name and mailing address of the ISA

European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk
Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax (+31-70) 340-3016

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Cleary, F

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<td>PROCEEDINGS OF THE IEEE 1989 CUSTOM INTEGRATED CIRCUITS CONFERENCE, 15 May 1989, SAN DIEGO, CALIFORNIA, US pages 2141 - 2144, XP000075566 VOGELSONG ET AL 'EXTENDING SPICE FOR ELECTRO-THERMAL SIMULATION' see page 2142, right column, line 35 - page 2143, left column, line 36; figures 2-5</td>
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